

## Original Article

# New approach for modelling size selectivity in shrimp trawl fisheries

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In the deep sea trawl fishery targeting shrimp (*Pandalus borealis*) and other cold-water shrimp species, fishers often use a Nordmøre sorting grid ahead of a small mesh codend to avoid bycatch. However, small fish can pass through the grid and are subsequently retained in the codend. This makes shrimp size selection complex and the size-dependent curve for both the shrimp and the bycatch species often exhibits a bell-shaped signature. In this study we developed a new model and method to estimate size selection in this fishery, conducted fishing trials in the Northeast Barents Sea, and applied the new method to quantify the individual and combined size selection of the Nordmøre grid and codend for deep water shrimp and two bycatch species. The size selectivity for both bycatch species showed the expected bell-shaped signature with low retention probability of very small and larger fish. The Nordmøre grid had high passage probability for all sizes, although it decreased slightly for the largest shrimps. The smallest shrimps were released by the codend.

**Keywords:** bycatch, Nordmøre grid, shrimps, size selectivity, trawl fishery.

## Introduction

Shrimps are a commercially important species fished over the world. Although the species and sizes of targeted shrimp vary, in many shrimp fisheries the selectivity of the gear is based upon a grid to exclude non-shrimp bycatch followed by a size selective codend. This is the case for the deep water shrimp (*Pandalus borealis*) fisheries in the Northeast Atlantic shrimp fishery, which have used such selectivity devices since the early 1990s.

The Nordmøre grid, first developed based on a device used to exclude jellyfish, proved to be efficient in excluding fish bycatch during shrimp trawling (Isaksen *et al.*, 1992). The grid typically consists of a guiding funnel, a 30–50° sloped grid, and a triangular fish outlet in the upper panel just in front of the grid. This bycatch reducing device was introduced in the Norwegian inshore shrimp fishery in 1990. The use of this sorting grid became

compulsory for the international deep sea shrimp trawl fishery in the Northeast Atlantic (i.e. the Norwegian Sea and the Barents Sea) in 1993 and the technique is today used in several other shrimp fisheries around the world (Eayrs, 2007; He and Balzano, 2007; García *et al.*, 2007; Suuronen and Sardà, 2007; Frimodig, 2008).

All vessels targeting shrimp in Norwegian waters are obliged to use a Nordmøre grid with a 19-mm bar spacing followed by a codend with a minimum mesh size of 35 mm (Norwegian Directorate of Fisheries, 2011). Thomassen and Ulltang (1975) tested several codend mesh sizes for the northern shrimp fisheries at the end of the 1960s and found acceptable retention lengths for deep water shrimps with the 35-mm mesh size. Despite the many changes in the northern shrimp fishery that have occurred since this investigation, the minimum codend mesh size remains at

35 mm. The introduction of the Nordmøre grid eliminated the issue of bycatch of larger sizes of fish because they are unable to pass through the grid into the trawl codend (Grimaldo and Larsen, 2005; Grimaldo, 2006). However, small-sized fish such as juveniles of various species are able to pass through the grid and enter the codend together with the targeted shrimps (He and Balzano, 2007, 2013).

The current regulations of the Northeast Atlantic shrimp fishery allow retention of low numbers of juvenile fish from regulated species. For example, the fishing areas are closed if a catch sample exceeds three redfish (*Sebastes* spp.), and three Greenland halibut (*Reinhardtius hippoglossoides*) per 10 kg shrimps. Additionally, the shrimp catch can contain no more than 10% by weight of undersized (i.e. < 15 mm carapace length) shrimps (Norwegian Directorate of Fisheries, 2011). These strict bycatch rules have led to frequent temporary closures of several large shrimp fishing grounds in the Northeast Atlantic over the last 20 years (Gullestad et al., 2015), often lasting for weeks or months until bycatch levels fall below the threshold. Bycatches of juvenile fish and undersized shrimps also cause practical problems when sorting the catch on-board the fishing vessels.

The use of a Nordmøre sorting grid ahead of a small mesh codend makes the size selection processes complex, and the size-dependent curve for both shrimp and bycatch often exhibits a bell-shaped signature. However, a selection model that can properly describe and estimate these signature curves is not available, which challenges an ability to assess size selectivity in these fisheries.

