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Species separation efficiency and effect of artificial lights with a horizonal grid in the Basque bottom trawl fishery

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ABSTRACT

Achieving effective size selectivity for different species within a fishing gear is a major challenge in mixed fisheries. Fish behaviour may be exploited to separate species into separate codends where different selective properties can then be applied. Within the Basque bottom trawl fishery such a set-up has never been tested despite species with different behaviours being present. In this study, we investigate if species separation can be achieved through the use of a horizontal grid, where species typically found close to the seabed are intended to pass through the horizontal grid into the lower codend, while maintaining other species in an upper codend. Furthermore, the effect of artificial light on grid passage probability was estimated. Results were obtained for five fish species of commercial interest in the Basque bottom trawl fishery. Less than 25% of the

individuals of all species analysed passed through the grid and were retained in the lower codend, and no significant differences were found when the grid was illuminated. The specific conditions under which the Basque bottom trawl fishery is conducted, i.e., high turbidity levels, high towing speed, may have influenced the performance of the gear in this fishery. Consequently, the design was found to have limited potential to improve species and size selection in the Basque bottom trawl fishery.

1. INTRODUCTION

During the last decade, many new trawl designs have been developed in an attempt to improve selectivity in commercial fisheries i.e., reduce the bycatch of unwanted species while maintaining high catch efficiency for the target species and sizes (Kennelly and Broadhurst, 2021). Selectivity in fishing gears is generally governed by a sorting process that has both a mechanical and a behavioural component (Broadhurst, 2000). The mechanical part is determined by whether or not a fish can physically pass through the selective device (e.g. netting meshes or spaces between bars in a grid), whereas the behavioural part determines how fish distribute inside the trawl gear and their reaction to specific selection devices. Research on fish behaviour relative to selectivity of fishing gears flourished in the 80s and 90s and has increased substantially in recent years (e.g. Campbell et al., 2010; Ferro et al., 2007; ICES, 2019, 2021; Krag et al., 2009a, 2014, 2017; Løkkeborg et al., 2010; Madsen et al., 2006; Melli et al., 2018, 2019). Research has shown that an understanding of fish behaviour facilitates the development of more efficient species or size selective trawl gears (Løkkeborg et al., 2010; Wardle, 1986).

The catch process by which fish enter and are retained in a trawl involves a complex sequence of events and corresponding fish behaviours (Winger et al., 2010). During the catch process, fish behaviour can differ in the pre-trawl zone, between trawl doors and trawl mouth, and inside the trawl and the codend. These differences have previously been used to select different fish species and sizes (Fryer et al., 2017; Krag et al., 2009b; Løkkeborg et al., 2010; Melli et al., 2018). In particular, species specific differences in vertical distribution inside the trawl have been used to reduce unwanted catches, i.e. by separating species that enter the gear low down from species that distribute themselves higher in the gear (Fryer et al., 2017; Karlsen et al., 2019; Krag et al., 2009a, 2009b; Larsen et al., 2021). Karlsen et al., (2015) for example, separated fish from Norway lobster (*Nephrops norvegicus*) using a horizontally divided codend and by encouraging fish to swim upwards with a frame at the entrance of the lower codend.

The Basque bottom trawl multispecies fishery includes more than 100 different species (Rochet et al., 2014). Hake (*Merluccius merluccius*), megrim (*Lepidorhombus* spp.) and anglerfish

(*Lophius* spp.) are main target species whereas horse mackerel (*Trachurus trachurus*), mackerel (*Scomber scombrus*) or blue whiting (*Micromesistius poutassou*) are important as choke species (Schrope, 2010). In between some of these fish species distinct behaviours inside trawl gear have been documented. Previous studies have revealed that hake tends to swim close to the lower netting in the trawl and is more likely to pass through devices placed in the lower panel than the top panel (Cuende et al., 2020a, 2020b). Similarly, megrim, like most flatfish, enter the trawl close to the seabed and remain there (Main and Sangster, 1982, 1981; Ryer, 2008; Thomsen, 1993). On the other hand, horse mackerel, mackerel and blue whiting, distribute more uniformly and show a more active swimming behaviour inside the trawl gear (Cuende et al., 2020a, 2020b). Thus, the range of behaviours in this fishery highlight its potential for bycatch and target species separation.

In this study we aim to separate species that typically enter the trawl gear close to the seabed (hake and megrim) from those distributed more uniformly within the trawl (horse mackerel, mackerel and blue whiting). While hake and megrim are target species throughout the whole year, horse mackerel, mackerel and blue whiting are usually considered target or bycatch species depending on their quota availability and market preferences (Rochet et al., 2014). Therefore, the effective separation of these species through a modified gear design would allow subsequent size selectivity processes to be applied to the relevant species groups and could support fishers to maintain target catch while releasing by-catch. It was proposed that a passage section inserted in the lower panel in the aft of the trawl would facilitate the access of those species swimming close to the lower panel (e.g. hake and megrim) to an additional lower codend. Contrary, those species with a more uniform distribution in the gear would continue to the upper codend. The separation of the different fish species would allow more specific size selectivity processes to be applied in the different codends.

The diversity of morphologies present in this fishery requires a passage suitable both for flat- and roundfish species. Since square meshes are more suited for the release of roundfish rather than flatfish due to fish morphology (Halliday et al., 1999; Robertson, 1989; Walsh et al., 1992), a horizontal passage section with rectangular gaps (with a grid-like shape) was used, as it is better suited for the passage of both targeted roundfish and flatfish species. However, these gaps were oriented longitudinally to the trawl body, which may reduce flatfish escape chances since they may not allow the body shape of flatfish to pass in natural swimming orientation (Herrmann et al., 2013). Therefore, to compensate and maximize its possibilities to pass through the passage section, wide bar-spacing was provided.

The passage device (hereafter referred to as grid) also provides a rigid structure that facilitates the attachment of devices such as lights and maintain the shape of the escape gaps. Previous studies have shown that artificial lights can improve the selective properties of trawl gears for some species (e.g. Hannah et al., 2015; Lomeli et al., 2018; Lomeli and Wakefield, 2019; O'Neill and Summerbell, 2019). Melli et al., (2018) confirmed their potential as behavioural stimulators and their role in vertical separation efficiency. Therefore, in this study we aim to test the effect of artificial light, with a wavelength of 450nm (visible as blue) on species separation when attached on the grid.

The present study was designed to answer the following research questions:

1) Can a horizontal grid be used for species separation?
2) Is fish passage probability through the grid species- and/or length-dependent?
3) Can artificial light be utilised to improve fish passage through a grid into the lower codend?

