

# 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 Nephropsdirected 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 roll 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.

<ul> <li>(Nephrops norvegicus) in a horizontally divided trawl codend?</li> <li>V. Melli<sup>1</sup>*, L.A. Krag<sup>1</sup>, B. Herrmann<sup>2,3</sup>, J.D. Karlsen<sup>1</sup></li> <li><sup>1</sup>DTU Aqua, National Institute of Aquatic Resources, North Sea Science Park, DK-9850, Hirtshals, Denmark</li> <li><sup>2</sup>SINTEF Fisheries and Aquaculture, Willemoesvej 2, DK-9850 Hirtshals, Denmark</li> <li><sup>3</sup>University of Tromsø, Breivika, N-9037 Tromsø, Norway</li> <li>Corresponding author: Valentina Melli, DTU Aqua, National Institute of Aquatic Resources, I</li> <li>Science Park, DK-9850, Hirtshals, Denmark. Telephone: +45 35883270; e-mail: <u>vmel@aqua.dtu.dk</u></li> </ul>	√orth Sea
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#### 25 Abstract

A promising design to improve selectivity in the *Nephrops*-directed trawl fishery is the horizontally 26 divided trawl codend. Previous studies have succeeded in separating the majority of fish from 27 28 Nephrops; however, cod (Gadus morhua), juvenile roundfish and flatfish still enter the lower 29 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 30 stimulators. These stimulators are designed to exploit fish avoidance behaviour and lead them into 31 32 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 33 34 separation and a set of rising float-lines inserted ahead of the point of separation. The length-35 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 36 parallel to the test trawl. The results showed that fish's vertical separation can be partially 37 improved by the addition of stimulators, without complicating fishing operations or increasing the 38 proportion of *Nephrops* that enters the upper compartment. However, the improvement was 39 40 limited and none of the two active stimulators tested managed to simultaneously improve the 41 separation of cod, juvenile roundfish and flatfish.

42

#### 43 Keywords

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

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#### 48 Introduction

Reducing bycatch of unwanted species and undersized individuals in mixed-species trawl fisheries 49 represents a challenge due to the different sizes and shapes of the species caught. A well-studied 50 example is the Nephrops-directed mixed trawl fishery in the northeast Atlantic (Catchpole and 51 52 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 53 (depending on region). However, the poor selective properties of these mesh sizes in relation to 54 minimum conservational reference sizes (MCRS) often result in high catches of fish (Kelleher, 55 2005; Krag et al., 2008). To appropriately select out some of the commercial northeast Atlantic fish 56 57 species caught, a mesh size of 120 mm should be adopted (Graham and Ferro, 2004), a solution 58 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) 59 whereas Nephrops has obtain an exemption, in some regions, due to its high survival rates 60 (European Commission, 2018). Therefore, fishermen are likely to fulfill their quota for fish before 61 that for Nephrops. Mandatory bycatch reduction devices, such as grids and square mesh panels, 62 63 have been introduced in many regions to mitigate the amount of bycatch and release undersized 64 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 65 66 and cause a loss of commercial size Nephrops (Catchpole and Revill, 2008; Drewery et al., 2010). 67 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-68 specific behaviours (Catchpole and Revill, 2008; Drewery et al., 2010). 69

A promising strategy to combine a behavioural and mechanical selection of the catch is to 70 71 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 72 73 appropriately select out without the risk of losing target catch. Previous studies have proved that, 74 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 75 Fryer, 2006; Krag et al., 2009a; Karlsen et al., 2015). Therefore, when encountering a horizontal 76 77 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 78 79 compartments. Fryer et al. (2017) reviewed studies that included a horizontal net panel, and 80 analysed the main factors affecting the separation of the commercial species caught by demersal 81 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 82 83 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 84 85 aft end of the trawl (Fryer et al., 2017) and designs including a horizontally separated trawl codend 86 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 87 species, with smaller individuals entering more frequently the lower compartment (Holst et al., 88 89 2009; Melli et al., 2018). Due to these differences, the horizontal separation alone might not be 90 sufficient to separate most fish from Nephrops.

