Stimulating release of undersized fish through a square mesh panel in the Basque otter trawl fishery

Elsa Cuende[a*], Luis Arregi[a], Bent Herrmann[bc], Manu Sistiaga[de], Iñigo Onandia[a]

[a] AZTI-Tecnalia, Marine Research Division, Txatxarramendi ugartea w/n, 48395 Sukarrieta, Spain
[b] SINTEF Ocean, Fishing Gear Technology, Willemoesvej 2, 9850, Hirtshals, Denmark
[c] The Arctic University of Norway, UiT, Breivika, N-9037 Tromsø, Norway
[d] SINTEF Ocean, Fishing Gear Technology, Brattørkaia 17C, 7010 Trondheim, Norway
[e] Institute of Marine Research, Postboks 1870 Nordnes, Bergen, 5817, Norway

[*]Corresponding author at: AZTI-Tecnalia, Marine Research Division, Txatxarramendi ugartea w/n, 48395 Sukarrieta, Spain
E-mail address: elsacuende@gmail.com (E. Cuende)

Abstract

Discards of regulated species in the Basque mixed trawl fishery are a challenge. In 2006, a square mesh panel (SMP) was introduced in the fishery to increase the release efficiency of undersized fish. However, studies have shown that the selectivity in this fishery is based on codend selectivity and the release through the SMP is inefficient due to low contact between fish and the SMP. In order to improve contact, we tested four different gear configurations that use different stimulators to lead fish to the panel: without stimulation, with stimulation based on ropes, with stimulation based on ropes and floats, and with stimulation based on LED lights. The experiment was carried out on three of the potential choke species for the fishery: hake (*Merluccius merluccius*), horse mackerel (*Trachurus trachurus*), and blue whiting (*Micromesistius poutassou*). The results showed that stimulators did not significantly improve the release efficiency of hake and horse mackerel through the panel. For blue whiting, stimulation with floats had a significant positive effect on release efficiency, whereas LED light-based stimulation had the opposite effect. In general, the contribution of the SMP to the overall release efficiency of the selective system (SMP+codend) was low. Underwater recordings confirmed that the stimulators generally were not able to lead fish towards the SMP.

Keywords: Square mesh panel (SMP); Basque bottom otter trawl; Release efficiency; Contact probability

1. Introduction

Fisheries in general have great social and economic implications for coastal communities in the Basque Country (Haig, 2008), which is a region located in the north of Spain. Basque bottom trawling began in the early twentieth century, and its productivity peaked in the late 1970s when 53% of the Spanish trawling fleet fishing in EU community waters (ICES VIab, VIIbcghj, VIIIabd) was Basque. The demersal trawl fishery in this area is a multispecies fishery that includes more than 100 different species (Rochet et al., 2014), but hake (*Merluccius merluccius*), megrim (*Lepidorhombus* spp.), and anglerfish (*Lophius* spp.) are the main target species. However, other species such as horse mackerel (*Trachurus trachurus*), blue whiting (*Micromesisitius poutassou*), and mackerel (*Scomber scombrus*) can be important as choke species (Schrope, 2010) depending on the fishing ground, season, quota availability, and commercial value (Iriondo et al., 2008, 2010; Rochet et al., 2014).

Awareness about discard reduction in fisheries has increased worldwide (Catchpole et al., 2005; Gillespie, 2000; Santurtún et al., 2014). Discards in fisheries can occur for several reasons, including capture of individuals below minimum legal size, exhaustion of quota, low commercial value, damaged or degraded individuals in the catch, or high grading (Anderson, 1994; Pascoe, 1997). Since 1980, several technical regulations have been implemented in the EU with the aim of reducing discards (Franco, 2007; Santurtún et al., 2014). However, discarding is still a common practice in some European fisheries (Uhlmann et al., 2013). Rochet et al. (2014) analyzed available data from observer discard monitoring, catch landings, and/or nominal fishing effort from 2011 to 2013 and found that the total discard of the Spanish fleet operating in ICES VIIIabd was around 60–65% of the total catch. Thus, unwanted catches and discards constitute a substantial waste that negatively affects the sustainable exploitation of marine resources (Kelleher, 2005). This perception has motivated the establishment of the Landing Obligation (LO) under the provisions of Article 15 of the 2013 reform (EU, 2013). Its main objective is to eliminate discards of commercially exploited stocks. By 2019, all EU fisheries are obliged to land the catches of regulated species to be counted against the quota.

In recent decades, several fishing regulations have been implemented specifically to stimulate the recovery of hake (EC, 2001a; 2001b; 2002; 2004). In 2002 (EC, 2002), the minimum codend mesh size for trawlers fishing the northern stock of European hake in the Bay of Biscay was changed from 70 mm to 100 mm diamond mesh. In 2006 (EC, 2006), fishermen were given the alternative of using a 70 mm diamond mesh codend combined with a square mesh panel (SMP) (2 m long, 1 m wide, 100 mm mesh size) inserted in the upper panel of the extension piece of the trawl instead of a 100 mm diamond mesh codend. Currently, the gear composed of the SMP with a 70 mm diamond mesh codend is the one most used by the fleet.

Several studies have investigated the functionality and release efficiency potential of SMPs (Briggs, 1992; Santos et al., 2016; Zuur et al., 2001). In general, results show that even if some species manage to escape through SMPs, less active species, such as hake, do not manage to escape through it efficiently (Alzorriz et al., 2016). In most cases, the authors concluded that the low release efficiency of the panel is a consequence of the low contact between the fish and the panel (Alzorriz et al., 2016; Brčić et al., 2017; Herrmann et al., 2014). To improve the contact, some mechanical (Kim and Whang, 2010) and visual stimulators (Glass and Wardle, 1995; Grimaldo et al., 2017) have been used to guide fish towards SMPs or netting walls (Grimaldo et al., 2018; Herrmann et al., 2014).

The main goal of the present study was to determine if the release efficiency of the SMP used in a demersal trawl in the Bay of Biscay could be improved by adding ropes, floats, and LED light-based stimulators. The study focused on individuals of hake, horse mackerel, and blue whiting, which may compromise the activity of the fleet due to their potential as choke species. Specifically, we aimed to answer the following research questions:

- What is the release efficiency of the selection system composed of a SMP and 70 mm diamond mesh codend for hake, horse mackerel, and blue whiting?
- What are the contributions of the SMP and the 70 mm diamond mesh codend to the combined selectivity of the system?

- Can the release efficiency of the SMP be improved by adding different stimulators based on ropes, floats, or LED lights for the three species investigated?

2. Material and methods

2.1. *Sea trials and data collection*

The sea trials were carried out on board the oceanographic vessel *Emma Bardan* (29 m length overall; 900 Kw) from 8 to 19 June 2017. The fishing was carried out in a specific area within ICES divisions VIIIc and VIIIb that correspond to Spanish and French waters (Figure 1). This area normally contains high densities of hake juveniles at this time of year and therefore was considered to be suitable for the experiments. During the experimental period, 32 valid hauls were conducted at depths that varied between 106 and 128 m.

Figure 1

The gear used in the experiments was a four-panel bottom trawl called GOC73 (Bertrand et al., 2000). This trawl is built according to the standard bottom trawl survey manual for the Mediterranean (MEDITS, 2016). The headline, sideline, and fishing line were 35.7, 7.4, and 40.0 m long, respectively. The trawl was rigged with a set of Morgère doors (Morgère WH S8 type, 2.6 m^2; 350 Kg), 100 m sweeps, and a light rockhopper ground gear (with 3 × 40 Kg chain + 15 Kg chain on the bosom). While fishing, the trawl had a horizontal opening of 16 m and a vertical opening between 2.7 and 3.2 m. The towing speed during the cruise was 3.0–3.3 knots which was the maximum for the vessel.

In this study, we used a SMP (mesh size 82.7 mm) inserted into the upper panel of the extension piece of the trawl, 1 m in front of the joint between the codend and the extension piece (Figure 2). A previous study carried out with a 100 mm SMP (Alzorriz et al., 2016) showed that the low release efficiency of the panel was due to poor contact between the fish and the panel rather than to an inappropriate mesh size. In fact, the results of the study showed that fish over Minimum Conservation Reference Size (MCRS) that managed to contact the panel were able to escape through it. Therefore, and in order to avoid the loss of valuable catch, the mesh size of the panel used in the present study was reduced to 82.7 mm (3 mm polyamide (PA) twine) (Table 1). The codend, used together with the panel, was 7.0 m long and made of 72.8 mm meshes (4 mm PA double twine). All meshes were measured with an electronic OMEGA mesh gauge (Fonteyne et al., 2007) according to the guidelines described in regulation EC, 2008.

The selectivity data were collected using the dual-cover method (Figure 2) described in Zuur et al. (2001) and Sistiaga et al. (2010). The cover used over the SMP was 13 m long with 26.1 mm mesh size (1.2 mm PA twine). It was built based on the design of Larsen and Isaksen (1993) and was equipped with nine floats (N-50/8 type; 135 mm diameter; 0.760 Kg buoyancy each) to ensure its expansion. The cover over the codend was 9 m long and constructed of 26.5 mm mesh size (1.3 mm PA twine) (Table 1; Figure 2). To expand the codend cover we used nine pairs of floats (N-25/5 type; 100 mm diameter; 0.300 Kg buoyancy each), eight kites (four per panel), and four chains (1 Kg each) in the lower panel. Table 1 summarizes details about the specifications of the different parts of the trawl.

Table 1

Figure 2

We tested four different gear configurations:

1. No-stimulation: used as baseline, consisted on the SMP with no stimulators added (Figure 3a);

2. Stimulation by ropes: consisted of six inclined elastic ropes attached on one side to the bottom panel of the square mesh section and on the other side to the upper panel at the end of the SMP. The purpose was to partially obstruct the passage of fish toward the codend, guiding them upwards towards the SMP (Figure 3b);

3. Stimulation by floats: this configuration added oval plastic floats to the inclined ropes described in the former configuration (3-4 floats on each rope, T80/5 type, 118x52 mm, 0.085 Kg buoyancy each). The floats provided vibration to the guiding ropes while towing (Figure 3c);

4. Stimulation by LED lights: ten blue LED lights (CENTRO Power Light, Standard model SW2) were placed over the SMP to attract fish towards the panel and increase contact probability (Figure 3d).

Figure 3

Each haul was carried out with one configuration at a time, completing a total of eight hauls for each configuration. The species included in the data analysis were hake *(Merluccius merluccius)*, horse mackerel, *(Trachurus trachurus)* and blue whiting *(Micromesistius poutassou)*. After each haul, these species were measured to the nearest centimeter below. When the catch exceeded a maneuverable quantity in terms of the available time and crew for processing the fish, randomly selected subsamples of the catch were taken, and the subsample ratio was calculated. In some specific hauls, once the subsample was sorted, and if the representation of some species was still too big to handle, a randomly selected sample from the sorted subsample was taken. Consequently, we expected that in those specific hauls the less abundant species would be weakly represented. Therefore, we established a protocol for acceptance, meaning that the hauls that did not pass the limits established in the protocol were discarded. The haul protocol acceptance was based on two conditions: 1) sampling factor for a compartment had to be at least 0.05 and 2) in case of subsampling in a compartment, the product of the number measured in the compartment and the compartment sampling factor needed to be at least 4.