2. MATERIAL AND METHODS

2.1. Gear design

Sea trials were carried out on board the commercial fishing vessel Kalamendi (43m length overall; 900 Kw) from 28 June to 4 July 2021. The fishing was carried out in ICES division 8a (Fig. 1). Towing occurred during day and night, at depths that varied between 89 and 124 m and towing speed over ground ranged from 3.9 to 4.2 knots. Each tow lasted 2.5 hours approximately, counting from when the vessel reached a constant towing speed to the beginning of gear hauling-back.

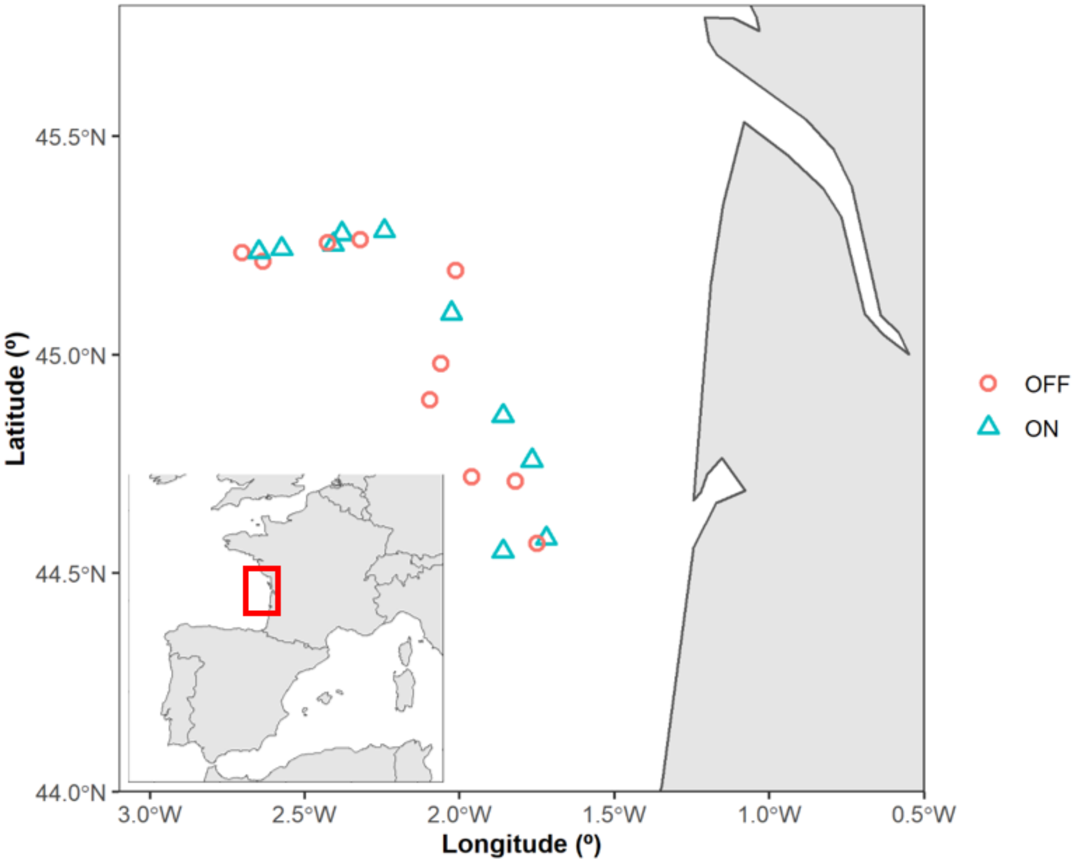

Figure 1.- Sampling area and fishing position for all hauls conducted during the cruise. Red circles represent hauls with lights switched off and blue triangles with lights switched on.

The gear used in the experiments was a two-panel bottom trawl with a 120 m long fishing line. The trawl was rigged with a set of Morgère doors (Morgère EXOCET EX07 type, 3.84 m^2; 988 Kg each), 385 m sweeps, and a light rockhopper ground gear (with 400 Kg chain).

The trawl configuration tested was attached to the aft part, just behind the body of the trawl net and was composed by three sections (Fig. 2). The trawl configuration tested an 80 mm two-panel netting section split into two compartments (i.e. upper and lower extension and codend) with an 80 mm horizontal separator panel that kept both extensions separated (Fig. 2). This section was made of 76.5 meshes long x 120 meshes round and constructed of 4 mm single PE twine (Fig. 2).

Ahead of this section, a guiding panel was installed forcing fish to swim into the upper extension and over the horizontal separator panel where a grid (described below) was installed, just below the main flow of fish. For fish to end up in the lower compartment they need to pass through the grid (Fig. 2). The horizontal separation contained an internal supporting hoop (internal radius 78 cm) to keep the netting spread (Fig. 2 and 3c).

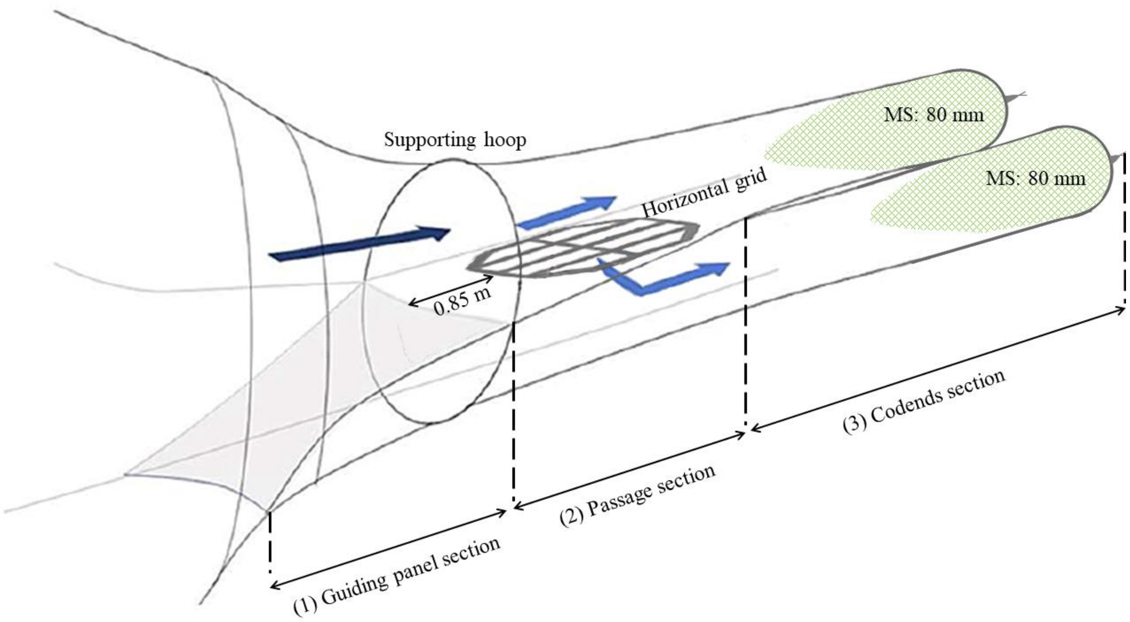

Figure 2.- Gear diagram and specification of different sections. MS: mesh size.