91 Additional devices can be inserted before or at the separation to increase the proportion of fish 92 entering the upper compartment. Graham and Fryer (2006) combined a grid with a horizontally

93 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 94 flexible solutions might be able to achieve a similar result by exploiting fish behavioural response 95 96 to mechanical and visual stimuli (Graham, 2010). For example, simple frames with few vertical 97 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; 98 99 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. 100 (2017) tested fluttering lines with floats to trigger fish escape responses and increased significantly 101 102 haddock's escape rate. Kim and Wang (2010) tested a fluttering net panel and a set of free ropes, 103 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 104 105 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. 106

The aim of this study was to investigate if and to which extent the separation of fish from 107 Nephrops in a horizontally divided trawl codend could be improved using active behaviour 108 109 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 110 stimulator aimed at maximizing the illusion of a blocked passage into the lower compartment 111 (Glass and Wardle, 1995). The second stimulator was designed to give fish with relatively poor 112 swimming capacities enough time to rise into the upper compartment, considering the towing 113 speed and possible states of fatigue. Indeed, small fish are likely to utilize most of their aerobic 114 swimming during the initial capture phase while attempting to swim ahead of the footrope 115

(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.

#### 122 Materials and methods

Two sea trials were conducted in September 2016 and 2017 with the research vessel "Havfisken" 123 (17 m, 373 kW). The vessel was equipped for three-wire, twin-trawling with two identical Combi 124 trawls (40 m long footrope, 420 meshes circumference of the trawl mouth, 80 mm mesh size) 125 towed in parallel. The twin-rig system was spread with two Type 2 Thyborøn doors (1.78 m<sup>2</sup>, 197 126 127 kg) and a 400 kg central roller clump. Each trawl spread was monitored throughout the haul with 128 distance sensors (Simrad PI) mounted on doors and clump. The trawls were rigged with 75 m long, 129 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 130 we refer to as the baseline for species vertical separation. The baseline design of the horizontally 131 132 divided trawl codend was previously tested and described in Karlsen et al., (2015) and Melli et al. 133 (2018). We investigated if active swimming stimulators could further improve fish separation from Nephrops. 134

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

138 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 139 lower one were tight together. The length of the extension section was approximately 4.5 m; then, 140 141 the two compartments separated into two independent codends (Fig. 1 A). The total length of the 142 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 143 the compartments, thus invalidating the haul (Melli et al., 2018). Consequently, to sustain the 144 additional length of the codends in 2017 and prevent them from sweeping the seafloor, these 145 were lifted with ten floats each. The lift of the floats was 680 g and 800 g lift for the upper and 146 147 lower codends, respectively.

148 The separation point was positioned at the transition between the tapered and non-tapered 149 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 12 150 151 floats (720 g lift) outside the upper netting (Fig 1 A). The entrance and the extension of the lower 152 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 153 Karlsen et al. (2015) already involved two vertical bars (30 cm apart) in the frame at the entrance 154 of the lower compartment to visually and mechanically stimulate fish to swim into the upper 155 compartment. 156

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

158 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.

166 2) *Rising float-lines* 

To increase the time available for rising into the upper compartment, we inserted a stimulator 167 starting 2 m in front of the separation into compartments (Fig. 1 C and E). Five lines (10 mm, 168 polypropylene) were attached to the lower netting panel with carabiner hooks (size 8 with lock, 64 169 170 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. 171 1 C). The first arc was approximately 8 cm high and each following arc was 3 cm higher, to finally 172 173 reach a height of approximately 20 cm in the last arc, at the separation point. In the middle of 174 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 175 176 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 177 obstacle to the lower compartment entrance. Moreover, this created an alternation of floats with 178 the other lines (Fig. 1 C). Led line (0.26 Kg/m, 3.6 m long) was added outside the lower netting 179 180 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.

183 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 184 separation efficiency. After every haul, the catch of each compartment was weighted and sorted 185 by species separately. The total length of all target fish species and the carapace length of 186 Nephrops were measured and rounded down to the nearest centimetre and millimetre, 187 respectively. Video footage was collected in shallow waters (15 m depth) to visualize the 188 189 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, 190 191 respectively.

