The vertical separation of fish in the aft end of a demersal trawl

Ludvig Ahm Krag, René Holst, and Niels Madsen

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Two multi-compartment separator frames were used to study the vertical separation of some commercially important fish species in the aft end of a trawl, with the aim of separating cod (*Gadus morhua*) from other species. A non-linear multinomial model with random effects was used to analyse the data and to compare the performance of the two frames. The vertical distribution of cod in the aft end of the trawl was close to uniform, whereas haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*), plaice (*Pleuronectes platessa*), and lemon sole (*Microstomus kitt*) showed more uneven distributions. The use of guiding bars in the separator frame significantly ($p < 0.05$) increased the catch of cod, plaice, and lemon sole in the upper compartment. The vertical separation of cod was density-dependent; high densities of fish resulted in a more uniform distribution of cod. The species separations found differ from those reported from the studies of species separation in the region of the trawl mouth.

Keywords: cod, fish behaviour, multinomial mixed effects models, species selectivity, trawl.

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L. A. Krag, R. Holst and N. Madsen: DTU Aqua, National Institute of Aquatic Resources, North Sea Science Park, 9850 Hirtshals, Denmark. Correspondence to L. A. Krag: tel: +45 33 963200; fax: +45 33 963260; e-mail: lak@aqua.dtu.dk.

Introduction

The Danish demersal trawl operations in the Skagerrak and the North Sea are primarily mixed species fisheries. The economically most important species are plaice (*Pleuronectes platessa*), Norway lobster (*Nephrops norvegicus*), cod (*Gadus morhua*), monkfish (*Lophius piscatorius*), sole (*Solea solea*), lemon sole (*Microstomus kitt*), and turbot (*Psetta maxima*; Anon., 2006). The general conditions for exploiting these species have changed during recent years. Increasing effort regulations and the mandatory use of selective devices, such as square-mesh panels, increased codend mesh size, and grids, have been implemented to help rebuild the declining North Sea and Skagerrak cod stocks. Effort regulations and closed areas impact the fishery of all species, not just cod, so an alternative to non-specific measures is to develop further more species-selective fishing gear. Glass (2000) stated that fish escapement can be influenced by species-specific behaviour patterns and mechanical sorting mechanisms based on size. Despite the distinct morphological differences among cod, flatfish, and *Nephrops*, it is not possible to exclude cod of all sizes by pure mechanical sorting without the loss of target species.

Behavioural studies in the trawl mouth have shown that haddock and, to a lesser extent, whiting and saithe (*Pollachius virens*) rise above the groundgear as they tire. Cod, flatfish, and *Nephrops* enter the trawl close to the groundgear (Main and Sangster, 1981; Thomsen, 1993; Bublitz, 1996). These findings have led to extensive studies of species separation in the mouth of the trawl (Main and Sangster, 1982, 1985; Cotter *et al*., 1997; Engås *et al*., 1998; Ferro *et al*., 2007). Behavioural aspects farther aft in the trawl have been studied less, but cod apparently rise towards the upper panel farther aft in trawls, whereas flatfish glide backwards closer to the lower panel (Thomsen, 1993). Scottish experiments have shown that rising ropes in a trawl mouth can divert cod towards the upper panel of trawls (R. S. T. Ferro, formerly FRS, pers. comm.).

The objective of this study was to investigate how efficiently cod can be separated from other fish species in the aft end of a trawl. It is important to be able to distinguish between different species and sizes when using camera observation techniques, and it is difficult, especially for flatfish (Thomsen, 1993; Bublitz, 1996). Here, we assess the vertical separation of the different species using a separator frame with three vertically stacked compartments. A second separator frame with guiding bars was tested to determine whether additional stimuli could improve the separation of cod from other fish. We used a non-linear multinomial model with random effects to analyse the catch data collected with the two separator frames. Further, the vertical separation of species by each of the two types of frame was quantified and compared.