Underwater recordings were carried out to check the correct performance of the gear and collect information about fish behavior relative to the stimulators tested. The camera

(Camera type: GoPro Hero 3) was attached at different locations in the trawl (Table 2) together with a CREE underwater torch (Brinyte DIV01; CREE XM-L2(U2) LED; max 1000 lm).

Table 2

2.2. Selectivity model for the gear

In the experimental setup used in this study, fish entering the trawl first encountered the SMP and could escape if they swam up to it and if their body size, shape, and orientation allowed them to pass through the meshes. If any of these requirements were not met, the fish entered the size selective codend, where a further selection process took place. If the fate of each individual fish is assumed to be independent of the others, the number of fish of length l retained in the three compartments, codend (*CD*), SMP cover (*PC*), and codend cover (*CC*) (Fig. 2), can be modelled using a multinomial distribution with length-dependent probability of being retained in the codend $r_{comb}(l)$; escapement through the SMP $e_{SMP}(l)$; and escapement through the codend $e_{codend}(l)$. The combined retention can be modelled as:

$$r_{comb}(l) = 1 - e_{SMP}(l) - e_{codend}(l), \tag{1}$$

where l represents fish length. This type of model has been previously used in several studies to investigate combined selection of SMPs and diamond mesh codends (Alzorriz et al., 2016; Brčić et al., 2017; O´Neill et al., 2006; Zuur et al., 2001).

The first selection process takes place when a fish encounters the SMP zone, where it can be size-selected if it makes contact with the panel. The contact parameter (*C*) quantifies the fraction of fish entering the selectivity area that makes contact with the device and, therefore, is subjected to a size-dependent probability of escaping through it. In this case, we assume that the probability for fish to come into contact with the panel can be modelled with the length-independent parameter C_{SMP}. This parameter can take values from 0.0 to 1.0 depending on the fraction of individuals contacting the panel. If C_{SMP} is equal to 1.0, all fish come into contact with the panel, whereas if C_{SMP} is equal to 0.0, none do. This leads to the following model for e_{SMP} (l):

$$e_{SMP}(l) = C_{SMP} \times (1 - rc_{SMP}(l, \boldsymbol{v}_{SMP})), \tag{2}$$

where $rc_{SMP}(l,\boldsymbol{v}_{SMP})$ is the selection model for fish making contact with the SMP and having a suitable orientation to achieve a size-dependent probability of passing through the SMP mesh, and $\boldsymbol{v}_{SMP}$ are the parameters of model $rc_{SMP}(l,\boldsymbol{v}_{SMP})$ and therefore, represented by a vector. A further assumption is that the probability $rc_{SMP}(l,\boldsymbol{v}_{SMP})$ can be described by standard S-shaped size selection models for trawl gears. We considered four S-shaped size selection curves: *Logit*, *Probit*, *Gompertz,* and *Richard*. Further information about these models, their respective parameters $\boldsymbol{v}$, and estimation of the selectivity parameters *L50* and *SR* (*L50* is the length at which a fish has a 50% chance of being retained by the gear, whereas *SR* is the difference between *L75* and *L25*) can be found in Wileman et al. (1996).

To model the size-dependent codend retention probability $rc_{codend}(l,\boldsymbol{v}_{codend})$, it was assumed that every fish entering the codend came into contact with the codend meshes and that $rc_{codend}(l,\boldsymbol{v}_{codend})$, like $rc_{SMP}(l,\boldsymbol{v}_{SMP})$, could be modelled by a *Logit*, *Probit*, *Gompertz,* or *Richard* model. Estimation of codend escape involves the fish that have not escaped through the SMP. The above considerations led to the following model for e_{codend} (l):

$$e_{codend}(l) = (1 - rc_{codend}(l, v_{codend})) \times (1 - e_{SMP}(l, C_{SMP}, v_{SMP})) \tag{3}$$

2.3. Model estimation

The values of C_{SMP}, $\boldsymbol{v}_{SMP}$, and $\boldsymbol{v}_{codend}$ for selection models (1)–(3) are species-specific and depend on the gear configuration. Therefore, the values were obtained separately for each species and gear configuration using Maximum Likelihood Estimation (MLE) by pooling the experimental data over the hauls *j* (*1* to *m*) with the specific gear configuration and minimizing:

$$-\sum_{l}\sum_{j=1}^{m}\left\{\frac{nCD_{lj}}{qCD_j}\times\ \ln\left(r_{comb}(l, C_{SMP}, v_{SMP}, v_{codend})\right)+\frac{nPC_{lj}}{qPC_j}\times\ln\left(e_{SMP}(l, C_{SMP}, v_{SMP})\right)\right.$$

$$\left.+\frac{nCC_{lj}}{qCC_j}\times\ \ln\left(e_{codend}(l, C_{SMP}, v_{SMP}, v_{codend})\right)\right\} \qquad (4)$$

where for each haul j and length class l, nCD_{lj}, nPC_{lj}, *and* nCC_{lj} are the numbers of individuals length-measured in the *CD*, *PC*, and *CC*, respectively; and qCD_j, qPC_j, and qCC_j are their respective subsampling factors (ratio of length-measured to total number of fish in each compartment). In total, 16 models were considered to describe the overall trawl size selectivity based on the combination of the four S-shaped functions considered for $rc_{SMP}(l)$ and $rc_{codend}(l)$. The 16 models were tested against each other and the one with the lowest AIC value (Akaike's Information Criterion; Akaike, 1974) was selected. MLE using equation (4) with (1) to (3) requires pooling experimental data over hauls. This results in stronger data for average size-selectivity estimation at the expense of not considering explicit variation in selectivity between hauls (Fryer, 1991). To account correctly for the effect of between-haul variation when estimating uncertainty in size selection, a double bootstrap method was used (Herrmann et al., 2012). We estimated the 95% Efron percentile confidence intervals (95% CIs) (Efron, 1982) for the parameters in equations (1)–(3) and for the resulting $e_{SMP}(l)$, $e_{codend}(l)$, and $r_{comb}(l)$ curves. To estimate the 95% CIs, 1000 bootstrap iterations were carried out. All analyses were done using the software tool SELNET (Herrmann et al., 2012).

The models were validated based on p-value estimations and model deviance versus degrees of freedom (Wileman et al., 1996). When the p-value was < 0.05 and deviance was much bigger than the degrees of freedom, the residuals were inspected to determine whether the discrepancy between model and experimental data was the result of overdispersion.

To infer the effect on the length-dependent SMP escape probability, $e_{SMP}(l)$ and on the combined retention, $r_{comb}(l)$, when changing from the no-stimulation configuration to a specific stimulation configuration, the difference in the estimated value for $p(l)$ was calculated as follows:

$$\Delta p(l) = p_{stim}(l) - p_{base}(l), \tag{5}$$

where $p_{base}(l)$ represents the value for $e_{SMP}(l)$ or $r_{comb}(l)$ for the no-stimulation design and $p_{stim}(l)$ is for the stimulator design. Efron 95% CIs for $\Delta p(l)$ were obtained based on the two bootstrap populations of results (1000 bootstrap repetitions in each) for both $p_{base}(l)$ and $p_{stim}(l)$. As they are obtained independently, a new bootstrap population of results was created for $\Delta p(l)$ by:

$$\Delta p(l)_i = p_{stim}(l)_i - p_{base}(l)_i \;\; i \in \; [1 \ldots 1000], \tag{6}$$

where *i* denotes the bootstrap repetition index. As the bootstrap resampling was random and independent for the two groups of results, it is valid to generate the bootstrap population of results for the difference based on (6) using the two independently generated bootstrap files (Herrmann et al., 2018). Based on the bootstrap population, Efron 95% CIs can be obtained for $\Delta p(l)$ as described above.

2.4. Estimation of exploitation pattern indicators

The effect of the SMP on the exploitation pattern of the gear was quantified by estimating the values for a number of indicators (described in detail below) using the data collected during the fishing trials. To quantify to what extent the experimental gear supports a sustainable and efficient fishery, the average percentage of retained individuals below (rP_{-}) and above (rP_{+}) MCRS were estimated for each species individually based on the population size structure for the different species entering the gear during the experimental fishing. The Minimum Conservation Reference Size (MCRS) for hake and horse mackerel are 27 and 15 cm length, respectively. For blue whiting, which does not have MCRS, we used its estimated marketable size limit, 18 cm length. This length is based on a regulation that establishes a maximum of 30 individuals of blue whiting per kilo for commercialization (Dorel, 1986; EC, 1996).

The formulae used to calculate rP_{-} and rP_{+} values are as follows (Brčić et al., 2017):

$$
\begin{aligned}
rP_{-} &= 100 \times \frac{\sum_j \sum_{l<MCRS} \left\{ \frac{nCD_{jl}}{qCD_j} \right\}}{\sum_j \sum_{l<MCRS} \left\{ \frac{nCD_{jl}}{qCD_j} + \frac{nCC_{jl}}{qCC_j} + \frac{nPC_{jl}}{qPC_j} \right\}} \\
rP_{+} &= 100 \times \frac{\sum_j \sum_{l>MCRS} \left\{ \frac{nCD_{jl}}{qCD_j} \right\}}{\sum_j \sum_{l>MCRS} \left\{ \frac{nCD_{jl}}{qCD_j} + \frac{nCC_{jl}}{qCC_j} + \frac{nPC_{jl}}{qPC_j} \right\}}
\end{aligned}
, \qquad (7)
$$

where the outer summation in (7) is over hauls *j* over the hauls with the specific gear configuration and the inner summation is over length classes *l*.

The indicators rP_{-} and rP_{+} quantify the effect of fishing on the population structure of the target species with the specific gear. A small value of rP_{-} means that the gear retains only a small fraction of individuals below MCRS. High rP_{+} values, preferably close to 100, would mean that most individuals over MCRS that enter the gear are retained. To quantify the extent to which the SMP releases the fish that entered the trawl, the averaged percentage of individuals below (esP_{-}) and above (esP_{+}) MCRS that escaped through the panel compared to those entering were estimated for the species investigated. The formulae used to calculate esP_{-} and esP_{+} values are as follows:

$$
\begin{aligned}
esP_{-} &= 100 \times \frac{\sum_j \sum_{l<MCRS} \left\{ \frac{nPC_{jl}}{qPC_j} \right\}}{\sum_j \sum_{l<MCRS} \left\{ \frac{nCD_{jl}}{qCD_j} + \frac{nCC_{jl}}{qCC_j} + \frac{nPC_{jl}}{qPC_j} \right\}} \\
esP_{+} &= 100 \times \frac{\sum_j \sum_{l>MCRS} \left\{ \frac{nPC_{jl}}{qPC_{jl}} \right\}}{\sum_j \sum_{l>MCRS} \left\{ \frac{nCD_{jl}}{qCD_j} + \frac{nCC_{jl}}{qCC_j} + \frac{nPC_{jl}}{qPC_j} \right\}}
\end{aligned}
\qquad (8)
$$

For the SMP to have a positive effect on the exploitation pattern of the targeted species, esP_{-} should be significantly above zero and esP_{+} close to zero. Furthermore, to quantify the SMP contribution to the overall escapement that occurs during the experimental fishing, an average percentage of individuals below ($resP_{-}$) and above ($resP_{+}$) MCRS escaping through the SMP, compared to the overall escapement, were estimated for the investigated species. The formulae used to calculate $resP_{-}$ and $resP_{+}$ values are as follows:

$$
\begin{aligned}
resP_{-} &= 100 \times \frac{\sum_j \sum_{l<MCRS} \left\{ \frac{nPC_{jl}}{qPC_j} \right\}}{\sum_j \sum_{l<MCRS} \left\{ \frac{nCC_{jl}}{qCC_j} + \frac{nPC_{jl}}{qPC_j} \right\}} \\
resP_{+} &= 100 \times \frac{\sum_j \sum_{l>MCRS} \left\{ \frac{nPC_{jl}}{qPC_{jl}} \right\}}{\sum_j \sum_{l>MCRS} \left\{ \frac{nCC_{jl}}{qCC_j} + \frac{nPC_{jl}}{qPC_j} \right\}}
\end{aligned}
\tag{9}
$$

For the SMP to have any major effect on the exploitation pattern for the fishing gear, at least one of the parameters in (9) should have a value much higher than zero. The 95% confidence bands for rP_{-}, rP_{+}, esP_{-}, esP_{+}, $resP_{-}$ and $resP_{+}$ values were estimated using the double bootstrap method described above, taking into account between-haul variation and within-haul variation in the exploitation pattern.