#### 192 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(I)* was defined as the probability of finding an individual of length *I* in the upper compartment given it was observed in either compartment. For each species and each haul, *VS(I)* was estimated using the catch data. In each haul *i*,  $nU_{Ii}$  and  $nL_{Ii}$  denoted the number of individuals of length class *I* caught and length-measured in the two compartments. Then, according to our definition, *VS<sub>II</sub>* was:

202 
$$VS_{li} = \frac{\frac{nU_{li}}{qU_i}}{\frac{nU_{li}}{qU_i} + \frac{nL_{li}}{qL_i}}$$
(1)

203 where  $qU_i$  and  $qL_i$  were the sampling factors (i.e. the proportion between the weight of the sample 204 length-measured and the weight of the total catch of that species) in the upper and lower 205 compartments, respectively, in haul *i*. A value of  $VS_{ii}$  above 0.5 implies that in the haul *i* there was a higher probability of finding an individual of length / in the upper compartment, given an equal 206 probability of entering either compartment. However, in this study the height of the entrance of 207 208 the upper compartment accounted for 67% of the total height of the funnel section. Therefore, 209 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<sub>li</sub> above or below 0.67 expressed a differential 210 distribution of individuals. We used the term "preference" to describe this differential distribution 211 212 (Melli et al., 2018).

The averaged length-dependent vertical separation efficiency, VS(l, v), was estimated using the 213 214 pooled data over hauls, assuming this to be a representative sample of how the vertical separation 215 would perform on average under different fishing conditions. Only hauls containing at least 10 216 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 217 218 function, often used for paired gears data (Krag et al., 2014; 2015), and adopted recent 219 improvements in model average estimation (Herrmann et al., 2017). The ability of the model to 220 describe the experimental data was assessed based on the *p*-value, which expresses the likelihood 221 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) 222

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.

227 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 228 accounted for uncertainty due to between-haul variation in vertical separation efficiency by 229 selecting *h* hauls with replacement from the *h* hauls available in the experiment during each 230 bootstrap repetition. Within-haul uncertainty in the size structure of the catch data was accounted 231 232 for by randomly selecting individuals with replacement from each haul and each length class. The 233 number of fish selected from each haul was the number of fish length-measured in that haul in respectively the upper and lower compartment. 234

### 235 *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  $\Delta VS(l, \mathbf{v})$  on the vertical separation by:

240 
$$\Delta VS(l, \mathbf{v}) = VSB(l, \mathbf{v}) - VST(l, \mathbf{v})$$
(2)

where VSB(*I*) is the length-based, average vertical separation efficiency of the baseline trawl and VST(*I*) 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(*I*,*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.  $\Delta VS(l, \mathbf{v})$  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  $\Delta VS(l, \mathbf{v})$  did not contain 0.0, we determined a significant effect of the stimulator in modifying the vertical separation efficiency.

251 Results

A total of 14 valid hauls were conducted with the chain curtain and 10 with the rising float-lines 252 (Table 1). Additional hauls were precautionary excluded from analyses when the catch exceeded 253 the point of separation (n=3) or when the entrance to the lower compartment was partially 254 blocked by marine litter or seaweed (n=3). The towing time was on average 74 ± 30 min (mean ± 255 256 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 257 in September was limited to shallower waters, or to collect video footage of the performance of 258 259 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

267 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, 268 269 Deviance >> DoF). These were the models for cod, plaice and *Nephrops* in the test trawl with the 270 chain curtain and the models for *Nephrops* (baseline trawl) and whiting (test trawl) in the rising 271 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, 272 we attributed the poor fit-statistics of these cases to overdispersion in the data and not to 273 structural problems in describing the experimental data with the combined model (Wileman et al., 274 275 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.

## 279 1) Stimulator at the separation point: chain curtain

280 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 281 282 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 283 284 the two compartments. In contrast, individuals above 17 cm showed a preference for the upper 285 compartment. The preference for the upper compartment was significant for haddock only at 17-286 24 cm and 36–47 cm. The two flatfish species showed different vertical distributions, with plaice 287 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).