The grid in the passage section was designed as an octagon with rectangular gaps (Fig. 3a). The grid was 25 mm thick high-density polyurethane with dimensions 1.20 m x 0.75 m. It had a horizontal bar dividing the grid in half and vertical bars on both halves at 0.145 m apart (to permit passage of legal sizes of all species under study). The grid was placed 0.85 m after the end of the guiding panel (Fig. 2).

The fishery studied here allows the use of a 100 mm codend mesh size or a 70 mm codend mesh size together with a 100 mm square mesh panel (SMP). The sea trials were carried out on commercial fishing grounds where catch of large-sized target individuals was expected. Therefore, as compromise between the mandatory codend mesh sizes and to ease the fishing operation onboard (by fishing smaller bulks), the upper and lower codends were made of 80 mm nominal mesh size. The upper codend was made of 4 mm single twine, 120 meshes round, 73 meshes long, and had an average mesh size of 81.75 (± 2.57 SD) mm. The lower codend was made of 4 mm single twine, 120 meshes round, 102 meshes long (longer than upper codend to facilitate the fishing operation) and had a mesh size of 81.25 (± 1.97 SD) mm (Fig. 3b). Both codends were rigged with 160 mm mesh size lifting/strengthening bags 17 meshes long x 30 meshes width constructed from 5 mm double PE twine.

The light source used to illuminate the grid was a 20 m long multi-strand side-emitting fibre optic cable, connected to a laser diode pod (LDP) at each end (SafetyNet Technologies Ltd) (Fig. 3de). Each of the two LDP emit coherent light from a laser diode at a wavelength of 450 nm, at 340 mW of optical power and were powered by an external 12V Li-Ion battery pack (Fig. 3d). Since lower wavelengths of the visible spectrum are faster absorbed than higher wavelengths, a 450 nm wavelength (visible as blue light) was selected for the experiments in this study (Carleton et al., 2020). Additionally, this may allow comparison of results with Cuende et al., (2020a) (Fig. 3f). We used a single trawl with the grid illuminated (hereafter treatment design) and without illumination (hereafter baseline design) in an alternating order.

Turbidity levels inside the gear were measured during trawling in every haul, as recommended by the International Council for the Exploration of the Sea (ICES) to improve comparability of results between light studies (ICES, 2018). Turbidity was measured with a Seapoint turbidity meter and recorded by an Aquatec AQUAlogger 210 series Data Logger (Fig. 3g). Underwater recordings were conducted when the artificial lights attached on the grid were switched on. By synchronising video camera and turbidity logger recording timers, we aimed to associate turbidity measures to specific video frames. Since the turbidity meter was positioned ~ 1.5 meter from the video camera, we calculated the mean turbidity (±SD) of each video frame by accounting on the 5 seconds before and after the targeted video frame. Besides, quantiles Q10, Q25, Q50, Q75 and Q90 were calculated to estimate the towing time percentage (10%, 25%, 50%, 75% and 90%) during which the turbidity did not exceed a certain level.

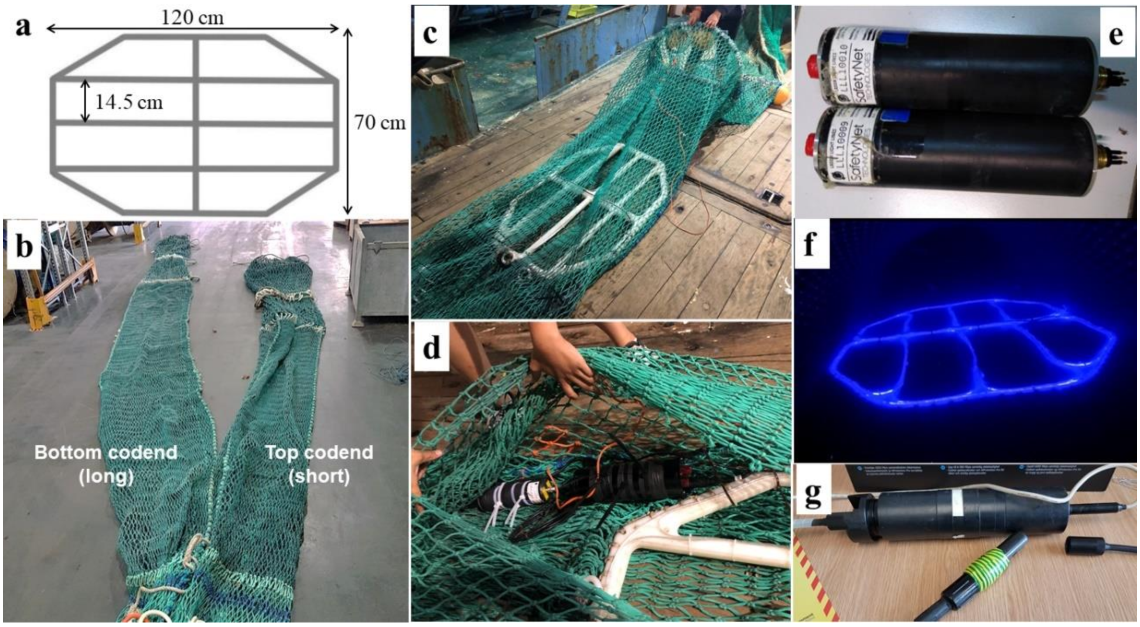

Figure 3.- (a) Technical characteristics of the grid used; (b) Gear picture, the grid and upper (short) and lower (long) codends are shown; (c) passage section and the internal supporting hoop; (d) battery housing and LDP attached to the gear; (e) LDPs; (f) underwater picture of the illuminated grid and (g) turbidity sensor.

The species included in the data analysis were hake, megrim, anglerfish, horse mackerel and mackerel due to their importance as target and bycatch species. Despite being an important species for the fishery, blue whiting was not included in the study because there were not enough catches. After each haul, all the catch in upper and lower codends was sorted by species and all individuals were measured to the nearest centimetre using a measuring board.