3. Results

3.1. Overview of the sea trials

During the experimental period, 32 hauls were carried out and length measurements for 5852 hake, 5720 horse mackerel, and 7524 blue whiting were taken (Table 3). However, based on the acceptance protocol established, the final pool of hauls included in the analysis consisted of 28 hauls for hake, 25 for horse mackerel, and 23 for blue whiting. The number of fish captured and length-measured in each of the configurations and species are provided in Table 3.

Table 3

3.2. Release efficiency

Table 4 summarizes the model combinations resulting in the lowest AIC value for each configuration tested. In some cases, there were alternative models with identical AIC values, meaning that the support for these other models was equally strong. In those cases, the simplest model was chosen. The fit statistics showed that, for hake and horse mackerel, models (2) and (3) were able to describe the experimental data well for most configurations (Table 4; Figures 4, 5). In the case with stimulation by floats, the low p-value associated with horse mackerel was attributed to overdispersion of the data because there was no clear pattern in the deviations between the experimental data and the fitted escape probability curve (Figure 5). This overdispersion was probably caused by the heavy subsampling in the data collection process.

Table 4

Among the tested configurations, the SMP release efficiency of hake and horse mackerel in the Bay of Biscay was low (Figures 4, 5), with an estimated escape below 1% in most cases (Table 4). The only exception was the LED light treatment for horse mackerel, in which the release efficiency was close to 4% for the smallest sizes (Figure 5*j*). This was also manifested in the C_{SMP} values obtained, which were estimated to be 0.01 for hake in every configuration and below 0.03 for horse mackerel in every case, meaning that only a low proportion of these fish made contact with the SMP (1 and 3%, respectively) (Table 4). Figures 4 and 5 show that most of the individuals of these species that escaped did so through the codend. Even so, in the case of hake, $L50_{comb}$ was around 17 cm (Table 4), and for individuals of 27 cm length (hake's MCRS) the retention probability was above 90% for every configuration.

Figure 4

Figure 5

Figure 6

The modelling enabled comparison of gear selectivity with and without stimulation. The results showed that the release efficiency of the panel with stimulation did not significantly differ from no-stimulation situation (Figure 7*a*, *c*, *e*). The release efficiency through the SMP for horse mackerel did not differ significantly among configurations (Figure 8*a*, *c*, *e*). However, the overall retention of this species was significantly lower when using rope stimulation (Figure 8*b*), reaching an estimated effect of 40% less escape for some length classes (between 12 and 20 cm in size). Differences in codend size selectivity when using ropes caused these differences in gear retention, as the $L50_{CD}$ for the rope configuration was significantly different from that of the baseline design (Table 4).

For blue whiting, the panel contact values were higher than for hake and horse mackerel in all configurations tested (between 20 and 53%), but the wide 95% confidence intervals made the inference for blue whiting uncertain (Table 4; Figure 6). $L50_{comb}$ values were estimated to be over its marketable size (18 cm; this species does not have a MCRS) in all configurations, and because the selection ranges (*SR*) were quite narrow, individuals below 18 cm had low probability of being retained. The poor p-values for almost all treatments (Table 4) were probably due to overdispersion in the data created by heavy subsampling ratios, as the experimental data and the fitted escape probability curve showed no clear deviation patterns.

The results show that the configuration with floats significantly improved the release of blue whiting through the SMP for a range of lengths (10–15 cm) (Figure 9*c*). However, the improved release of this configuration was not manifested in the combined retention of the gear (Figure 9*d*). In this case, $L50_{CD}$ values (between 19.3–22.4; Table 4) show that the small fish not released in the first selection process through the panel would escape anyway in the second process through the codend due to its selection properties. In contrast, LED lights over the SMP had a statistically significant negative effect on the release of this species through the panel (between 15 and 27 cm; Figure 9*e*). Consequently, the combined retention of blue whiting between 21 and 27 cm was significantly higher (Figure 9*f*).

Figure 7

Figure 8

Figure 9

Regarding the exploitation pattern, the values obtained for rP_{-} and rP_{+} show that the exploitation pattern of the selective system, consisting of SMP and codend, was species-dependent (Table 5). For hake, rP_{+} was high (above 96.0%) for every configuration, although rP_{-} was estimated to be relatively high too, meaning that a large fraction of small hake was also retained (around 46% for ropes and floats stimulation treatments and around 41% for LED light stimulation). For blue whiting, rP_{-} was estimated to be below 1.3% for every configuration. In contrast, for horse mackerel with no-stimulation and LED light treatments rP_{-} values were estimated to be 27.8% (CI: 12.2–46.6%) and 22.1% (CI:17.4–27.3%), respectively, implying that a larger fraction of undersized individuals of these species entering the gear were retained. For horse mackerel, the rP_{+} value was relatively high, as the retention rate was above 69.7% for every configuration, except for rope stimulation (40.5% (CI: 16.9–64.1)). Blue whiting above 18 cm had a retention of almost 90% when lights were used, but it was below 66% for the rest of the tested configurations.

The results show that the SMP does not affect the exploitation pattern of hake or horse mackerel much, as the values for esP_{-} and esP_{+} for every configuration were low. For undersized hake, the estimated values (esP-) were below 1%, with the upper confidence limit never exceeding 2%. For undersized horse mackerel, the estimated values never exceeded 3%, and upper confidence limit was always below 7%. $resP_{-}$ and $resP_{+}$, which quantify how much the SMP contributes to the total escape, also demonstrated the low effect of the panel. The estimated $resP_{-}$ values for hake were below 1.5%, and the upper confidence limit never exceeded 3.7%. $resP_{-}$ and $resP_{+}$ for horse mackerel also show the low effect of the SMP on the total escape, and especially for sizes below MCRS, the estimated value never exceeded 3.9% with the upper confidence limit always below 8.6%. However, the contribution of the SMP to the overall escapement of legal sizes of horse mackerel was higher, reaching 17.5% (CI: 6.4–29.2%) when LED light-based stimulation was used. In contrast to hake and horse mackerel, a higher proportion of small blue whiting escaped through the SMP, with esP_{-} estimated to be between 19.9 and 52.6% depending on configuration.

Table 5

3.3. Underwater observations

Underwater video recordings showed that the SMP and codend meshes remained open during the recorded trials (Table 2) and that the covers did not mask the meshes. Further, they showed that the stimulation devices were physically functioning as intended. With respect to fish behavior in relation to the SMP, none of the configurations seemed to affect fish behavior differently from the no-stimulation treatment. Hake individuals usually swam next to the bottom, passively drifted backwards towards the codend, and did not show any reaction to the SMP. Horse mackerel and blue whiting exhibited more active behavior, mostly swimming in the towing direction along the extension piece (close to the SMP area) until they became exhausted and drifted towards the codend. In addition, blue whiting showed more active and erratic behavior in front of the SMP; many of these individuals turned and swam quickly either towards the panel or the codend. This behavior resulted in greater physical contact with the SMP, although most of the time they were not properly oriented and therefore most of them did not manage to escape through it.

4. Discussion

The LO represents a big challenge for multi-species trawl fisheries (De Vos et al., 2016) such as the Basque bottom otter trawl fishery. It has been shown that undersized fish release efficiency through the 70 mm diamond mesh codend and the SMP is low (Rochet et al., 2014) due to low contact with the panel (Alzorriz et al., 2016). In the present study, we aimed to increase contact of fish. We attempted to stimulate escape behavior of hake, horse mackerel, and blue whiting through a panel made of 82.7 mm square meshes.

In general, the results obtained in this study showed that the stimulators, based on ropes, floats, or LED lights, barely increased the contact probability of the species tested with the SMP. For hake, escape probability was low for all stimulators tested, and it was not significantly different compared to the treatment without stimulation. Herrmann et al. (2014) and Krag et al. (2016a) reported that to improve fish escapement in non-tapered netting sections, additional stimuli are needed because in the absence of these stimuli, most fish drift towards the codend without seeking escape through the selection device. However, in the present study, despite the implementation of different stimuli, hake had very low probability of encountering the SMP. This, together with the SMP's release efficiency curves, underscores the low effectiveness of the

SMP in releasing undersized individuals of this species when inserted in the upper panel of the extension piece and regardless of the presence of the stimuli. In addition, underwater observations made during the cruise demonstrated that hake did not display any active escape behavior; instead they fell back through the extension piece until reaching the aft end of the gear. This behavior and the observed preference for swimming close to the lower panel, also observed in other species (e.g. cod (*Gadus morhua*)) (Sistiaga et al., 2011, 2017), makes it difficult to improve the efficiency of the SMP (Alzorriz et al., 2016; Nikolic et al., 2015). Previous research (Grimaldo et al., 2017) also documented the low effectiveness of similar stimulators on the release efficiency of cod through a square mesh section.

Horse mackerel showed a contact probability of between 0 and 3% for the different configurations tested. Thus, the estimated release efficiency of the SMP for this species was low and not significantly different from the no-stimulation treatment. Earlier studies (Herrmann et al., 2014; Krag et al., 2016b) showed that escape stimulation by similar floats through a SMP, placed on the upper part of the codend and the extension piece, respectively, significantly improved the escapement of cod. Grimaldo et al. (2017) also indicated that the use of mechanical stimulation based on floats could improve the release efficiency of 40 cm haddock (*Melanogrammus aeglefinus*) through a square mesh section by 50% (although these results were not statistically significant). In this study, we observed that fish tried to avoid contact with the stimulators based on ropes and floats by swimming in front of them until reaching exhaustion and then drifting towards the codend.

Blue whiting, compared to hake and horse mackerel, showed higher contact probability with the panel, which was between 20 and 26% for no-stimulation, stimulation by ropes, and LED light-based stimulation treatments. In general, and supported by underwater observations, their active swimming behaviour seemed to increase the contact probability with the SMP. In particular, when stimulation by floats was used to trigger fish escape, blue whiting showed higher contact probability (53%), and the estimated release efficiency of the SMP for individuals below 18 cm was between 47.6 and 53.1%. Compared to the treatment without stimulation, the estimated release efficiency for blue whiting between 10 and 15 cm was significantly improved, by almost 30%. However, this effect had no impact on codend size selectivity because codend selection properties would release any small individual retained in the first selection process by the panel. Therefore, any change in panel selectivity for small blue whiting would not be evident in the combined retention probability. Additionally, the assessment of the release efficiency with float stimulation was based on few hauls (3 hauls). The hauls not included were heavily subsampled, which would have highly affected the results. This resulted in a weaker experimental base for these results, which is reflected in the wider confidence bands for the size selection curves obtained. Therefore, following the protocol established, the analyses were carried out with a considerably lower number of hauls. Even if limiting the number of hauls in the analysis meant using fewer hauls than often applied for such assessment, we considered this as the most correct approach. The number of hauls with these configurations was lower than we would normally recommend for making definitive conclusions. Therefore, our results for these designs should be considered as preliminary, but still relevant.

