

The use of vision modelling to design bycatch reduction devices using light

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Abstract

Artificial light can be used to deter unwanted non-target catch (bycatch) from fishing gear, which is thought to be achieved by repelling bycatch, or highlighting escape routes on nets. To select for responses in bycatch species, light should (1) cause the bycatch species to avoid capture, and (2) not invoke the same reaction in target species. One way to maximise the chance of a bycatch species responding to light is to ensure the light colour used is more visible to bycatch species. Some studies have considered the visual sensitivity of certain species to address this. In particular, the wavebands of light that a species is sensitive to. However, using this measurement alone is incomplete as it does not consider other factors that affect visibility, such as the ambient light spectrum, and wavelength-dependant light attenuation in different water types and depths. To account for these variables, and to more accurately predict how both target and bycatch species view light colours in a fishing context, we used a model of the vision of commercially relevant species in fisheries across the world. From this, we show whether a light colour is more visible to a bycatch species compared to a target species in a particular depth and water type, and how modelling can be used to make informed assessments of the selection of relevant light colours in fishing. We also discuss the limitations of using vision models alone and the need for corresponding behaviour and/or fishing trials with lights.

KEYWORDS

artificial light, bycatch-mitigation, bycatch-reduction, vision model, visual ecology

1 | INTRODUCTION

Historically, light in fishing has been used to attract catch to nets, where records indicate that fishermen first used fire to attract fish to shallow waters (Arimoto et al., 2010). This exploits the natural behaviours of some marine organisms towards light within their environment (Melli et al., 2018), where natural sources of light can be an important cue for many biological and behavioural processes (Marangoni et al., 2022). For example, the mass movement of fish and plankton through the water column can be determined by light,

which is known as diel vertical migration (Berge et al., 2020). Light is also important in aiding visual cues for crucial behaviours such as mating and hunting (Maggi et al., 2020), as well as influencing spawning events in some marine taxa (Davies et al., 2023). As such, light is an essential part of the life cycles of marine species (Marangoni et al., 2022).

Research is now focusing on light use for manipulating the behaviour of bycatch species (non-target catch; Lewison et al., 2004) to enable them to avoid capture in nets, particularly for unwanted bycatch species that do not have commercial use (Nguyen &

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Winger, 2019). Laboratory experiments have shown that species can have varied responses to light colour modes; for example, in one study, European seabass (*Dicentrarchus labrax*) were repelled by green and blue light, whereas the common grey mullet (*Mugil cephalus*) were attracted to shorter-wavelength light (Ciriaco et al., 2003; Marchesan et al., 2005). Additionally, Chinook salmon (*Oncorhynchus tshawytscha*) showed an increased aversion to white light compared to blue light (Yochum et al., 2022), and Atlantic horse mackerel (*Trachurus trachurus*, Carangidae) have shown attraction to blue light (Sardo et al., 2020).

When applying lights to fishing gears, bycatch-reduction has been demonstrated with turtles, whitefish (haddock *Merlangius aeglefinus*, Gadidae and whiting *Merlangius merlangus*, Gadidae) and elasmobranchs (Bielli et al., 2020; Senko et al., 2022; Southworth et al., 2020; Wang et al., 2013). For example, in a gillnet fishery where turtles were regularly bycaught, researchers used UV LEDs (light-emitting diodes) to reduce green turtle (*Chelonia mydas*, Cheloniidae) bycatch (Wang et al., 2013). This was based on the knowledge that turtles had UV vision, whereas the target catch did not (Wang et al., 2013). Subsequently, there was a 39.7% reduction in green turtle bycatch whilst the target catch was unaffected, which was likely due to the increased visibility of the net to turtles (Wang et al., 2013). Other successful examples have occurred in trawl scenarios, where white LEDs added to an escape panel increased the reduction of undersized whiting bycatch, which was thought to be achieved by increasing the visibility of exit routes on the net (Southworth et al., 2020).

However, light may not be effective in all fisheries. For example, researchers found that when adding white and green light to the headrope of a trawl in an experimental trawling scenario, the catch rate of both target (deep water rose shrimp; *Parapenaeus longirostris*, Penaeidae) and undersized bycatch species (horse mackerel and European hake *Merluccius merluccius*, Gadidae) increased in the Mediterranean Sea (Geraci et al., 2021). In another study, researchers found no effect of light in separating bycatch fish from shellfish when placing green LEDs in upper and lower compartments of a trawl in the North Sea (Melli et al., 2018). Therefore, for bycatch-reduction with light to be successful, the target and bycatch species need to be simultaneously achieving desired behavioural responses towards light in a given fishing context. For example, target species need to be unaffected by/attracted to light, and bycatch species need to be attracted to an escape route on the net or, more easily able to see the net to avoid it.

To exploit these differences, researchers have previously concentrated on the spectral sensitivity of target and bycatch species (Utne-Palm et al., 2018), where spectral sensitivity is the wavebands of light that a species is sensitive to (van der Kooij et al., 2021). Specifically, marine vertebrates and invertebrates process light through specialised photoreceptor cells within the retinas of the eyes (Arimoto et al., 2010). For vertebrates, photoreceptor types include rods and cones, where rods process light in dim environments, and cones detect certain wavelengths of light in brightly lit habitats (Lythgoe & Partridge, 1989). Species with more

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than one cone type often, though not necessarily, have the ability to discriminate between parts of the light spectrum, or colour vision (Lythgoe & Partridge, 1989). Marine invertebrates possess either rhabdom or ciliary cells, which tend to have a smaller spectral range than cones (Cronin, 1986). In oceans and seas, as a general guide, visual adaptations are tuned to the light environment, such as different depths; for example, deep sea species are less likely to have colour vision due to the limited ambient light, and tend to have vision shifted towards shorter and medium wavelength 'blue-green' light due to a lack of longer-wavelength cone cells since longer wave light is absent in deeper water (Warrant & Lockett, 2004). By contrast, shallow living species are more exposed to sunlight and may therefore possess colour vision capabilities utilising several cone types with greater sensitivity to a wider range of wavelengths (Lythgoe & Partridge, 1989).

As well as photoreceptors, ocular media (e.g. the lens and other structures) within the eyes can act as filtering mechanisms by controlling light intake and are also often linked to ecology (Thorpe et al., 1993). For example, the lens can either allow or block UV from entering the retina (Thorpe et al., 1993). In coral reef fish species, researchers found that 49.8% of fish possessed ocular media that absorbed and blocked UV light (Siebeck & Marshall, 2001), where this mechanism has likely evolved to reduce damage from the increased levels of UV light in coral reefs (Siebeck & Marshall, 2001).