Material and methods

Experimental set-up

Two combined fish and *Nephrops* trawls of a design typically used by the Danish fleet in the North Sea mixed fishery were manufactured by Cosmos Trawl in Hirtshals, Denmark. Both were modified with identical four-panel aft ends by inserting two wedges into the original two-panel design (Figure 1). The four-panel construction provided a stable cavity in the aft section. Both trawls were mounted with a square, rigid, separator frame that separated fish into three vertically stacked compartments. The square cavity in the extension section, in which the separator frames were installed, was ~0.9 m wide and 1.0 m high. The separator frames were installed two meshes behind the joint between the last tapered belly section and the extension, at an angle of ~50°, which equals 12 m in front of the codline. The frames were installed at an angle and not vertically to allow haul-back of the

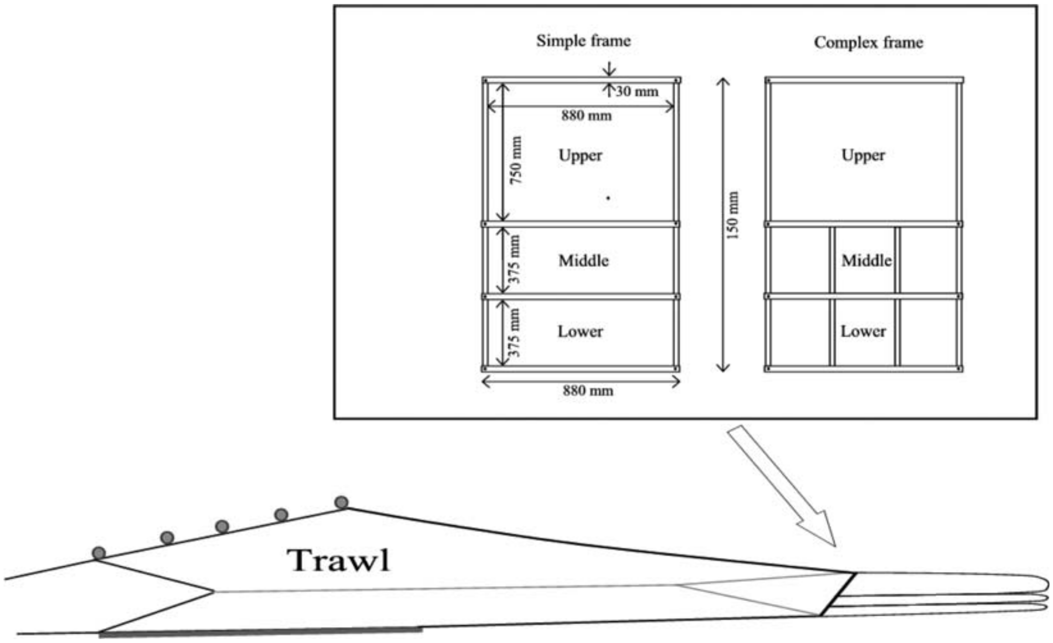

Figure 1. A drawing of the separation section in the trawl and the simple and complex separator frames, each with three vertical compartments.

gear through the vessel's relatively narrow stern ramps and the frames to be rolled up onto the net drums. The two frame types are denoted simple (S) and complex (C), and the three compartments in each frame are denoted lower, middle, and upper. Small-mesh codends (42 mm full mesh) were attached to each compartment. The complex frame differs from the simple frame in its presence of two vertical guiding bars across the lower and middle compartments. The distance of 28 cm between the two vertical bars in the complex frame was too large to cause mechanical selection of most fish species. The upper compartment covered 50% of the frame opening, and the middle and lower compartments covered 25% each in both frames. The compartments were of unequal size to obtain more detailed information about the separation of cod and flatfish in the lower part of the gear. The frames were constructed of horizontal polyamide bars and vertical fibreglass bars.

