NRC Research Press

ARTICLE

Improving release efficiency of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the Barents Sea demersal trawl fishery by stimulating escape behaviour

Eduardo Grimaldo, Manu Sistiaga, Bent Herrmann, Roger B. Larsen, Jesse Brinkhof, and Ivan Tatone

Abstract: We tested the ability of stimulators to improve the release efficiency of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) through the meshes of a square mesh section installed in a trawl. The section was tested in three different configurations: without any stimulation device, with a mechanical stimulation device, and with LED light stimulation devices. We analysed and compared the behaviour of cod and haddock in all three configurations based on release results and underwater recordings. Parallel to the fishing trials, we carried out fall-through tests to determine the upper physical size limits for cod and haddock to be able to escape through the square meshes in the section. This enabled us to infer whether lack of release efficiency was due to fish behaviour or release potential of the square meshes in the section. The results showed that the escape behaviour of haddock can be triggered by mechanical stimulation. In contrast, cod did not react significantly to the presence of mechanical stimulators. LED light stimulation had some effect on the behaviour of haddock, but not on cod.

Résumé : Nous avons vérifié la capacité de stimulateurs d'améliorer l'efficacité de la libération de morues (*Gadus morhua*) et d'aiglefins (*Melanogrammus aeglefinus*) par les mailles d'une section de mailles carrées installée dans un chalut. La section a été mise à l'essai selon trois configurations différentes, soit sans aucun instrument de stimulation, avec un instrument de stimulation mécanique et avec des instruments de stimulation à lumière DEL. Nous avons analysé et comparé le comportement des morues et des aiglefins dans les trois configurations à la lumière des résultats de libération et d'enregistrements sous l'eau. Parallèlement aux essais de pêche, nous avons mené des essais de passage par gravité afin de déterminer les limites supérieures des tailles auxquelles les morues et aiglefins peuvent s'évader par les mailles carrées dans la section. Cela nous a permis d'établir si l'absence d'une libération efficace était due au comportement des poissons ou au potentiel de libération des mailles carrées dans la section. Les résultats montrent que le comportement d'évasion des aiglefins peut être déclenché par une stimulation mécanique. Les morues, au contraire, n'ont pas présenté de réaction significative à la présence de stimulateurs mécaniques. La stimulation à la lumière DEL a eu un certain effet sur le comportement des aiglefins, mais pas sur celui des morues. [Traduit par la Rédaction]

Introduction

In 2015 the stock of Northeast Arctic cod (*Gadus morhua*) was estimated to be around 3.2 million tonnes (www.imr.no). Because of this abundance, the trawlers fishing in the Barents Sea often encounter high densities of this species, which compromises the effectiveness of the fish release processes in the gear and the control of catch sizes. The compulsory size selectivity device for the trawlers targeting cod and haddock (*Melanogrammus aeglefinus*) in the Barents Sea consists of a rigid sorting grid with a minimum bar spacing of 55 mm and a diamond mesh cod end with a minimum mesh size of 130 mm. Fishermen are allowed to use three different grid systems: the Sort-X double grid system (Larsen and Isaksen 1993); the Sort-V single grid system (Jørgensen et al. 2006; Herrmann et al. 2013); and the Flexigrid double grid system (Sistiaga et al. 2016). The sorting area of these grids is limited, and fishermen report that fish accumulate in front and behind the sorting grids at high catch rates (>10 t·h^{-1}). Because fish do not fall back to the rearmost part of the cod end, the catch sensors placed in the cod end do not provide a true picture of the amount of fish that actually is in the gear.

Alternative selectivity devices for fish release, such us square mesh panels, can provide a larger sorting area than that provided by sorting grids. They can also be strategically inserted in front of the cod end so that fish have the opportunity to escape before entering the rearmost part of the cod end, where risk for injury is highest (Suuronen et al. 1996; Madsen 2007). However, obtaining satisfactory escape patterns with square mesh panels can be challenging. Fish tend to stay clear of the netting in the trawl and are often reluctant to change swimming direction inside the trawl, which is why trawls are such an effective fishing gear (Wardle 1993). Cod, for example, are known to enter the trawl close to the fishing line and mainly follow a path close to the lower netting panel in the trawl unless stimuli are used to raise their vertical position (Main and Sangster 1981, 1985; Ferro et al. 2007; Krag et al. 2009; Rosen et al. 2012). Furthermore, unlike haddock (Tschernij and Suuronen 2002; Grimaldo et al. 2007), cod appear to have a low activity level when inside trawls (Briggs 1992; Rosen et al. 2012).

Received 4 January 2017. Accepted 26 April 2017.

E. Grimaldo* and M. Sistiaga.* SINTEF Fisheries and Aquaculture, Brattørkaia 17C, N-7010 Trondheim, Norway.
B. Herrmann.* SINTEF Fisheries and Aquaculture, Brattørkaia 17C, N-7010 Trondheim, Norway; The Arctic University of Norway, UiT, Breivika, N-9037 Tromsø, Norway.
R.B. Larsen, J. Brinkhof, and I. Tatone. The Arctic University of Norway, UiT, Breivika, N-9037 Tromsø, Norway.
Corresponding author: Eduardo Grimaldo (email: Eduardo.Grimaldo@sintef.no).
*Equal authorship.

These behaviours make it particularly challenging to achieve sufficient release efficiency for cod through square mesh panels, which often are inserted in the upper (or side) panel(s) of the trawl. Grimaldo et al. (2009, 2014) showed that the escape of cod through square mesh panels placed in the cod end is mainly related to the haul back operation and that decompression is the stimulus that triggers the escape behaviour.

Over the years, different stimulating devices designed to trigger fish escape behaviour have been tested in different fisheries around the world with different degrees of success. Glass and Wardle (1995) found that a black tunnel increased the proportion of haddock and whiting (*Merlangius merlangus*) escaping through a square mesh panel positioned 5–7 m in front of the cod line. Kim and Whang (2010) reported that introducing physical contact stimuli reduced the retention rate of juvenile red sea bream (*Pagrus major*) in the cod end. In a more recent study, Herrmann et al. (2014) showed how stimulating devices can increase the escape of cod through a square mesh panel. Light stimulation devices have shown potential for inducing escape behaviour of fish from bottom trawls. Rose and Hammond (2014) showed that while green Lindgren–Pitman Electralume LED lights attached to the footrope of a survey trawl had no significant effect on escape rates of flathead sole (*Hippoglossoides elassodon*) and Alaska pollock (*Gadus chalcogrammus*), use of the same lights resulted in an approximately three times higher escape rate for southern rock sole (*Lepidopsetta bilinetata*). Hannah et al. (2015) attached the same lights to a shrimp trawl footgear to illuminate the escape path under the net, and their results consistently showed a fish bycatch reduction of 90% for eulachon (*Thaleichthys pacificus*), 82% and 56% for darkblotched rockfish (*Sebastes crameri*) and other rockfish species (*Sebastes* spp.), respectively, and 69% for diverse flatfish. As documented in these studies, both mechanical and light-based stimulators can trigger fish escape behaviour and increase the escape rate of different species of fish.

The main goal of the present study was to determine if the escape behaviour of cod and haddock in a square mesh section can be improved by mechanical and (or) light-based stimulation. Specifically, we conducted experiments designed to answer the following research questions:

- Does mechanical or light-based stimulation increase the release efficiency of cod and haddock in a square mesh section?
- Do cod and haddock react to the same extent to the stimulation devices?
- What are the size limits on the release of cod and haddock from the square mesh section, and how does assessment of these limits contribute to understanding the behaviour of cod and haddock in the square mesh section?
- Are the release properties for cod and haddock from the square mesh section comparable to or better than those of the compulsory grid sections?

Materials and methods

Research vessel, study area, and gear setup

Experimental fishing was conducted on board the R/V *Helmer Hanssen* (63.8 m length overall and 4080 horsepower; 1 horsepower = 746 W) between 29 February and 9 March, 2016. The fishing grounds chosen for the tests were located off the coast of Finnmark (northern Norway) between 70°29′N–70°52′N and 30°08′E–31°44′E.

We used an Alfredo No. 3 two-panel Euronete trawl built entirely of 155 mm nominal mesh size (nms) polyethylene (PE) netting (single diameter (Ø) 4 mm braided knotted twine). The trawl had a headline of 36.5 m, a fishing line of 19.2 m, and 454 meshes of circumference. It was rigged with a set of bottom trawl doors (Injector Scorpion type, 8 m², 3200 kg each), 60 m sweeps, and 111 m ground gear. Each of the sides of the ground gear had five 53 cm (diameter) steel bobbins distributed on a 46 m chain (Ø 19 mm). We installed a 19.2 m long rockhopper in the centre of the ground gear. The rockhopper was built with 53 cm rubber discs and attached to the fishing line of the trawl. To facilitate opening of the trawl, the headline of the trawl was equipped with 170 (Ø 20 cm diameter) plastic floats.

We built a four-panel square mesh section of single Ø 10 mm braided knotless Ultracross netting. The mean mesh size of the section, estimated from 40 measurements (2 × 20 mesh rows) taken with an International Council for the Exploration of the Sea gauge (Westhoff et al. 1962), was 141.03 ± 1.67 mm (mean ± SD). The section was 56 meshes long (~4.3 m) and had 48 meshes of circumference (approximate Ø 1.2 m under operation). All four selvedges in the section were strengthened with 30 mm Danline PE ropes. We built a transition diamond mesh section to connect the two-panel trawl belly to the four-panel square mesh section. It was made using 138 mm nms Euroline Premium PE knotted netting (single Ø 8.0 mm braided twine) and was 35.5 meshes long.

A four-panel diamond-mesh cod end was attached to the four-panel square mesh section. It was made from 138 mm nms Euroline Premium PE knotted netting (Polar Gold) (single Ø 8 mm braided twine). The cod end was 40 meshes long (~6.2 m) and had 80 meshes of circumference (approximate Ø 1 m). All four selvedges were strengthened by 30 mm Danline PE ropes. The cod end was completely blinded by an inner net constructed of 52 mm nms Euroline Premium PE knotted netting (Ø 2.2 mm single twine).

Stimulation devices

We tested three different square mesh section configurations: (*i*) without a stimulation device (Fig. 1*a*), (*ii*) with a mechanical stimulation device (Fig. 1*b*), and (*iii*) with an LED light-based stimulation device (Fig. 1*c*). Mechanical stimulation was created in the square mesh section by inserting two rows of fluttering lines with floats in the lower panel of the section. Each row consisted of seven lines of floats, and each 120 cm line contained seven smaller floats (JD115 type, 0.115 kg buoyancy each) and a bigger one at the top (SP5 type, 0.850 kg buoyancy each). The lines were attached to the bottom panel of the square mesh section using spring hooks. When towing, the fluttering lines with floats covered approximately two-thirds of the cross-sectional area of the square mesh section (Fig. 1*b*). This stimulation device was designed to create a physical barrier with dynamic movements that would trigger the escape behaviour of fish entering the section.

