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Published in:
Fisheries Research

Link to article, DOI:
10.1016/j.fishres.2018.11.027

Publication date:
2019

Document Version
Peer reviewed version

Elsevier Editorial System(tm) for Fisheries Research
Manuscript Draft

Manuscript Number: FISH8683R1

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Article Type: Research Paper

Keywords: Horizontally divided codend; behavioural stimulators; vertical separation; Nephrops; bycatch

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Manuscript Region of Origin: DENMARK

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Can active behaviour stimulators improve fish separation from *Nephrops* (*Nephrops norvegicus*) in a horizontally divided trawl codend?

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Abstract

A promising design to improve selectivity in the *Nephrops*-directed trawl fishery is the horizontally divided trawl codend. Previous studies have succeeded in separating the majority of fish from *Nephrops*; however, cod (*Gadus morhua*), juvenile roundfish and flatfish still enter the lower compartment in relative high proportions. In this study we investigated if and to which extent it is possible to improve the vertical separation of fish from *Nephrops* by adding active behaviour stimulators. These stimulators are designed to exploit fish avoidance behaviour and lead them into the upper compartment while *Nephrops* move into the lower compartment. We tested two types of behaviour stimulators: a chain curtain at the entrance of the lower compartment at the point of separation and a set of rising float-lines inserted ahead of the point of separation. The length-dependent vertical separation of five important commercial fish species and *Nephrops* was analysed in comparison to the horizontally divided trawl codend with no stimulator, towed in parallel to the test trawl. The results showed that fish's vertical separation can be partially improved by the addition of stimulators, without complicating fishing operations or increasing the proportion of *Nephrops* that enters the upper compartment. However, the improvement was limited and none of the two active stimulators tested managed to simultaneously improve the separation of cod, juvenile roundfish and flatfish.

Keywords

Horizontally divided codend; behavioural stimulators; vertical separation; *Nephrops*; bycatch

Introduction

Reducing bycatch of unwanted species and undersized individuals in mixed-species trawl fisheries represents a challenge due to the different sizes and shapes of the species caught. A well-studied example is the *Nephrops*-directed mixed trawl fishery in the northeast Atlantic (Catchpole and Revill, 2008). This fishery catches several commercially important fish species including roundfish and flatfish. To target *Nephrops*, the fishery adopts a minimum mesh size of 70 or 90 mm (depending on region). However, the poor selective properties of these mesh sizes in relation to minimum conservational reference sizes (MCRS) often result in high catches of fish (Kelleher, 2005; Krag et al., 2008). To appropriately select out some of the commercial northeast Atlantic fish species caught, a mesh size of 120 mm should be adopted (Graham and Ferro, 2004), a solution not compatible with targeting *Nephrops* (Krag et al., 2008). Moreover, the majority of the bycatch species are now subjected to the European Union's landing obligation (European Union, 2013) whereas *Nephrops* has obtain an exemption, in some regions, due to its high survival rates (European Commission, 2018). Therefore, fishermen are likely to fulfill their quota for fish before that for *Nephrops*. Mandatory bycatch reduction devices, such as grids and square mesh panels, have been introduced in many regions to mitigate the amount of bycatch and release undersized individuals (Catchpole and Revill, 2008). Grids mechanically filter the catch according to size and are relatively independent from species behaviour; however, they can be subjected to clogging and cause a loss of commercial size *Nephrops* (Catchpole and Revill, 2008; Drewery et al., 2010). Square mesh panels reduce the catch of roundfish without affecting the catch of *Nephrops,* but their efficiency depends on species contacting the panel and, thus, varies according to species-specific behaviours (Catchpole and Revill, 2008; Drewery et al., 2010).

A promising strategy to combine a behavioural and mechanical selection of the catch is to introduce a horizontal net panel that separates the trawl into compartments leading to independent codends. Ideally, if all fish species are separated from *Nephrops,* they can be more appropriately select out without the risk of losing target catch. Previous studies have proved that, when inside the trawl, *Nephrops* move passively towards the codend (Main and Sangster, 1985; Briggs, 1992) and only few big individuals manage to rise vertically during towing (Graham and Fryer, 2006; Krag et al., 2009a; Karlsen et al., 2015). Therefore, when encountering a horizontal separation, the majority of *Nephrops* enter the lower compartment. On the contrary, fish behaviour in the trawl is affected by several factors, and so is their separation into different compartments. Fryer et al. (2017) reviewed studies that included a horizontal net panel, and analysed the main factors affecting the separation of the commercial species caught by demersal trawls. The height of the horizontal panel from the lower netting and the horizontal distance from the groundgear to the start of the separator panel, were identified as the main factors affecting the proportion of fish entering the upper compartment (Fryer et al., 2017). In particular, cod separation from *Nephrops* was significantly better when the horizontal panel was inserted in the aft end of the trawl (Fryer et al., 2017) and designs including a horizontally separated trawl codend managed to segregate the majority of the fish in the upper compartment (Krag et al., 2009a; Melli et al., 2018). However, length-dependent differences in vertical separation were observed in most species, with smaller individuals entering more frequently the lower compartment (Holst et al., 2009; Melli et al., 2018). Due to these differences, the horizontal separation alone might not be sufficient to separate most fish from *Nephrops*.