290 The main changes in the vertical distribution in the test trawl equipped with the chain curtain 291 were observed in cod and plaice. Cod juveniles (7–16 cm) were significantly raised into the upper 292 compartment, losing their preference for the lower one (Fig. 2, delta). In the test trawl, cod 293 between 27 and 59 cm showed a preference for the upper compartment (Fig. 2, test trawl); 294 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 295 lower compartment (Fig. 2, test trawl), although the difference was significant only for individuals 296 between 27 and 32 cm (Fig. 2, delta). 297

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

299 Respect to the experiment conducted in 2016, wider CIs were obtained for some species and size 300 groups (e.g. cod above 37 cm and haddock above 17 cm; Fig. 3). In particular, very few haddock 301 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 302 303 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; 304 305 small cod (9–15 cm) showed a preference for the lower compartment and a uniform distribution 306 for the bigger length classes. Plaice showed a preference for the lower compartment (11–31 cm), 307 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 308

309 compartment and bigger individuals distributing uniformly. *Nephrops* maintained a strong
 310 preference for the lower compartment.

311 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 312 313 compartment in greater numbers, eliminating the length-dependency in vertical distribution. 314 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 (14-40 315 cm; Fig. 3, test trawl), which resulted significant for individuals between 17 and 30 cm (Fig. 3, 316 delta). A preference for the upper compartment emerged also in cod between 22 and 54 cm (Fig. 317 3, test trawl); however, the difference respect to the vertical separation in the baseline trawl was 318 not significant statistically (Fig. 3, delta). No difference in vertical distribution was observed in 319 320 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 321 322 compartment.

#### 323 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.

338 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 339 and length-groups needed to be further stimulated to rise into the upper compartment: small 340 haddock and whiting, cod and flatfish. These groups showed either a random distribution or a 341 342 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 343 344 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 345 vertical separation of all these groups can be partially improved by adding simple behaviour 346 347 stimulators, without complicating the fishing operation or increasing the amount of *Nephrops* that 348 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 349 improvement was so limited that it would unlikely be considered by the legislation or the 350 fishermen. 351

The chain curtain was significantly effective in raising small cod (7–16 cm) and, for a limited length 352 range, plaice (27–32 cm). Both species lost their preference for the lower compartment in favour 353 of a more uniform distribution. As cod and flatfish are, among the species considered, those 354 showing the strongest tendency to swim in close proximity to the lower netting panel (Fryer et al., 355 356 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 357 358 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 359 Wardle, 1995). However, considering the strong mechanical stimulus represented by the moving 360 361 chains we expected a stronger effect. The lack of a strong response to the stimulation can be 362 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 363 extension are assumed to rely on anaerobic swimming which allows short bursts but not 364 continuous extended swimming (Webb, 1994). Moreover, studies in laboratory conditions proved 365 that the maximum swimming speed is often length-dependent (He, 1993; Winger et al., 1999). On 366 367 the other hand, video observations in shallow water revealed that the chains were bending 368 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 369 370 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

375 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, 376 undersized Nephrops (17-27 cm) were affected by the rising float-lines and entered almost 377 exclusively the lowest compartment. The difference, although significant, is minimal due to the 378 379 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 380 interest as *Nephrops*, and especially the smaller individuals, are usually considered to be passive in 381 this section of the trawl (Main and Sangster, 1985). It is unclear what might have caused this 382 effect, but it is likely a consequence of the contact between Nephrops and the components of the 383 384 stimulator (i.e. floats and lines).