2.2. Modelling the length-dependent probability for capture in the lower codend

Previous studies working with behaviour-based selectivity have shown a size-dependent entry pattern of fish in trawls (Karlsen et al., 2019; Melli et al., 2018). Therefore, we conducted an analysis to determine for each species the length-dependent probability for being captured in the lower codend conditioned capture $PL(l)$, i.e., the probability for passage through the grid. We used the numbers and length measurements of the fish caught in upper and lower codend, respectively. The analysis was carried out independently for each species and gear configurations (with and without the LDP turned on) following the description below.

The expected probability for a fish of length l to be captured in the lower codend will be:

$$PL_l = \frac{\sum_{j=1}^{h} nL_{lj}}{\sum_{j=1}^{h}\{nL_{lj}+nU_{lj}\}} \qquad (1)$$

where nL_{lj} and nU_{lj} are the number n of fish of the species investigated caught per length class l in respectively, lower (L) and upper (U) codend in haul j and h is the total number of hauls with the specific gear configuration. The functional description of the capture probability in the lower codend was obtained using maximum likelihood estimation by minimising Equation (2):

$$-\sum_{j=1}^{h}\sum_{l}\{nL_{lj} \times ln[PL(l,\boldsymbol{v})] + nU_{lj} \times ln[1.0 - PL(l,\boldsymbol{v})]\} \qquad (2)$$

In Equation (2), $\boldsymbol{v}$ represents the parameters describing the capture probability curve defined by $PL(l,\boldsymbol{v})$, that spans the value range [0.0;1.0]. Equation (1) and (2) together is similar in form to what is often used for modelling and estimating the length-dependent catch comparison rate between two fishing gears (Krag et al., 2014). Therefore, we adapted the same approach for modelling $PL(l,\boldsymbol{v})$ as is often applied for catch comparison studies based on binominal count data (Herrmann et al., 2017):

$$PL(l,\boldsymbol{v}) = \frac{exp[f(l,v_0,\ldots,v_k)]}{1+exp[f(l,v_0,\ldots,v_k)]} \qquad (3)$$

In Equation (3), f is a polynomial of order k with coefficients $v_0 - v_k$, so that $\boldsymbol{v} = (v_0,\ldots,v_k)$. The values of the parameters $\boldsymbol{v}$ describing $PL(l,\boldsymbol{v})$ are estimated by minimising Equation (2). We considered f of up to an order of 4. Leaving out one or more of the parameters $v_0 \ldots v_4$, at a time resulted in 31 additional candidate models for the capture probability function $PL(l,\boldsymbol{v})$. Among these models, the capture probability was estimated using multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017). The ability of the combined model to describe the experimental data was based on the p-value, which is calculated based on the model deviance and degrees of freedom (Herrmann et al., 2017; Wileman et al., 1996). This p-value quantifies the probability to obtain at least as big a discrepancy between the fitted model and experimental data as observed by coincidence. For the applied model to describe the experimental data at an acceptable level, this p-value should be > 0.05 (see Wileman et al., 1996). We used a double bootstrapping method (1000 bootstrap repetitions) to estimate the 95% confident intervals (CIs) for the capture probability curve following the description in (Lomeli et al., 2019).

The average probability of being retained in the lower codend integrating the Minimum Conservation Reference Size (MCRS), $PL_{average}$, was quantified by calculating the values for a number of indicators. Specifically, based on the population size structure caught during the trials, the average value for the capture probability in the lower codend of individuals below MCRS (PL_{-}), above MCRS (PL_{+}) and of the total catch (PL_{total}) were estimated:

$$PL_{average} = \frac{\sum_l \sum_{j=1}^{h} nL_{lj}}{\sum_l \sum_{j=1}^{h} \{nL_{lj} + nU_{lj}\}} \qquad (4)$$

where the outer summations include the size classes in the catch during the experimental fishing period. The equation (4) used, both summed-over undersized fish (PL_{-}), target sized fish (PL_{+}) and all fish (PL_{total}), respectively. In contrast to the length-dependent evaluation of the capture probability curve for the lower codend $PL(l, \boldsymbol{v})$, $PL_{average}$ is specific for the population structure encountered during the experimental trials and cannot be extrapolated to other scenarios in which the size structure of the specific fish species may be different. The MCRS values for each species were: hake: 27 cm; megrim: 20 cm; horse mackerel: 15 cm; and mackerel 20 cm. Anglerfish has a minimum marketable weight of 500 gr (without guts) per individual (EC, 1996), which is equivalent to 32 cm length according to Dorel (1986). We used the statistical software SELNET (Herrmann et al., 2012) to analyse the catch data and ggplot2 (Wickham, 2016) for graphical output in R statistical software (R, 2021).

2.3. Inferring the effect of artificial light on probability for capture in the lower codend

The difference in $PL(l, \boldsymbol{v})$ between using treatment and baseline designs was obtained species-wise by estimating the difference in the probability of ending up in the lower codend between treatment and baseline designs ($\Delta PL(l) = PL_{light}(l) - PL_{base}(l)$). Where $PL_{base}(l)$ and $PL_{light}(l)$ represent $PL(l, \boldsymbol{v})$ obtained by using (3) in (2) for two different gear configurations compared. 95% CIs for $\Delta PL(l)$ was obtained based on the two bootstrap populations for both $PL_{light}(l)$ and $PL_{base}(l)$ by the method described in Larsen et al., (2018).

3. RESULTS

3.1. Overview of sea trials

A total of 20 valid hauls were conducted, 10 hauls with the baseline design and 10 hauls with the treatment design. Sufficient data for analysis were collected for hake, megrim, anglerfish, horse mackerel and mackerel, although some species were not present in all hauls (Table 1). In total, 24,008 individuals comprising all species were included in the analysis, from which 20,343 entered the upper codend while 3,665 individuals went through the grid and ended up in the lower codend. Although most individuals entered the upper compartment, the level of separation differed among the species (Table 1).

Table 1.- Overview of the hauls conducted during the experimental sea trials and the numbers of hake, anglerfish, megrim, horse mackerel and mackerel in the upper (*nU*) and lower (*nL*) codends.