Additional devices can be inserted before or at the separation to increase the proportion of fish entering the upper compartment. Graham and Fryer (2006) combined a grid with a horizontally divided trawl and achieved to separate the majority of fish bycatch from *Nephrops*. However, the size and rigidity of the grid raised concerns for its use under commercial conditions. Other, more flexible solutions might be able to achieve a similar result by exploiting fish behavioural response to mechanical and visual stimuli (Graham, 2010). For example, simple frames with few vertical bars at the entrance of the lower compartment succeeded in leading fish into the upper compartment despite not representing a real physical obstacle to their passage (Krag et al., 2009a; Karlsen et al., 2015). Stimulators tested to increase fish contact with square mesh panels may also be applied to improve species separation (Herrmann et al., 2015; Krag et al., 2016). Grimaldo et al. (2017) tested fluttering lines with floats to trigger fish escape responses and increased significantly haddock's escape rate. Kim and Wang (2010) tested a fluttering net panel and a set of free ropes, successfully stimulating the escapement of juvenile red sea bream (*Pagrus major*) in laboratory conditions. These active stimulating devices rely on fish reaction to the stimulus. Thus, for the stimulator to successfully improve fish separation from *Nephrops*, fish must have enough time and energy to react and the reaction must be directed to the upper compartment.

The aim of this study was to investigate if and to which extent the separation of fish from *Nephrops* in a horizontally divided trawl codend could be improved using active behaviour stimulators. We tested two different stimulators : a chain curtain at the entrance of the lower compartment and a set of rising float-lines, in the section forward to the separation. The first stimulator aimed at maximizing the illusion of a blocked passage into the lower compartment (Glass and Wardle, 1995). The second stimulator was designed to give fish with relatively poor swimming capacities enough time to rise into the upper compartment, considering the towing speed and possible states of fatigue. Indeed, small fish are likely to utilize most of their aerobic swimming during the initial capture phase while attempting to swim ahead of the footrope

(Winger et al., 2010). Inside the trawl, they are assumed to depend upon anaerobic swimming and, thus, any burst-swimming activity is unlikely to be at maximum speed or sustainable for extended periods (Webb, 1994). Moreover, fish swimming speed, endurance and maneuverability vary among species in addition to sizes (Videler and Wardle, 1991; Wardle 1993). Therefore, the efficacy of the active stimulators on species vertical separation was investigated by species and length class.

Materials and methods

Two sea trials were conducted in September 2016 and 2017 with the research vessel "Havfisken" (17 m, 373 kW). The vessel was equipped for three-wire, twin-trawling with two identical Combi trawls (40 m long footrope, 420 meshes circumference of the trawl mouth, 80 mm mesh size) towed in parallel. The twin-rig system was spread with two Type 2 Thyborøn doors (1.78 m^2, 197 kg) and a 400 kg central roller clump. Each trawl spread was monitored throughout the haul with distance sensors (Simrad PI) mounted on doors and clump. The trawls were rigged with 75 m long, single wire sweeps with 4.3 cm (diameter) rubber discs. One trawl was equipped with one of the active swimming stimulators while the other had no stimulator and was used as a control, which we refer to as the baseline for species vertical separation. The baseline design of the horizontally divided trawl codend was previously tested and described in Karlsen et al., (2015) and Melli et al. (2018). We investigated if active swimming stimulators could further improve fish separation from *Nephrops*.

The trawls were made of two net panels until the separation into the two compartments where each compartment (i.e. extension and codend) was constructed of four net panels (Fig. 1 A). Both compartments had 41.65 ± 1.33 mm diamond meshes (mean ± SD; dry measurement) made of 1.8

mm braided twine, that were turned 45 degree to obtain square meshes. In the extension section of the compartments, the lower netting of the upper compartment and the upper netting of the lower one were tight together. The length of the extension section was approximately 4.5 m; then, the two compartments separated into two independent codends (Fig. 1 A). The total length of the compartments, from the separation point, was 6 m in 2016 whereas 6 m more where added to the codends sections in 2017. This modification was introduced to prevent the catch from exceeding the compartments, thus invalidating the haul (Melli et al., 2018). Consequently, to sustain the additional length of the codends in 2017 and prevent them from sweeping the seafloor, these were lifted with ten floats each. The lift of the floats was 680 g and 800 g lift for the upper and lower codends, respectively.

The separation point was positioned at the transition between the tapered and non-tapered section of the gear (circumference 140 meshes; Fig 1 A). The entrance of the upper compartment was approximately 60 cm high (based on underwater video observations) and sustained by 12 floats (720 g lift) outside the upper netting (Fig 1 A). The entrance and the extension of the lower compartment were fixed at 30 cm high due to two frames (90 cm x 30 cm, 20 mm stainless steel pipes) that secured the opening of the extension section (Fig 1 A). Moreover, the original design of Karlsen et al. (2015) already involved two vertical bars (30 cm apart) in the frame at the entrance of the lower compartment to visually and mechanically stimulate fish to swim into the upper compartment.

We tested two active behaviour stimulators in 2016 and 2017, respectively:

1) *Chain curtain*

To increase the visual and physical occlusion of the entrance of the lower compartment, chains (L: 26.5 cm, W: 0.71 Kg/m, Ø: 5 mm thick) were added to the frame (Fig. 1 B). The chains were fixed to the upper pipe of the frame with twine (nylon, 2 mm) and left free to move in the lower end. A total of 12 chains was inserted in the frame, four in each of its three sections (30x30 cm) approximately every 7 cm (Fig. 1 B and D). Fishing was conducted in commercial *Nephrops* and fish grounds in the Skagerrak Sea, at depths between 31 m and 87 m. Experimental hauls were performed at day time, at least one hour after sunrise and until one hour before sunset.