LED light stimulation was created using eight green Electralume underwater fishing lights (Lindgren–Pitman, Pompano Beach, Florida, USA). These lights feature power-sparing LEDs, and two AA batteries provide approximately 350 h of battery life. Four of these lights were placed at the centre of the square mesh section to scare fish towards the side panels. These lights were maintained in the centre by SP5 floats. The other four lights were attached to each of the selvedges of the section; they were located 20 meshes further back from the first four lights to stimulate fish escapement through the square meshes (Fig. 1*c*).

Collection of release efficiency data and underwater recordings

We applied the covered-cod-end method to collect all fish escaping through the meshes of the square mesh section (Wileman et al. 1996). The cover (CC in Fig. 2) was constructed of four panels and was made entirely of square meshes of 60 mm nms Euroline Premium PE knotted netting (single Ø 2.2 mm braided twine). It had a total length of approximately 14 m and a diameter of 2.4 m. The cover covered the square mesh section and the blinded cod end from approximately 2 m in front of the square mesh section. At the front of the cover six plastic floats (Ø 20 cm) were attached to its upper panel, and a 3 m long 8 mm chain (weighing ~12 kg) was fixed to its lower panel. In addition, three kites were attached to each of the side panels of the cover to help it expand around the square mesh section. Twelve additional kites (three per panel) were fixed to the cover to secure its expansion in front of the bulk

Fig. 1. Schematic representation of the experimental setup showing the square mesh section without stimulators (*a*), with the mechanical stimulation devices (*b*), and with the LED light stimulation devices (*c*). The position of the lights is indicated in green. [Colour online.]

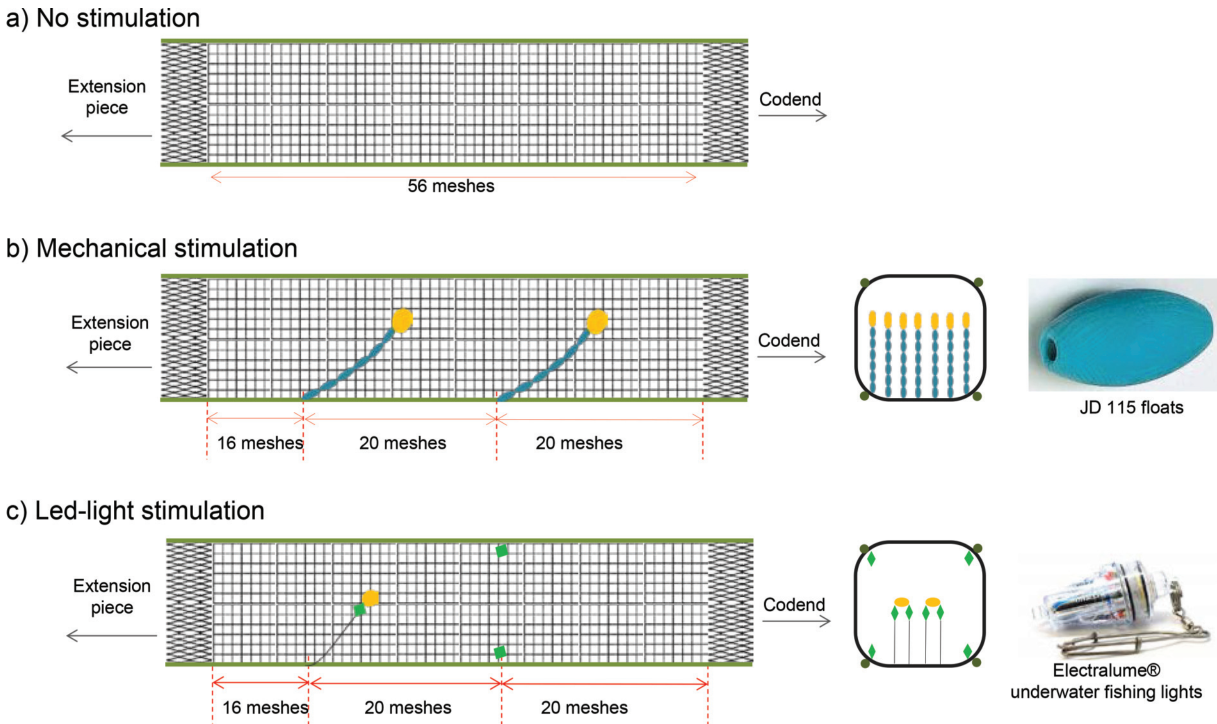
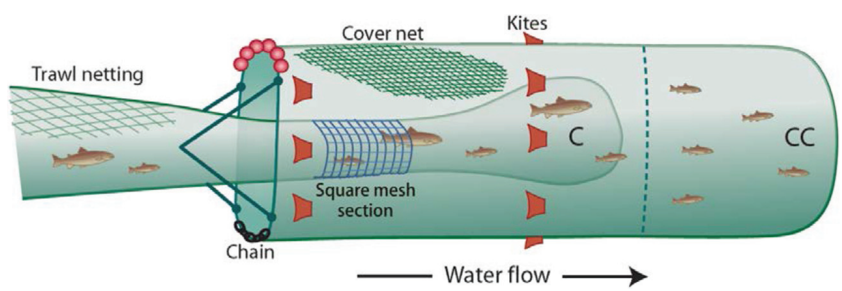


Fig. 2. Schematic representation of the experimental setup showing the square mesh section, the cod end (C), and the small mesh cod end (CC). [Colour online.]



catch in the cod end (C in Fig. 2). All cod and haddock above 20 cm in total length present in the cod end or the cover were measured to the nearest centimetre. There was no subsampling.

Underwater video observations were done to determine if the cover was functioning correctly and to study fish behaviour with respect to the stimulation devices. We used a GoPro Hero 4 black edition HD camera system (Riverside, California, USA) for the recordings. During daylight and depths down to approximately 70 m, we did not use artificial light for the recordings. Otherwise, to provide appropriate illumination, we used a Metalsub FL 1255 halogen lamp (1500 lm and 3200 K) connected to a Metalsub FX 1209 Dual battery pack (http://www.metalsub.nl/). A piece of red plastic film was fixed to the halogen lamp to turn the white light to red light to reduce the impact of artificial light on fish behaviour (Anthony and Hawkins 1983). The camera was attached to the top panel of the square mesh section facing backwards towards the stimulation devices.

Modelling the size-dependent release efficiency for fish entering the square mesh section

Two conditions must be met for a fish entering the square mesh section of the trawl to escape through one of the meshes in the section: first, the fish needs to contact the mesh and attempt to pass or squeeze itself through; second, the fish attempting to pass or squeeze itself through the meshes needs to be morphologically able to do so. The first condition is related to the behaviour of the fish inside the square mesh section, whereas the second relates to the morphology of the fish and the size-selective properties of the square mesh netting. In fishing gear selectivity studies involving square mesh panels, this dual condition for escapement is often modelled by a contact factor. This contact factor quantifies the fraction of fish making contact with the netting in a way that provides the fish with a size-dependent probability of being able to escape. For the fish contacting the meshes, the probability that they subsequently escape by passing or squeezing themselves through a mesh is quantified by a logistic size selection curve. Examples for using this modelling approach for studying size selection of square mesh panels in trawls include Zuur et al. (2001), O'Neill et al. (2006), and Alzorriz et al. (2016). A limitation of this modelling approach is that it assumes the contact probability to be the same for all sizes of fish that would be able to pass or squeeze themselves through the meshes. Therefore, when using this modelling approach, a potential length-dependent contact probability is only compensated for in the curve by the values estimated for the selection parameters. This results in strong limitations on which types of size-dependent escape behaviour it would be able to model.

In the current study in which we investigated two different species and three different section configurations, considerably different length-dependent escape behaviours could occur. Thus, the model applied by Zuur et al. (2001), O'Neill et al. (2006), and Alzorriz et al. (2016) would probably not be sufficiently flexible to describe the size-dependent release efficiency in the square mesh section for all of our cases. Furthermore, we could not decide beforehand on a specific model structure for each of the individual cases. Considering this, we chose to describe the size-dependent release efficiency in the square mesh section using a flexible empirical group of models that avoided the problem of having to choose one specific model for each of the tested cases. The drawback of this modelling approach is the loss of explicit quantification of the contribution of fish behaviour to the size-dependent release efficiency (contact probability). However, in the next section (Estimation of release size limits) we describe how we regain this ability.

The size-dependent release efficiency was established by analysing the catch data. The catch data included numbers and sizes of cod and haddock collected separately in the cod end and in the cover for the group of hauls ([1, …, h]). The haul data belonging to the three cases investigated (no stimulation, mechanical stimulation, LED light stimulation) were analysed following the procedure described below.

The experimental data consisted of binominal count data for the different length groups of each of the species (1 cm wide). They were binominal because fish were observed either in the cod end or in the cover. We used these data to estimate the curvature of a model for size-dependent release efficiency in the square mesh section $r(l)$. $r(l)$ was averaged over hauls for the specific case investigated using maximum likelihood estimation by minimizing the following equation:

$$(1)\qquad -\sum_{l}\sum_{i=1}^{h}\{\mathrm{nc}_{li}\times\ln[r(l,\boldsymbol{v})]+\mathrm{ncc}_{li}\times\ln[1-r(l,\boldsymbol{v})]\}$$

where $\boldsymbol{v}$ represents the parameters describing the release efficiency curve $r(l, \boldsymbol{v})$ and nc_{li} and ncc_{li} are the numbers of fish belonging to length class l that were retained in haul i in the cod end and the cover, respectively.

The next step was to find an empirical model for $r(l, \boldsymbol{v})$ that was sufficiently flexible to account for the curvature considering all of the different cases. We adapted a flexible model for $r(l, \boldsymbol{v})$ often applied for evaluating the efficiency of fishing gear in catch comparison studies (Krag et al. 2014, 2015). This model has also been applied to model size selection of Greenland halibut (*Reinhardtius hippoglossoides*) in a sorting grid (Herrmann et al. 2013):

$$(2)\qquad r(l,\boldsymbol{v})=\frac{\exp[f(l,\boldsymbol{v})]}{1.0+\exp[f(l,\boldsymbol{v})]}$$

where f is a polynomial of order k with coefficients $v_0, \ldots, v_k$, so $\boldsymbol{v} = (v_0, \ldots, v_k)$. We used $f(l, \boldsymbol{v})$ of the following form:

$$(3)\qquad f(l,\boldsymbol{v})=\sum_{i=0}^{4}v_i\times\left(\frac{l}{100}\right)^i=v_0+v_1\times\frac{l}{100}+v_2\times\frac{l^2}{100^2}+\ldots+v_4\times\frac{l^4}{100^4}$$

Leaving out one or more of the parameters $v_0 \ldots v_4$ in eq. 3 provided 31 additional models that were considered as potential models to describe $r(l, \boldsymbol{v})$. Based on these models, model averaging was applied to describe $r(l, \boldsymbol{v})$. We called the resulting model the combined model. In the combined model, the individual models were ranked and weighted according to their Akaike's information criterion (AIC) values (Akaike 1974; Burnham and Anderson 2002). Models yielding AIC values within +10 of the value of the model with the lowest AIC were considered to contribute to $r(l, \boldsymbol{v})$ based on the procedure described by Katsanevakis (2006) and Herrmann et al. (2014). One advantage of using this combined model approach is that we did not have to choose one specific model to describe the release efficiency among the different candidates. The ability of the combined model to describe the experimental data was assessed based on the p value, which expresses the likelihood of obtaining at least as large a discrepancy as that observed between the fitted model and the experimental data by coincidence. Therefore, for the combined model to be a candidate model, the p value should not be <0.05 (Wileman et al. 1996). In cases with poor fit statistics (p value <0.05; deviance $\gg$ degrees of freedom), the deviations between the experimental observed ground gear efficiency points and the fitted curve were examined to determine whether the discrepancy was due to structural problems in describing the experimental data with the combined model or to data overdispersion.