Haul no.	Light	Depth (m)	Tow starting time	Tow ending time	Hake		Anglerfish		Megrim		Horse mackerel		Mackerel	
					nU	*nL*	*nU*	*nL*	*nU*	*nL*	*nU*	*nL*	*nU*	*nL*
1	ON	102.8	8:20	10:20	171	88	118	4	95	7	837	78	81	0
2	OFF	102.8	11:00	13:30	234	48	-	-	115	10	750	98	84	13
3	ON	102.0	14:10	16:40	292	67	74	4	103	12	1603	163	23	0
4	OFF	112.8	17:20	19:50	241	35	90	10	221	28	824	137	244	4
5	OFF	115.4	0:25	2:55	255	58	102	17	76	16	25	8	-	-
6	ON	116.2	3:50	6:20	155	31	116	29	84	16	75	6	6	1
7	OFF	109.5	10:45	13:30	559	100	53	8	200	43	2126	326	73	3
8	ON	90.3	14:10	16:30	310	113	54	13	134	64	475	181	15	1
9	ON	114.5	21:15	23:45	147	30	135	56	186	46	387	67	27	1
10	OFF	111.2	0:35	3:05	82	29	160	80	131	65	-	-	-	-
11	OFF	117.0	7:45	10:15	350	60	124	19	396	138	440	48	111	1
12	ON	106.2	11:05	13:35	-	-	96	32	-	-	598	63	94	0
13	ON	112.8	22:15	0:45	63	11	180	44	190	48	12	7	-	-
14	OFF	112.0	1:35	4:05	114	12	190	27	213	19	-	-	-	-
15	OFF	109.5	8:55	11:25	370	111	93	20	270	82	398	78	16	0
16	ON	109.5	12:10	14:40	339	90	117	29	272	101	346	61	25	1
17	ON	92.8	20:05	22:35	246	59	69	12	156	51	150	16	9	0
18	OFF	92.8	23:25	1:55	179	26	82	11	53	21	30	11	-	-
19	ON	98.6	20:15	22:45	218	47	110	17	85	13	577	38	194	2
20	OFF	99.5	23:35	2:05	209	11	103	9	108	5	-	-	-	-

Underwater recordings of the light on the grid were not visible from the video camera for long periods while towing, this was due to the sediment resuspension and high presence of invertebrates in the area. Figure 4 shows low turbidity levels in video frames with a clear view of the illuminated grid (e.g., 3.09±0.28 FTU) whereas a high turbidity level occurred in video frames where the illuminated grid is not visible (e.g., 58.17 ± 14.39 FTU). Considering turbidity values in every haul, Table 2 shows that, for most hauls, 90% of the towing time the values were above 100 FTU, significantly higher than the value in the dark frame in Figure 4.

Table 2.- Quantiles (10, 25, 50, 75 and 90) of the turbidity data (FTU) registered during each haul. Shadowed rows correspond to hauls with baseline design.

Haul nº	Q10	Q25	Q50	Q75	Q90
1	39.77	85.01	133.31	185.15	236.50
2	105.69	131.28	147.42	170.92	196.10
3	66.63	92.42	119.19	143.84	175.08
4	66.36	92.38	170.86	416.86	527.87
5	312.40	369.40	426.28	482.59	528.60
6	318.89	370.13	441.92	499.86	558.84
7	113.11	141.78	177.43	221.47	276.21
8	94.55	131.21	171.78	213.38	254.09
9	114.27	144.13	187.71	247.06	294.37
10	167.41	194.08	226.92	268.78	326.61
11	169.42	216.24	271.31	341.10	406.17
12	101.79	130.32	157.40	186.68	218.91
13	151.85	242.36	379.68	486.25	547.63
14	193.13	275.15	350.17	495.06	630.67
15	172.67	201.52	248.15	310.54	364.53
16	193.50	241.52	315.02	446.46	528.32
17	120.45	153.53	187.61	231.16	305.21
18	170.31	207.95	254.69	349.53	432.96
19	99.05	137.15	276.49	405.16	470.23
20	158.10	188.74	233.06	284.75	330.87

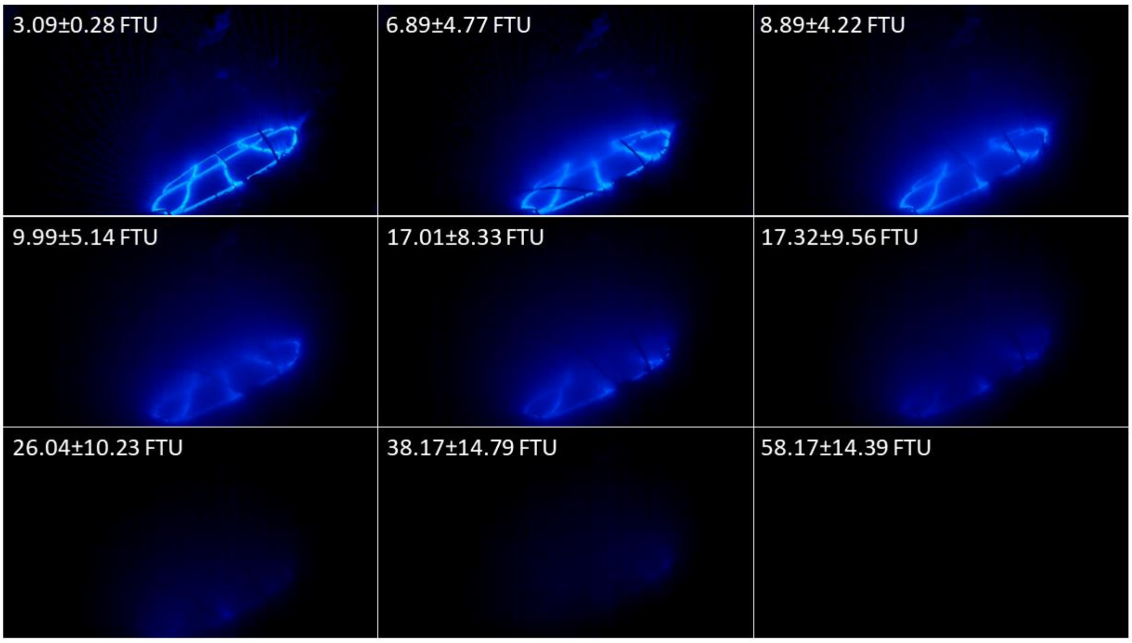

Figure 4.- Underwater video captures during an illuminated haul. Each video frame shows the associated turbidity mean value (±SD) given by the turbidity meter.

3.2. Passage probability into lower codend

Estimation of the passage probability into the lower codend was conducted fitting the combined model to the experimental data. The fit statistics for the model show that, in most cases, *p*-values were > 0.05, meaning that the applied model describes the experimental data at an acceptable level (Table 3). Only the model for megrim on the treatment design had poor fit statistics (*p*-value < 0.05, deviance >> DOF), for which the residual deviations between the data and the modelled curves were investigated. No systematic structure was detected, and the low *p*-value was considered a consequence of overdispersion in the data. Therefore, we were confident that the model could also be used for megrim to describe the length-dependent probability to be captured in the lower codend.