Sea trials were conducted on board a 511-kW commercial vessel using the twin-trawl technique (Wileman *et al*., 1996) on commercial fishing grounds in the Skagerrak (ICES rectangle 44F9). In all, 11 hauls were taken between sunrise and sunset in depths varying from 30 to 90 m. Haul duration was 90 min at 3.1 knots. Experimental conditions were recorded for each haul. The catch in the six compartments (three from each trawl) was kept separate during all stages of the handling process. All commercially important species (plaice, lemon sole, cod, haddock, saithe, and whiting) were measured to the nearest centimetre, and the midpoints of the length classes were used in subsequent data analysis.

Statistical modelling

The aim of the analysis was to model the separation of fish into the three stacked compartments and to compare the catches of the two frames. Each haul was considered a cluster, and random variation between the hauls was assumed (Fryer, 1991).

Single-haul model

The numbers of fish collected from the compartments are denoted $n_{f,g}$, where $f = \{S, C\}$ for the simple and complex frames and $g = \{L, M, U\}$ for lower, middle, and upper compartments. The numbers of fish collected from each of the two frames are denoted n_{S+} and n_{C+}, and the grand total is $n_{+} = n_{C+} + n_{S+}$.

The conditional distribution for the number of fish entering each compartment given the total number for each frame is multinomial, i.e. $(n_{f,U}, n_{f,M}, n_{f,L} \mid n_{f+}) \sim \mathrm{MN}(n_{f+}; \pi_{f,U}, \pi_{f,M}, \pi_{f,L})\ f = \{S, C\}$; $\pi_{f,U} + \pi_{f,M} + \pi_{f,L} = 1$. This model implicitly assumes independence among fish movements. Schooling behaviour or local abundance effects may violate this assumption and cause overdispersion in the data. Using the upper compartment as baseline category, the probabilities can be written as

$$\pi_{f,U} = \frac{1}{1 + \exp\left(\eta_{f,M}\right) + \exp\left(\eta_{f,L}\right)}$$
$$\pi_{f,M} = \frac{\exp\left(\eta_{f,M}\right)}{1 + \exp\left(\eta_{f,M}\right) + \exp\left(\eta_{f,L}\right)} \qquad f = \{S, C\}.$$
$$\pi_{f,L} = \frac{\exp\left(\eta_{f,L}\right)}{1 + \exp\left(\eta_{f,M}\right) + \exp\left(\eta_{f,L}\right)}$$

This model is linear in the sense that

$$\mathrm{logit}\left(\pi_{f,g}\right) = \log\left(\frac{\pi_{f,g}}{\pi_{f,U}}\right) = \eta_{f,g} \text{ and } f = \{S, C\};\ g = \{M, L\}.$$

A split parameter, p, that gives the conditional probability that a fish enters, say, rig C given that it entered one of the rigs is required for simultaneous modelling of all six compartment probabilities. The conditional distribution for the six compartments given the grand total is a multinomial:

$$(n_{C,U}, n_{C,M}, n_{C,L}, n_{S,U}, n_{S,M}, n_{S,L}|n_+) \sim \mathrm{MN}(n_+; \varphi_{C,U}, \varphi_{C,M}, \varphi_{C,L}, \varphi_{S,U}, \varphi_{S,M}, \varphi_{S,L}),$$

where

$$\varphi_{C,g} = \frac{\pi_{C,g}}{p} \text{ and } \varphi_{S,g} = \frac{\pi_{S,g}}{1-p} g = \{U, M, L\}.$$

This model is not linear in the sense described above. Apart from the usual concerns for non-linear models (Hougaard, 1982), the non-linearity may also be of relevance for the choice of tool for fitting the model.