Confidence intervals (CIs) for the size-dependent release efficiency were estimated using a double bootstrap method (Millar 1993). The procedure accounted for uncertainty due to between-haul variation (Fryer 1991) in size selection in the square mesh section by selecting h hauls with replacement from the h hauls available from the pool of hauls for the specific case investigated during each bootstrap repetition. Within-haul uncertainty in the size structure of the catch data in the cod end and in the cover was accounted for by randomly selecting fish with replacement from each of the selected hauls separately from the cod end and the cover, respectively. The number of fish selected from each haul was the number of fish length measured in that haul in the cod end and cover, respectively. One thousand bootstrap repetitions were performed, and the Efron 95% CI (Efron 1982) was calculated for the size selection curve. Incorporating this combined model approach in each of the bootstrap repetitions enabled us to account for additional uncertainty in the release efficiency curve due to uncertainty in model selection (Herrmann et al. 2017). The release efficiency analysis was conducted using the software tool SELNET (Herrmann et al. 2012).

Estimation of release size limits

To determine whether the release efficiency was limited by fish behaviour (with the fish not making selectivity contact with the meshes in the square mesh section) or by the ability of the meshes in the section to release those sizes of fish, we conducted fall-through experiments. Fall-through experiments determine whether or not a fish can physically pass through a certain rigid shape (Sistiaga et al. 2011). These experiments were used to determine whether cod and haddock of different sizes could physically pass through the meshes of the square mesh section (pressed by the force of gravity). If a fish passed through the square meshes without deforming the mesh or fish tissue, it was classified as "YY". If a fish passed through the square meshes but deformed the mesh and (or) fish tissue, it was classified as "YN". Finally, if a fish could not pass through the squares meshes at all, it was classified as "NN". One hundred and ten cod and 83 haddock were first length-measured to the nearest centimetre and then used for fall-through experiments (see Herrmann et al. (2009) for further information about this methodology). Based on these measurements, we fitted a logistic size selection model to the data, treating them as covered-cod-end selectivity data (Wileman et al. 1996), to estimate two curves that describe the upper release limits: release without squeezing (free passage) (fish classified as YY versus fish classified as YN or NN) and release with squeezing (tight passage) (fish classified as YY or YN versus fish classified as NN). This analysis was conducted following the procedures described in Wileman et al. (1996) for estimating size selectivity in a single trawl haul based on covered-cod-end size selectivity data. The analysis was carried out using the software tool SELNET (Herrmann et al. 2012). To quantify

Table 1. Overview of the number of fish captured and length measured in each of the hauls included in the selectivity analyses.

		Cover				Cod end			
Stimulation device	Haul No.	*n* measured cod	Sampling rate	*n* measured haddock	Sampling rate	*n* measured cod	Sampling rate	*n* measured haddock	Sampling rate
None	2	0	1	23	1	84	1	122	1
	3	0	1	14	1	74	1	68	1
	4	2	1	1	1	28	1	11	1
	5	7	1	72	1	138	1	312	1
	6	3	1	699	0.18	62	1	938	0.39
	7	2	1	33	1	43	1	206	1
	8	0	1	16	1	116	1	63	1
	9	0	1	11	1	15	1	50	1
	10	0	1	9	1	16	1	36	1
	11	66	1	560	1	637	1	832	1
	12	22	1	244	1	601	1	653	1
Mechanical	13	7	1	1750	1	81	1	2386	1
	14	6	1	3762	1	52	1	2385	1
	15	3	1	242	1	8	1	247	1
	16	6	1	186	1	10	1	259	1
	17	4	1	159	1	22	1	145	1
	18	3	1	242	1	19	1	168	1
	19	2	1	697	1	30	1	399	1
	20	2	1	473	1	9	1	405	1
	21	2	1	45	1	8	1	56	1
	22	28	1	0	1	438	1	0	1
LED light	41	0	1	127	1	59	1	612	1
	42	0	1	72	1	25	1	303	1
	43	0	1	24	1	68	1	238	1
	44	0	1	71	1	57	1	593	1
	45	0	1	591	1	16	1	517	1
	46	4	1	7	1	43	1	43	1
	47	120	1	3	1	695	1	52	1

the release size limits based on the fall-through results, we calculated the size at which 95% of the fish would be able to escape given they made selectivity contact (L_{05}) and the size of fish at which only 5% would be able to escape given they made selectivity contact (L_{95}). This was done based on the estimated selection parameters L_{50} (length of fish with 50% probability of being retained) and SR (difference in length of fish with respectively 75% and 25% probability of being retained) and for both selectivity with and without squeezing separately. For a logistic size selection with selection parameters L_{50} and SR, L_{05}, and L_{95} can be calculated as follows (Krag et al. 2015):

$$(4) \quad \begin{aligned} L_{05} &= L_{50} + \frac{\mathrm{SR}}{\ln(9)} \times \ln\left(\frac{0.05}{0.95}\right) \\ L_{95} &= L_{50} + \frac{\mathrm{SR}}{\ln(9)} \times \ln\left(\frac{0.95}{0.05}\right) \end{aligned}$$

The release efficiency curves obtained for the fall-through experiments helped us interpret the release efficiency curves obtained for the square mesh section tested in the experimental fishing and identify behavioural patterns of cod and haddock.

Results

Overview of the sea trials

Fifty-seven hauls were carried out during the cruise, and release efficiency data were collected from 28 of them: 11 hauls without any stimulation device (baseline hauls), 10 hauls with mechanical stimulation, and seven hauls with LED light stimulation. Fish were not measured in the hauls in which underwater video recordings and artificial lights were used, and therefore they were not included in the release efficiency analyses. These hauls were used solely to identify behavioural patterns of cod and haddock in trawls with the three different square mesh section configurations. The tow duration during the cruise varied from 15 to 107 min, and the depth range covered varied between 46 and 410 m. The hauls that were used for release efficiency analysis with their respective description of the catch are presented in Table 1.

Underwater observations

Underwater video recordings showed very few cod attempting to escape through the meshes of the square mesh section when no stimulation device was used. Most cod simply glided backwards towards the cod end, staying clear of the netting and not showing any sign of panic. In a similar way, many haddock that would be able to escape through the meshes simply followed the clear path in the section away from the netting. Few fish showed erratic or escape behaviour in their path towards the cod end (Fig. 3).

When mechanical stimulators were introduced in the section (Fig. 4*a*), fish did react to the lines with floats and stopped in front of them (Fig. 4*b*). Most of the haddock stopped in front of the stimulator device. At this point most haddock started making escape attempts, and those that hit the net with the right orientation and were able to physically pass through the meshes escaped (Fig. 4*c*). Most cod also reacted to the stimulators by stopping in front of them (Fig. 4*d*), and some cod actually attempted and managed to escape through the meshes of the square mesh section (Fig. 4*e*). However, the percentage of haddock that was observed attempting to escape through the section meshes was substantially higher than that of cod. Thus, the experiments with the mechanical stimulators showed that cod and haddock react differently to the stimulators, as haddock seemed to react more actively to their presence.

When LED light stimulation was introduced in the section, haddock showed erratic behaviour when approaching the LED lights. In their attempts to avoid the light, many haddock turned and swam

Fig. 3. Underwater images showing the square mesh section without any stimulation device. Panel (*a*) shows three cod (C) swimming in the direction of the tow. Panel (*b*) shows few haddock (H) inside the section. Note that none of them attempts to escape. [Colour online.]

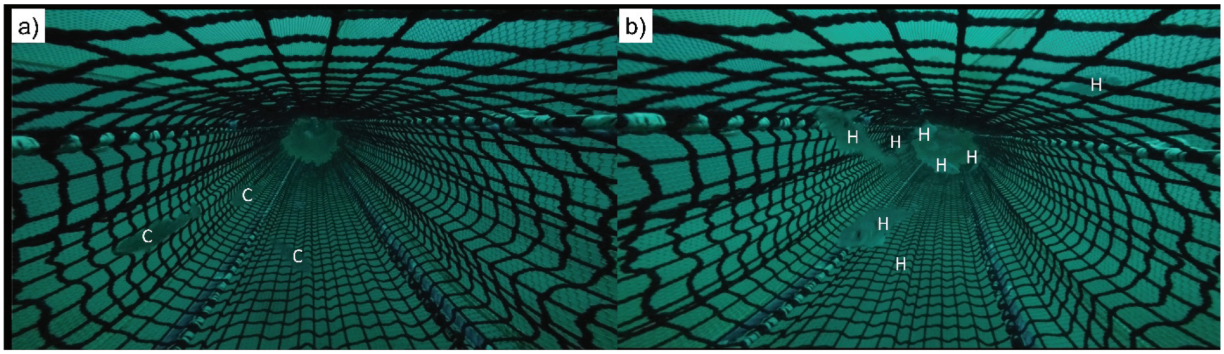
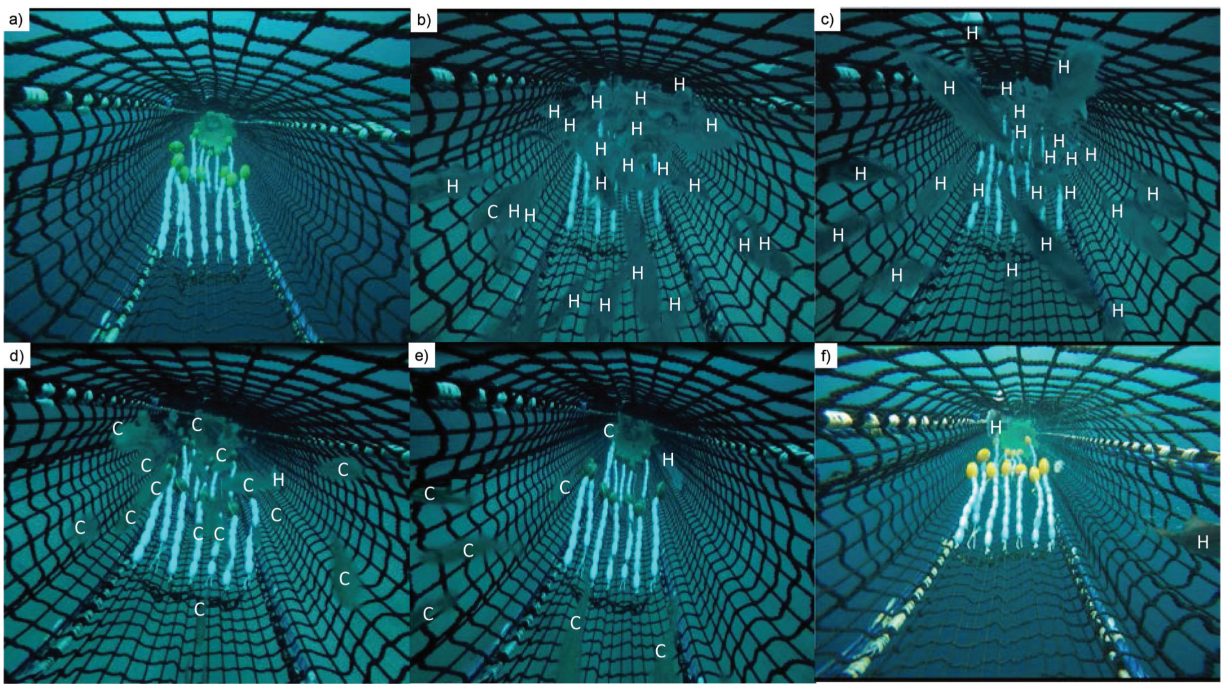