Table 3.- Fit statistics for the modelled grid passage probabilities of the experiments with the light switched on or off. DOF denotes the degrees of freedom and was calculated by subtracting the number of model parameters from the number of length classes in the dataset. *p*-values marked

with * show the cases where the residual variation between the models fit and the experimental data required further investigation.

Species	Light	p-Value	Deviance	DOF
Hake	OFF	0.1270	62.65	51
	ON	0.7583	39.92	47
Anglerfish	OFF	0.8995	35.97	48
	ON	0.6814	43.85	49
Megrim	OFF	0.5751	30.84	33
	ON	0.0179*	43.31	26
Horse mackerel	OFF	0.3326	25.35	23
	ON	0.3605	17.40	16
Mackerel	OFF	0.6078	10.09	12
	ON	0.7866	8.82	13

The catch comparison curves described well the experimental data, especially for some length classes (Fig. 5 and 6). For the lengths where fewer individuals were caught, the certainty to explain the experimental data decreased, as shown by the increasing size of the confidence intervals. The catch comparison analysis show that the probability for being retained in the lower codend is significantly lower than in the upper codend for all species using both the baseline (Fig. 5) and treatment design (Fig. 6). In general, the probability of passing through the grid tends to decrease for larger individuals of all species.

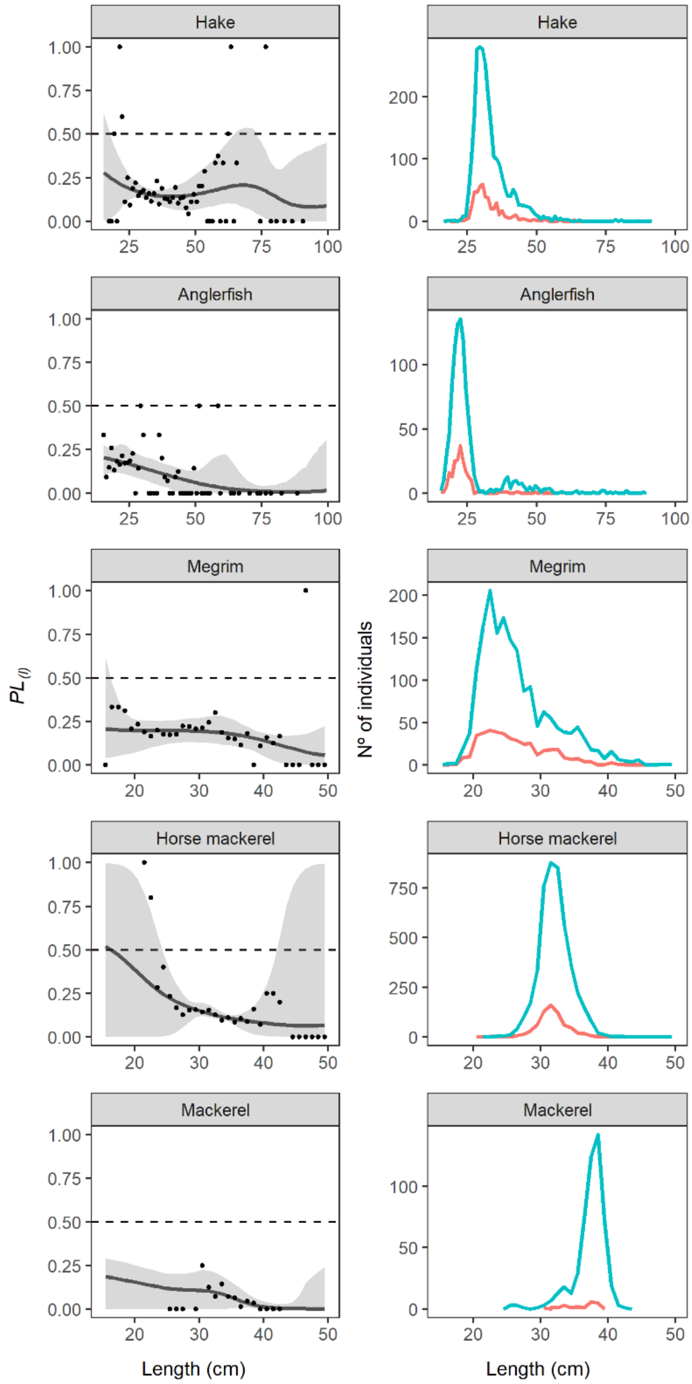

Figure 5.- (Left) Length dependent probability for individuals to be caught in the lower codend conditioned that they are retained when baseline design was used. (Right) Number of individuals retained in upper (blue) and lower (red) codend. Horizontal line represents equal probability to be captured in both codends.