Contrary to our expectations, moving the stimulator ahead of the separation to increase the time 385 386 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 387 388 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 389 vertical separation, although increasing the proportion of individuals entering the lower 390 391 compartment. Another possibility is that the type of stimulation did not cause a response. 392 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., 393 2017). However, these studies applied the stimulators in bigger section of the trawls respect to the 394 one used in this study. Possibly, in a narrower section fish are overstimulated or stressed for this 395 type of stimulation to be effective. 396

In conclusion, despite applying relatively strong stimuli and in different position respect to the 397 point of separation we were not able to substantially improve the separation of fish from 398 Nephrops. The baseline design of the horizontally divided trawl codend offers already an efficient 399 400 separation, and could be at present adopted by the industry. Perhaps, the Northeast Atlantic 401 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. 402 However, the responses to the stimulators identified in this study could be applied to other trawl 403 404 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 405 406 their level of stress and exhaustion is lower.

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#### 537 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.

544 Figure 2. Length-based vertical separation efficiency of the six species analysed during the chain curtain experiment. 545 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 546 547 represent the 95% Efron CIs and the dash-dot line is the length distribution of the data. The dashed horizontal line, 548 located at 0.67, describes an equal preference for entering either compartment. In the third column, the solid line 549 represents the difference (Delta) in vertical separation between the baseline and test trawls, accounting for 550 synchronized hauls. The grey bands are the 95% Efron CIs and the dashed line represents no difference in vertical 551 separation.

552

**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.

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#### 563 Tables

564

565 Table 1

566 Overview of the experimental hauls, showing the technical and environmental parameters and total catch (kg) per 567 each of the four compartments. BU = baseline upper compartment; BL = baseline lower compartment; TU = test upper 568 compartment; TL = test lower compartment. Hauls were separated by stimulator (Stim.), i.e. chain curtain (C) and 569 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	С	Р	13:20	01:00	120	6	2.7	326	132	448	138
2	2016	С	Р	16:00	01:00	105	7	2.6	271	130	75	120
3	2016	С	Р	08:15	02:00	63	8	2.6	100	175	125	170
4	2016	С	S	15:20	02:00	61	-	2.6	95	157	120	135
5	2016	С	S	08:10	01:00	31	3	2.6	154	218	197	163
6	2016	С	Р	10:50	01:30	38	3	2.6	144	180	133	213
7	2016	С	Р	14:45	01:00	86	3	2.6	176	79	375	230
8	2016	С	Р	16:55	01:05	87	3	2.7	136	158	550	182
9	2016	С	Р	07:25	01:10	78	3	2.6	721	380	1179	360
10	2016	С	Р	12:40	00:50	85	8	2.6	643	190	330	161
11	2016	С	Р	16:30	00:40	87	9	2.6	298	240	238	143
12	2016	С	Р	07:20	00:45	84	9	2.6	420	183	288	114
13	2016	С	S	09:45	01:00	61	9	2.6	33	18	53	25
14	2016	С	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	Р	05:30	02:00	39	4	2.7	101	144	170	180
8	2017	F	Р	12:30	01:30	91	6	2.7	513	232	660	200
9	2017	F	Р	06:00	01:00	38	10	2.7	87	163	66	118
10	2017	F	Р	11:10	01:30	76	10	2.7	315	330	230	91

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**Table 2**. Number of hauls and number of individuals per species per compartment included in the two experiments. U

573 = upper compartment; L = lower compartment. Species that were subsampled are indicated with the raised total

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

574 number and the actual number of individuals measured (in brackets).

**Table 3.** Fit statistics for the modelled vertical separation efficiencies of the two experiments. DoF denotes the degree586of freedom and was calculated by subtracting the number of model parameters from the number of length classes in587the dataset. Significant *p*-values (p<0.05; indicated by \*) express that the residual variation between the models fit</td>

588	and the experimental	data required	further investigation.
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Exporimont	Spacios	<b>Baseline trawl</b>			Test trawl		
Laperintent	species	<i>p</i> -value	Deviance	DoF	<i>p</i> -value	Deviance	DoF
	Cod	0.54	59.28	61	0.03*	89.73	66
	Haddock	0.08	45.17	33	0.64	26.60	30
Chain aurtain	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
	Cod	0.66	48.30	53	0.09	68.57	54
	Haddock	0.32	23.43	21	0.18	27.86	22
<b>Rising float-</b>	Whiting	0.06	45.38	32	< 0.01*	55.70	32
lines	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

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Length

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Length