2) *Rising float-lines*

To increase the time available for rising into the upper compartment, we inserted a stimulator starting 2 m in front of the separation into compartments (Fig. 1 C and E). Five lines (10 mm, polypropylene) were attached to the lower netting panel with carabiner hooks (size 8 with lock, 64 g, 6 hooks per rope) every 40 cm (approximately 6 stretched 80 mm meshes). The line between two carabiners was set to create an arc of increasing height while approaching the separation (Fig. 1 C). The first arc was approximately 8 cm high and each following arc was 3 cm higher, to finally reach a height of approximately 20 cm in the last arc, at the separation point. In the middle of each arc we inserted a float (115 g lift) blocked by twine (5 floats per rope). The five lines were spaced approximately 15 cm at the frame end (i.e. entrance to the lower compartment) and followed the mesh orientation in the tapered section. The two lines ending in correspondence to the vertical bars of the frame were moved 20 cm forward as the bar already represented an obstacle to the lower compartment entrance. Moreover, this created an alternation of floats with the other lines (Fig. 1 C). Led line (0.26 Kg/m, 3.6 m long) was added outside the lower netting panel to compensate for the total lift exercised by the floats. Fishing was conducted in commercial

Nephrops and fish grounds in the Skagerrak Sea, at depths between 17 and 91 m. Experimental hauls were performed at day time or right before dawn.

During both experiments, the position of the stimulator was shifted from one trawl to the other every few hauls, to compensate for systematic differences deriving from trawl-dependent vertical separation efficiency. After every haul, the catch of each compartment was weighted and sorted by species separately. The total length of all target fish species and the carapace length of *Nephrops* were measured and rounded down to the nearest centimetre and millimetre, respectively. Video footage was collected in shallow waters (15 m depth) to visualize the performance and dynamic of the stimulators during fishing. A GoPro Hero 4 was attached on the upper netting panel approximately 0.5 and 1.5 m before the separation in 2016 and 2017, respectively.

Statistical analyses

The vertical separation efficiency was first estimated separately for each trawl (baseline and test) and for each of the two experiments (chain curtain and rising float-lines), following the same procedure described in Melli et al. (2018). All the analyses were performed using the software SELNET (Herrmann et al., 2012).

The vertical separation efficiency *VS(l)* was defined as the probability of finding an individual of length *l* in the upper compartment given it was observed in either compartment. For each species and each haul, *VS(l)* was estimated using the catch data. In each haul *i*, nU_{li} and nL_{li} denoted the number of individuals of length class *l* caught and length-measured in the two compartments. Then, according to our definition, VS_{li} was:

$$VS_{li} = \frac{\frac{nU_{li}}{qU_i}}{\frac{nU_{li}}{qU_i}+\frac{nL_{li}}{qL_i}} \qquad (1)$$

where qU_i and qL_i were the sampling factors (i.e. the proportion between the weight of the sample length-measured and the weight of the total catch of that species) in the upper and lower compartments, respectively, in haul *i*. A value of VS_{li} above 0.5 implies that in the haul *i* there was a higher probability of finding an individual of length *l* in the upper compartment, given an equal probability of entering either compartment. However, in this study the height of the entrance of the upper compartment accounted for 67% of the total height of the funnel section. Therefore, the probability of an individual entering the upper compartment if it was randomly distributed in the trawl section was 67% and only values of VS_{li} above or below 0.67 expressed a differential distribution of individuals. We used the term "preference" to describe this differential distribution (Melli et al., 2018).

The averaged length-dependent vertical separation efficiency, VS(*l*,***v***), was estimated using the pooled data over hauls, assuming this to be a representative sample of how the vertical separation would perform on average under different fishing conditions. Only hauls containing at least 10 individuals of that species in the upper and lower compartments summed were included (Krag et al., 2014). Following the procedure described in Melli et al. (2018), we applied a highly flexible function, often used for paired gears data (Krag et al., 2014; 2015), and adopted recent improvements in model average estimation (Herrmann et al., 2017). The ability of the model to describe the experimental data was assessed based on the *p*-value, which expresses the likelihood to obtain by coincidence a discrepancy between the fitted model and the experimental data at least as big as the one observed. Therefore, poor fit statistics (p-value < 0.05; deviance >>DOF) might indicate structural problems in describing the experimental data with the model (Wileman et al., 1996). In such cases, the deviation between the observed data and the fitted curve was examined and if no pattern was identified the result was attributed to data overdispersion and the model was accepted.

The 95% Efron confidence intervals (CIs; Efron, 1982) for the averaged vertical separation were estimated using a double bootstrap method with 1000 repetitions (Millar, 1993). The procedure accounted for uncertainty due to between-haul variation in vertical separation efficiency by selecting *h* hauls with replacement from the *h* hauls available in the experiment during each bootstrap repetition. Within-haul uncertainty in the size structure of the catch data was accounted for by randomly selecting individuals with replacement from each haul and each length class. The number of fish selected from each haul was the number of fish length-measured in that haul in respectively the upper and lower compartment.