When considering how marine species might view light in a fishing context, the emitted light spectra from LEDs (or any

light-emitting device) also need to be quantified. Specifically, radiant light needs to be quantified, which is either a combination of reflectance and irradiance (ambient light spectra under certain conditions), or light directly produced by an object such as an LED (Endler, 1993). Additionally, background light will play a role in how an LED is viewed by marine species, which can change at different depths due to light attenuation (Lythgoe, 1988). For example, in a shallow ocean setting where ambient light availability is high, LEDs may contrast less against the background and therefore be less visible. By contrast, at greater depths with little ambient light, LEDs will have a greater contrast to the background. Additionally, oceanic, coastal and freshwater environments differentially absorb and transmit light, due to sediment and suspended particle types, which can affect the background colour of the water body (Jerlov, 1968; Lythgoe & Partridge, 1989). Therefore, an LED's contrast to the background may change depending on water type and/or depth.

A model that exists in order to quantify how animals might view an object against a background is a quantum-catch model (Lagorio, 2012). These models predict how many light units (photons) are absorbed by an animal's photoreceptor(s) cells, based on the animal's photoreceptor types and sensitivity, and the radiant light arriving from an object in an environment (Endler, 1991). In the marine environment, quantum-catch models have been used to determine whether fish visual adaptations can be linked to their habitats (Hárosi, 1996; Wilkins et al., 2016). As of yet, they have not been applied to fishing with light.

As vision alone does not consider how light attenuates in an ocean environment, or how contrasting an LED is against a given ocean background, we aimed to quantify how different coloured lights might be viewed in ocean contexts to target and bycatch species, by using a quantum-catch model. From this, we discuss how LEDs could potentially be trialled as a bycatch-reduction device (BRD; Brewer et al., 1998) in four example fisheries.

2 | MATERIALS AND METHODS

2.1 | LEDs

For LED radiance, we used a product called *Pisces* (SafetyNet Technologies) which is a circular waterproof LED that is specifically designed to fit on fishing gear at depths of up to 250 m. *Pisces* has the possibility of different colour modes (Figure 1), where we included seven different options in our model. LED radiances were measured in dark conditions from a distance of 50 cm in air, using spectroradiometer JETI specbos 1211-2, to produce spectral curves across the visible light spectrum (300–700 nm) for each LED colour mode.

2.2 | Ocean backgrounds

Water bodies have previously been categorised into several broad types by Jerlov (1968), which were based on their background irradiances. Water types were either coastal or open ocean, each with differing levels of turbidity and thus background colour (Jerlov, 1968). Jerlov (1968) quantified irradiances of global water bodies from direct measurements, by using a photometer with different optical filters to measure light availability at various depths (Williamson & Hollins, 2022). The classifications have since expanded to consider additional water parameters and greater depths for more accurate under water irradiance values (Williamson & Hollins, 2022).

To account for different background conditions in the model, we used the irradiances of two different ocean types at several depths, to ascertain how LEDs might be viewed against them. We used data extracted from Sticklus et al. (2018) using Graphreader, which is a free online graph extractor programme (Larson, 2022), where data were replotted (Figure 2) using the statistical programme R (R Core Team, 2021) and R package 'ggplot2' (Wickham, 2016). The data are based on Jerlov's (1968) quantifications of a clear ocean (JIB) and

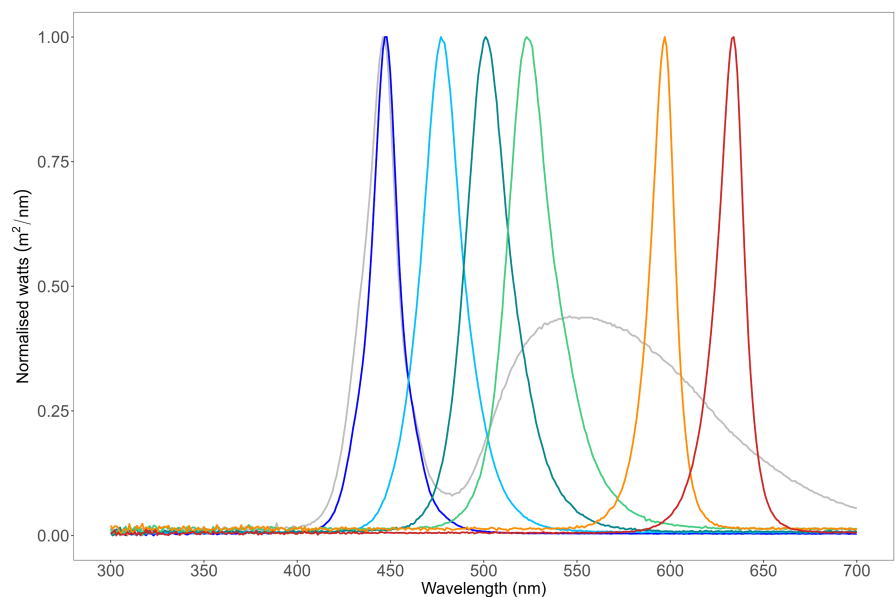


FIGURE 1 Light emission spectra for seven different colour modes of SafetyNet Technologies' LED *Pisces*. The peak wavelength are as follows: White, 456 nm; Royal blue, 447 nm; Blue, 471 nm; Cyan, 499 nm; Green, 518 nm; Amber, 592 nm; Red, 627 nm.