Our results also suggest that blue LED light stimulation decreased the escape probability through the SMP of blue whiting individuals between 15 and 27 cm. In general, blue LED light affected the escape probability of blue whiting negatively, although these results were only significant for a specific length range. This effect was reflected in the combined retention of the trawl, which was significantly higher for some length classes. Quality of the underwater images for the light treatment was not sufficient to analyze fish behaviour, but active behavior of this species was observed in the other three treatments when light was used to obtain underwater images (Table 2). The behavior of blue whiting could be compared with what Grimaldo et al. (2017) described for haddock when they got close to the green light stimulators placed on the extension piece of the trawl. These haddocks exhibited erratic behaviour when approaching the LED lights, which led them to hit the netting in a way that did not allow them to make contact with the SMP. This could explain the low release efficiency of blue whiting when LED lights were used compared to no-stimulation treatment. Many studies have demonstrated that visual stimulation may affect fish behaviour and the selective properties of trawl gear (Hannah et al., 2015; Larsen et al., 2018; Lomeli and Wakefield, 2014; Ryer and Olla, 2000; Walsh and Hickey, 1993). The processes through which light affects marine fish are still not completely understood because being attracted or repulsed by light depends on many factors, including species, ontogenetic development, ecological factors, light intensity, and light wavelength (Marchesan et al., 2005). In this study, lights were used during many hauls to illuminate the recordings (Table 2), which could have affected fish behaviour. However, lights were needed to check for adequate performance of the trawl and the research trials were time limited, thus we could not repeat these hauls to include non-illuminated hauls in the data analysis.

For all species and treatments, most of the escape was observed in the codend, and the contribution of the SMP was low. These results are in agreement with the observations of Brčić et al. (2016, 2018), who concluded that a SMP inserted in front of the codend had little effect on the escapement of hake, horse mackerel, and other species in a Mediterranean bottom trawl fishery. Alzorriz et al. (2016) also reported 47% escape of undersized hake through the codend, and less than 1% through the SMP. Our findings revealed no improvement in size selection for hake by inserting a SMP together with any of the stimulators and that individuals below their MCRS still had a high probability of being retained by the gear.

Previous studies on Portuguese crustacean trawl fishery (Campos and Fonseca, 2004) showed that a window made of 100 mm square meshes positioned in the upper panel of the belly section, 3.3 m before the codend, was efficient at excluding blue whiting but not horse mackerel. Graham et al. (2003) found that moving the panel closer to the codline increased the *L50* for haddock. Herrmann et al. (2014) found that the release efficiency of the SMP in the BACOMA codend largely depended on how close the panel was to the catch-accumulation zone (0–6 m from the codline). Compared to these studies, the panel distance from the codline in our study (10 m) may have been one of the reasons for the poor efficiency of the panel, as fish in the extension piece had no chance to change direction and swim up through the panel meshes even if stimulated. Other researchers also have mentioned that fish are exhausted when they reach the SMP area, so they are unable to attempt active escape (Winger et al., 2010) or may be reluctant to change swimming direction to save energy (Peake and Farrell, 2006). Besides, the towing speed during the hauls in our study was around 3 knots, whereas in real conditions a commercial trawl would tow at 4 knots, which could lead to greater exhaustion when the catch arrives in the extension piece.

Alzorriz et al. (2016) demonstrated that under commercial fishing operations, the selective properties of the trawls deployed by the Basque bottom otter trawl fleet in the Bay of Biscay did not satisfactorily release undersized individuals due to low contact. In the present study, we showed that the stimulators used to increase contact probability with the SMP were mostly ineffective, and the retention of undersized fish was still high. Hake did not react significantly to any of the stimulation treatments, whereas a significantly higher proportion of horse mackerel and blue whiting escaped through the SMP. These results indicate a clear behavioral difference compared to hake. Although this study provided greater understanding of fish behaviour inside the trawl, the contribution of the SMP to overall escape was unsatisfactory. Considering the new CFP, unwanted catches still represent a major challenge for this fishery. In order to comply with the LO, this may have a direct influence on each vessel's ability to optimize its economic revenue. Therefore, future studies should focus on maximizing SMP contact probability or improving codend release efficiency. Alternatively, future studies could also consider investigating the applicability of other bycatch reduction devices like sorting grids in this fishery.

5. Acknowledgements

We are grateful to the crew of *Emma Bardan* for their valuable assistance during the cruise. We also thank the two anonymous reviewers for the comments that helped to improve this manuscript. Finally, we are thankful to the MAPAMA for funding the research and lending the *RV Emma Bardan*.

6. References

Akaike, H., 1974. A new look at the statistical model identification. IEEE Trans. Autom. Control, 19, 716–722. doi:10.1109/TAC.1974.1100705. https://10.1109/TAC.1974.1100705

Alzorriz, N., Arregi, L., Herrmann, B., Sistiaga, M., Casey, J., Poos, J. J., 2016. Questioning the effectiveness of technical measures implemented by the Basque bottom otter trawl fleet: Implications under the EU landing obligation. Fish. Res. 175, 116-126. https://doi.org/10.1016/j.fishres.2015.11.023

Anderson, L. G., 1994. An economic analysis of highgrading in ITQ fisheries regulation programs. Mar. Res. Econ. 9(3), 209-226. https://doi.org/10.1086/mre.9.3.42629081

Bertrand, J. A., De Sola, L. G., Papaconstantinou, C., Relini, G., Souplet, A., 2000. An international bottom trawl survey in the Mediterranean: the MEDITS programme. Actes de Colloques-IFREMER, 76-96. http://www.ices.dk/sites/pub/CM%20Doccuments/1997/Y/1997_Y03.pdf

Brčić, J., Herrmann, B., Sala, A., 2016. Can a square-mesh panel inserted in front of the codend improve the exploitation pattern in Mediterranean bottom trawl fisheries?. Fish. Res. 183, 13-18. https://doi.org/10.1016/j.fishres.2016.05.007

Brčić, J., Herrmann, B., Sala, A., 2017. Can a square-mesh panel inserted in front of the cod end improve size and species selectivity in Mediterranean trawl fisheries?. Can. J. Fish. Aq. Sci. 75(5), 704-713. https://doi.org/10.1139/cjfas-2017-0123

Briggs, R. P., 1992. An assessment of nets with a square mesh panel as a whiting conservation tool in the Irish Sea Nephrops fishery. Fish. Res. 13(2), 133-152. https://doi.org/10.1016/0165-7836(92)90023-M

Catchpole, T. L., Frid, C. L. J., Gray, T. S. 2005. Discards in North Sea fisheries: causes, consequences and solutions. Mar. Pol. 29(5), 421-430. https://doi.org/10.1016/j.marpol.2004.07.001

Campos, A., Fonseca, P., 2004. The use of separator panels and square mesh windows for by-catch reduction in the crustacean trawl fishery off the Algarve (South Portugal). Fish. Res. 69(2), 147-156. https://doi.org/10.1016/j.fishres.2004.05.009

De Vos, B. I., Döring, R., Aranda, M., Buisman, F. C., Frangoudes, K., Goti, L., Machere, C., Maravelias, C. D., Murillas-Maza, A., van der Valk, O., Vasilakopoulos, P., 2016. New modes of fisheries governance: implementation of the landing obligation in four European countries. Mar. Pol. 64, 1-8. https://doi.org/10.1016/j.marpol.2015.11.005

Dorel, D. 1986. .Poissons de l'Atlantique nord-est: Relations taille-poids. IFREMER Report. pp. 165. https://archimer.ifremer.fr/doc/1986/rapport-1289.pdf

EC, 1996. COUNCIL REGULATION (EC) No 2406/96 of 26 November 1996 laying down common marketing standards for certain fishery products. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31996R2406&from=ES

EC, 2001a. Commission Regulation (EC) No 1162/2001 of 14 June 2001 establishing measures for the recovery of the stock of hake in ICES sub-areas III, IV, V, VI and VII and ICES divisions VIII a, b, d, e and associated conditions for the control of activities of fishing vessels. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32001R1162&qid=1507798251399&from=EN

EC, 2001b. Commission Regulation (EC No 2602/2001 of 27 December 2001 establishing additional technical measures for the recovery of the stock of hake in ICES subareas III, IV, V, VI and VII and ICES Divisions VIIIa,b,d,e, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32001R2602&qid=1507798298100&from=EN

EC, 2002. Commission Regulation (EC) No 494/2002 of 19 March 2002 establishing additional technical measures for the recovery of the stock of hake in ICES sub-areas III, IV, V, VI and VII and ICES divisions VIII a, b, d, e. Official Journal of the European Communities L77/8.http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32002R0494&from=EN.

EC, 2004. Council Regulation (EC) No 811/2004 of 21 April 2004 Establishing Measures for the Recovery of the Northern Hake Stock (2004). http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32004R0811&qid=1507799156511&from=EN

EC, 2006. Council Regulation (EC) No. 51/2006 of 22 December 2005 fixing for 2006 the fishing opportunities and associated conditions for certain fish stocks and groups of fish stocks, applicable in Community waters and, for Community vessels, in waters where catch limitations are required. Official Journal of the European UnionL. 16, 148-149. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006R0051&from=EN

EC, 2008. Commission Regulation (EC) No 517/2008 of 10 June 2008 laying down detailed rules for the implementation of Council Regulation (EC) No 850/98 as regards the determination of the mesh size and assessing the thickness of twine of fishing nets. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008R0517&from=GA

Efron, B., 1982. The jackknife, the bootstrap and other resampling plans. SIAM Monograph No. 38, CBSM-NSF.

EU, 2013. Regulation (EU) No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013R1380&from=EN

Fonteyne, R., Buglioni, G., Leonori, I., O'Neill, F.G., Fryer, R.J., 2007. Laboratory and field trials of OMEGA, a new objective mesh gauge. Fish. Res. 85, 197–201. https://doi.org/10.1016/j.fishres.2007.02.006

Franco, J. 2007. Environmental effects of fishing gears and the socioeconomic consequences of their modification, substitution or suppression. IP/B/PECH/IC/2006-179. PE 375.312. pp. 180. http://www.europarl.europa.eu/RegData/etudes/etudes/join/2007/375312/IPOL-PECH_ET(2007)375312_EN.pdf (accessed 22 March 2019)

Fryer, R.J., 1991. A model of between-haul variation in selectivity. ICES J. Mar. Sci. 48, 281–290. https://doi.org/10.1093/icesjms/48.3.281

Gillespie, A., 2002. Wasting the oceans: searching for principles to control bycatch in international law. Int. J. Mar. Coast. Law. 17(2), 161-193. https://doi.org/10.1163/157180802X00017

Glass, C.W., Wardle, C.S., 1995. Studies on the use of visual stimuli to control fish escape from codends. II. The effect of a black tunnel on the reaction behaviour of fish in otter trawl codends. Fish. Res. 23, 165–174. https://doi.org/10.1016/0165-7836(94)00331-P

Graham, N., Kynoch, R. J., Fryer, R. J., 2003. Square mesh panels in demersal trawls: further data relating haddock and whiting selectivity to panel position. Fish. Res. 62, 361–375. https://doi.org/10.1016/S0165-7836(02)00279-5

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

Haig, N. 2008. EAE-ko arrantzarako plan estrategikoa 2008-2003 Plan estratégico de pesca de la CAPV. Sustrai: revista agropesquera, ISSN 0213-330X, 84, pp. 42-46.