Quantifying the effect of the stimulator

According to the method described in Melli et al. (2018), while calculating the length-based vertical separation efficiencies with 95% Efron CIs, we synchronized the hauls selected for the outer bootstrap loop for baseline and test trawls and calculated in each bootstrap the device effect $\Delta VS(l,\boldsymbol{v})$ on the vertical separation by:

$$\Delta VS(l,\boldsymbol{v}) = VSB(l,\boldsymbol{v}) - VST(l,\boldsymbol{v}) \quad (2)$$

where VSB(l) is the length-based, average vertical separation efficiency of the baseline trawl and VST(l) is the length-based, average vertical separation efficiency of the test trawl. By this synchronization in the haul selection and the direct calculation of $\Delta VS(l,\boldsymbol{v})$ in each bootstrap we removed part of the between-haul variation in vertical separation efficiency deriving from environmental factors and fishing dynamics, thus increasing the power of the analysis to infer the effect of the active swimming stimulator. $\Delta VS(l,\boldsymbol{v})$ spans between -1 and 1, where values above 0.0 imply that the stimulator increased the probability of finding an individual of length l in the upper compartment. Similarly, values below 0.0 imply a lower probability. For those length-classes in which the 95% confidence intervals for $\Delta VS(l,\boldsymbol{v})$ did not contain 0.0, we determined a significant effect of the stimulator in modifying the vertical separation efficiency.

Results

A total of 14 valid hauls were conducted with the chain curtain and 10 with the rising float-lines (Table 1). Additional hauls were precautionary excluded from analyses when the catch exceeded the point of separation (n=3) or when the entrance to the lower compartment was partially blocked by marine litter or seaweed (n=3). The towing time was on average 74 ± 30 min (mean ± SD) and in 2016 and 75 ± 25 min (mean ± SD) in 2017, according to the vessel eco-sounder and the observed catch levels. Hauls at low depths were conducted to target *Nephrops*, whose availability in September was limited to shallower waters, or to collect video footage of the performance of the stimulators during fishing.

In both experiments, sufficient data for analysis were collected for six commercial species (Table 2): three roundfish species, cod, haddock (*Melanogrammus aeglefinus*), and whiting (*Merlangius merlangus*); two flatfish species, plaice (*Pleuronectes platessa*) and lemon sole (*Microstomus kitt*); and *Nephrops*.

Fit statistics for each of the models are reported in Table 3. In most cases, *p*-values were above 0.05, implying that the deviation between the experimental data and the modelled fits could well be a coincidence. Therefore, the model could be trusted to describe the trends in the experimental data. However, three models in the first experiment (chain curtain) and two models in the second experiment (rising float-lines) resulted in poor fit statistics (p-value below 0.05, Deviance >> DoF). These were the models for cod, plaice and *Nephrops* in the test trawl with the chain curtain and the models for *Nephrops* (baseline trawl) and whiting (test trawl) in the rising float-lines experiment (Table 3). The residual deviations between the data and the modelled curves were investigated for each of these cases but no systematic structure was detected. Thus, we attributed the poor fit-statistics of these cases to overdispersion in the data and not to structural problems in describing the experimental data with the combined model (Wileman et al., 1996).

All the separation efficiency curves described well the experimental data (Fig. 2 and 3). Where fewer individuals were caught, an increasing binominal noise was observed through the increasing width of the CIs.

1) *Stimulator at the separation point: chain curtain*

In the baseline trawl, cod showed a length-dependent vertical distribution, with small cod (7–18 cm) preferring the lower compartment and bigger cod (31–45, 69–82 cm) having a preference for the upper compartment (Fig. 2). Juveniles of both haddock and whiting were distributed uniformly, meaning that their vertical separation reflected the proportion between the heights of the two compartments. In contrast, individuals above 17 cm showed a preference for the upper compartment. The preference for the upper compartment was significant for haddock only at 17–24 cm and 36–47 cm. The two flatfish species showed different vertical distributions, with plaice having a preference for the lower compartment (20–39 cm) and lemon sole having a uniform distribution. *Nephrops* showed a strong preference for the lower compartment for all the length classes well represented in the data (20–65 mm).

The main changes in the vertical distribution in the test trawl equipped with the chain curtain were observed in cod and plaice. Cod juveniles (7–16 cm) were significantly raised into the upper compartment, losing their preference for the lower one (Fig. 2, delta). In the test trawl, cod between 27 and 59 cm showed a preference for the upper compartment (Fig. 2, test trawl); however, the difference respect to the vertical separation in the baseline trawl was not significant for this size group according to the delta. Similarly, plaice below 35 cm lost their preference for the lower compartment (Fig. 2, test trawl), although the difference was significant only for individuals between 27 and 32 cm (Fig. 2, delta).

2) *Stimulator before the separation point: rising float-lines*

Respect to the experiment conducted in 2016, wider CIs were obtained for some species and size groups (e.g. cod above 37 cm and haddock above 17 cm; Fig. 3). In particular, very few haddock were caught in 2017, but the species was included as a significant change in vertical distribution emerged for the few length classes represented. In the baseline trawl, species vertical distributions were consistent with those observed in 2016, with the exception of lemon sole. Haddock (15–26 cm) and whiting (16–37 cm) showed a preference for the upper compartment; small cod (9–15 cm) showed a preference for the lower compartment and a uniform distribution for the bigger length classes. Plaice showed a preference for the lower compartment (11–31 cm), although a stronger length-dependency emerged respect to 2016. Lemon sole also distributed similarly to plaice, with small individuals (14–20 cm) having a preference for the lower compartment and bigger individuals distributing uniformly. *Nephrops* maintained a strong preference for the lower compartment.