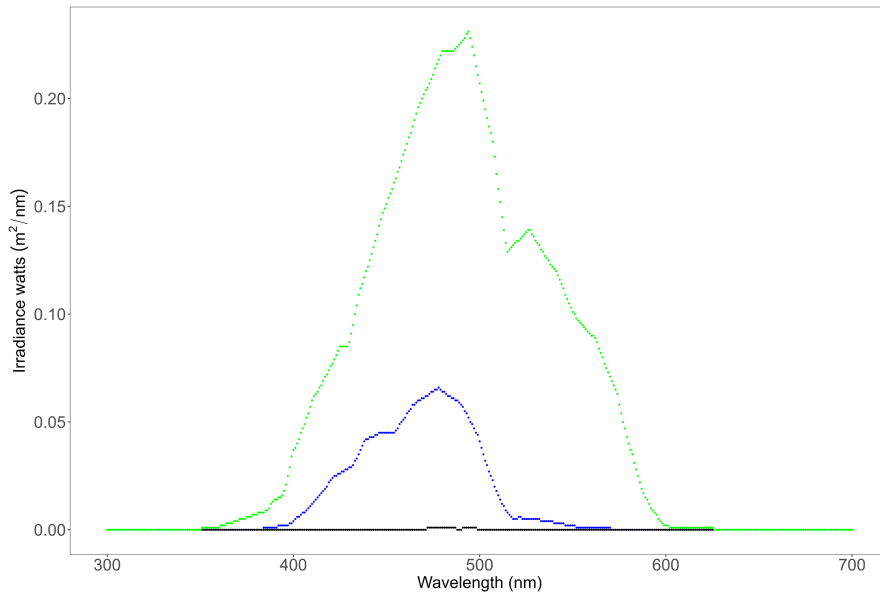


FIGURE 2 Ocean irradiance data, based on Jerlov's (1968) ocean-type classifications across the visible light spectrum. The green dots represent ocean type III at 20m depth, which has the highest irradiance values. The blue dots represent the clearest ocean-type IB at 100m depth, which shows that some ambient light is still available at this depth. By contrast, the black dots represent ocean type III at 100m, which is the most turbid ocean type and hence there is less ambient light due to absorption by suspended particles.

a slightly more turbid ocean (JIII), with the additional consideration of absorption and scattering properties of each water type (Sticklus et al., 2018). The data were derived from measurements made in clear sky conditions, with the sun at zenith angle at 30° (Sticklus et al., 2018).

2.3 | Vision modelling

To assess how target and bycatch species view different light colours in ocean contexts, we quantified the potential visibility of LEDs using the following equation:

$$Q_c = \int_{300}^{700} I(\lambda) A_c(\lambda) d(\lambda)$$

where Q_c is the summed photoreceptor quantum-catch for the background, or each LED colour mode. Q_c is calculated from the normalised product of photoreceptor sensitivity type c of an animal $A_c(\lambda)$ (derived from the product of ocular media transmission and photoreceptor sensitivity at every 1 nm interval) and the normalised irradiance of each ocean background or LED colour mode radiance $I(\lambda)$, integrated in 1 nm intervals across the spectrum $d(\lambda)$ (300–700 nm). Thorpe et al. (1993) lens transmission categories or direct lens measurements from the literature (Nelson et al., 2003) were used for ocular media. Photoreceptor sensitivity curves were generated from inputting peak photoreceptor sensitivities into the Govardovskii et al. (2000) visual pigment template model. This widely used pigment model is a mathematical equation that generates standardised photoreceptor sensitivity curves from peak sensitivity values of a photoreceptor (λ_{max}) where the full spectral sensitivity curve has not been directly measured.

To understand how visible each LED colour mode is against the ocean background (background contrast), we defined the model output as 'visual stimulation', which was calculated using the following equation (Crothers & Cummings, 2013),

$$\text{Visual stimulation} = \frac{\left(\frac{\sum Q_c (\text{light colour})}{\sum Q_c (\text{ocean background})} \right)}{n(c)}$$

where the output is the ratio of the predicted total number of photons reaching the eye of the animal, combined across all receptor types, for the specific LED Q_c against the ocean background spectrum Q_c , and divided by the number of photoreceptor types $n(c)$ that an animal possesses. Therefore, the model produces a measure that predicts how stimulated the visual system of a species is when viewing an LED colour mode of *Pisces* in a particular ocean context from irradiance data (Figures 1 and 2). However, the model does not tell us how a species will react to the light (e.g. if they will be attracted or repelled). For full quantum-catch modelling methodology, see Endler and Mickle (2005) and Stevens et al. (2009) and Data Availability Statement.

Photoreceptor sensitivity and ocular media information were based on available information from the literature (see Data Availability Statement—*Bycatch and target species vision data.xlsx*). Ocular media transmission curves were also extracted from the literature using Graphreader (Larson, 2022). Where ocular media information was unavailable in the literature, closely related species were used instead. For invertebrates, photoreceptor sensitivity curves were used due to the lack of ommatidium (ocular media in invertebrates) information in the literature. For three out of eight species used in the model, ocular media and/or photoreceptor sensitivity information was obtained from juvenile species (see specific case studies below and Data Availability Statement).

3 | RESULTS

Here we have applied the model to four example bycatch issues around the world, where light could be considered as a potential BRD. Model outputs show the visual stimulation values of species,

and whether the bycatch or target species is more stimulated by light colours. We discuss how to consider the appropriate light colour modes to trial in fishing with light from the model outputs.

4 | CASE STUDIES

4.1 | Case study 1—Eastern Bering Alaska Pollock fishery

Target: Alaska pollock (*Gadus chalcogrammus*, Gadidae)

Bycatch: Chinook salmon (*Oncorhynchus tshawytscha*, Salmonidae)

Waters: Bering Sea, North Pacific

Depth: 100m and greater (Fissel et al., 2013)

Gear type: Pelagic trawl nets (Ianelli & Stram, 2015)

Chinook salmon are taken as bycatch in the Alaska pollock fishery (Ianelli & Stram, 2015). From the year 2000, there were marked declines in salmon runs in western Alaska, compared to runs from the previous 20 years (Witherell et al., 2002). As 40% of global whitefish are

produced from the Eastern Bering Pollock fishery (Fissel et al., 2013), there has since been pressure to greatly reduce salmon bycatch.

Chinook salmon have three cone cell sensitivities of 434, 510 and 565 nm, and a rod cell sensitivity of 508 nm, meaning they are trichromatic (Flamarique, 2005). By contrast, Alaska pollock have a peak sensitivity of 498 nm (Beatty, 1969). Salmon are therefore likely to be more sensitive to longer-wavelengths than pollock, which have medium-wavelength sensitivity (Figure 3a).