Considering the challenges described above, the aim of the current study was to:

- Develop a new model to estimate size selection in shrimp trawls using a Nordmøre grid and a small mesh codend.
- Quantify the size selectivity of deep water shrimp using a Nordmøre grid with a 19-mm bar spacing followed by a diamond mesh codend with 35-mm mesh size.
- Quantify the size selectivity of juveniles of some of the most important bycatch species using the Nordmøre grid and diamond mesh codend

## Material and methods

### Research vessel, study area, and experimental design

The fishing trials were conducted using a commercial shrimp trawl with Nordmøre grid followed by a size selective codend. Using a procedure described in Wileman et al. (1996), the bar spacing in the Nordmøre grid was  $18.8 \pm 0.4$  mm (mean  $\pm$  SD) and the meshes in the codend were  $33.8 \pm 1$  mm (mean  $\pm$  SD).

In order to independently assess the contribution of the grid and the codend to the overall selectivity of the trawl, shrimp and fish released by the grid and the codend could be collected separately using two independent covers: one over the opening of the grid and the other surrounding the entire codend. Such double cover setups have been used previously to collect selectivity data in finfish fishery (Sistiaga et al., 2010). However, in a shrimp fishery, the mesh size of the cover is very small and may affect selectivity by masking codend meshes or affecting water flow adjacent codend meshes. In addition, using two covers significantly complicates the selectivity study because the covers can become entangled, they can modify trawl performance or alter shrimp and fish behaviour, and they create operational challenges on-

board. Therefore, to avoid these challenges, we used two different experimental setups during the sea trials to evaluate size selectivity of shrimp and bycatch. In the test haul setup, we fished with a standard Nordmøre grid and 35 mm codend with a small-mesh cover [mesh size  $16.4 \pm 0.5$  mm (mean  $\pm$  SD)] collecting fish and shrimps escaping from the opening in front of the Nordmøre grid (Figure 1). In the control haul setup, the codend contained a small-meshed inner net [mesh size  $18.5 \pm 0.9$  mm (mean  $\pm$  SD)] installed with a low hanging ratio to prevent the escape of fish and shrimp. In this setup, fish and shrimps that escaped in front of the Nordmøre grid were collected in a small-meshed cover [mesh size  $18.9 \pm 1.2$  mm (mean  $\pm$  SD)] (Figure 1). Test and control hauls were deployed in the same fishing area during the same cruise.

For the test hauls, the catch was collected in the test grid cover (GT) and in the test codend (CT), whereas for control hauls, the catch was collected in the control grid cover (GC) and in the blinded codend (CC). For each haul, the catch was sorted by species, length measured, and sorted into 1-cm wide length groups for fish and 1-mm wide length groups for shrimp. Thus, the catch data consisted of count numbers ( $n$ ) representing the number of individuals of the different species collected in each of the compartments. The total length of the fish was measured using a measuring board, and the carapace length of the shrimps was measured using a calliper.

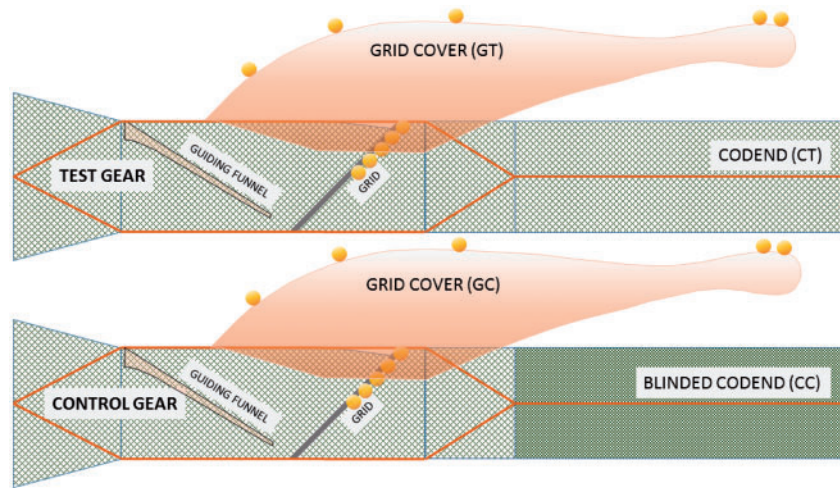
The fishing trials were performed on board the research trawler (R/V) “Helmer Hanssen” (63.8 m LOA and 4080 HP) from 16 to 28 February, 2016 at the fishing grounds located at the Central bank, east of Hopen Island in the north of the Barents Sea). The trials were carried out using two identical Campelen 1800# trawls built entirely of 80–40 mm meshes in the wings and belly [2 mm polyethylene (PE) twine]. Thyboron T2 (6.5 m<sup>2</sup> and 2200 kg) trawl doors were used, and an 8-m long rope was linked between the warps 80 m in front of the doors, which kept the distance between the doors at 48–52 m during the tows. The Campelen trawl has a 19.2 m fishing line and is believed to work at its optimal wingspread (ca. 15 m) and height (ca. 6.5 m) when the door distance is kept in this range. We used 40 m double sweeps and a 19.2 m long rock hopper gear built of three sections with 46 cm rubber discs.