In the test trawl equipped with the rising float-lines, the vertical separation of juvenile haddock and whiting were affected by the stimulator. Small haddock were raised into the upper compartment in greater numbers, eliminating the length-dependency in vertical distribution. However, the effect was significant for few length classes (13–16 cm). A stronger preference for the upper compartment was shown by whiting of all the main length classes represented (14–40 cm; Fig. 3, test trawl), which resulted significant for individuals between 17 and 30 cm (Fig. 3, delta). A preference for the upper compartment emerged also in cod between 22 and 54 cm (Fig. 3, test trawl); however, the difference respect to the vertical separation in the baseline trawl was not significant statistically (Fig. 3, delta). No difference in vertical distribution was observed in either flatfish species. Small *Nephrops* (17–27 mm) entered in significant higher numbers the lower compartment, with almost no individual of these length classes caught in the upper compartment.

Discussion

The results obtained in this study reiterate the efficiency of the design used as baseline, originally developed by Karlsen et al. (2015) and partially modified in Melli et al. (2018), in separating fish from *Nephrops*. In previous studies, as well as in the baseline trawl of this study, cod and often whiting showed a strongly length-dependent distribution, with small individuals showing a significant preference for the lower compartment (Valdemarsen et al., 1985; Ferro et al., 2007; Krag et al., 2009a). However, in this study and in Melli et al. (2018) the length-dependent preference for the lower compartment of cod was limited to individuals below 18 cm and most whiting above 17 cm had a strong preference for the upper compartment. Similarly, plaice and lemon sole were described to have a preference for the lower compartment (Krag et al., 2009a) but in this study (in 2016) and in the baseline trawl of Melli et al. (2018), lemon sole showed a uniform distribution. These differences in vertical separation between studies are difficult to interpret and may be associated to many environmental and technical factors such as current direction and intensity, water flow intensity in the trawl, circumference of the tapered section of the trawl before the separation, etc.

Active behaviour stimulators could play a role in stabilizing the vertical separation efficiency, thus reducing the described variability across experiments. According to our results, only few species and length-groups needed to be further stimulated to rise into the upper compartment: small haddock and whiting, cod and flatfish. These groups showed either a random distribution or a preference for the lower compartment. Although roundfish below 15 cm are likely to be selected out in a lower compartment made of 90 mm diamond mesh size, i.e. the commercial mesh size in the Skagerrak Sea, separating them from shellfish can reduce physical damages to the individuals (Karlsen et al., 2015), enhancing their survival. The results of the current study proved that the vertical separation of all these groups can be partially improved by adding simple behaviour stimulators, without complicating the fishing operation or increasing the amount of *Nephrops* that enters the upper compartment. However, of the two stimulators tested in this study, none managed to improve simultaneously the separation of all these three groups. Furthermore, the improvement was so limited that it would unlikely be considered by the legislation or the fishermen.

The chain curtain was significantly effective in raising small cod (7–16 cm) and, for a limited length range, plaice (27–32 cm). Both species lost their preference for the lower compartment in favour of a more uniform distribution. As cod and flatfish are, among the species considered, those showing the strongest tendency to swim in close proximity to the lower netting panel (Fryer et al., 2017), we believe that the chain curtain was successful in stimulating fish avoidance behaviour. Fish that are forced to encounter an obstacle or to pass through a dark area have been observed to speed up and attempt to keep position ahead of it (Glass and Wardle, 1995; He et al., 2008; Krag et al., 2009b). This eventually has led them to rise into the upper compartment (Glass and Wardle, 1995). However, considering the strong mechanical stimulus represented by the moving chains we expected a stronger effect. The lack of a strong response to the stimulation can be explained by both physiological constrains and behaviour. On one hand, fish could be too exhausted to react to the stimulator when this is located at the separation point. Fish in the trawl extension are assumed to rely on anaerobic swimming which allows short bursts but not continuous extended swimming (Webb, 1994). Moreover, studies in laboratory conditions proved that the maximum swimming speed is often length-dependent (He, 1993; Winger et al., 1999). On the other hand, video observations in shallow water revealed that the chains were bending backwards due to the strong water flow. Therefore, smaller individuals might have found a preferred path below the chains, similarly to what described as a response to the footrope before fish enter the trawl (Winger et al., 2010).

In contrast, the rising float-lines significantly affected small haddock (13–16 cm) and whiting (18–27 cm), although the improvement in vertical separation was minimal due to the already good separation achieved in the baseline trawl for these species. Moreover, the low number of haddock caught during the survey caused wide CIs, which prevented any conclusion about the effect on bigger length classes. No effect was detected on the two flatfish species analysed, despite the substantial obstacle represented by the ropes and floats on the lower netting panel. In contrast, undersized *Nephrops* (17–27 cm) were affected by the rising float-lines and entered almost exclusively the lowest compartment. The difference, although significant, is minimal due to the already strong preference for the lower compartment of this species. Even though few individuals in this length-range would be retained with the mesh sizes used commercially, this result is of interest as *Nephrops*, and especially the smaller individuals, are usually considered to be passive in this section of the trawl (Main and Sangster, 1985). It is unclear what might have caused this effect, but it is likely a consequence of the contact between *Nephrops* and the components of the stimulator (i.e. floats and lines).

Contrary to our expectations, moving the stimulator ahead of the separation to increase the time available to fish to react to the stimulus did not improve considerably the vertical separation. One possible explanation is that the distance covered by the stimulator was not sufficient to trigger a response in time to affect the separation. However, in Melli et al. (2018) a visual stimulation (LED lights) was similarly applied ahead of the separation (2 m) and for most species it did modify the vertical separation, although increasing the proportion of individuals entering the lower compartment. Another possibility is that the type of stimulation did not cause a response. Previous studies using fluttering ropes and floats were relatively successful in stimulating fish escape through a square mesh panel (Herrmann et al., 2015; Krag et al., 2016; Grimaldo et al., 2017). However, these studies applied the stimulators in bigger section of the trawls respect to the one used in this study. Possibly, in a narrower section fish are overstimulated or stressed for this type of stimulation to be effective.