For the visual model output, in both clear and turbid ocean conditions in the typical fishing depths of 100 m, salmon is more visually stimulated by light than pollock for all colour modes apart from blue and cyan in clean oceans (Figure 3b). In general, both species are more visually stimulated in more turbid oceans, as there is less ambient light and therefore, the LEDs are more contrasted against the background. Both species are least stimulated by red light, and most visually stimulated by white light. However, white light provides the biggest difference in visual stimulation values between both species, with salmon being much more stimulated. We would therefore recommend trialling white light. It may also be worthwhile avoiding blue and cyan light, as both fish are similarly

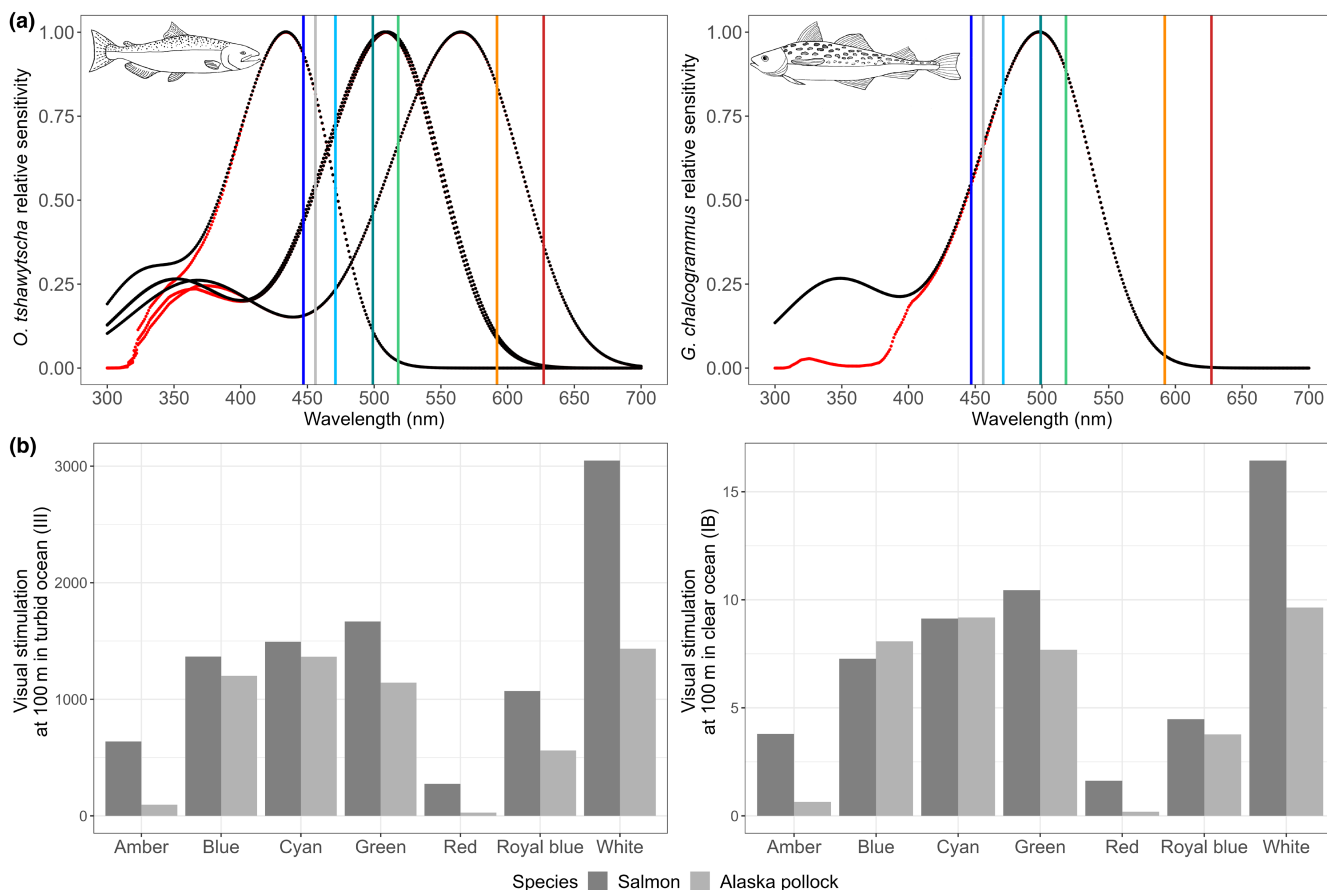


FIGURE 3 (a) Photoreceptor sensitivities for Alaska pollock (left) and Chinook salmon (right). The black curves represent the photoreceptor sensitivities of each species, and the red curves represent the inclusion of ocular media sensitivity, where both indicate reduced sensitivity to shorter wavelengths of light. The vertical lines represent the peak wavelength (nm) of each colour mode of the *Pisces* LED. (b) The visual model output for each LED colour mode against two different ocean backgrounds. The x axis is each LED colour mode, and the y axis is a prediction of how visually stimulated a species would be when viewing that colour mode in a particular ocean condition.

stimulated by these colours, which could lead to similar behaviour, although this would need to be tested.

4.2 | Case study 2—Scottish Nephrops mixed demersal fishery

Target: Nephrops (*Nephrops norvegicus*, Nephropidae)

Bycatch: Undersized cod (*Gadus morhua*, Gadidae)

Waters: North Sea, Atlantic Ocean

Depth: 100m (Cosgrove et al., 2019)

Gear type: Single and/or Multi-rig trawls (Cosgrove et al., 2019)

Nephrops are shellfish which had the highest value across all landed species from EU demersal trawls in 2010, with a value of €322M (Cosgrove et al., 2019). Nephrops mixed fisheries can also legally land whitefish like haddock, cod and whiting. However, size selectivity on gears can be an issue, where undersized whitefish below minimum conservation reference size (MCRS; European Parliament, 2019) are often bycaught (Catchpole & Revill, 2008; Cosgrove et al., 2019). As such, escape panels on nets have been

used to allow undersized fish such as cod to escape (Catchpole & Revill, 2008; Palder et al., 2023).

In terms of vision, Nephrops have rhabdom with a peak sensitivity of 515 nm (Johnson et al., 2002). To our knowledge, juvenile cod photoreceptors have not yet been anatomically measured. However, a genomic analysis revealed that cod of all life stages express SWS2 and RH2 cone opsins, which are visual pigment types that indicate a sensitivity to blue and green parts of the visible light spectrum respectively (Valen et al., 2014). This is in line with the two cone cell sensitivities of 446 and 517 nm which were measured in adult cod (Bowmaker, 1990). The genomic study also found that larval and juvenile cod are likely to express three medium-wavelength cone opsin subtypes (RH2 types), whereas adults possess one. This suggests that juveniles are more sensitive to medium-wavelength light, which is likely due to them frequenting greater depths than adults, where there is less light available (Valen et al., 2014). When comparing cod vision to Nephrops, cod are likely to have an additional shorter-wavelength sensitivity.