Fig. 4. Underwater images showing the mechanical stimulation device during the fishing operation: (*a*) the trawl at the fishing depth (79 m); (*b*) mostly haddock accumulated in front of the stimulators; (*c*) haddock in front of the stimulator and individuals escaping; (*d*) cod accumulated in front of the mechanical stimulators; (*e*) cod in front of the stimulators and one individual escaping; (*f*) a single haddock escaping from an empty section. [Colour online.]



quickly either towards the panels in the section or the cod end. The erratic and stressful movements of haddock resulted in many fish hitting the netting, but they were not optimally oriented for escape. The few haddock that oriented themselves correctly and could physically pass through the meshes escaped (Fig. 5*a*). Cod did not show the same dramatic escape behaviour as haddock, even though most of them stopped in front of the LED lights. They mostly kept swimming in front of the lights for a while before they fell back towards the cod end. However, a few cod did attempt to escape (Fig. 5*b*).

Fall-through results and release limits

The fit statistics for using the logistic curve to describe the size-dependent release efficiency of the square mesh section showed that the model, which in every case had a p value > 0.05, represented the fall-through data collected during the trials well (Table 2; Fig. 6). For free passage, 95% (L_{05}) of the haddock below 45 cm would freely be able to pass through the meshes, whereas few haddock up to 51 cm would be able to do so (L_{95}) (Table 2; Fig. 6). For tight passage, 95% (L_{05}) of haddock up to approximately 51 cm would be able to pass through the meshes, whereas few individuals of up to 61 cm (L_{95}) would be able to pass through. For cod with free passage, 95% (L_{05}) all individuals below 45 cm would freely be able to pass through the meshes, whereas few cod up to 58 cm would be able to do so (L_{95}). For tight passage, 95% (L_{05}) of cod up to approximately 52 cm would be able to pass through the meshes, whereas few individuals of up to 69 cm (L_{95}) would be able to pass through (Table 2; Fig. 6).

Release efficiency results

The models used to describe the size-dependent release efficiency in each of the three configurations of the square mesh section used represented the data well (see the fit statistics and p values in Table 3 and Fig. 7). Without any stimulation device in the section, the release efficiency of haddock smaller than 40 cm, which is the minimum size for haddock in the Barents Sea and which easily would be able to escape through the square meshes based on the fall-through results, was low and decreased with increasing size. For example, at 30 cm only 32% of the haddock was released, and the release efficiency decreased to 23% at 40 cm. This implies that the escape behaviour of haddock is size-dependent, with larger fish being more reluctant to utilize their possibility to

Fig. 5. Underwater images showing the LED light stimulation device during the fishing trials. Panel (*a*) shows how haddock (H) reacts to the LED lights by swimming away from them. Note the random swimming direction of haddock. Panel (*b*) shows the reaction of cod (C) to the LED lights. The cod stops in front of the lights, but the erratic and panicking movements observed for haddock were not triggered. [Colour online.]

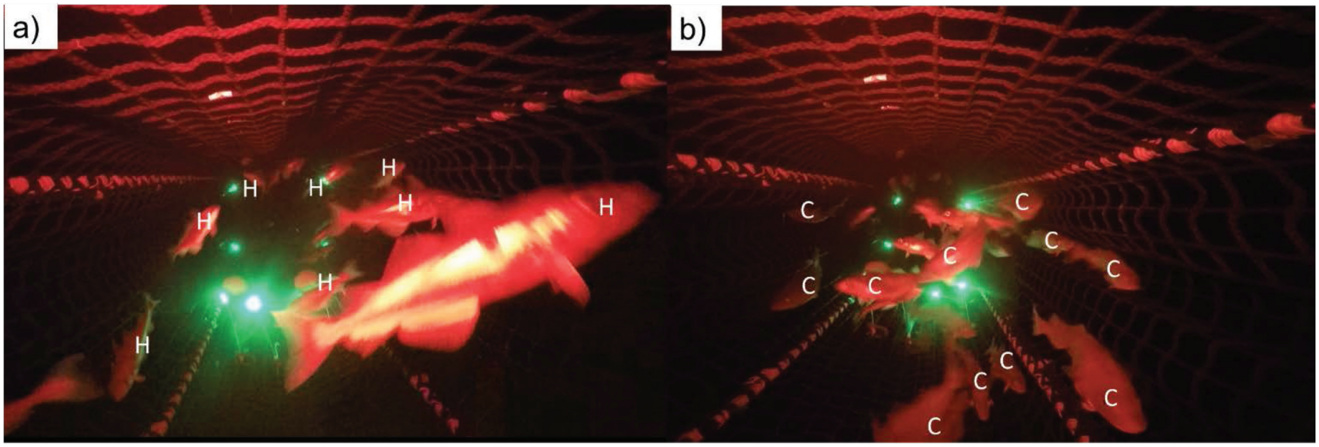


Table 2. Results from the fall-through experiments.

Fall-through type	Parameter	Haddock	Cod
Free	Length span (cm)	32–61	35–68
	No. retained	52	62
	No. passed through	31	48
	L_{05} (cm)	45.07 (43.71–47.13)	44.53 (42.04–48.65)
	L_{50} (cm)	48.14 (47.09–49.20)	51.26 (49.54–53.02)
	L_{95} (cm)	51.20 (49.38–52.46)	57.99 (55.11–60.12)
	SR (cm)	2.29 (1.23–3.05)	5.02 (2.99–6.40)
	p value	0.9993	0.7349
	Deviance	6.63	20.22
	df	22	25
Tight	Length span (cm)	32–61	35–67
	No. retained	8	21
	No. passed through	75	89
	L_{05} (cm)	50.90 (48.76–54.14)	52.11 (49.12–55.11)
	L_{50} (cm)	55.91 (54.16–58.16)	60.62 (58.45–62.94)
	L_{95} (cm)	60.91 (57.37–65.36)	69.13 (64.53–73.54)
	SR (cm)	3.73 (1.80–5.71)	6.35 (3.83–8.36)
	p value	0.9955	0.8618
	Deviance	8.53	17.53
	df	22	25

Note: Values in parentheses represent 95% confidence limits. SR, difference in length of fish with respectively 75% and 25% probability of being retained.

escape. When the mechanical stimulation device was applied, we estimated that the release efficiency for haddock at 30 and 40 cm nearly doubled from the configuration without stimulation. With light stimulation the estimated release efficiency for haddock at 30 cm was even higher (67%). However, this release efficiency decreased strongly with increasing size of haddock, being only 23% for haddock of 40 cm. For haddock of 50 cm, our fall-through results showed that 95% of the fish should be able to squeeze through the square mesh section meshes. However, for the three configurations tested, the release efficiency for this size of haddock never exceeded 16%, meaning that haddock are reluctant to try to squeeze through the mesh (Table 3; Fig. 7).

For cod at 30 cm, the release efficiency was in general much lower than that of haddock. For the configurations without any stimulation device and with mechanical stimulation, the release efficiency values were estimated to be around 10%, whereas the release efficiency was estimated to be about 18% for the configuration with light stimulation. For cod at 40 cm, the estimated release efficiencies were 4%, 8%, and 6%, respectively, for the three configurations tested. Considering that 95% (L_{05}) of all cod below 45 cm should be able to pass through the meshes easily, these results demonstrate that cod are very reluctant to utilize the escape opportunities through the square meshes in the section. This shows that cod are passive in the section, and this seems to be a difficult behaviour to overcome using stimulation (Table 3; Fig. 7).

Pairwise comparisons of the release efficiency curves estimated for each species and each of the gear configurations tested showed that the behaviour of haddock can be influenced by mechanical stimulation. Compared with no stimulation, significantly more haddock between 32 and 47 cm escaped through the square mesh section when mechanical stimulation was applied (Fig. 8*a*). LED light stimulation seemed to improve the release efficiency of the smallest sizes of haddock, but the results were inconclusive due to the wide CIs (Fig. 8*b*). The release efficiency for 38–51 cm haddock differed significantly between mechanical stimulation and LED light stimulation, with the release efficiency for mechanical stimulation being higher (Fig. 8*c*). For cod, neither mechanical stimulation nor LED light stimulation had a significant effect on escape behaviour, and the release efficiency curves showed wide CIs, especially for fish below 30 cm (Figs. 8*d*–8*f*).