Both trawls were equipped with 4-panel Nordmøre grid sections that are equivalent in dimensions and construction to the 2-panel standard Nordmøre grid section used by the Norwegian coastal fleet targeting shrimp. Each Nordmøre grid is made of stainless steel and measures 1510 mm high and 1330 mm wide. The grid in both trawls used was mounted so that it would maintain an angle of  $45 \pm 2.5^\circ$  while fishing.

### Model for size selection

The size selection system consists of two main parts.

- The first part is a Nordmøre grid, which the fish and shrimps must pass through to enter the codend. If they do not pass through this grid they are excluded during this first part of the selection process. To pass through the grid, two conditions need to be fulfilled: (a) they need to contact the grid and (b) morphologically they must be able to pass through the grid, which is dependent on their size and orientation when they reach with the grid.



**Figure 1.** Experimental gear configuration: with separate group of hauls with test gear (top) and control gear (bottom). The gear configuration consisting of a forward Nordmøre grid and a small mesh codend is compulsory in the Northeast Atlantic trawl fishery targeting deep-water shrimps.

- (ii) The second part is a codend that collects fish and shrimp that pass through the grid. The codend is also size selective, and its size selection is the second part of the combined selection process.

Thus, for a fish or deep water shrimp to be retained by the gear [ $r_{\text{combined}}(l)$ ], it must be retained by selectivity process of the Nordmøre grid [ $r_{\text{grid}}(l)$ ] and the codend [ $r_{\text{codend}}(l)$ ]:

$$r_{\text{combined}}(l) = r_{\text{grid}}(l) \times r_{\text{codend}}(l) \quad (1)$$

where  $l$  denotes the length of the fish or the length of the shrimp carapace. This system can be defined as a sequential dual selection system. It is a dual system because it consists of two processes and it is sequential because the second process follows the first.

The next step is to model each of the two size selection processes individually. For the grid selectivity process we need to consider that some fish or shrimps might not contact the Nordmøre grid at all [see Larsen *et al.* (2016) for the explanation of contact in this context] or that they might do so orientated in a way that independent of length they have no chance of passing through the grid. The probability of length-independent exclusion from the Nordmøre grid,  $C_{\text{grid}}$ , is specified as a parameter with a range of 0.0 to 1.0, where 1.0 means that every individual of the species contacts the grid in a way that gives it a length-dependent chance of passing through the grid. For an individual contacting the grid with sufficiently good orientation to give it a length-dependent chance of passing through grid ( $r_{\text{contact}}_{\text{grid}}(l)$ ), the following logit model was used [see Wileman *et al.* (1996) for further information about the logit model]:

$$\begin{aligned} r_{\text{contact}}_{\text{grid}}(l, L50_{\text{grid}}, SR_{\text{grid}}) &= 1.0 - \text{logit}(l, L50_{\text{grid}}, SR_{\text{grid}}) \\ &= \frac{1.0}{1.0 + \exp\left(\frac{\ln(9)}{SR_{\text{grid}}} \times (l - L50_{\text{grid}})\right)} \end{aligned} \quad (2)$$

Model (2) considers that the probability of being able to pass through the grid is length dependent and will decrease for larger individuals.  $L50_{\text{grid}}$  denotes the length of fish or shrimp with 50%

probability of being retained, and  $SR_{\text{grid}}$  (selection range) describes the difference in length between fish or shrimp with 75 and 25% probability of being retained, respectively.