For the model output, at 100m depth in turbid ocean (III), cod is more visually stimulated by royal blue, and slightly more stimulated by white and blue light compared to Nephrops (Figure 4b). In clear

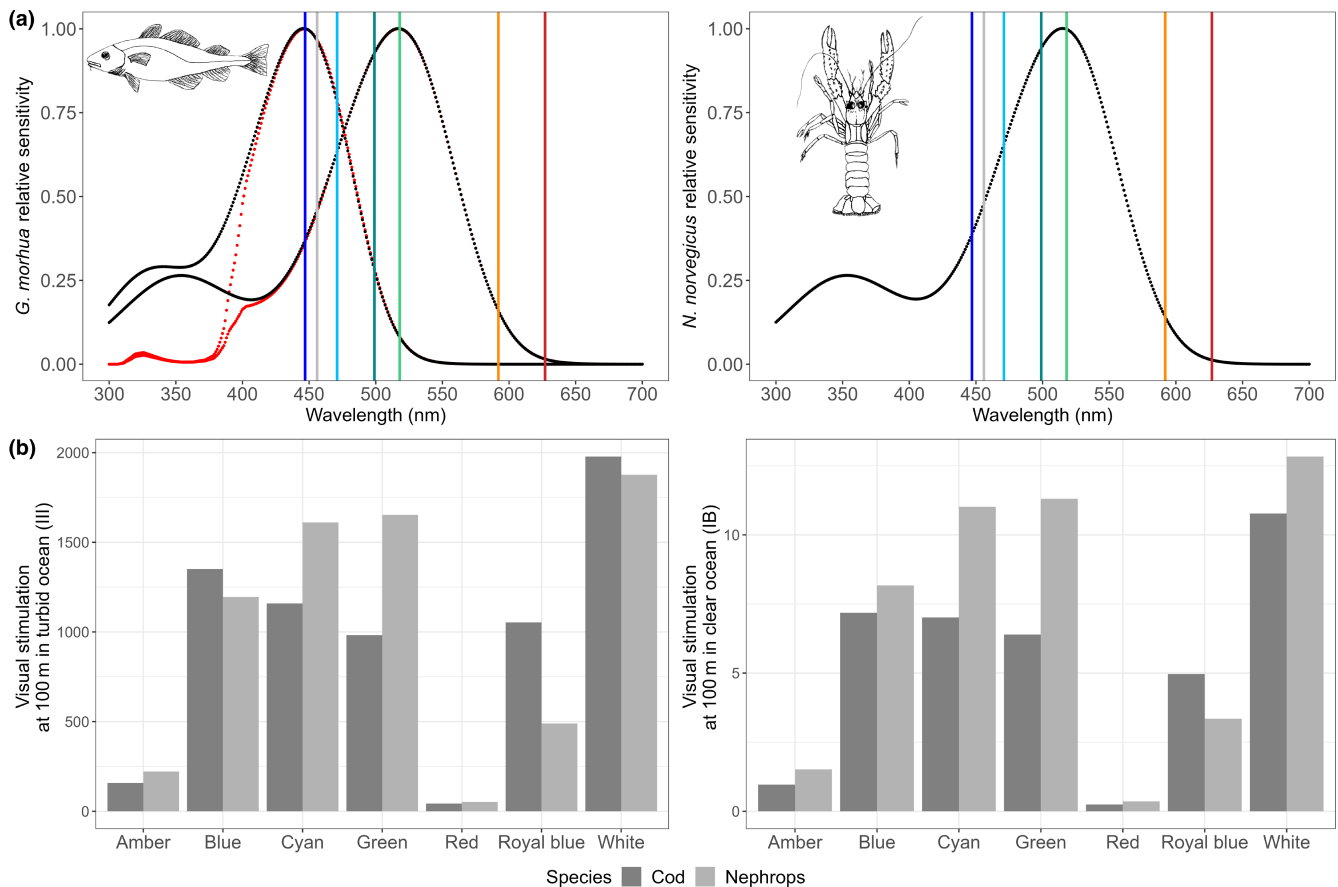


FIGURE 4 (a) Photoreceptor sensitivities for Nephrops (left) and cod (right). The black lines represent the photoreceptor sensitivities of each species, and the red curve represents the inclusion of ocular media sensitivity for cod, which indicates a reduced sensitivity to shorter wavelengths of light. The vertical lines represent the peak wavelength (nm) of each colour mode of *Pisces*. (b) The visual model output for each LED colour mode against two different ocean backgrounds. The x axis is each LED colour mode, and the y axis is a prediction of how visually stimulated a species would be when viewing that colour mode in a particular ocean condition.

ocean at the same depth, Nephrops become more stimulated by all colour modes apart from royal blue. In particular, white becomes more visible to Nephrops compared to cod, with the reverse effect in turbid waters. However, visual stimulation decreases for both species in clearer conditions, due to more ambient light availability. Therefore, for fishing gears that catch Nephrops and also use an escape panel to reduce the capture of MCRS cod, we recommend using white light to reduce undersized cod bycatch, as although it is also highly stimulating for Nephrops (and more stimulating to them in clear conditions) the selectivity panel should not allow for Nephrops' escape. If the gear type cannot guarantee Nephrops' containment, then royal blue light could be trialled, as there is a greater difference in visual stimulation values between both species, which is consistent across both turbid and clear waters.

4.3 | Case study 3—Portuguese trammel net mixed fishery

Target: Common sole (*Solea solea*, Soleidae)

Bycatch: Thornback ray (*Raja clavata*, Rajidae)

Waters: Atlantic Ocean

Depth: 10–100m (Baeta et al., 2010),

Gear type: Trammel net

The trammel net mixed fisheries in Portugal are mainly artisanal, where the main target species are flatfish such as common sole (Baeta et al., 2010). Other target species can include cuttlefish (*Sepia officinalis*, Sepiidae; Batista et al., 2009). A prominent bycatch issue within this fishery is elasmobranchs such as skate species, which can be caught in nets between 10 and 100m depths across seasons (Baeta et al., 2010). Although some individuals can be retained for commercial use, closed seasons have been implemented for skates, as well as a ban on the capture of undersized individuals (Silva et al., 2021). We chose to use thornback ray to represent skate in this case study, which is based on its prominence in the fishery (Baeta et al., 2010) and the availability of vision data in the literature. We modelled vision within depths of 20 and 50m to represent this fishery.