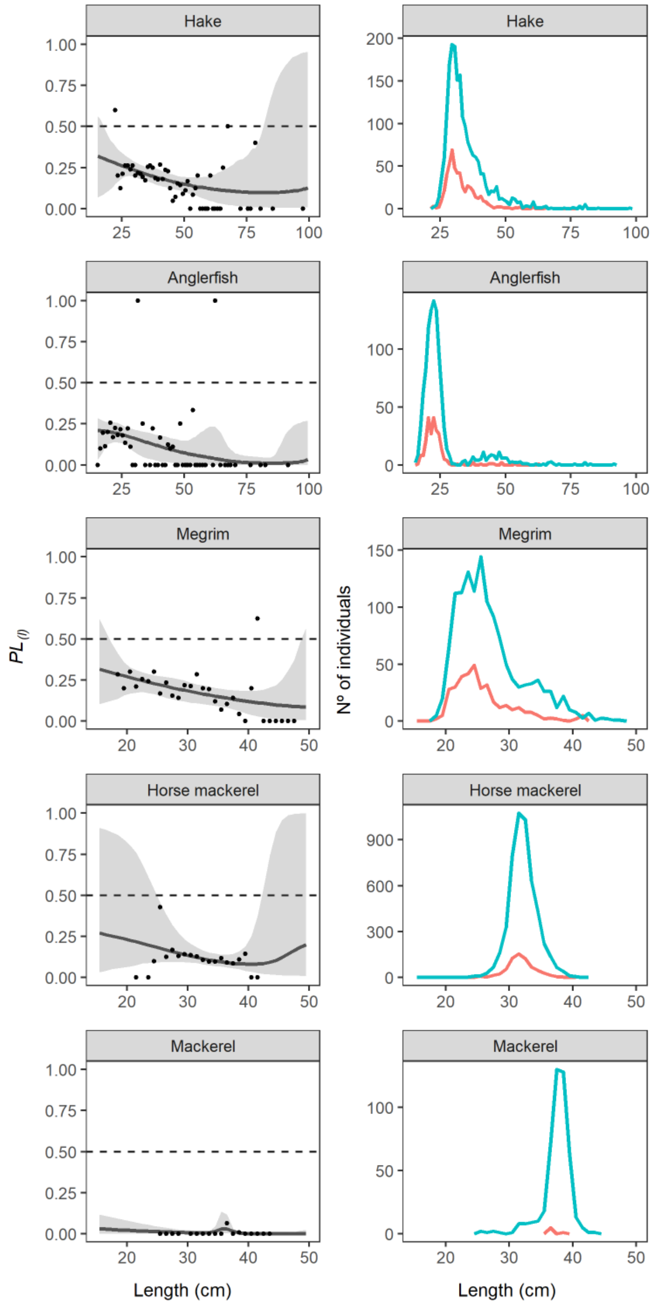

Figure 6.- (Left) Length dependent probability for individuals to be caught in the lower codend conditioned that they are retained when the treatment design was used. (Right) Number of individuals retained in upper (blue) and lower (red) codend. Horizontal line represents equal probability to be captured in both codends.

3.3. Effect of artificial light

The difference in retention probability in the lower codend when the lights were on compared to when lights were off for the different species was plotted to show the effect of artificial lights

(Fig. 7). Figure 7 shows that there are not significant differences on grid passage probability between treatment and baseline design except for hake. Hake shows significantly higher retention in the lower codend when the grid is illuminated for individuals between 28 and 36 cm length.

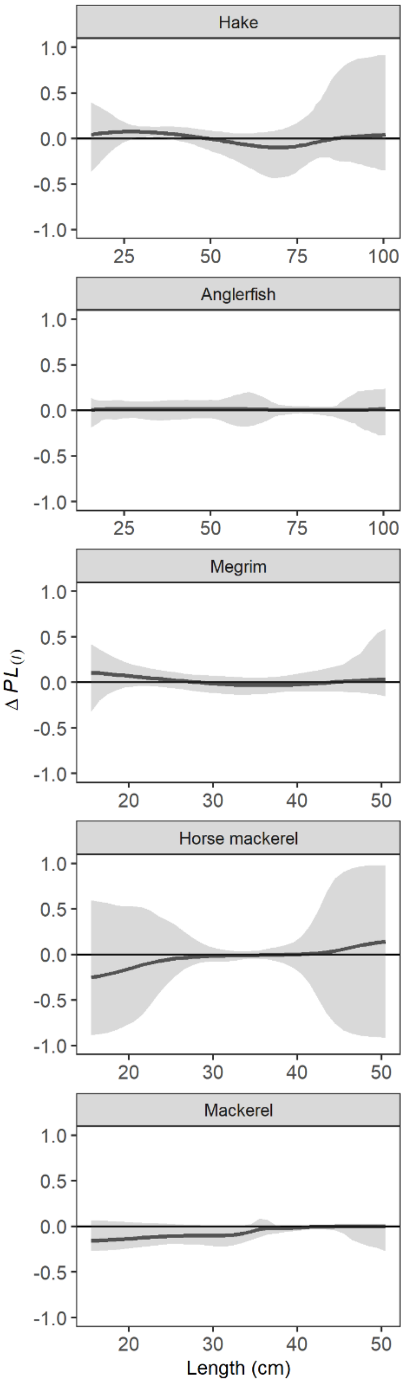

Figure 7.- Probability of fish ending up at the lower codend when treatment design was used with respect to baseline design. Horizontal line represents equal probability for both designs. Mean curve and CIs above or below horizontal line means significantly higher or lower probability to being retained in the lower codend when treatment design is used.

When the average capture probability in the lower codend for each species is analysed, which depend directly on the size structure of the population caught, it is observed that light does not significantly affect fish probability for passing through the grid since any of the indicators calculated were significantly different in between designs (Fig. 8).

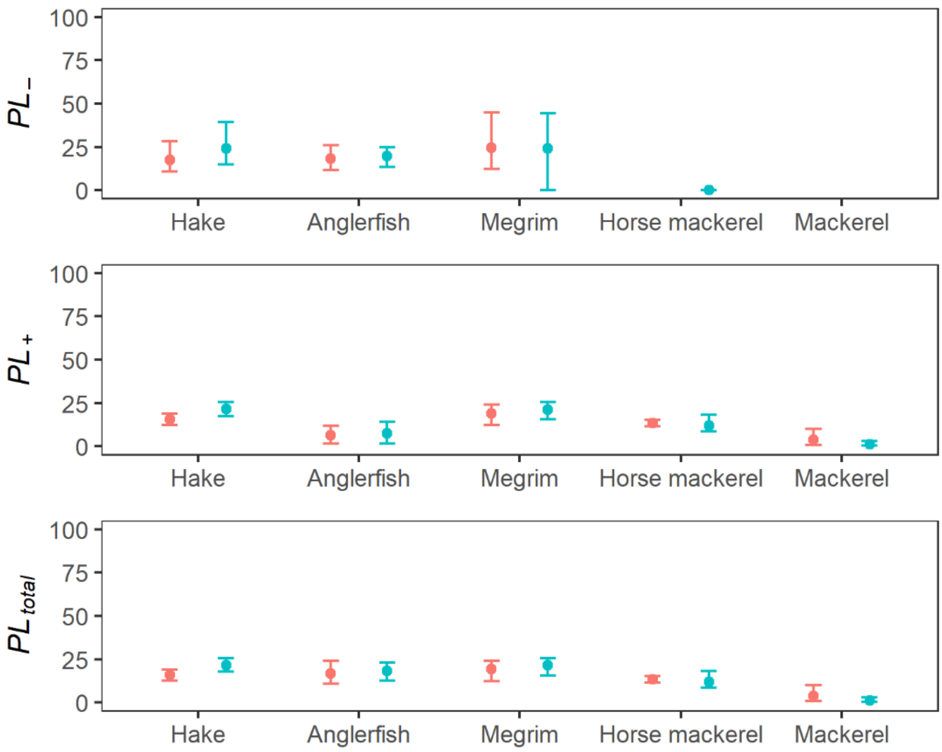

Figure 8.- The average probability (%) for individuals below MCRS (PL_-), above MCRS (PL_+) and of the total catch (PL_{total}) to be retained in the lower codend when light is on (blue) and off (red), conditioned capture.