In conclusion, despite applying relatively strong stimuli and in different position respect to the point of separation we were not able to substantially improve the separation of fish from *Nephrops*. The baseline design of the horizontally divided trawl codend offers already an efficient separation, and could be at present adopted by the industry. Perhaps, the Northeast Atlantic *Nephrops*-directed trawl fishery, which is characterized by narrow trawl sections and muddy bottoms, does not represent the right application for this type of active swimming stimulators. However, the responses to the stimulators identified in this study could be applied to other trawl fisheries that could benefit from species separation. Finally, active swimming stimulators are more likely to be effective at an earlier stage in the capture process, when fish are more responsive and their level of stress and exhaustion is lower.

Acknowledgements

This study has received funding from the European Maritime and Fisheries Fund (https://ec.europa.eu/fisheries/cfp/emff_en) and the Ministry of Environment and Food of Denmark. Project: Vision - Development of an optimal and flexible selective system for trawl by use of new technology and underexploited fish behaviour (Grant Agreement No 33113-I-16-015).

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Figures labels

Figure 1. Schematic illustration of the baseline trawl and of the active behaviour stimulators tested in 2016 and 2017. A) Baseline design of the horizontally divided trawl codend. Full grey lines represent selvedges. Each compartment includes an extension (4.5 m) and a codend. The length of the codends varied between experiments: (1) length of codends in 2016, (2) length of codends in 2017. Floats on the codends (dashed) were added only in 2017. Underwater pictures are oriented towards the point of separation, viewing the two compartments. D) and E), the position of the stimulator is indicated by a white arrow.

Figure 2. Length-based vertical separation efficiency of the six species analysed during the chain curtain experiment. Lengths are in cm for fish species and mm for *Nephrops*. In the first two columns, the curve (solid line) represents the modelled vertical separation fitted to the experimental points (dots) in the baseline and test trawls. The grey bands represent the 95% Efron CIs and the dash-dot line is the length distribution of the data. The dashed horizontal line, located at 0.67, describes an equal preference for entering either compartment. In the third column, the solid line represents the difference (Delta) in vertical separation between the baseline and test trawls, accounting for synchronized hauls. The grey bands are the 95% Efron CIs and the dashed line represents no difference in vertical separation.

Figure 3. Length-based vertical distribution efficiency of the six species analysed during the rising float-lines experiment. Lengths are in cm for fish species and mm for *Nephrops*. In the first two columns, the curve (solid line) represents the modelled vertical distribution fitted to the experimental points (dots) in the baseline and test trawls. The grey bands represent the 95% Efron CIs and the dash-dot line is the length distribution of the data. The dashed horizontal line, located at 0.67, describes an equal preference for entering either compartment. In the third column, the solid line represents the difference (Delta) in VS between the baseline and test trawls, accounting for synchronized hauls. The grey bands are the 95% Efron CIs and the dashed line represents no difference in vertical distribution.

Tables

Table 1

Overview of the experimental hauls, showing the technical and environmental parameters and total catch (kg) per each of the four compartments. BU = baseline upper compartment; BL = baseline lower compartment; TU = test upper compartment; TL = test lower compartment. Hauls were separated by stimulator (Stim.), i.e. chain curtain (C) and rising float-lines (F). The position of the stimulator was shifted from the Starboard trawl (S) to the Port trawl (P).

Haul No.	Year	Stim.	Test trawl	Start time (hh:mm)	Towing time (hh:mm)	Depth (m)	Wind (m/s)	Speed (kn)	BU (kg)	BL (kg)	TU (kg)	TL (kg)
1	2016	C	P	13:20	01:00	120	6	2.7	326	132	448	138
2	2016	C	P	16:00	01:00	105	7	2.6	271	130	75	120
3	2016	C	P	08:15	02:00	63	8	2.6	100	175	125	170
4	2016	C	S	15:20	02:00	61	-	2.6	95	157	120	135
5	2016	C	S	08:10	01:00	31	3	2.6	154	218	197	163
6	2016	C	P	10:50	01:30	38	3	2.6	144	180	133	213
7	2016	C	P	14:45	01:00	86	3	2.6	176	79	375	230
8	2016	C	P	16:55	01:05	87	3	2.7	136	158	550	182
9	2016	C	P	07:25	01:10	78	3	2.6	721	380	1179	360
10	2016	C	P	12:40	00:50	85	8	2.6	643	190	330	161
11	2016	C	P	16:30	00:40	87	9	2.6	298	240	238	143
12	2016	C	P	07:20	00:45	84	9	2.6	420	183	288	114
13	2016	C	S	09:45	01:00	61	9	2.6	33	18	53	25
14	2016	C	S	12:45	02:15	62	8	2.6	70	32	149	50
1	2017	F	S	10:00	00:30	17	8	2.7	73	153	166	128
2	2017	F	S	15:30	01:30	70	8	2.7	487	209	725	226
3	2017	F	S	07:40	01:00	85	12	2.7	260	136	420	140
4	2017	F	S	11:35	01:00	87	10	2.7	210	102	375	114
5	2017	F	S	14:55	01:10	87	10	2.7	260	130	605	250
6	2017	F	S	12:00	01:20	42	5	2.7	65	62	40	40
7	2017	F	P	05:30	02:00	39	4	2.7	101	144	170	180
8	2017	F	P	12:30	01:30	91	6	2.7	513	232	660	200
9	2017	F	P	06:00	01:00	38	10	2.7	87	163	66	118
10	2017	F	P	11:10	01:30	76	10	2.7	315	330	230	91

Table 2. Number of hauls and number of individuals per species per compartment included in the two experiments. U = upper compartment; L = lower compartment. Species that were subsampled are indicated with the raised total number and the actual number of individuals measured (in brackets).