In terms of vision, common sole has two medium-wavelength sensitivity peaks of 523 and 536 nm, a shorter peak of 472 nm and a longer-wavelength peak of 559 nm, as well as a rod cell sensitivity of 511 nm (Frau et al., 2020), which was based on measurements of

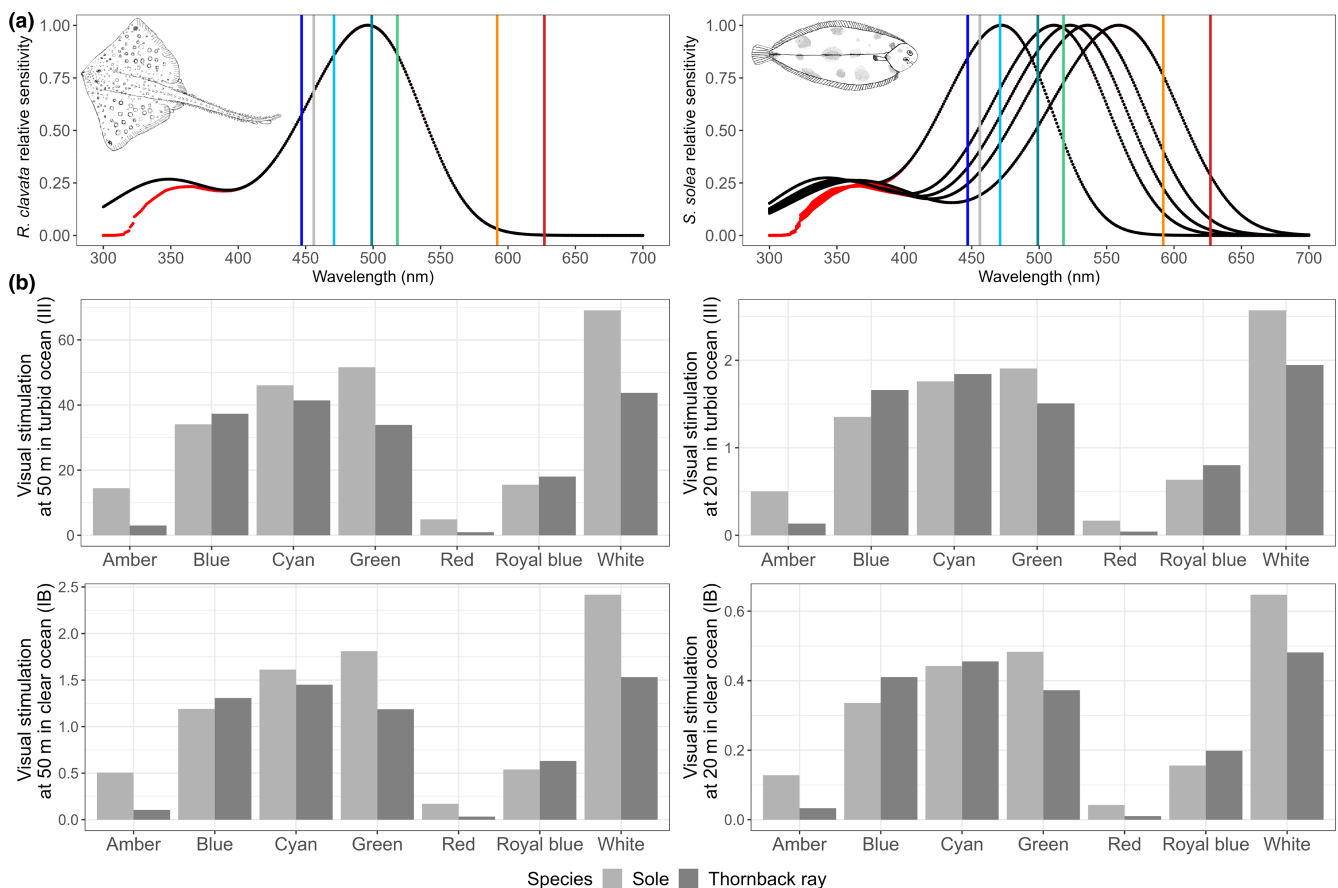


FIGURE 5 (a) Photoreceptor sensitivities for thornback ray (left) and common sole (right). The black lines represent the photoreceptor sensitivities of each species, and the red curve represents the inclusion of ocular media sensitivity, which indicates a reduced sensitivity to shorter wavelengths of light for both species. The vertical lines represent the peak wavelength (nm) of each colour mode of *Pisces*. (b) The visual model output for each LED colour mode against two different ocean types, where the top row is 50 and 20m depth in turbid ocean, and the bottom row is 50 and 20m depth in clear ocean.

juvenile sole. Thornback ray, on the other hand, has one rod sensitivity peak of 496 nm (Govardovskii & Lychakov, 1977; Figure 5a). It is worth noting that the size of the skate used for this photoreceptor measurement remains unknown. Therefore, it remains unknown whether possible differences in vision exist between juveniles and adults, although *Raja* species are thought to have mainly rod-dominated retina with sensitivity to medium-wavelength light (Ripps & Dowling, 1990).

For the model output, at 50 m depth, sole is slightly more visually stimulated by all colour modes apart from royal blue and blue in both ocean types. At 20 m depth, the pattern is the same except that thornback ray is slightly more stimulated by cyan in both ocean types. For both species, visual stimulation values are higher at 50 m depth due to less ambient light, and white and red are the most and least visually stimulating colour modes, respectively, for all ocean types and depths. For the colour modes where thornback ray has higher visual stimulation values, blue or royal blue may be the best options to trial as there is a greater difference to the comparable outputs for sole, but only slightly. LEDs may be more effective to trial at 50 m depth or greater due to generally higher stimulation values.

4.4 | Case study 4—Brazilian longline tuna fishery

Target: Yellowfin tuna (*Thunnus albacares*)

Bycatch: Scalloped hammerhead shark (*Sphyrna lewini*)

Waters: Atlantic Ocean

Depth: 100 m (Bezerra et al., 2016)

Gear type: Longline

Longline fisheries are one of the main contributors to shark bycatch globally, where longlines can target tuna and swordfish (Bezerra et al., 2016). Of the shark bycatch, hammerheads (*Sphyrna* spp.) are classified as endangered under the International Union for the Conservation of Nature (IUCN; Bezerra et al., 2016).

In terms of vision, yellowfin tuna have peak cone sensitivities of 426 and 485 nm, with a rod sensitivity of 482 nm (Loew et al., 2002). Scalloped hammerheads (measured from a juvenile) have a cone sensitivity peak of 530 nm (McComb et al., 2010), suggesting that hammerheads are more adapted to viewing medium-wavelength light, compared to the shorter-wavelength sensitivity of tuna (Figure 6a).