4. DISCUSSION

The results obtained in this study show that the catch rate of all species in the lower codend compared to the total catch was low, showing fish were unlikely to pass through the grid. The results suggest that the swimming preferences of the species tested were not strong enough driver to trigger a downwards escape reaction and separate them into upper and lower codend in the fishery under study. The low probability values observed could be a consequence of factors such as low contact ratio between the fish and the grid. Cuende et al., (2022) showed that a square mesh panel located on the bottom panel of the extension piece of the trawl significantly increased the escape of undersized hake, probably due to its tendency to swim towards the bottom. However, Grimaldo et al., (2015) showed that for achieving satisfactory selectivity results for some species, guiding fish to a size selective sorting grid by means of a guiding panel is essential. Therefore, a guiding panel that directs the fish towards the grid, opposite to the current set-up, could increase encounter rates and the likelihood the fish contact the grid and escape through it.

A potential alternative driving out the need for increasing contact probability of target species with the grid can be the use of a horizontally divided codend. This gear design has been often tested in crustaceans and finfish fisheries with different degrees of success (e.g., Karlsen et al., 2019; Krag et al., 2009b), and its optimization is based on additional devices or simple gear modifications. Karlsen et al., (2015) for example, improved fish and Norway lobster (*Nephrops norvegicus*) separation in a horizontally divided codend by encouraging fish to swim upwards with a frame at the entrance of the lower codend. Dividing the codend would eliminate the potential visual effect of the grid, which could make fish more reluctant to pass through than if clearer passage is available (Glass et al., 1995). Additionally, it would provide longer time to fish to swim upwards or downwards and also may constitute a simpler gear design to construct and deploy.

In general, the results suggest a length-dependent capture pattern in the lower codend, since a higher proportion of small individuals pass through the grid regarding the total catch. Previous studies have reported a length-dependent behaviour related to the swimming capacity; with smaller individuals entering the lower compartment more frequently (Melli et al., 2018). In this study, length-dependent effect was identified for all species however, it is believed that the grid bar-spacing may be affecting the passage probability of larger fish. This may be especially relevant for large megrim individuals since longitudinally oriented bars together with narrow bar-spacing may not allow the body shape of flatfish to pass in natural swimming orientation. Santos et al., (2016) were able to reduce up to ~68% of flatfish bycatch by implementing escape grid with horizontal gaps in front of the codend. Therefore, further research on a passage section that minimises physical constrains would be worth to test.

Our results show that the passage probability through the illuminated grid is not significantly different when compared to baseline grid (except for hake, which was only slightly affected by the lights). The estimations showed significantly higher passage probability for hake between 28 and 36 cm length during the illuminated trials. However, these values are far too low to be useful in a commercial fishery. Despite that, the average probability estimations, which are specific for the population structure encountered during the experimental trials, did not show any significant differences between designs for any species.

According to the study carried out by Melli et al., (2018), green LED lights were found to have a significant effect on the vertical separation of some species. Specifically, fish showed a preference for the bottom panel in a horizontally divided codend in the presence of green LED lights. Although they were not able to specify how this effect was given because fish responded differently when the artificial lights were placed in different positions, they suggested that lights could be triggering other behavioural responses such as increased awareness of the surroundings, panic, or species-specific escape behaviours. In our case, considering the poor effect of lights on the passage probability of the species tested, we cannot discard that other factors may be affecting the properties of the artificial light or how the fish perceive the light. According to the turbidity data in our study and the underwater recordings, it is observed that high turbidity levels occurred for extensive periods in different hauls. More specifically, turbidity levels were severe enough to affect viewing capabilities for 75% of the video recordings made. Since our interpretation of the turbidity data is based on our capacity for seeing any light trace from video recordings, we cannot conclude whether the lights used were not visible to fish. Other factors such as the ability of fish to perceive light and physical properties of the light need to be investigated to draw strong conclusions (Nguyen and Winger, 2019). Our turbidity readings show high sediment resuspension, which may compromise fish vision and consequently, affect their reaction towards the grid.

Fishing gears need to be developed so they can perform in the environmental conditions they are intended to be used. The towing speed in the fishery presented here is between 3.9 and 4.2 knots, which can imply that the fish entering the aft of the gear passes by the grid area at ca. 2 metres per second. Thus, fish have limited time to react to towards the grid before being drifted back to the codend. In addition to the limited visibility due to the high turbidity values, the drifting speed may limit the ability of the fish to perceive and interact with the grid therefore, potentially impacting the likelihood for fish to enter the lower codend.

The high towing speed and high turbidity values, typical for the fishery under study, may impede the ability of fish to respond to the visual stimulus used. Two conditions need to be fulfilled to ensure fish make contact with the grid based on visual stimulation. First, the fish need to respond to the light stimulus in some way and second, the fish need to have the physical swimming capability to interact with the grid. In this specific fishery, the extreme conditions experienced from the high towing speed and turbidity could significantly affect the ability of the fish to reach the grid or even perceive the artificial light. Therefore, it is not possible to conclude whether the species examined in this study have a positive, negative or no reaction to artificial light based on the grid passage probability obtained.

During the cruise, large quantities of invertebrates (mainly echinoderms and cephalopods) and fish individuals got meshed in the netting section preceding the grid, specifically around the lifting panel. We believe that this meshing was a consequence of halving the transversal area in the section with the lifting panel, and that as it took place in the section prior to the grid we assume it did not affect the results presented in this study.

Finally, the results demonstrated that we were not able to efficiently separate species by means of hake and megrim passage through the grid. However, we cannot rule out a more efficient species separation by using the opposite approach, i.e., guiding the main flow of fish through the lower panel and driving the species separation by means of passage of horse mackerel and mackerel through the grid to the upper codend. Even though a simpler approach could probably be used to take advantage of the behavioural differences between species in this fishery (in the line of those proposed by Karlsen et al., (2019) or Melli et al., (2018)), in more favourable environmental conditions a further developed configuration of the device tested in this study may provide better results. For example, a longer grid or a guiding panel that directs the fish towards the grid, could improve contact probability with the grid and subsequently increase the likelihood for that fish can perceive the artificial light.

The experiments carried out here showed that the probability of fish passing through the grid, under the conditions described, was very low and the additional use of lights did not significantly affect the results. However, it is important to emphasize the relevance of reporting any result, as an experimental outcome, so that future experiments can build upon (Weintraub, 2016). Publishing only selective information, provides a biased view and understanding of the processes, while reporting on all results may help to interpret results obtained in related studies. In addition, reporting all results can help other scientists to adjust their experimental designs and increase chances of success, saving time and resources.

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