Multiple-haul model

We extended the model to all hauls, using index h for a given haul and H for the total number of hauls. A random haul effect was introduced by adding a random variable to each of the four linear predictors:

$$\eta_{f,g,h} = \eta_{f,g} + b_{f,g,h} \quad f = \{S, C\}; g = \{M, L\}, h = \{1, \ldots, H\},$$

where $\eta_{f,g}$ now denotes the mean predictor for compartment g in frame f. The vector of random effects for haul h was assumed to be multivariate normally distributed:

$$\mathbf{b}_h = (b_{C,M,h}, b_{C,L,h}, b_{S,M,h}, b_{S,L,h})^T \sim \mathrm{MVN}(\mathbf{0}, \mathbf{\Omega}), h = \{1, \ldots, H\}.$$

Testing for differences between frames

The single haul model described above is general in that it allows for the two frames to have different (conditional) cell probabilities. A more parsimonious model was assessed by testing whether corresponding compartments had identical (conditional) cell probabilities:

$$\mathrm{H}_0 : \pi_{S,U} = \pi_{C,U} \text{ and } \pi_{S,M} = \pi_{C,M} (\text{and hence } \pi_{S,L} = \pi_{C,L})$$

$$\mathrm{H}_1 : \text{at least one of the pairs differed.}$$

This test was suitable for choosing the frame best suited for species separation across all species. The hypothesis was tested using a likelihood ratio test. The constrained model 2, corresponding to the null hypothesis, was fitted, and twice the difference in the log-likelihood is referred to as the $\chi^2_{\mathrm{d.f.}=2}$ distribution with 2 degrees of freedom (d.f.) reflecting the difference in the number of parameters.

We used the software package ADMB-RE (Fournier, 2006) for parameter estimation. We encountered numerical problems when trying to estimate a full variance–covariance $\mathbf{\Omega}$ matrix. The matrix was therefore assumed to be of diagonal form, setting all covariances to zero.

Results

Sea trials

The separator frames proved to be simple to use on commercial vessels. Operational conditions experienced during the 11 hauls were similar, with windspeed ranging from 2 to 13 m s^{-1} and door spread from 145 to 189 m. The length distributions and catch size in the upper, middle, and lower compartments for the simple and complex frames were similar for most species, when taking into account the fact that the upper compartment was twice as large as the other two (Figure 2). The catch of cod, haddock, saithe, and whiting consisted primarily of smaller fish below their respective minimum landing sizes (MLS). The total numbers of fish caught by the two trawls differed for whiting and saithe, for which larger numbers were caught in the trawl with the simple frame. The number of individuals per species varied from a few hundred (saithe) to several thousand (cod).

Statistical modelling

In model 1, separate probabilities for each compartment and frame were estimated, whereas model 2 assumes equal probabilities for corresponding compartments of the two frames. Model 2 was compared with model 1 using a likelihood ratio test. The drop in deviance (i.e. the χ^2_2 value) was significant ($p < 0.05$) for all species: 163.2 for cod, 84.8 for haddock, 108.6 for whiting, 48.9 for plaice, and 228.3 for lemon sole. Therefore, the vertical separation of all species was significantly affected by the guiding bars in the complex separator frame.

Vertical separation

Table 1 gives the estimated conditional mean catch probabilities for each compartment in the two separator frames for all species (model 1). The catch of cod in the upper compartment was estimated to be 54% for the simple frame and 67% for the complex frame. Haddock and whiting were caught mainly in the upper compartment in both separator frames, whereas plaice and lemon sole were caught primarily in the lower compartments of the simple frame. Higher catch proportions of plaice, lemon sole, and whiting were estimated in the upper compartment in the complex frame relative to the simple frame; in particular, the proportions of plaice and lemon sole in the simple frame were almost double those in the upper compartment in the complex frame. The catch proportion in the upper compartment in the complex frame was higher than that in the simple frame for all species except haddock, for which it was 87% in the simple frame and 78% in the complex frame. Saithe were caught in a few tows only, so were excluded.

A variant of model 1, which used total counts of fish by frame as a covariate, converged only for cod. The vertical separation of cod was density-dependent (Figure 3). The catch proportion of cod in the upper compartment was highest at low densities of fish, but decreased towards a uniform distribution at higher levels of mean density of fish caught during the tow (Figure 3).