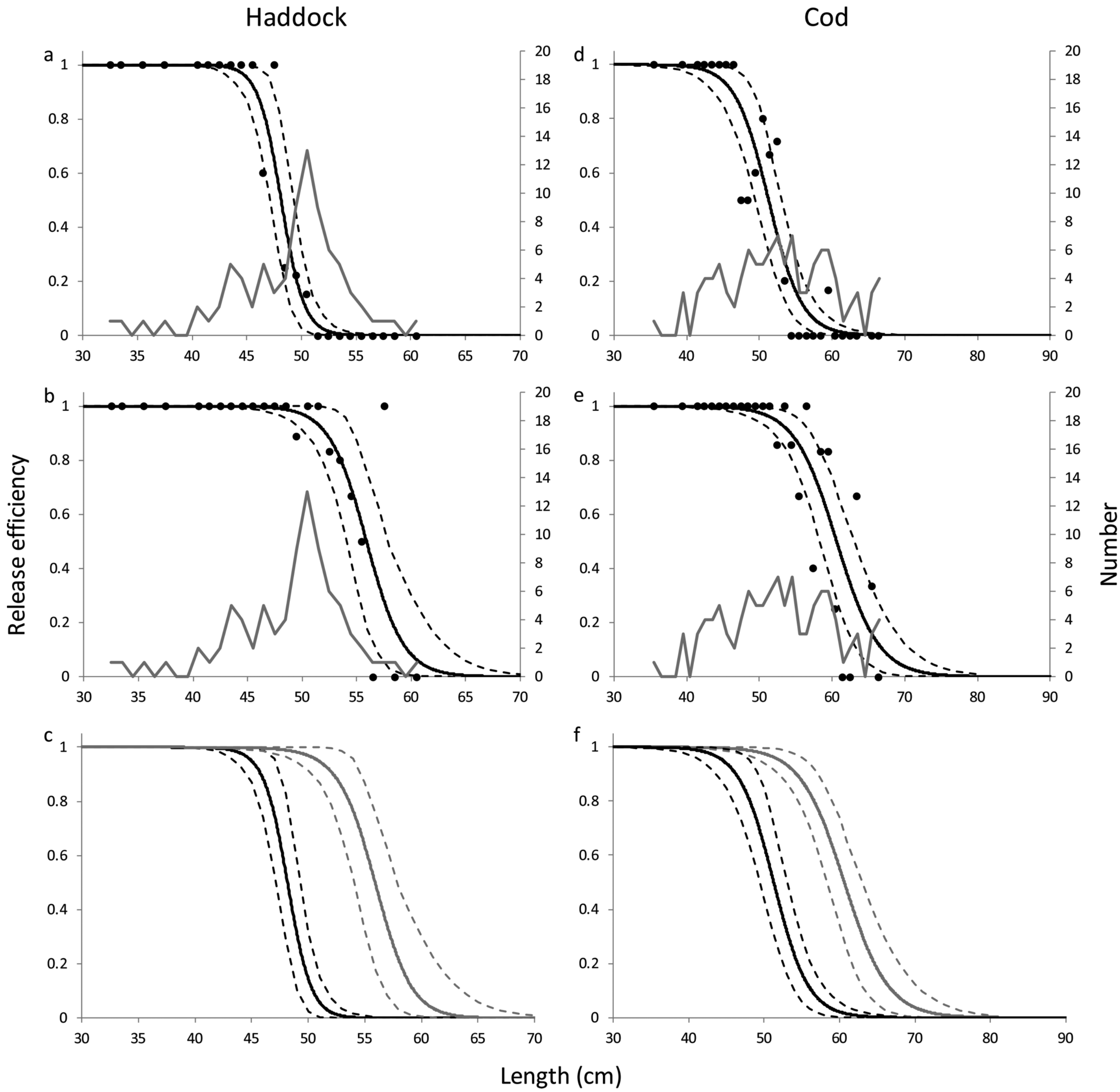
Behaviour differences between cod and haddock in the square mesh section

The selectivity results obtained for cod and haddock showed clear differences in the escape behaviour of these two species. Direct comparison of the release efficiency curves obtained for the two species show that for the same sizes of fish, the release efficiency for haddock was on average higher than that for cod. These differences were significant for fish between 27 and 53 cm for the configuration with no stimulation device and between 25 and 45 cm for the configuration with the mechanical stimulation device (Figs. 9*a*–9*b*). These differences may be due to morphological differences between cod and haddock (Sistiaga et al. 2011). However, the fall-through results show that the L_{05} for both free and tight passage for both species were almost equal (Table 2). This means that the differences observed between cod and haddock are not related to differences in the possibility that each species can pass through the square meshes in the section. Instead, the differences are strictly associated with behavioural differences between cod and haddock in the section.

Comparison with existing selectivity devices in the Barents Sea fishery

The release efficiencies for the three configurations of the square section were compared with release efficiencies previously estimated for a 55 mm Sort-V grid (Sistiaga et al. 2010). For all configurations for undersized haddock and cod, the release

Fig. 6. Release size limits for haddock (left) and cod (right) based on fall-through tests. Panels (*a*) and (*d*) show the data, estimated release efficiency curve (solid black line), and CIs (dashed lines) for free passage. Panels (*b*) and (*e*) show the data, release efficiency curves (solid black line), and CIs (dashed lines) for tight passage. Panels (*c*) and (*f*) compare free (black) and tight (grey) passage curves. The grey curve in panels (*a*–*b*) and (*d*–*e*) show the distribution of the fish measured.



efficiencies in the section were significantly lower than those previously reported for the Sort-V steel grid, which is one of the grid systems most commonly used in the fishery today (Fig. 10).

Discussion

For a fish to be able to escape through a size selection device installed in a trawl, the individual first needs to come into contact with the device and then it needs to be able to pass through the meshes in the device. The first condition depends on the physical characteristics (size, compressibility, etc.) of the individual, whereas the second depends almost entirely on fish behaviour. In this study, we were able to understand better these two conditions by applying fall-through experiments, which established the extent to which the fish can freely pass through the square meshes in the section tested and the upper size limit for the fish to actually have a chance to escape through the square meshes. Thus, we were able to isolate the behavioural condition from the length-dependent contact selectivity condition in the overall size selection process for cod and haddock.

In this study, we evaluated the effect of a square mesh section installed in the extension piece in front of the cod end on the escapement of cod and haddock. Earlier experiments with devices installed in the extension piece showed that the efficiency of the device depends largely on how close the device is to a catch accumu-

Table 3. Release efficiency for haddock and cod and the three square mesh section configurations included in the study (no stimulation, mechanical stimulation, and LED light stimulation) at sizes between 20 and 70 cm.

	Haddock			Cod		
	No stimulation	Mechanical stimulation	LED light stimulation	No stimulation	Mechanical stimulation	LED light stimulation
No hauls in analysis	10	9	6	6	4	3
Length span (cm)	20–71	20–61	23–68	23–125	24–100	22–101
No. in cod end	7608	6450	2306	1597	601	806
No. in cover	2759	7556	892	100	43	124
Release efficiency (%) at:						
20 cm	37 (22–64)	68 (36–67)	88 (41–96)	39 (0–97)	18 (0–81)	45 (3–76)
25 cm	35 (24–53)	65 (44–62)	81 (39–90)	19 (0–32)	13 (0–35)	31 (2–63)
30 cm	32 (24–49)	61 (47–67)	67 (33–76)	11 (2–23)	10 (0–17)	18 (1–54)
35 cm	29 (24–40)	54 (47–61)	46 (25–56)	7 (3–10)	9 (0–21)	11 (0–30)
40 cm	23 (20–29)	44 (40–52)	23 (14–34)	4 (3–10)	8 (4–39)	6 (0–16)
45 cm	16 (13–20)	30 (24–41)	8 (5–17)	2 (0–4)	6 (1–25)	4 (0–9)
50 cm	8 (5–12)	16 (8–28)	2 (1–7)	1 (0–1)	3 (0–10)	3 (0–13)
55 cm	3 (0–6)	7 (1–21)	1 (0–3)	0 (0–1)	1 (0–2)	1 (0–11)
60 cm	1 (0–3)	2 (0–27)	0 (0–2)	0 (0–0)	1 (0–1)	1 (0–2)
65 cm	0 (0–2)	0 (0–68)	0 (0–3)	0 (0–0)	0 (0–0)	0 (0–1)
70 cm	0 (0–6)	0 (0–81)	99 (0–13)	0 (0–0)	0 (0–0)	0 (0–1)
p value	0.0372	0.3586	0.4155	1.00	1.00	0.9999
Deviance	63.29	37.42	35.11	31.89	26.79	27.94
df	45	35	34	81	62	61

Note: Values in parentheses represent 95% confidence limits.

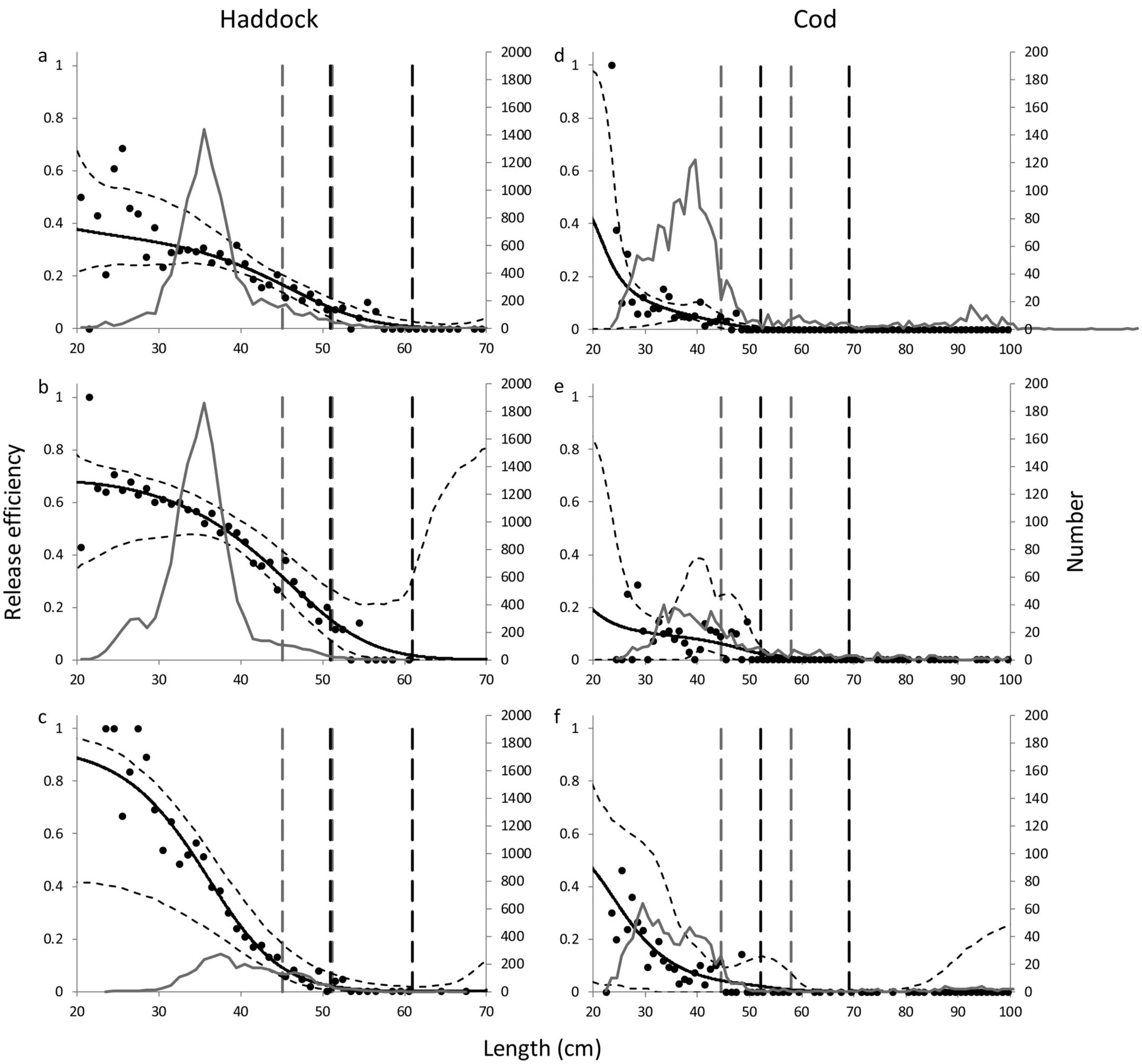
lation zone such as the cod end (Bullough et al. 2007; Herrmann et al. 2014). Thus, devices that do not form, or have, an obstacle (i.e., lifting panel, guiding panel, sorting grid, etc.) in the passage of fish towards the trawl cod end may not function well. Fish seem to have a preference for following the passage that is most open in the trawl and stay clear of the netting (Wardle 1993; Glass et al. 1995). The square mesh section tested herein was basically a square mesh tunnel, as it had no tapering. Thus, for a fish to escape through the meshes in the section, it would need to change its swimming direction and actively seek the section meshes. However, fish generally tend to continue in the path of the trawl and not try to change direction, as a change in direction consumes energy (Peake and Farrell 2006). In addition, fish may already be exhausted when they reach this point in the trawl and therefore may be reluctant to change swimming direction (Winger et al. 2010). This may explain why the release results obtained in the experiment without stimulators were poor even though open square meshes were available in all directions. Fryer et al. (2016) found a seasonal dependency in the contact probability of haddock to square mesh panels. However, as our experiment was carried out in a specific cruise and season, the results do not account for potential seasonal dependency in the release efficiency of the square mesh section.