Hannah, R. W., Lomeli, M. J., Jones, S. A., 2015. Tests of artificial light for bycatch reduction in an ocean shrimp *(Pandalus jordani)* trawl: strong but opposite effects at the footrope and near the bycatch reduction device. Fish. Res. 170, 60-67. https://doi.org/10.1016/j.fishres.2015.05.010

Herrmann, B., Sistiaga, M., Nielsen, K.N., Larsen, R.B., 2012. Understanding the size selectivity of redfish (Sebastes spp.) in North Atlantic trawl codends. J. North Atl. Fish. Sci. 44, 1-13. http://hdl.handle.net/10037/5030

Herrmann, B., Wienbeck, H., Karlsen, J. D., Stepputtis, D., Dahm, E., Moderhak, W., 2014. Understanding the release efficiency of Atlantic cod *(Gadus morhua)* from trawls with a square mesh panel: effects of panel area, panel position, and stimulation of escape response. ICES J. Mar. Sci, 72(2), 686-696. https://doi.org/10.1093/icesjms/fsu124

Herrmann, B., Krag, L. A., & Krafft, B. A., 2018. Size selection of Antarctic krill *(Euphausia superba)* in a commercial codend and trawl body. Fish. Res. 207, 49-54. https://doi.org/10.1016/j.fishres.2018.05.028

Iriondo, A., Prellezo, R., Santurtún, M., Garcia, D., Quincoces, I., Mugerza, E., 2008. Basque trawl metier definition for 2003–2007 period. In: Working Document for the ICES WGHMM 2008, (Copenhagen, Denmark 30 April 6 May 2008). https://www.azti.es/rim/wp-content/uploads/2014/01/revista_marina_03.pdf

Iriondo, A., Prellezo, R., Santurtún, M., Garcia, D., Quincoces, I., Mugerza, E., 2010. A multivariate approach for metier definition: a case study of Basque Country trawlers. Rev. Invest. Mar. 17(6), 2010. https://www.azti.es/rim/wp-content/uploads/2010/05/rim17_6.pdf

Kelleher, K., 2005. Discards in the world's marine fisheries. An update. *FAO Fisheries Technical Paper.* 470, pp131.

Kim, Y. H., Whang, D. S., 2010. An actively stimulating net panel and rope array inside a model cod-end to increase juvenile red seabream escapement. Fish. Res. 106(1), 71-75. https://doi.org/10.1016/j.fishres.2010.07.005

Krag, L. A., Herrmann, B., Feekings, J., Lund, H. S., Karlsen, J. D., 2016a. Improving escape panel selectivity in Nephrops-directed fisheries by actively stimulating fish behavior. Can. J. Fish. Aq. Sci. 74(4), 486-493. https://doi.org/10.1139/cjfas-2015-0568

Krag, L. A., Herrmann, B., Feekings, J., Karlsen, J. D., 2016b. Escape panels in trawls–a consistent management tool?. *Aq. Liv. Res.*, 29(3), 306. https://doi.org/10.1051/alr/2016028

Larsen, R.B., Isaksen, B., 1993. Size selectivity of rigid sorting grids in bottom trawls for Atlantic cod *(Gadus morhua)* and haddock *(Melanogrammus aeglefinus)*. ICES Mar. Sci. Symp. 196, 178–182. http://www.ices.dk/sites/pub/Publication%20Reports/Marine%20Science%20Symposia/ICES%20Marine%20Science%20Symposia%20-%20Volume%20196%20-%201993%20-%20Part%2039%20of%2045.pdf

Larsen, R. B., Herrmann, B., Sistiaga, M., Brčić, J., Brinkhof, J., Tatone, I., 2018. Could green artificial light reduce bycatch during Barents Sea Deep-water shrimp trawling?. Fish. Res. 204, 441-447. https://doi.org/10.1016/j.fishres.2018.03.023

Lomeli, M. J. M., Wakefield, W. W., 2014. *Examining the potential use of artificial illumination to enhance Chinook salmon escapement out a bycatch reduction device in a Pacific hake midwater trawl*. NMFS Northwest Fisheries Science Center Report, pp. 15. https://www.psmfc.org/bycatch/documents/LomeliWakefield2014Chinook.pdf

Marchesan, M., Spoto, M., Verginella, L., Ferrero, E. A., 2005. Behavioural effects of artificial light on fish species of commercial interest. Fish. Res., 73, 171–185. https://doi.org/10.1016/j.fishres.2004.12.009

MEDITS, 2016. MEDITS-Handbook Version 8, MEDITS Working Group, pp. 25-31. http://www.sibm.it/MEDITS%202011/docs/Medits_Handbook_2016_version_8_042016.pdf

Nikolic, N., Diméet, J., Fifas, S., Salaün, M., Ravard, D., Fauconnet, L., Rochet, M.J., 2015. Efficacy of selective devices in reducing discards in the Nephrops trawl fishery in the Bay of Biscay. ICES J. Mar. Sci. 72(6), 1869-1881 http://dx.doi.org/10.1093/icesjms/fsv036.

O'Neill, F.G., Kynoch, R.J., Fryer, R.J. 2006. Square mesh panels in North Sea demersal trawls: separate estimates of panel and codend selectivity. Fish. Res. 78, 333–341. https://doi.org/10.1016/j.fishres.2005.12.012

Pascoe,S.,1997.Bycatch management and the economics of discarding. In: FAO Fisheries Technical Paper 370. FAO, Rome, p. 137.

Peake, S.J., Farrell, A.P. 2006. Fatigue is a behavioural response in respirometer confined smallmouth bass. J. Fish Biol. 68, 1742–1755. https://doi.org/10.1111/j.0022-1112.2006.01052.x

Rochet, M.J., Arregi, L., Fonseca, T., Pereira, J., Pérez, N., Ruiz, J., Valeiras J., 2014. Demersal discard atlas for the South Western Waters. pp. 121. http://www.repositorio.ieo.es/e-ieo/handle/10508/9074

Ryer, C. H., Olla, B. L., 2000. Avoidance of an approaching net by juvenile walleye pollock *Theragra chalcogramma* in the laboratory: The influence of light intensity. Fish. Res. 45(2), 195–199. https://doi.org/10.1016/S0165-7836(99)00113-7

Santos, J., Herrmann, B., Otero, P., Fernandez, J., Pérez, N., 2016. Square mesh panels in demersal trawls: does lateral positioning enhance fish contact probability?. Aq. Liv. Res. 29(3), 302. https://doi.org/10.1051/alr/2016025

Santurtún, M., Prellezo, R., Arregi, L., Iriondo, A., Aranda, M., Korta, M., Onandia, I., Garcia, D., Merino, G., Ruiz, J., Andonegi, E., 2014. Characteristics of multispecific fisheries in the European Union. IP/B/PECH/IC/2013-088. PE 529.053. pp. 102. http://www.europarl.europa.eu/RegData/etudes/etudes/join/2014/529053/IPOL-PECH_ET(2014)529053_EN.pdf (accessed 20 October 2018)

Schrope, M., 2010. What's the catch?. Nature. 465, 540-542. DOI: 10.1038/465540a

Sistiaga, M., Herrmann, B., Grimaldo, E., Larsen, R. B., 2010. Assessment of dual selection in grid based selectivity systems. Fish. Res. 105(3), 187-199. https://doi.org/10.1016/j.fishres.2010.05.006

Sistiaga, M., Herrmann, B., Nielsen, K. N., Larsen, R. B., 2011. Understanding limits to cod and haddock separation using size selectivity in a multispecies trawl fishery: an application of FISHSELECT. Can. J. Fish. Aq. Sci. 68(5), 927. https://doi.org/10.1139/f2011-0173

Sistiaga, M., Herrmann, B., Grimaldo, E., Larsen, R. B., Olsen, L., Brinkhof, J., Tatone, I., 2017. Combination of a sorting grid and a square mesh panel to optimize size selection in the North-East Arctic cod *(Gadus morhua)* and redfish (*Sebastes* spp.) trawl fisheries. ICES J. Mar. Sci. 75(3), 1105-1116. https://doi.org/10.1093/icesjms/fsx231

Uhlmann, S. S., van Helmond, A.T. M., Stefánsdóttir, E. K., SigurÐardóttir, S., Haralabous, J., Maria Bellido, J., Carbonell, A., Catchpole, T., Damalas, D., Fauconnet, L., Feekings, J., Garcia, T., Madsen, N., Mallold, S., Margeirsson, S., Palialexis, A., Readdy, L., Valeiras, J., Vassilopoulou, V., Rochet, M.J., 2013. Discarded fish in European waters: general patterns and contrasts. ICES J. Mar. Sci. 71, 1235–1245. http://dx.doi.org/10.1093/icesjms/fst030

Walsh, S. J., Hickey, W. M., 1993. Behavioural reactions of demersal fish to bottom trawls at various light conditions. ICES Mar. Sci. Symp 196: 68–76. http://www.ices.dk/sites/pub/Publication%20Reports/Marine%20Science%20Symposia/ICES%20Marine%20Science%20Symposia%20-%20Volume%20196%20-%201993%20-%20Part%2017%20of%2045.pdf

Wileman, D. A., Ferro, R. S. T., Fonteyne, R., Millar, R. B., (Ed.), 1996. Manual of methods of measuring the selectivity of towed fishing gears. ICES Coop. Res. Rep. No. 215. ISBN 10: UCSD:31822025768078.

Winger, P. D., Eayrs, S., Glass, C. W., 2010. Fish behaviour near bottom trawls. In Behavior of marine fishes: capture processes and conservation challenges. Edited by P. He. Wiley–Blackwell, Ames, Iowa. pp. 67–103. ISBN: 978-0-81381536-7.

Zuur, G., Fryer, R. J., Ferro, R. S. T., Tokai, T., 2001. Modelling the size selectivities of a trawl codend and an associated square mesh panel. ICES J. Mar. Sci. 58(3), 657-671. https://doi.org/10.1006/jmsc.2001.1049

TABLES

Table 1. Specifications of the gear used during the cruise.

	Codend *(CD)*	**Codend cover *(CC)***	**SMP**	**SMP cover *(PC)***	**Extension piece**
Twine material	Doubled braided Polisteel	Single braided PA	Single braided PA	Single braided PA	Single braided PE
Thickness (mm)	4	1.3	3	1.3	3
Mesh size* (mm)	72.8	26.5	82.7	26.1	75.3
Length (m)	7	9	2.2	13	5
Width (m)	-	-	1.2	-	-

*Measured with an OMEGA gauge (Fonteyne et al., 2007) according to EC, 2008.

Table 2.- Camera specifications corresponding to each haul and configuration tested. Light color corresponds to the light attached to the camera.