For the model output, at 100 m depth, the hammerhead is more stimulated by six out of seven colour modes for both ocean types,

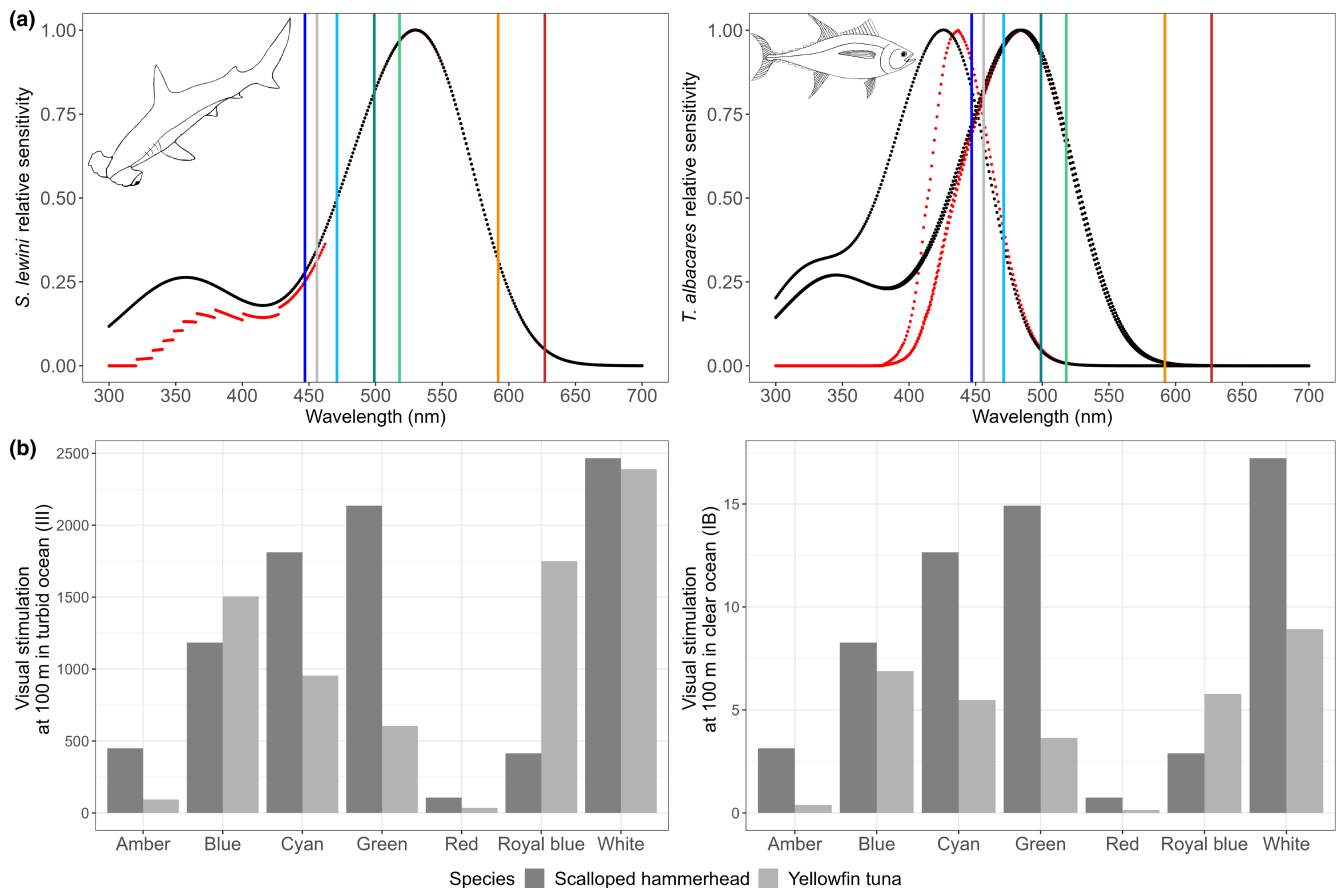


FIGURE 6 (a) Photoreceptor sensitivities for scalloped hammerhead (left) and yellowfin tuna (right). The black lines represent the photoreceptor sensitivities of each species, and the red curve represents the inclusion of ocular media sensitivity, which indicates a reduced sensitivity to shorter wavelengths of light for both species, with quite a pronounced shift for tuna. Note that the tuna ocular media information was based on juvenile lens transmission (Thorpe et al., 1993). The vertical lines represent the peak wavelength (nm) of each colour mode of *Pisces*. (b) The visual model output for each LED colour mode against two different ocean backgrounds.

but tuna is more stimulated by royal blue. This suggests that medium to long-wavelength modes are more suited to hammerheads in both ocean types. The biggest difference between hammerheads and tuna is the green light, which could therefore be the best option to trial on longlines.

5 | DISCUSSION

We used a vision model in the form of a quantum-catch model, to explore how commercially relevant species might view LEDs in different fishing conditions, to help assess the visibility of light as a BRD. The model predicts that target and bycatch species are differentially stimulated by light colour modes across different fishing contexts and that values can change across depth and water type.

In terms of general trends, white light was the most visually stimulating colour mode for all target and bycatch species, which is likely due to the broader spectrum that white light covers compared to the other monochromatic LEDs. As such, white light is likely to excite a broader range of photoreceptors, but may not be the best choice for selective fishing for some gears, since it would be most visible to both target and bycatch species. By contrast, red light was the least visually stimulating for all species. As red light attenuates with depth, red becomes less of a prominent colour in deep oceans (Johnsen, 2012; Marshall, 2017). Hence, many marine species do not possess longer-wavelength photoreceptor cells (Marshall, 2017). Instead, shorter-wavelength photoreceptors are more prominent, as blue light can transmit to greater depths (Johnsen, 2012; Marshall, 2017). This is reflected in the model outputs, where longer-wavelength colour modes tend to be less visually stimulating.

Visual stimulation values were also lower in shallow and clear ocean conditions, which is likely due to higher background light levels. The irradiance data used in this model are derived from Jerlov's (1968) quantifications, which were measured when the sun was directly overhead at a fixed time point (Sticklus et al., 2018). However, the irradiance in the sea during fishing will fluctuate as cloud cover and sun position changes. Therefore, having darker ambient light conditions compared to the measurements we used are likely to only increase visual stimulation values for all colour modes, where the LEDs become more greatly contrasted to the background. Future models could look at considering real-time irradiance data, to get a more accurate model output.