Discussion

Our study investigated the potential for separating different fish species at the aft end of a demersal trawl, in contrast to most other studies in which species are separated in the trawl mouth (Main and Sangster, 1982, 1985; Engås *et al.*, 1998; Ferro *et al.*, 2007). Most individuals of each species were caught either in the upper or in the lower compartment during studies describing separation at the trawl mouth. The separation of species between compartments was not as consistent at the aft end of a trawl as in the trawl mouth area. The vertical separation of cod shifted from a preference for the lower compartment in the trawl mouth to a more uniform distribution at the trawl aft end, illustrated by the catch proportions in the compartments being almost proportional to the size of the compartments. This shift in vertical behaviour agrees with the camera observations

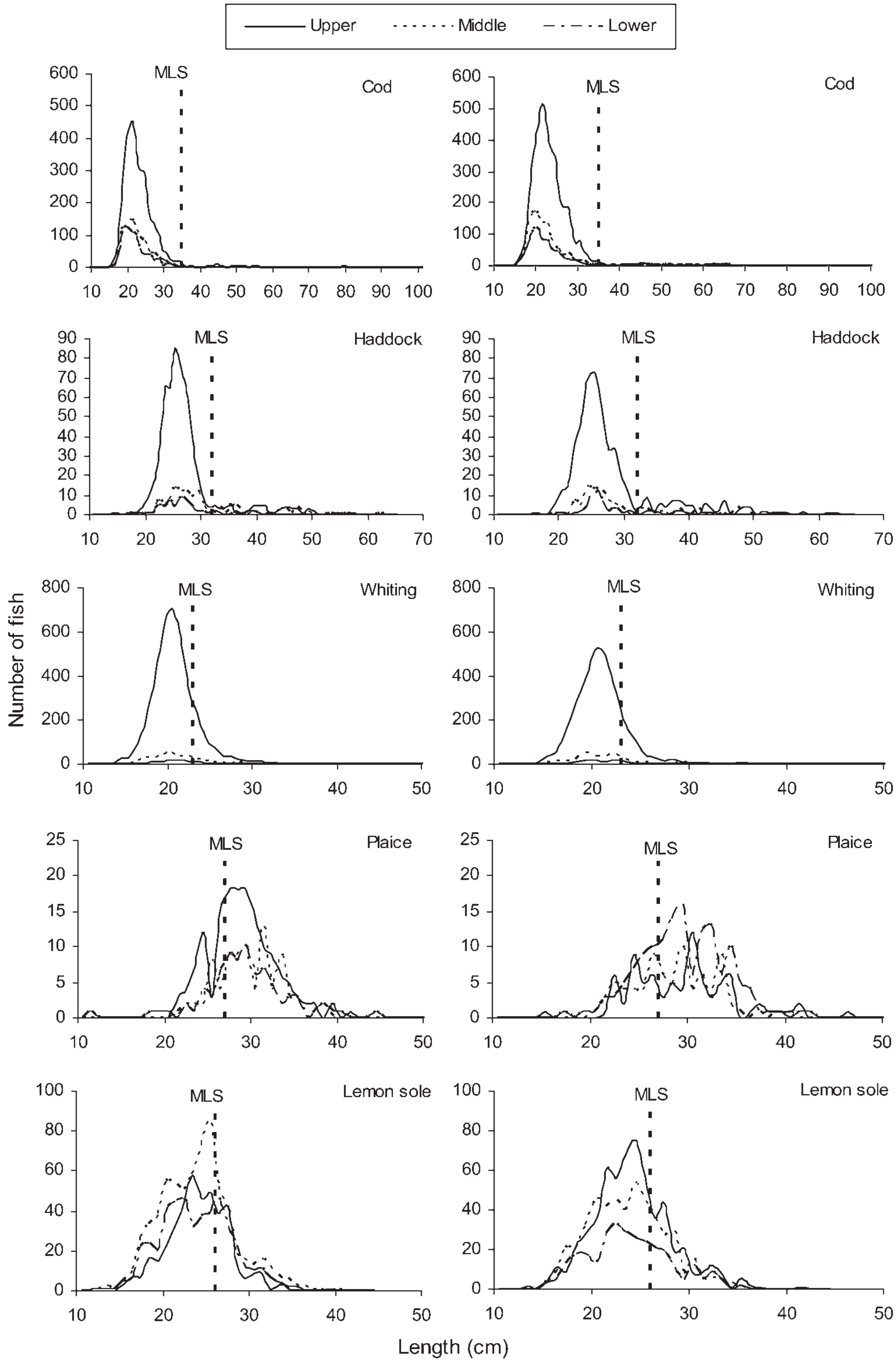

Figure 2. Length frequency of vertical catch distributions of cod, haddock, whiting, plaice, and lemon sole for all hauls combined. Catch values for the simple frame are in the left column and for the complex frame in the right column. MLS is the minimum landing size.

described by Thomsen (1993). The vertical separation of plaice and lemon sole also differed from that reported from trawl mouth studies. Those species rose towards the upper panel at the aft end, as observed for cod, but in lesser proportions. These findings for aft separation of flatfish are in accord with results from the western Atlantic (He *et al.