Haul nº	**Stimulator**	**Position of the cameras (light color: red (R) or white (W) or none (N))**
8	None	Lower panel, joint between codend and extension piece (W)
13	Ropes	Lower panel, behind the SMP (W).
14	Ropes	Lower panel, behind the SMP (W).
15	Ropes	Lower panel, behind the SMP (W).
16	Ropes	Lower panel, behind the SMP (W) and Upper panel, before the SMP (R).
18	Ropes	Lower panel, behind the SMP (W).
23	LED lights	Upper panel, before the SMP (N).
25	LED lights	Over the codend, in between the codend cover and the codend (W).
26	LED lights	Over the codend, in between the codend cover and the codend (W) and Upper panel, before the SMP (W).
28	Floats	Lower panel, behind the SMP (W).
31	Floats	Upper panel, before the SMP (W).
32	Floats	Over the codend cover (W) and Lower panel, behind the SMP (W).
34	Floats	In the codend (W) and on the float line, behind the floats (W).
35	Floats	On the float line, behind the floats (W).
36	None	Over the codend, in between the codend cover and the codend (W) and over the codend cover (W).
37	None	On the float line, behind the floats (W).

Table 3. Summary of hauls used, no. of individuals retained in the codend (*CD*), codend cover (*CC*), and SMP cover (*PC*), no. of individuals < MCRS, and length range of all individuals caught. The number of fish measured is given in brackets. [1]MCRS for hake: 27 cm; [2]MCRS for horse mackerel: 15 cm; [3]blue whiting does not have a MCRS but it has a minimum marketable size of 30 individuals/Kg (EC, 1996). This is equivalent to 18 cm in length according to the weight-length ratio for this species (Dorel, 1986).

Stimulation/design	**No-stimulation**	**Ropes**	**Floats**	**LED lights**
Hake				
No. of hauls used	8	6	6	8
Lenght range (cm)	7-58	7-56	8-58	7-60
Total no. in *CD*	1015 (1015)	543 (543)	832 (832)	1045 (1045)
No. in *CD* < MCRS[1]	621 (621)	325 (325)	412 (412)	497 (497)
Total no. in *CC*	986 (986)	375 (267)	473 (473)	697 (647)
No. in *CC* < MCRS[1]	983 (983)	367 (263)	465 (465)	695 (645)
Total no. in *PC*	16 (16)	6 (6)	11 (11)	11 (11)
No. in *PC* < MCRS[1]	10 (10)	4 (4)	7 (7)	7 (7)
Horse mackerel				
No. of hauls used	7	5	6	7
Lenght range (cm)	10-35	10-36	10-35	10-39
Total no. in *CD*	1222 (926)	2378 (465)	1344 (876)	1745 (768)
No. in *CD* < MCRS[2]	292 (235)	300 (65)	419 (245)	502 (257)
Total no. in *CC*	839 (644)	6500 (476)	3839 (838)	1886 (496)
No. in *CC* < MCRS[2]	733 (564)	3491 (249)	3442 (739)	1705 (440)
Total no. in *PC*	37 (37)	69 (69)	19 (19)	106 (106)
No. in *PC* < MCRS[2]	23 (23)	23 (23)	13 (13)	68 (68)
Blue whiting				
No. of hauls used	8	6	3	6
Lenght range (cm)	7-31	8-31	10-32	10-31
Total no. in *CD*	1619 (936)	1037 (556)	333 (333)	1209 (513)
No. in *CD* < MCRS[3]	47 (40)	21 (11)	17 (17)	67 (39)
Total no. in *CC*	5512 (1033)	2894 (544)	2132 (533)	4290 (471)
No. in *CC* < MCRS[3]	5184 (914)	2570 (459)	2016 (504)	4213 (461)
Total no. in *PC*	2387 (1015)	1227 (609)	2438 (598)	1121 (383)
No. in *PC* < MCRS[3]	1914 (606)	926 (395)	2258 (550)	1060 (358)

Table 4. Selected models based on the lowest AIC values, selectivity results and fit statistics are shown for the different species, configuration, and compartment (square mesh panel (*SMP*); codend (*CD*) and combined effect of the codend and the SMP (Comb)). 95% CIs (in brackets).

		Hake			
Stimulation/Design		**No-stimulation**	**Ropes**	**Floats**	**LED lights**
Models	***SMP***	*CLogit*	*CLogit*	*CLogit*	*CLogit*
	CD	*Richard*	*Gompertz*	*Gompertz*	*Logit*
***L50* (cm)**					
SMP		37.07 (21.22–37.10)	30.03 (0.10–30.07)	36.06 (0.10–36.08)	29.99 (24.05–30.04)
CD		16.95 (16.02–17.92)	17.32 (15.43–19.53)	17.37 (16.18–18.28)	17.35 (16.20–18.40)
Comb		16.98 (16.05–17.95)	17.36 (15.45–19.59)	17.42 (16.21–18.32)	17.37 (16.23–18.44)
***SR* (cm)**					
SMP		0.10 (0.10–7.42)	0.10 (0.10–19.16)	0.10 (0.10–0.10)	0.10 (0.10–0.10)
CD		4.37 (3.45–5.11)	5.88 (3.58–8.02)	5.51 (4.33–7.00)	3.71 (2.90–4.34)
Comb		4.41 (3.48–5.17)	5.96 (3.60–8.11)	5.59 (4.43–7.03)	3.74 (2.92–4.38)
C_{SMP}		0.01 (0.00–0.02)	0.01 (0.00–0.03)	0.01 (0.00–0.02)	0.01 (0.00–0.02)
Deviance		59.29	82.57	53.72	44.51
DOF		82	77	77	89
p-Value		0.972	0.311	0.980	1.000

		Horse mackerel			
Stimulation/Design		**No-stimulation**	**Ropes**	**Floats**	**LED lights**
Models	***SMP***	*CLogit*	*CLogit*	*CPogit*	*CProbit*
	CD	*Gompertz*	*Gompertz*	*Gompertz*	*Logit*
***L50* (cm)**					
SMP		28.00 (0.10–56.70)	23.04 (17.58–61.92)	24.05 (15.03–62.02)	30.01 (0.10–30.02)
CD		14.11 (13.23–14.69)	16.96 (15.61–20.13)	15.48 (14.24–16.49)	14.77 (14.48–15.09)
Comb		14.16 (13.34–14.74)	16.99 (15.65–20.13)	15.49 (14.25–16.49)	14.84 (14.54–15.18)
***SR* (cm)**					
SMP		0.10 (0.10–53.69)	0.10 (0.10–6.34)	0.10 (0.10–6.67)	0.10 (0.10–43.11)
CD		2.71 (2.26–3.38)	3.94 (2.67–6.22)	3.03 (2.47–4.06)	2.61 (2.16–3.24)
Comb		2.80 (2.30–3.48)	3.99 (2.72–6.18)	3.05 (2.50–4.10)	2.70 (2.23–3.36)
C_{SMP}		0.02 (0.01–0.66)	0.01 (0.00–0.02)	0.00 (0.00–0.01)	0.03 (0.01–0.32)
Deviance		45.57	36.45	67.61	53.82
DOF		47	35	45	49
p-Value		0.532	0.401	0.016	0.295

		Blue whiting			
Stimulation/Design		**No-stimulation**	**Ropes**	**Floats**	**LED lights**
Models	***SMP***	*CGompertz*	*CGompertz*	*CGompertz*	*CGompertz*
	CD	*Richard*	*Logit*	*Richard*	*Logit*
***L50* (cm)**					
SMP		27.62 (23.14–34.76)	30.59 (0.10–38.43)	25.75 (11.77–94.93)	20.57 (0.10–25.14)
CD		20.76 (19.06–21.59)	21.36 (20.36–22.20)	22.42 (21.44–22.99)	19.31 (16.77–20.76)
Comb		21.70 (20.47–22.25)	22.33 (21.12–23.63)	23.73 (21.81–25.45)	19.74 (17.09–21.20)
***SR* (cm)**					
SMP		8.99 (0.10–15.73)	15.48 (0.10–66.87)	10.93 (0.10–60.27)	6.12 (1.80–14.75)
CD		3.44 (2.67–4.41)	3.94 (2.87–4.59)	3.16 (1.87–4.35)	3.71 (2.88–4.25)
Comb		4.81 (3.26–10.56)	5.55 (3.65–7.58)	5.05 (2.56–69.53)	3.98 (3.06–4.61)
C_{SMP}		0.27 (0.21–0.38)	0.26 (0.10–0.86)	0.53 (0.46–1.00)	0.20 (0.13–0.90)
Deviance		105.10	105.10	51.84	79.07
DOF		40	40	34	31
p-Value		<0.001	<0.001	0.026	<0.001

Table 5. Values of exploitation pattern indicators and their 95% CIs (in brackets) for all species in the different panel configurations. [1]MCRS for hake: 27 cm; [2] MCRS for horse mackerel: 15 cm; [3]blue whiting does not have a MCRS but it has a minimum marketable size of 30 individuals/Kg (EC, 1996), and this is equivalent to 18 cm in length according to the weight:length ratio for this species (Dorel, 1986).

	Hake[1]			
Stimulation/Design	**No-stimulation**	**Ropes**	**Floats**	**LED lights**
rP-	38.48 (34.76–41.81)	46.63 (32.94–61.78)	46.61 (36.40–55.16)	41.45 (30.31–54.30)
rP+	97.77 (95.61–99.45)	96.04 (87.14–100)	97.22 (94.07–98.82)	98.92 (97.33–100.00)
esP-	0.62 (0.22–1.15)	0.57 (0.00–1.41)	0.79 (0.00–1.93)	0.58 (0.09–1.13)
esP+	1.49 (0.25–3.19)	0.88 (0.00–3.14)	0.93 (0.00–1.86)	0.72 (0.00–2.44)
resP-	1.01 (0.36–1.86)	1.08 (0.00–3.18)	1.48 (0.00–3.61)	1.00 (0.16–1.93)
resP+	66.67 (12.50–100)	22.22 (0.00–100)	33.33 (0.00–88.89)	66.67 (0.00–100.00)
	Horse mackerel[2]			
Stimulation/Design	**No-stimulation**	**Ropes**	**Floats**	**LED lights**
rP-	27.77 (12.17–46.57)	7.87 (2.18–16.34)	10.81 (4.23–34.91)	22.12 (17.35–27.33)
rP+	88.57 (84.04–94.69)	40.48 (16.92–64.09)	69.65 (53.35–85.19)	85.13 (74.30–90.87)
esP-	2.19 (0.56–4.64)	0.60 (0.21–1.51)	0.34 (0.03–0.82)	2.99 (1.14–6.82)
esP+	1.33 (0.43–2.25)	0.90 (0.43–1.75)	0.45 (0.06–1.13)	2.60 (1.21–4.31)
resP-	3.04 (0.86–7.50)	0.65 (0.23–1.66)	0.38 (0.03–0.93)	3.83 (1.46–8.56)
resP+	11.67 (5.31–20.75)	1.51 (0.76–4.57)	1.49 (0.17–5.88)	17.51 (6.38–29.17)
	Blue whiting[3]			
Stimulation/Design	**No-stimulation**	**Ropes**	**Floats**	**LED lights**
rP-	0.66 (0.26–1.57)	0.60 (0.06–1.19)	0.40 (0.00–1.09)	1.25 (0.37–4.21)
rP+	66.29 (61.03–72.01)	61.95 (54.12–71.75)	51.63 (36.17–84.38)	89.36 (80.32–98.35)
esP-	26.78 (20.98–37.25)	26.34 (4.87–38.81)	52.62 (45.41–63.87)	19.87 (9.93–29.94)
esP+	19.96 (13.42–30.30)	18.35 (11.14–25.85)	29.41 (0.00–42.75)	4.69 (0.69–8.95)
resP-	26.96 (21.06–37.57)	26.49 (4.92–38.87)	52.83 (45.44–64.56)	20.12 (10.26–30.54)
resP+	59.20 (40.77–84.42)	48.24 (34.79–69.38)	60.81 (0.00–71.54)	44.12 (17.33–84.38)