Based on the fall-through results, 95% of the cod below 45 cm should be able to pass through the square mesh section meshes without needing to compress themselves at all. However, <11% of the cod above 30 cm actually escaped through the section meshes when no stimulation device was used. This means that to a large extent cod did not contact the square meshes, and the majority of individuals simply drifted towards the cod end following the path of the trawl netting without making an escape attempt. If we consider the cod that would actually be able to pass through the square meshes if they squeezed themselves through, the results show that hardly any cod did actually do so. For haddock, 95% of all fish up to 45 cm should be able to pass through the square meshes in the section without having to compress themselves. However, most of the haddock below this size did not actually escape. For example, for haddock of 30 and 40 cm, only 32% and 23%, respectively, actually escaped through the meshes. The release efficiencies observed for both cod and haddock were length-dependent and always higher for the smaller fish, which means that the smaller fish contacted and attempted to escape through the square meshes more frequently. Overall, these escape rates were not satisfactory for either type of fish considering the minimum catch size for these species in the Barents Sea (44 and 40 cm for cod and haddock, respectively). However, a significantly higher proportion of haddock escaped through the square mesh section compared with cod (Fig. 9), which is indicative of clear behavioural differences between the two species. These differences show that haddock are much more active than cod in seeking an outlet when trapped in the gear, which has been reported previously in the literature (Tschernij and Suuronen 2002; Grimaldo et al. 2007).

The results of the experiment also showed the extent to which fish behaviour can be influenced to induce escapement by two types of stimulators: mechanical stimulators consisting of lines of floats and LED light-based stimulators. For cod, the probability of escapement remained low with mechanical stimulation, with no significant difference detected between mechanical stimulation versus no stimulation. For example, the escape rate for cod of 40 cm increased from 4% without stimulation to 8% with mechanical stimulation, which was not statistically significant. Moreover, an escape rate of 8% is far below what would be expected for this length class, because all cod should be able to freely pass through the meshes. For cod at 50 cm, where most fish would need to compress themselves to pass through the meshes, only 1% escaped without stimulation versus 3% with stimulation. For haddock, however, use of mechanical stimulation resulted in a clear and significant improvement in escape probability. For example, the escape probability for a haddock of 40 cm increased from 23% without stimulation to 44% with mechanical stimulation, which represents an increase of almost 50%. For haddock at 50 cm, where most fish would need to compress themselves to pass through the meshes, the escape probability was 8% without stimulation versus 16% with stimulation. Despite this difference, the CIs for the two cases overlapped, and therefore we cannot conclude that there was a difference between the two cases.

Respectively 11, 10, and 7 hauls were carried out with the three experimental configurations (no stimulation, mechanical stimulation, LED stimulation) of the square mesh section tested during the trials (Table 1). However, some of those hauls did contain low numbers of haddock and cod below the estimated release limits

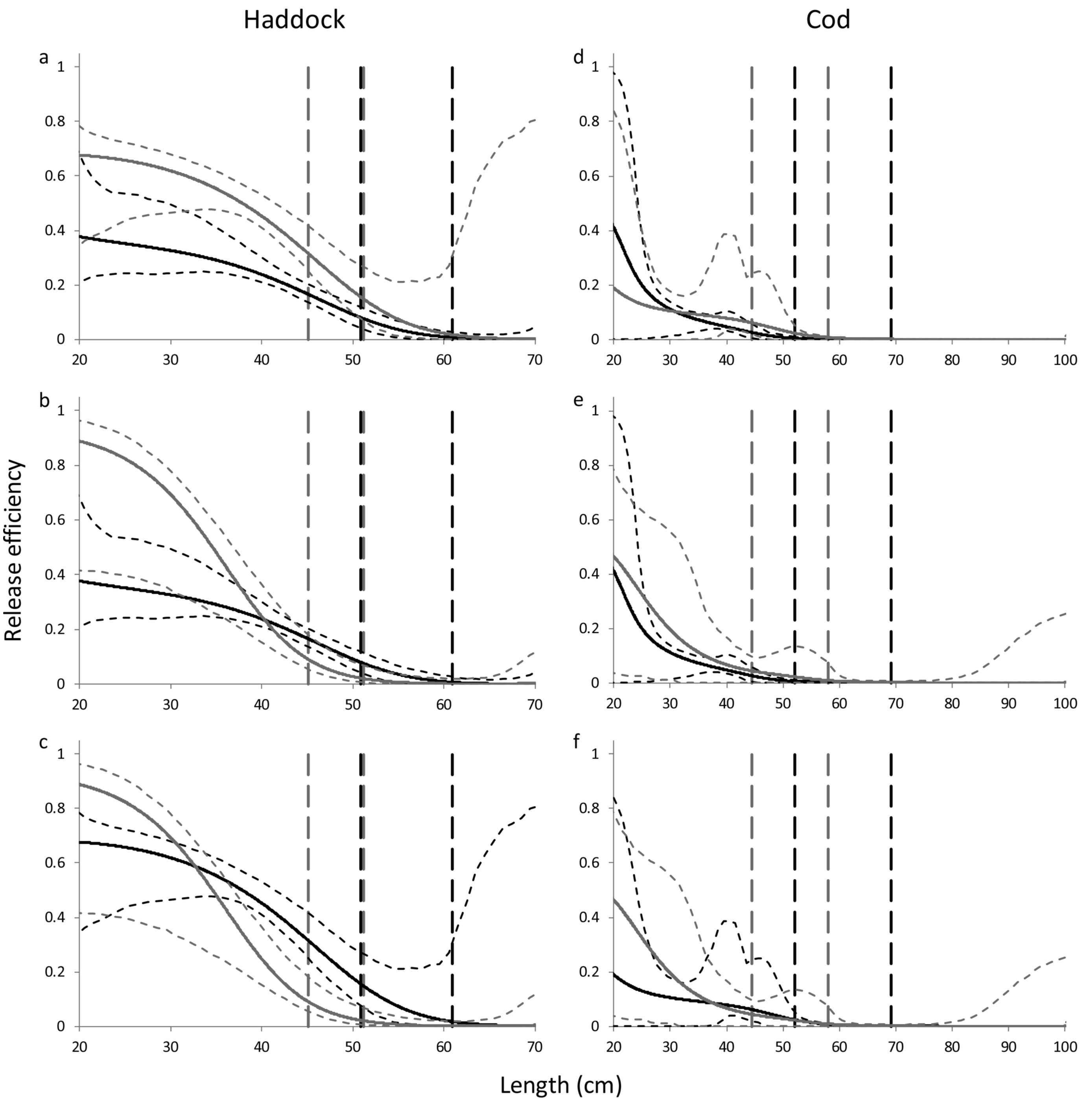
Fig. 7. Experimental data (black circles), estimated release efficiency curve (solid black line) with CIs (dashed black curves), and distribution of the fish measured for the three square mesh section configurations tested during the experiments for haddock (left) and cod (right). Panels (*a*) and (*d*) show the "No stimulation" case, whereas panels (*b*, *e*) and (*c*, *f*) show, respectively, the mechanical stimulation and LED light stimulation cases. In all panels, the dashed grey vertical lines show the free passage L_{95} and L_{05} limits, whereas the dashed black vertical lines show the tight passage L_{95} and L_{05} limits.



(L_{95} values in Table 2) for the square mesh section. Therefore, the assessment of the release efficiencies for the three configurations was based on the hauls with sufficient number of fish below the release limit. Particularly for cod, this meant that the analysis was carried out on a considerably lower number of hauls (six, four, and three hauls for no stimulation, mechanical stimulation, and LED stimulation, respectively; Table 3). In principle, we could have carried out the analysis including all hauls, which would only affect the estimated mean release efficiency curves marginally (Fig. 7). In contrast, it would have widened the confidence bands for fish below the release limits, as the bootstrap iterations would then contain some samples without any fish below the release limits. However, this would imply extrapolating the release efficiency curve, which is not advisable for the flexible type of models used and represented by eqs. 2 and 3. Although 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 data suggest that LED light stimulation may improve the escape probability for smaller sizes of haddock. However, due to the wide CIs in the models, the results obtained are rather inconclusive. For the larger sizes of haddock, LED light stimulation seemed to have little or a negative effect on escapement. For fish of 40 cm, which could actually escape without squeezing themselves through the meshes, the escapement percentage was the same as without stimulation (23%). For haddock of 50 cm, on the

Fig. 8. Pairwise comparison of the release efficiency curves (solid lines) and CIs (dashed lines) obtained using the three gear setups tested (no stimulation, stimulation, and lights) for haddock (left) and cod (right). Panels (*a*) and (*d*) compare the "no stimulation" (black) with the "stimulation" (grey) case. Panels (*b*) and (*e*) compare the "no stimulation" (black) with the "lights" (grey) case. Panels (*c*) and (*f*) compare the "stimulation" (black) with the "lights" (grey) case. In all panels, the dashed grey vertical lines show the free passage L_{05} and L_{95} limits, whereas the dashed black vertical lines show the tight passage L_{05} and L_{95} limits.



other hand, the escape percentage when using LED light stimulation decreased from 8% to 2%, although this difference was not statistically significant. For cod, LED light stimulation resulted in a minimal improvement in escape percentage of 2% for fish of 40 cm and 1% for fish of 50 cm. These marginal differences were not statistically significant and demonstrate that LED light stimulation had little effect in the escape behaviour of cod. The underwater recordings showed that contrary to cod, haddock reacted strongly to LED light and suffered a panic reaction that made them contact the netting often. However, the panicked reaction seemed to make haddock unable to orientate themselves optimally to escape, as the observed escapement rates were low. With increasing size, the quality of the contact decreases and the dependence on a more controlled and well-orientated escape attempt increases. In contrast, smaller fish do not depend on orientating themselves optimally to be able to escape through the square meshes in the section. Thus, there may be a size difference in the escape probability changes achieved by the use of LED light, with improvement observed for

Pagination not final (cite DOI) / Pagination provisoire (citer le DOI)

Fig. 9. Pairwise comparison of the release efficiency curve (solid lines) and CIs (dashed lines) obtained for haddock (black) and cod (grey) for the three gear configurations tested: no stimulation (*a*), mechanical stimulation (*b*), and LED light stimulation (*c*).