Experiment	**Species**	**No. of hauls**	**Baseline trawl**		**Test trawl**	
			nU	**nL**	**nU**	**nL**
Chain curtain	Cod	11	640	502	1002	322
	Haddock	8	1714	518	1160	250
	Whiting	11	5111 (4123)	670	5479 (3650)	485
	Plaice	11	1490 (870)	1505	2823 (1635)	2116
	Lemon sole	8	432	173	562	154
	Nephrops	6	1731	5380 (2750)	1801	5642 (2794)
Rising float-lines	Cod	9	2803	1081	4234	1473
	Haddock	6	473	189	547	110
	Whiting	10	8462 (8025)	1376	12640 (11636)	838
	Plaice	10	1063	1270	1205	1584
	Lemon sole	8	382	411	671	580
	Nephrops	4	799	6215 (4136)	615	7756 (4327)

Table 3. Fit statistics for the modelled vertical separation efficiencies of the two experiments. DoF denotes the degree of freedom and was calculated by subtracting the number of model parameters from the number of length classes in the dataset. Significant *p*-values ($p<0.05$; indicated by *) express that the residual variation between the models fit and the experimental data required further investigation.

Experiment	Species	Baseline trawl			Test trawl		
		***p*-value**	**Deviance**	**DoF**	***p*-value**	**Deviance**	**DoF**
Chain curtain	Cod	0.54	59.28	61	0.03*	89.73	66
	Haddock	0.08	45.17	33	0.64	26.60	30
	Whiting	0.09	37.27	27	0.50	30.34	31
	Plaice	0.06	39.02	27	0.02*	41.70	25
	Lemon sole	0.09	26.35	18	0.45	19.08	19
	Nephrops	0.22	44.33	38	0.03*	57.10	39
Rising float-lines	Cod	0.66	48.30	53	0.09	68.57	54
	Haddock	0.32	23.43	21	0.18	27.86	22
	Whiting	0.06	45.38	32	<0.01*	55.70	32
	Plaice	0.20	40.75	34	0.47	32.86	33
	Lemon sole	0.25	22.62	19	0.26	21.30	18
	Nephrops	<0.01*	74.28	41	0.45	43.46	43

Figure
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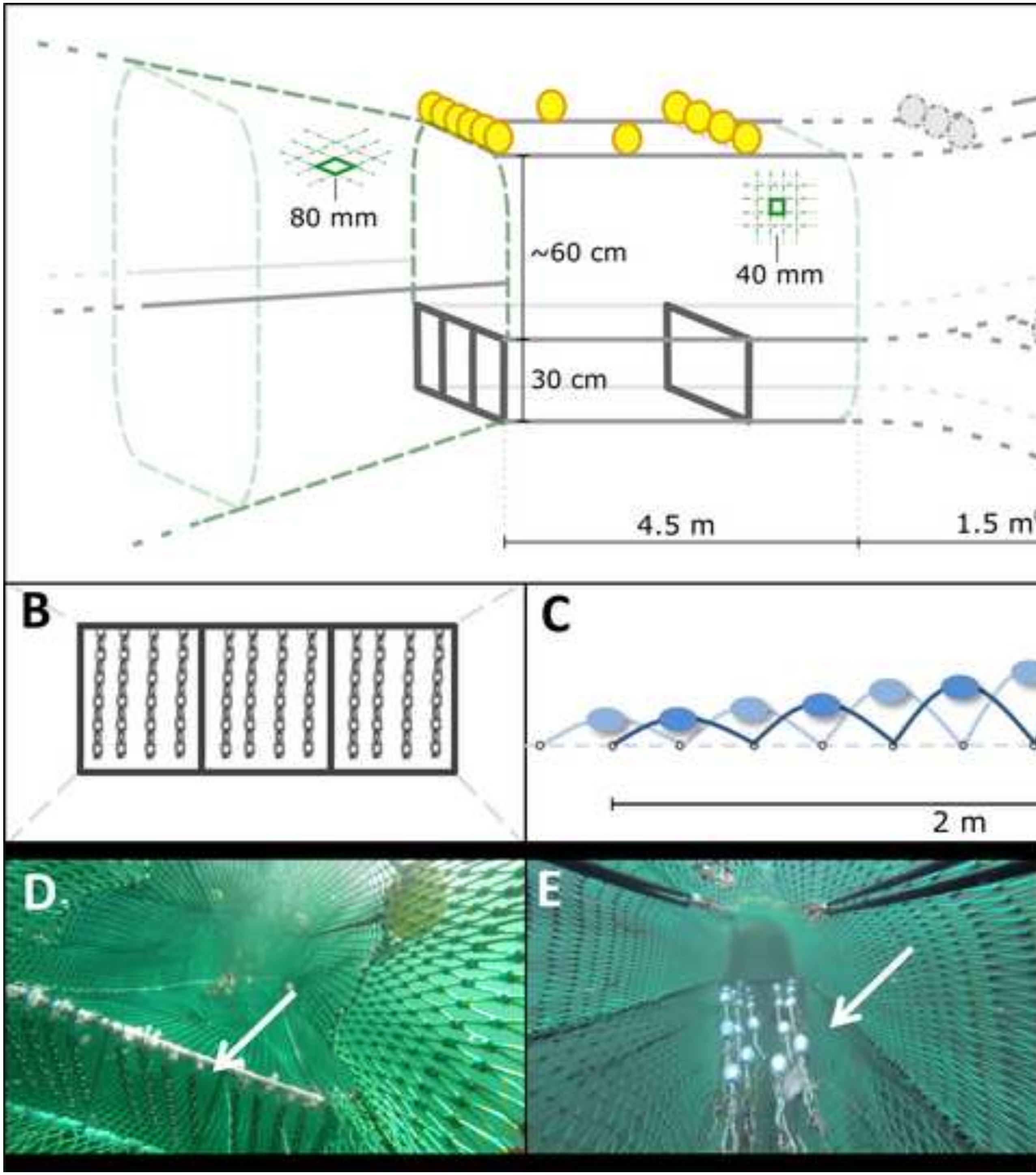