FIGURES

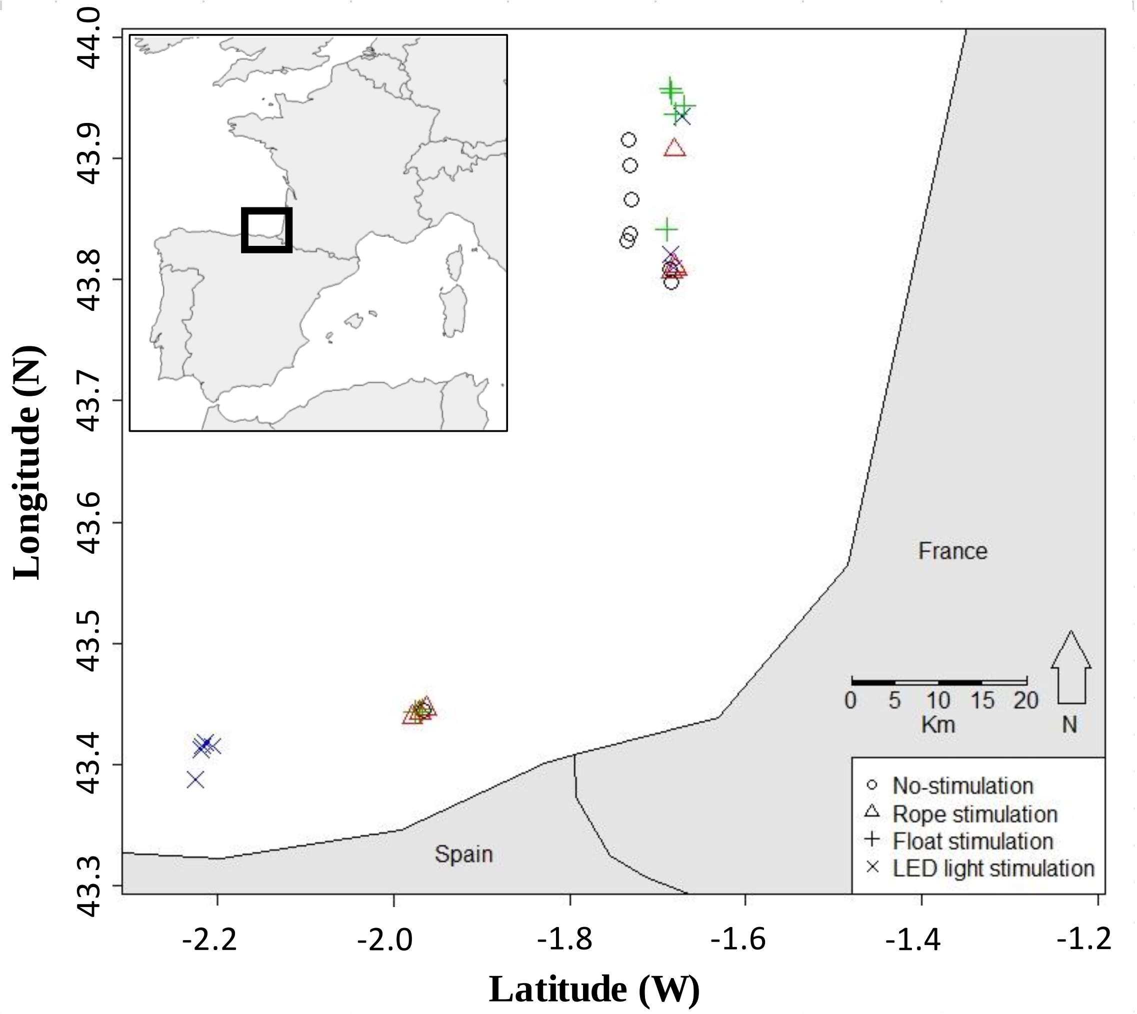

Figure 1. Sampling area and fishing position for all hauls conducted during the cruise.

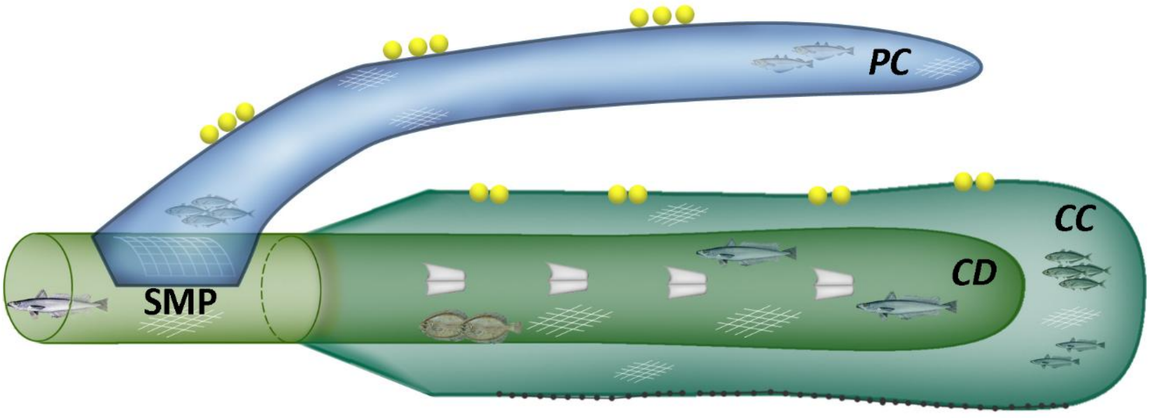

Figure 2. Scheme of the module built with the square mesh panel (SMP), codend (*CD*), and the different net covers (SMP cover (*PC*) and codend cover (*CC*)) used to collect the escapement.

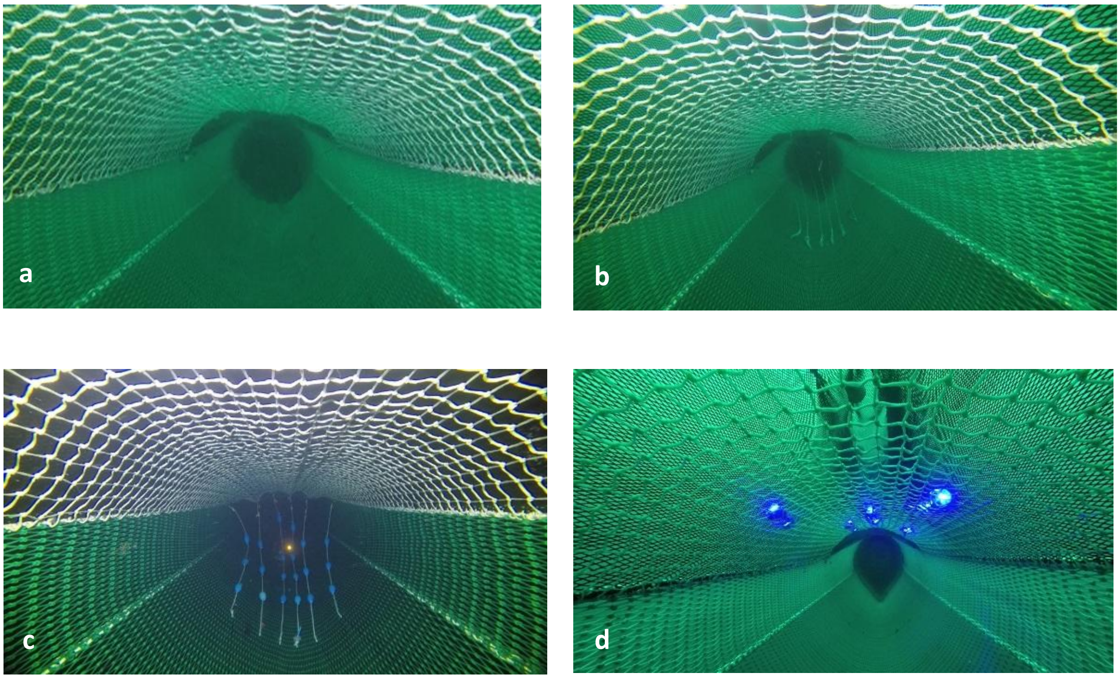

Figure 3. Different configurations tested on the SMP: (a) no-stimulation; (b) stimulation by ropes; (c) stimulation by floats; (d) LED light-based stimulation.

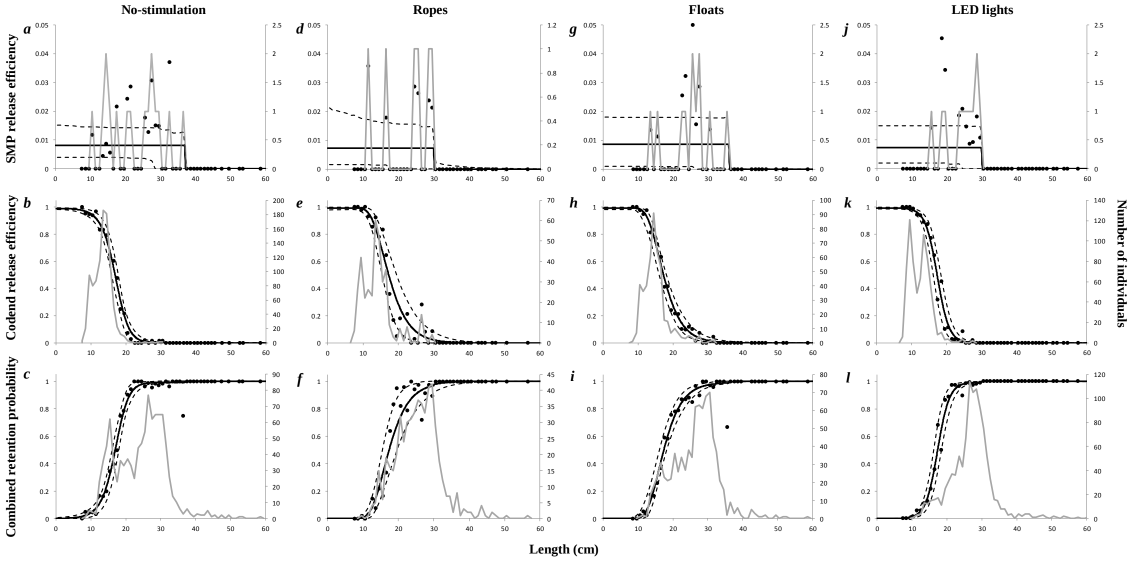

Figure 4. Relative catch size-frequency distributions (grey lines) of hake retained in the codend (*CD*), codend cover (*CC*), and SMP cover (*PC*), the mean escapement curves (solid black lines) for SMP escapement (*a*, *d*, *g*, *j*), codend escapement (*b*, *e*, *h*, *k*), and combined retention (combined effect of the codend and the SMP) (*c*, *f*, *i*, *l*). All of them

show 95% CIs (dashed lines). *Note that the y-axis for SMP release efficiency has a different order of magnitude in order to properly observe the data.