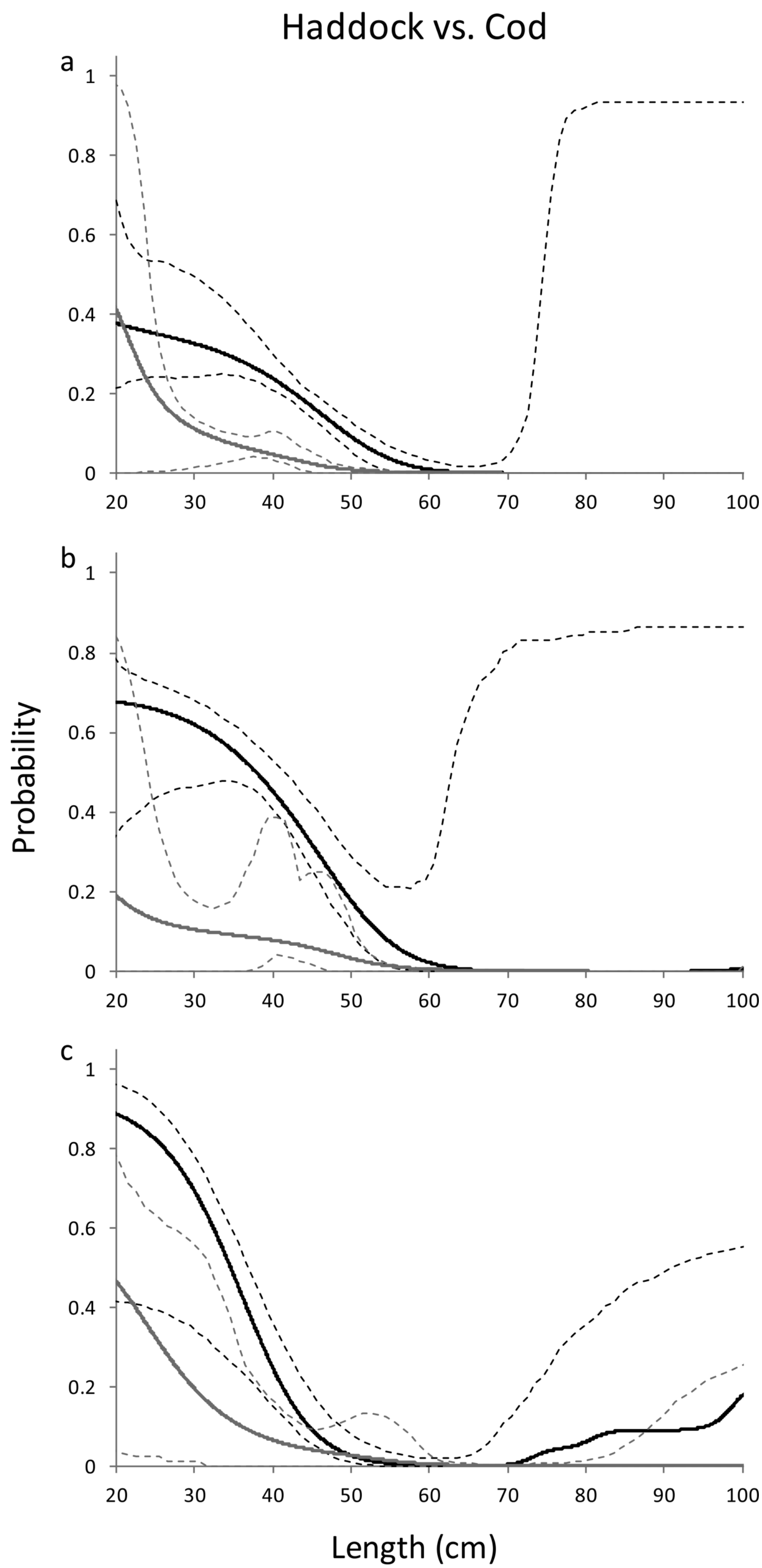
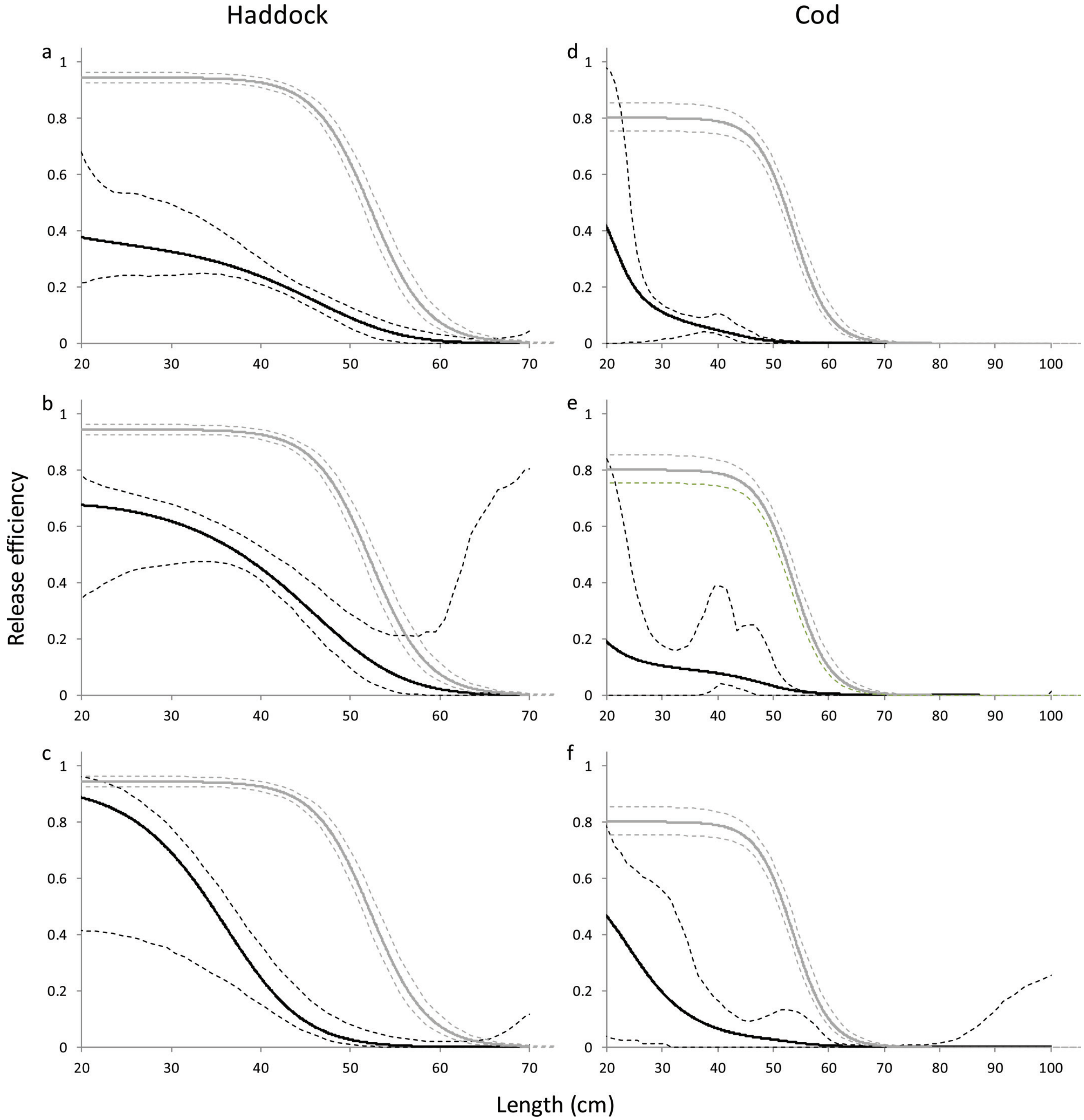


Fig. 10. Comparison of release efficiency among the three square mesh section configurations tested in the present study (black) and a Sort-V grid section (grey) (source: Sistiaga et al. 2010). Panels (*a*) and (*d*) show the cases where no stimulation device was applied, (*b*) and (*e*) show the cases where mechanical stimulation was applied, and (*c*) and (*f*) show the cases where LED light stimulation was applied.



smaller fish, but the results are inconclusive because the CIs of the no stimulation and LED light stimulation cases overlap. LED light stimulation also seemed to have a positive influence on escapement of small cod, but the results were inconclusive due to the width of the CIs.

In this study, we documented the effect of one particular green LED light (~50 lx) on cod and haddock behaviour. The green colour is part of the short wavelength of the light spectrum and therefore is less absorbed by sea water (penetrates deeper) than long wavelength colours (i.e., red, yellow, or orange). The effect of other colours on the behaviour of cod and haddock is likely to differ from those estimated in this study. Many explanations have been offered to explain why fish respond to light, including conditioned responses to light gradients, curiosity, social behaviour, phototaxis, optimum light intensity for feeding, and disorientation and immobilization due to high light levels (Arimoto et al. 2010). According to Marchesan et al. (2005), the functional explanation for response to light, whether it is repulsion or attraction, depend on species, ontogenetic development, ecological factors, and physical characteristics of the light source (intensity and wavelength). LED light potentially can be used to improve size and species selectivity in trawls, but the position, number, colour, and luminous flux of the lights should be carefully studied. There is considerable potential for artificial light to be used constructively in the development of more efficient and responsible fishing methods.

In the Barents Sea gadoid fishery, Grimaldo et al. (2015) recently showed the importance of the lifting panel for the performance of a rigid sorting grid system. Removing the lifting panel from the grid section had a significant effect on the behaviour of fish and consequently on the contact of the fish with the gear. Krag et al. (2017) and Herrmann et al. (2014) reported that additional stimuli are needed to improve fish escapement in nontapered netting sections. In the absence of these stimuli, fish passively fall back through the section without seeking escape through the selection device. In the current study, we detected significant differences in the escapement rates of haddock when mechanical stimulation was applied. However, the contact of cod and haddock with the netting in the section and the escapement rates obtained even when the stimulators were used were not satisfactory. The release efficiency obtained with the square mesh section was considerably lower than that estimated previously for a mandatory sorting grid (Sistiaga et al. 2010). This result shows that the design of the section as it was used in this study does not represent a real alternative to the compulsory grids currently in use. However, the behavioural results obtained in this study show that haddock react to different types of stimulation and that there is great potential for improving the design of square mesh sections.