Figure 1. Gear and stimulators designs **A** Baseline design; **B** Chain curtain (frontal view); **C** Rising float-lines (lateral view); **D** Underwater picture of the chain curtain; **E** Underwater picture of the rising float-lines (frontal view).

Figure

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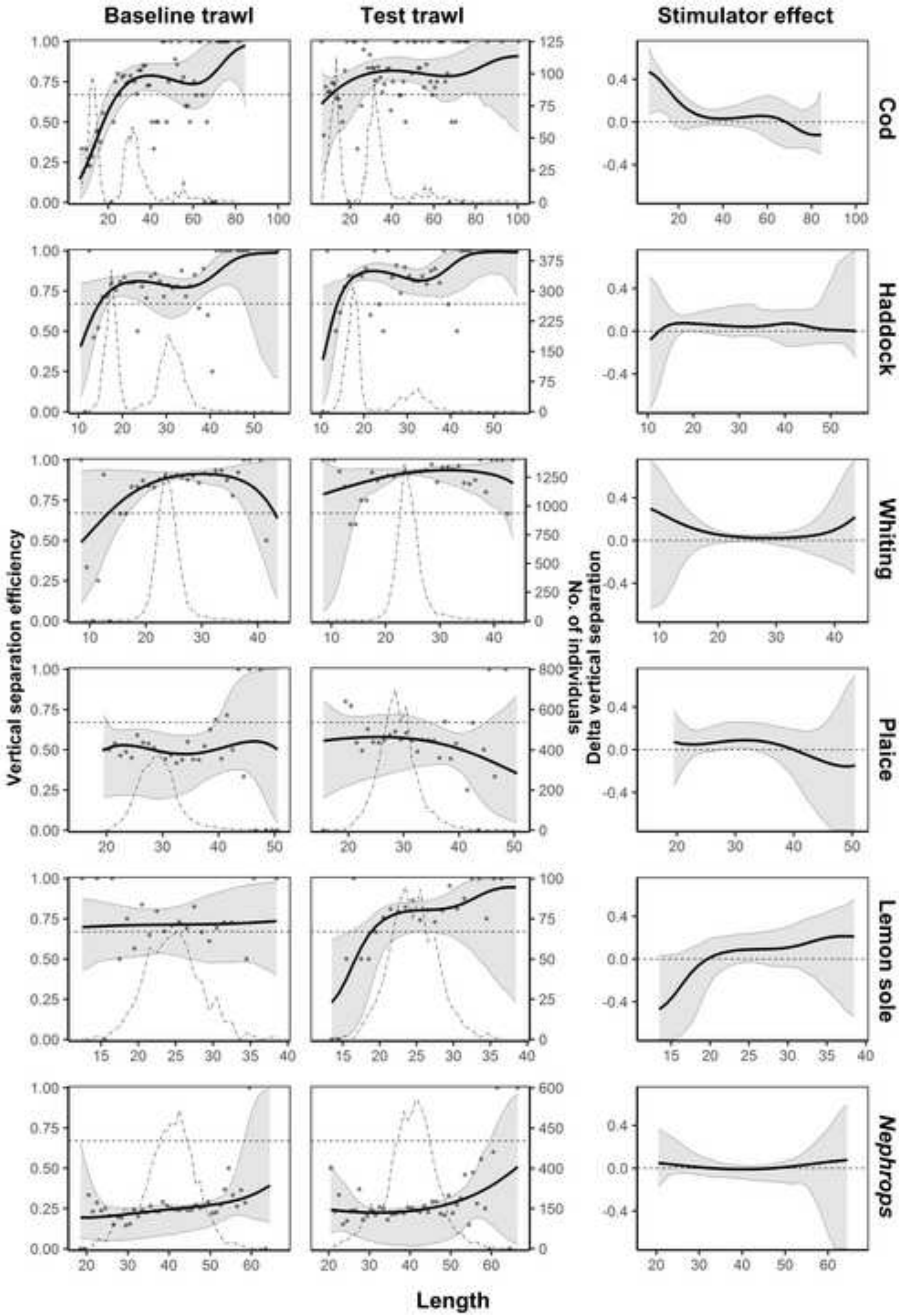

Figure
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