*, 2008). The apparent strong affinity for the lower panel at the trawl mouth therefore appears to be less obvious in the narrow extension leading to the codend. Thomsen (1993) reported that flatfish were frequent close to the upper panel at the aft end of a tapered section; that section had a diameter of ~1 m, a similar dimension to the separation section used in the present study. A better separation of cod

Table 1. Estimated conditional catch proportions for the three compartments in the simple separator frame and in the complex separator frame, by species.

		Simple frame		Complex frame	
Species	**Compartment**	**Estimate**	**s.e.**	**Estimate**	**s.e.**
Cod	Upper	0.540	0.051	0.671	0.044
	Middle	0.282	0.033	0.194	0.027
	Lower	0.178	0.021	0.136	0.019
Haddock	Upper	0.872	0.088	0.777	0.075
	Middle	0.088	0.061	0.151	0.055
	Lower	0.040	0.028	0.072	0.026
Whiting	Upper	0.906	0.029	0.951	0.011
	Middle	0.082	0.027	0.038	0.009
	Lower	0.011	0.003	0.011	0.003
Plaice	Upper	0.268	0.033	0.538	0.069
	Middle	0.265	0.026	0.209	0.041
	Lower	0.468	0.031	0.253	0.043
Lemon sole	Upper	0.326	0.042	0.502	0.038
	Middle	0.385	0.027	0.305	0.027
	Lower	0.289	0.021	0.194	0.018

Model 1 was used to estimate the catch proportions. s.e., standard error.

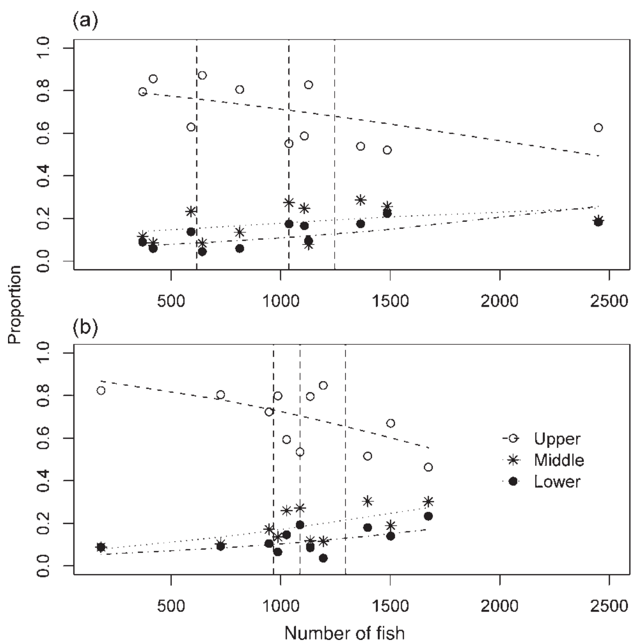

Figure 3. Estimated separation success for cod in numbers from the upper, middle, and lower compartments as a function of fish density: (a) simple frame, and (b) complex frame. The dashed vertical lines indicate from the left the lower quartile, the median, and the third quartile.