Acknowledgements

We thank the crew of the R/V *Helmer Hanssen* for their valuable assistance on board the vessel. We are grateful for financial support from the Research Council of Norway through project No. 243627 (“Managing trawl catches by improving the hydrodynamic performance of sorting grid sections and codends”) and from the Directorate of Fisheries through the fund for research cruises.

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.

Alzorriz, N., Arregi, L., Herrmann, B., Sistiaga, M., Casey, J., and 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. doi:10.1016/j.fishres.2015.11.023.

Anthony, P.D., and Hawkins, A.D. 1983. Spectral sensitivity of the cod, *Gadus morhua* L. Mar. Behav. Physiol. **10**: 145–166. doi:10.1080/10236248309378614.

Arimoto, T., Glass, C., and Zhang, X. 2010. Fish vision and its role in fish capture. *In* Behaviour of marine fishes: capture process and conservation challenges. *Edited by* P. He. Blackwell Publishing Ltd., Iowa, USA. pp. 25–40. ISBN: 978-0-8138-1536-7.

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**: 133–152. doi:10.1016/0165-7836(92)90023-M.

Bullough, L.W., Napier, I.R., Laurenson, C.H., Riley, D., Fryer, R.J., Ferro, R.S.T., and Kynoch, R.J. 2007. A year-long trial of a square mesh panel in a commercial demersal trawl. Fish. Res. **83**: 105–112. doi:10.1016/j.fishres.2006.09.008.

Burnham, K.P., and Anderson, D.R. 2002. Model selection and multimodel inference: a practical information-theoretic approach. 2nd ed. Springer, New York. ISBN 978-0-387-22456-5.

Efron, B. 1982. The jackknife, the bootstrap and other resampling plans. SIAM Monogr. No. 38. CBSM-NSF. ISBN: 978-0-89871-179-0.

Ferro, R.S.T., Jones, E.G., Kynoch, R.J., Fryer, R.J., and Buckett, B.E. 2007. Separating species using a horizontal panel in the Scottish North Sea whitefish trawl fishery. ICES J. Mar. Sci. **64**: 1543–1550. doi:10.1093/icesjms/fsm099.

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

Fryer, R.J., O'Neill, F.G., and Edridge, A. 2016. A meta-analysis of Haddock size-selection data. Fish Fish. **17**: 358–374. doi:10.1111/faf.12107.

Glass, C.W., and 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. doi:10.1016/0165-7836(94)00331-P.

Glass, C.W., Wardle, C.S., Gosden, S.J., and Racey, D.N. 1995. Studies on the use of visual stimuli to control fish escape from codends. I. Laboratory studies on the effect of a black tunnel on mesh penetration. Fish. Res. **23**: 157–164. doi:10.1016/0165-7836(94)00330-Y.

Grimaldo, E., Larsen, R.B., and Holst, R. 2007. Exit windows as an alternative selective system for the Barents Sea demersal fishery for cod and haddock. Fish. Res. **85**: 295–305. doi:10.1016/j.fishres.2007.03.005.

Grimaldo, E., Larsen, R.B., Sistiaga, M., Madsen, N., and Breen, M. 2009. Selectivity and escape percentages during three phases of the towing process for codends fitted with different selection systems. Fish. Res. **95**: 198–205. doi:10.1016/j.fishres.2008.08.019.

Grimaldo, E., Sistiaga, M., and Larsen, R.B. 2014. Development of catch control devices in the Barents Sea cod fishery. Fish. Res. **155**: 122–126. doi:10.1016/j.fishres.2014.02.035.

Grimaldo, E., Sistiaga, M., Herrmann, B., Gjøsund, S.H., and Jørgensen, T. 2015. Effect of the lifting panel on selectivity of a compulsory grid section (Sort-V) used by the demersal trawler fleet in the Barents Sea cod fishery. Fish. Res. **170**: 158–165. doi:10.1016/j.fishres.2015.05.028.

Hannah, R.W., Lomeli, M.J.M., and 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. doi:10.1016/j.fishres.2015.05.010.

Herrmann, B., Krag, L.A., Frandsen, R.P., Madsen, N., Lundgren, B., and Stæhr, K. 2009. Prediction of selectivity from morphological conditions: methodology and a case study on cod (*Gadus morhua*). Fish. Res. **97**: 59–71. doi:10.1016/j.fishres.2009.01.002.

Herrmann, B., Sistiaga, M., Nielsen, K.N., and Larsen, R.B. 2012. Understanding the size selectivity of redfish (*Sebastes* spp.) in North Atlantic trawl codends. J. North Atl. Fish. Sci. **44**: 113. doi:10.2960/J.v44.m680.

Herrmann, B., Sistiaga, M., Larsen, R.B., Nielsen, K.N., and Grimaldo, E. 2013. Understanding sorting grid and codend size selectivity of Greenland halibut (*Reinhardtius hippoglossoides*). Fish. Res. **146**: 59–73. doi:10.1016/j.fishres.2013.04.004.

Herrmann, B., Wienbeck, H., Karlsen, J.D., Stepputtis, D., Dahm, E., and 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**: 686–696. doi:10.1093/icesjms/fsu124.

Herrmann, B., Sistiaga, M., Rindahl, L., and Tatone, I. 2017. Estimation of the effect of gear design changes on catch efficiency: Methodology and a case study for a Spanish longline fishery targeting Hake (*Merluccius merluccius*). Fish. Res. **185**: 153–160. doi:10.1016/j.fishres.2016.09.013.

Jørgensen, T., Ingólfsson, Ó.A., Graham, N., and Isaksen, B. 2006. Size selection of cod by rigid grids: is anything gained compared to diamond mesh codends only? Fish. Res. **79**: 337–348. doi:10.1016/j.fishres.2006.01.017.

Katsanevakis, S. 2006. Modelling fish growth: model selection, multi-model inference and model selection uncertainty. Fish. Res. **81**: 229–235. doi:10.1016/j.fishres.2006.07.002.

Kim, Y.H., and 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**: 71–75. doi:10.1016/j.fishres.2010.07.005.

Krag, L.A., Holst, R., and Madsen, N. 2009. The vertical separation of fish in the aft end of a demersal trawl. ICES J. Mar. Sci. **66**: 772–777. doi:10.1093/icesjms/fsp034.

Krag, L.A., Herrmann, B., and Karlsen, J. 2014. Inferring fish escape behaviour in trawls based on catch comparison data: model development and evaluation based on data from Skagerrak, Denmark. PLoS ONE, **9**(2): e88819. doi:10.1371/journal.pone.0088819. PMID:24586403.

Krag, L.A., Herrmann, B., Karlsen, J.D., and Mieske, B. 2015. Species selectivity in different sized topless trawl designs: does size matter? Fish. Res. **172**: 243–249. doi:10.1016/j.fishres.2015.07.010.

Krag, L.A., Herrmann, B., Feekings, J., Lund, H.S., and Karlsen, J.D. 2017. Improving escape panel selectivity in *Nephrops*-directed fisheries by actively stimulating fish behavior. Can. J. Fish. Aquat. Sci. **74**(4): 486–493. doi:10.1139/cjfas-2015-0568.

Larsen, R.B., and 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.

Madsen, N. 2007. Selectivity of fishing gears used in the Baltic Sea cod fishery. Rev. Fish Biol. Fish. **17**: 517–544. doi:10.1007/s11160-007-9053-y.

Main, J., and Sangster, G.I. 1981. A study of the fish capture process in a bottom trawl by direct observations from a towed underwater vehicle. Scott Fish. Res. Rep. **23**: 1–23.

Main, J., and Sangster, G.I. 1985. Trawling experiments with a two-level net to minimise the undersized gadoid bycatch in a *Nephrops* fishery. Fish. Res. **3**: 131–145. doi:10.1016/0165-7836(85)90014-1.

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

Millar, R.B. 1993. Incorporation of between-haul variation using bootstrapping and nonparametric estimation of selection curves. Fish. Bull. **91**: 564–572.

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

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

Rose, C., and Hammond, C.F. 2014. Addition of light to an experimental footrope caused increased escapement of one flatfish species. *In* ICES 2014. First Interim Report of the ICES–FAO Working Group on Fishing Technology and Fish Behavior (WGFTFB), 5–9 May 2014, New Bedford, USA. ICES CM 2014/SSGESST:08.

Rosen, S., Engås, A., Fernö, A., and Jørgensen, T. 2012. The reactions of shoaling adult cod to a pelagic trawl: implications for commercial trawling. ICES J. of Mar. Sci. **69**: 303–312. doi:10.1093/icesjms/fsr199.

Sistiaga, M., Herrmann, B., Grimaldo, E., and Larsen, R.B. 2010. Assessment of dual selection in grid based selectivity systems. Fish. Res. **105**: 187–199. doi:10.1016/j.fishres.2010.05.006.

Sistiaga, M., Herrmann, B., Nielsen, K.N., and 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. Aquat. Sci. **68**(5): 927–940. doi:10.1139/f2011-017.

Sistiaga, M., Brinkhof, J., Herrmann, B., Grimaldo, E., Langård, L., and Lilleng, D. 2016. Size selective performance of two flexible sorting grid designs in the Northeast Arctic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) fishery. Fish. Res. **183**: 340–351. doi:10.1016/j.fishres.2016.06.022.

Suuronen, P., Perez-Comas, J.A., Lethonen, E., and Tschernij, V. 1996. Size-related mortality of herring (*Clupea harengus* L.) escaping through a rigid sorting grid and trawl codend meshes. ICES J. Mar. Sci. **53**: 691–700. doi:10.1006/jmsc.1996.0088.

Tschernij, V., and Suuronen, P. 2002. Improving trawl selectivity in the Baltic. Nordic Council of Ministers, Copenhagen, Denmark. TemaNord 2002. No. 512. ISBN 92-893-0750-1.

Wardle, C.S. 1993. Fish behaviour and fishing gear. *In* Behaviour of teleost fishes. 2nd ed. *Edited by* T. Pitcher. Chapman and Hall, London. pp. 609–643. ISBN 978-0-412-42930-9.

Westhoff, C.J.W., Pope, J.A., and Beverton, R.J.H. 1962. The ICES mesh gauge. Charlottenlund Slot, Charlottenlund, Denmark.

Wileman, D.A., Ferro, R.S.T., Fonteyne, R., and Millar, R.B. (*Editors*). 1996. Manual of methods of measuring the selectivity of towed fishing gears. ICES Cooperative Research Report No. 215. ISBN 10: UCSD:31822025768078.

Winger, P.D., Eayrs, S., and Glass, C.W. 2010. Fish behaviour near bottom trawls. *In* Behavior of marine fishes: capture processes and conservation challenges. *Edited by* P. He. pp. 67–103. Wiley–Blackwell, Ames, Iowa. ISBN: 978-0-8138-1536-7.

Zuur, G., Fryer, R.J., Ferro, R.S.T., and Tokay, T. 2001. Modelling the size selectivity of a trawl codend and an associated square mesh panel. ICES J. Mar. Sci. **58**: 657–671. doi:10.1006/jmsc.2001.1049.