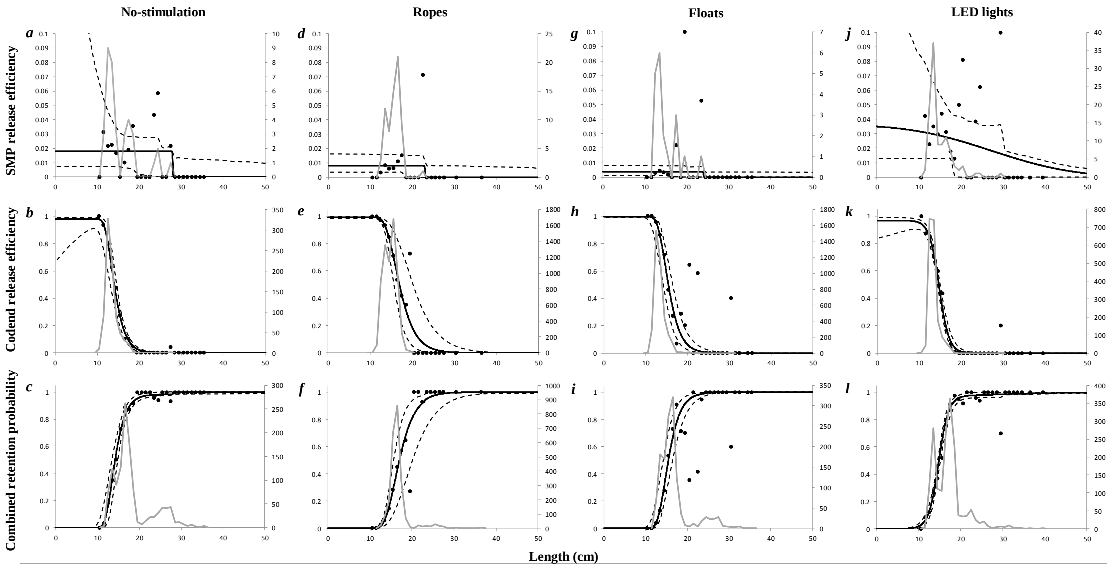

Figure 5. Relative catch size-frequency distributions (grey lines) of horse mackerel retained in the codend (*CD*), codend cover (*CC*), and SMP cover (*PC*), the mean escapement curves (solid black lines) for SMP escapement (*a*, *d*, *g*, *j*), codend escapement (*b*, *e*, *h*, *k*), and combined retention (combined effect of the codend and the SMP) (*c*, *f*, *i*, *l*). All of them show 95% CIs (dashed lines). *Note that the y-axis for SMP release efficiency has a different order of magnitude to properly observe the data.

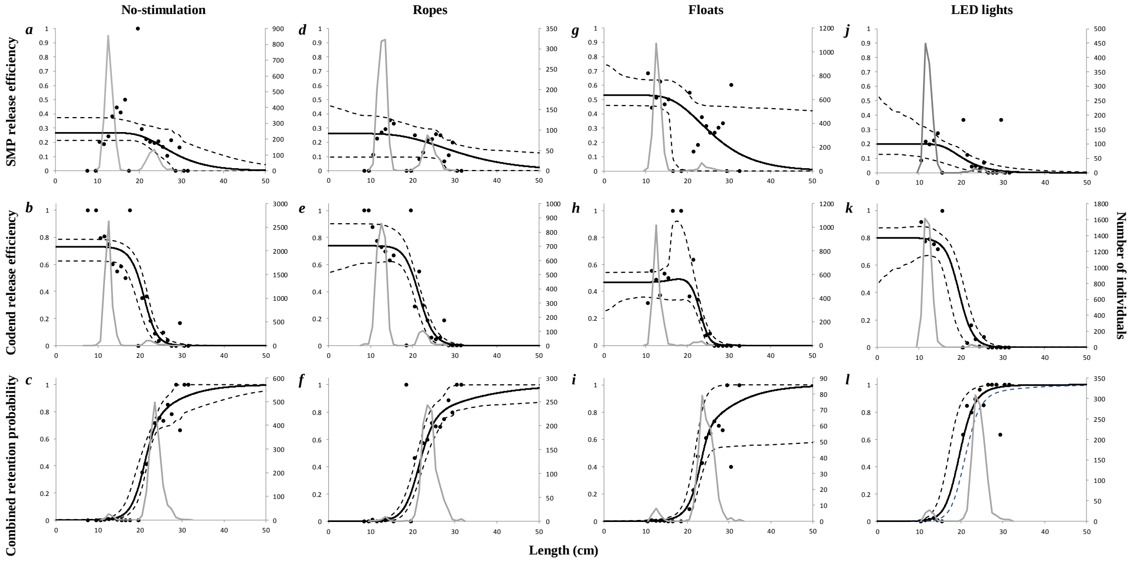

Figure 6. Relative catch size-frequency distributions (grey lines) of blue whiting retained in the codend (*CD*), codend cover (*CC*), and SMP cover (*PC*), the mean escapement curves (solid black lines) for SMP escapement (*a*, *d*, *g*, *j*),

codend escapement (*b, e, h, k*), and combined retention (combined effect of the codend and the SMP) (*c, f, i, l*). All of them show 95% CIs (dashed lines).

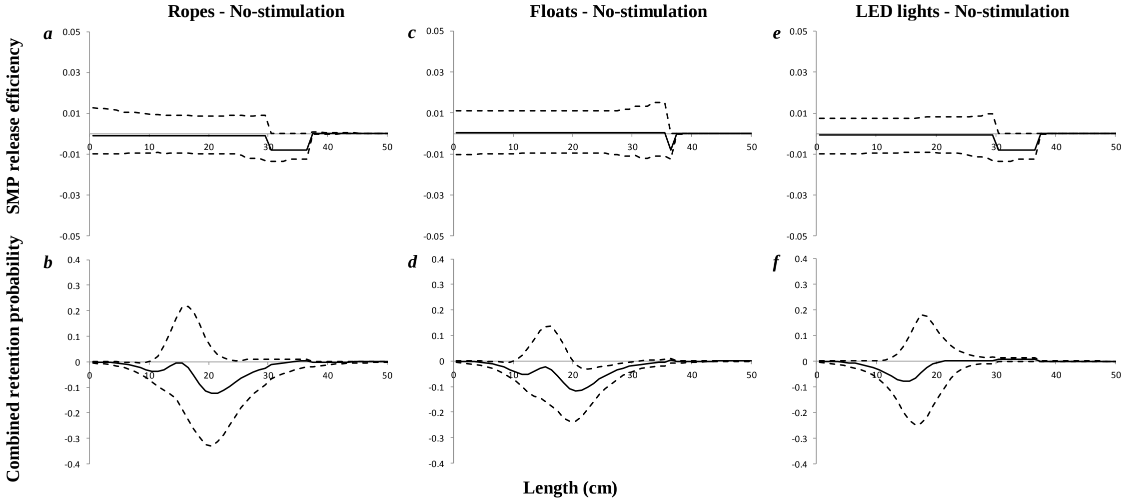

Figure 7. Change in SMP release efficiency (*a, c, e*) and in combined retention (*b, d, f*) for hake. Dashed lines represent 95% CIs. * Note that the y-axis for SMP release efficiency has a different order of magnitude to properly observe the data.

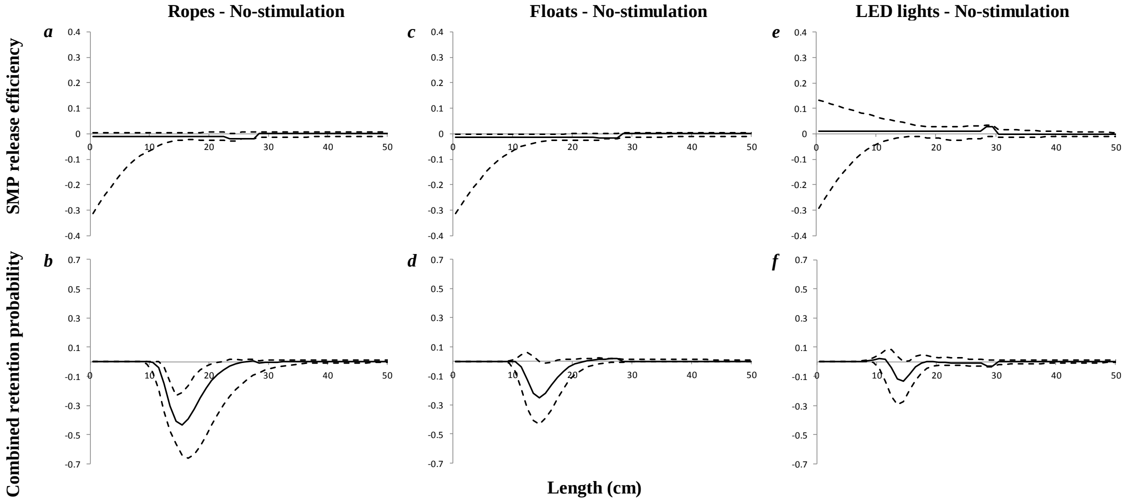

Figure 8. Change in SMP release efficiency (*a, c, e*) and in combined retention (*b, d, f*) for horse mackerel. Dashed lines represent 95% CIs. * Note that the y-axis for SMP release efficiency has a different order of magnitude to properly observe the data.

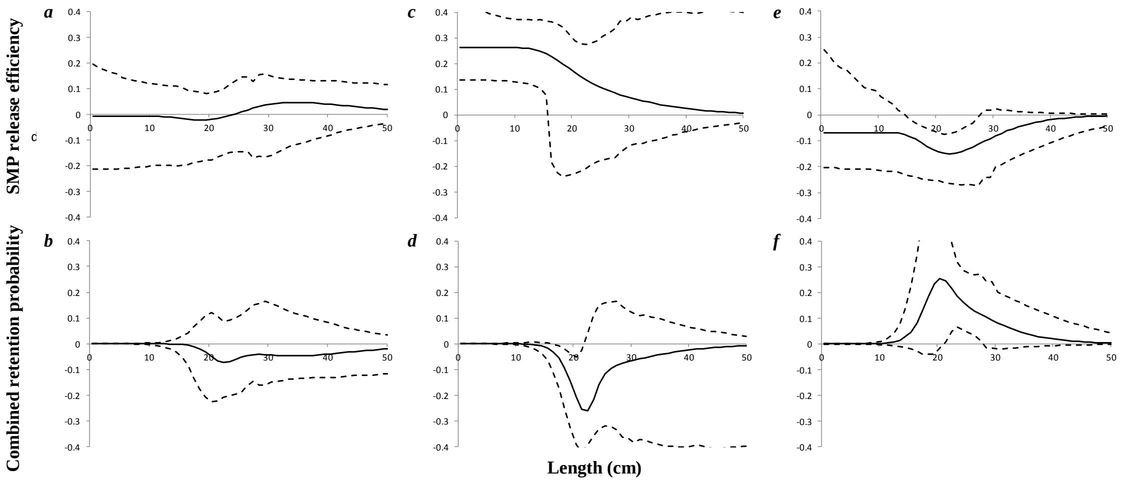

Figure 9. Change in SMP release efficiency (*a, c, e*) and in combined retention (*b, d, f*) for blue whiting. Dashed lines represent 95% CIs. * Note that the y-axis for SMP release efficiency has a different order of magnitude to properly observe the data.