and flatfish may therefore be obtained farther forward in the gear. Haddock and whiting in the current study, however, exhibited vertical separation at the narrow aft end, similar to that reported in trawl mouth studies. Some 90% of haddock and whiting entered the upper compartment along with about half the cod. Results from experiments with square-mesh panels at the aft end of demersal trawls show that such devices are more effective in separating juvenile haddock and whiting than they are in separating out juvenile cod (Madsen *et al.*, 1999; Krag *et al.*, 2008). The species-specific differences in vertical preferences within the trawl extension may provide an explanation as to why some species escape through square-mesh panels more efficiently than others. The vertical separation of fish shown here was based primarily on fish smaller than their respective MLS, except for plaice. The vertical behaviour may be different in a population containing mainly large fish.

The catch proportion of cod in the upper compartment (54%) of the simple frame corresponded well with the size of the openings of the upper compartment (50%). In contrast, the complex frame elevated more cod into the upper compartment (67%) than did the simple frame. Similar results for stimulated separation of cod are presented by He *et al.* (2008), ∼60% being caught in the upper codend during separation in the extension of the trawl. He *et al.* (2008) used a visual illusion created by a black tunnel (see also Glass and Wardle, 1995) to enhance vertical separation. The catch of plaice and lemon sole in the upper compartment also increased considerably. In contrast to all other species and expectation, haddock separation into the upper compartment was less in the complex frame than in the simple frame. We have no explanation for this observation. The guiding bars in the complex frame clearly influenced vertical separation, but the complex frame did not improve the separation of cod from other roundfish or from flatfish. The results from the complex frame with guiding bars indicate that a relatively large proportion of fish can be elevated in the trawl cavity by a simple stimulus. Traditional sorting grids are made with a fixed bar spacing to provide mechanical selection when the behaviour of fish is of less importance for the selection process. Such sorting systems are efficient in releasing fish below or above a certain size, but they can also incur relatively high losses of target species (Fonseca *et al.*, 2005).

The vertical separation of cod was density-dependent. Most cod were caught in the upper compartment at low fish density, but the catch was more proportional to the area of the frame opening at higher densities. A possible explanation for this finding is that many fish species have a predisposition to stay a certain distance away from other fish and netting or other fishing gear components and that this will tend to space them out evenly. The variations in the vertical separation of fish may therefore be larger from haul to haul and within hauls in narrow gear sections than in larger gear sections, such as the trawl mouth.

All catch data in this study were obtained during daylight. Ferro *et al.* (2007) found that a significantly greater proportion of cod, plaice, and lemon sole entered the lower compartment by day than by night and that the rising behaviour of gadoids in the catching process appeared to be more pronounced during daylight. Fishing gear designs making use of behavioural differences must obviously rely on these differences to be relatively consistent over time and across regions. Anything that alters the standard gear design might affect how fish behave inside the gear. This seems to be the case with the separator frame, but direct observations of how fish behave as they encounter the separator frame in the trawl are necessary to quantify fully the possible effects of the sampling device.

In summary, the rather distinct vertical fish separation reported from species separation studies conducted in the trawl mouth area was not found at the narrow aft end of the trawl. Behaviour-based efficient vertical separation of cod from other roundfish, such as haddock, saithe, or whiting, is therefore difficult at that point in the trawl. The separation success between cod and flatfish was higher than for cod and other roundfish, but was still relatively poor. Cod and flatfish were, however, separated better at the aft end than in the area of the trawl mouth. The guiding bars in the complex frame showed that fish behaviour within a trawl can be affected by simple means. The approach could be used to separate fish from *Nephrops* in the *Nephrops* fisheries, where discard rates are high (Krag *et al*., 2008). Moreover, simple guiding systems could be used to increase the probability of contact with selective devices such as square-mesh panels.

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