The model also assumes that animals are a fixed distance from the LEDs, which is based on the distance that the light was measured with the spectroradiometer (50cm in a dark room). The LED colours were also measured in air, which does not take horizontal water attenuation into account. However, previous models have found that attenuation can occur after 3–4m for red colours, and 15–20m for blue (Zhou et al., 2022). In most fishing scenarios, animals are also likely to be very close to LEDs on nets, and so it was assumed that all light from the LEDs reached the eyes of species within 50cm. However, further models could explore horizontal attenuation, especially for predicting when marine species are able to first notice an LED on fishing gear in

different water conditions, which may be more applicable to passive gear types where fish are not contained in a moving net.

In terms of vision, developmental changes can occur from juvenile to adult fish (Carleton et al., 2020). For example, in flounders, juveniles have visual pigments with shorter-wavelength sensitivity, which is lost in the adults and then replaced with longer-wavelength sensitivity (Savelli et al., 2018). This is likely due to a movement towards deeper waters and away from shallow nursery grounds as juveniles develop into adults (Savelli et al., 2018; Siebeck & Marshall, 2007), although this is not the case for cod as previously mentioned (Valen et al., 2014). With regards to tuna, hammerhead and sole, juvenile vision information was used, which was based on the availability of visual adaptations in the literature. Therefore, the model output for these species may not be as accurate if fisheries are looking to effect adult bycatch species with light. This also applies to the case studies where we used adult vision data when juvenile information was lacking, or where the size of species was unknown.

For our case study examples, we only looked at one target and bycatch species respectively. However, it is often the case that fisheries target and/or want to avoid multiple species, such as in Case studies 2 and 3 (Batista et al., 2009; Catchpole & Reville, 2008; Palder et al., 2023). The model can still be applied to multiple species, but it may be harder to ascertain an optimal light colour that can select between multiple species. Therefore, we only considered the main target and bycatch species for ease of application.

From our results, hypotheses should be explored around the model output and behavioural responses. For example, research could explore whether light colour modes that are more visible to species can cause greater behavioural responses, which could be easily observed and quantified in a controlled tank setting (Sardo et al., 2020; Yochum et al., 2022). However, these behaviours may not be comparable to a fishing context, as other sensory stimuli during fishing could affect and override any responses to light that were exhibited in a laboratory such as vessel noise, turbidity and stress (De Robertis & Handegard, 2013; Heard et al., 2014; Utne-Palm, 1999).

Additionally, the behaviour of marine species can vary in passive versus active gears (Diaz Pauli et al., 2015; Wilson et al., 2011). For example, in trawls, if a bycatch species is already in the net, an escape response could be induced by adding light to an escape panel (Lomeli & Wakefield, 2019; Southworth et al., 2020). This could be applied to Case study 2 with undersized cod, but would not work for species that are too large to fit through escape panels. An alternative method could be to add light to the headrope or footrope of a trawl, which has previously been shown to reduce bycatch (Hannah et al., 2015; Lomeli et al., 2018). However, whether the bycatch species are swimming out of the nets after capture, or avoid initial capture in the trawl remains unknown. Although some studies have previously deployed cameras to assess the general behaviour of species within trawl scenarios (Abangan et al., 2023; Fakioglu et al., 2022), direct observations with cameras can be difficult to obtain due to low light availability and harsh conditions during trawling (Rose et al., 2005). For fishing with light trials, a video camera

has previously been deployed in a trawl, where footage showed Chinook salmon exiting a net via an illuminated escape panel (Lomeli & Wakefield, 2012, 2019). With camera hardware improvements, as well as the development of A.I. (Artificial Intelligence) behavioural analyses of fish in nets (Abangan et al., 2023), the deployment of cameras is likely to be more widespread in future trials. This will be valuable for assessing behavioural responses to light in fishing, and for understanding optimal light placement in trawls.

For passive gear types such as gill nets, the bycatch species would need to exhibit an avoidance response towards lights on the net, before being caught. Light would therefore need to function by increasing the visibility of the net, or acting as a deterrent itself. However, caution may be needed, as like previously mentioned, light can be an attractant to marine species (Nguyen & Winger, 2019). In Case studies 3 and 4, where both examples have passive gear types, previous knowledge of light-mediated behaviour may be useful here in order to determine whether elasmobranchs are attracted to light. However, several studies have found that elasmobranch bycatch is reduced when static gears are illuminated, which suggests a net-avoidance response (Bielli et al., 2020; Senko et al., 2022).

If there is no prior light-mediated behaviour available for species, an alternative method may be to investigate the physiology and ecology of the target and bycatch species, where differences have previously been exploited to improve catch selectivity with BRDs (Glass, 2000; Yu et al., 2023). For example, gridded escape panels on nets have been successful in reducing flatfish bycatch whilst maintaining roundfish catch, due to the body shape of flatfish (Yu et al., 2023). Additionally, differences in swim speeds of target and bycatch species can be utilised when positioning BRDs on nets, to allow for bycatch escapement or avoidance (Breen et al., 2004; Broadhurst & Millar, 2023; He, 1993; Ryer, 2008).

By contrast, if target and bycatch species have similar physiology and ecology, light could invoke similar reactions. For example, in Case study 3, both flatfish and skate are bottom-dwelling, sedentary species, and often bury for camouflage when threatened (Gilman, 2019; Hammerschlag et al., 2017; Spinner et al., 2016). Hence, if both species perceive light as a threat and bury in sediment, this could lead to a loss of target catch (flatfish) within a passive fishing scenario, whereas in a bottom-trawling scenario, it may lead to an increase in bycatch (skate) if the gear makes contact with the seabed.

With the use of the model, our study's main aim was to quantify the vision of both target and bycatch species when viewing different coloured LEDs underwater. From this, we propose further behavioural testing and fishing trials based on the model predictions, to optimise bycatch-reduction and target catch-maintenance with lights. In all circumstances, once vision, behaviour and fishing gears have been considered, it may still be the case that light is not a useful bycatch reducing tool for certain fisheries, and other bycatch-reduction methods should be considered.

AUTHOR CONTRIBUTIONS

JS conceptualised the study, conducted investigation, wrote the original draft, developed the methodology and acquired the data. JB and

MS supervised the study, reviewed and edited the manuscript and contributed to conceptualisation, visualisation and methodology.

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CONFLICT OF INTEREST STATEMENT

The work was funded by the University of Exeter and SafetyNet Technologies as part of the first author's PhD. SafetyNet Technologies manufacture the LED product (*Pisces*) used in this research.

DATA AVAILABILITY STATEMENT

Data for model components can be accessed here: <https://github.com/j-somerville/Light-Vision-Model>

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