Based on the above, the following model was used for the size selection in the first process [ $r_{\text{grid}}(l)$ ]:

$$r_{\text{grid}}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}) = \frac{C_{\text{grid}}}{1.0 + \exp\left(\frac{\ln(9)}{SR_{\text{grid}}} \times (l - L50_{\text{grid}})\right)} \quad (3)$$

The escape probability through the outlet in front of the Nordmøre grid was therefore modelled by:

$$\begin{aligned} e_{\text{grid}}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}) &= 1.0 - r_{\text{grid}}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}) \\ &= 1.0 - \frac{C_{\text{grid}}}{1.0 + \exp\left(\frac{\ln(9)}{SR_{\text{grid}}} \times (l - L50_{\text{grid}})\right)} \end{aligned} \quad (4)$$

For the small mesh codend selectivity process, we assumed that the retention probability can be modelled by a logit model:

$$\begin{aligned} r_{\text{codend}}(l, L50_{\text{codend}}, SR_{\text{codend}}) &= \text{logit}(l, L50_{\text{codend}}, SR_{\text{codend}}) \\ &= \frac{\exp\left(\frac{\ln(9)}{SR_{\text{codend}}} \times (l - L50_{\text{codend}})\right)}{1.0 + \exp\left(\frac{\ln(9)}{SR_{\text{codend}}} \times (l - L50_{\text{codend}})\right)} \end{aligned} \quad (5)$$

Thus, by inserting (3) and (5) into (1), we arrived at the following combined size selection model:

$$\begin{aligned} r_{\text{combined}}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}, L50_{\text{codend}}, SR_{\text{codend}}) &= \frac{C_{\text{grid}}}{1.0 + \exp\left(\frac{\ln(9)}{SR_{\text{grid}}} \times (l - L50_{\text{grid}})\right)} \\ &\times \frac{\exp\left(\frac{\ln(9)}{SR_{\text{codend}}} \times (l - L50_{\text{codend}})\right)}{1.0 + \exp\left(\frac{\ln(9)}{SR_{\text{codend}}} \times (l - L50_{\text{codend}})\right)} \end{aligned} \quad (6)$$

Model (6) is a so-called structural model because it is based on modelling the individual processes expected to be involved in the

combined size selection in the system. One advantage of applying a structural model compared to an empirical-based model is that once the values of the parameters in the model are estimated, they can be applied to investigate not only the combined processes in the system but also the individual processes. In this context, each of the model parameter values obtained can be directly interpreted.

In the case of model (6), five parameters need to be estimated to be able to describe the size selection in the system:  $C_{\text{grid}}$ ,  $L50_{\text{grid}}$ ,  $SR_{\text{grid}}$ ,  $L50_{\text{codend}}$ , and  $SR_{\text{codend}}$ . If all individuals contact the grid with a mode of contact that provide a length dependent probability to pass through, then the value for  $C_{\text{grid}}$  should be 1.0. However, this is not necessarily the case, as some individuals may escape through the escape outlet in front of the Nordmøre grid (Figure 1) without contacting the grid first. Other individuals may be so poorly orientated when they meet the grid that the probability of them passing through will be similar to those not contacting the grid, which will also be reflected in the value of  $C_{\text{grid}}$ . Thus,  $L50_{\text{grid}}$  and  $SR_{\text{grid}}$  are respectively the L50 and SR values for individuals contacting the grid with a reasonable mode of orientation.  $L50_{\text{codend}}$  and  $SR_{\text{codend}}$  are the L50 and SR values for the codend selection conditional upon organisms contacting and passing through the Nordmøre grid (Figure 1). As different species have different morphology and behaviour, values of the parameters  $C_{\text{grid}}$ ,  $L50_{\text{grid}}$ ,  $SR_{\text{grid}}$ ,  $L50_{\text{codend}}$ , and  $SR_{\text{codend}}$  for the same combined system will be species specific. Therefore, the analysis was applied separately for the different fish species and for the deep water shrimp.

### Data analysis and parameter estimation

Catch data were collected in two groups. One of the groups consisted of control hauls obtained by summing compartments GC and CC (Figure 1). Together, they sampled the size and species composition of fish entering the selective parts of the trawl (section with the Nordmøre grid and codend), and in this respect the control hauls can be paired with the test hauls so that a paired-gear estimation method can be used (Wileman *et al.*, 1996). However, compared to the standard paired-gear method in which none of the selective parts of the system uses covers to collect fish or shrimps escapees, our test hauls are special because they use a cover (GT) to collect fish and shrimp escaping ahead of the Nordmøre grid. Therefore, our experimental data collection design represents a combination of the paired and covered data collection and estimation methods (Wileman *et al.*, 1996).

To estimate the average size selection of the Nordmøre grid and codend in the test trawl, we paired the pooled catch data with the pooled catch data from the control hauls. Based on this approach, the experimental data in the analysis were treated like three compartment data. Fish or shrimp caught were observed in GT, CT, or (GC + CC). For the estimation based on the size selection model established in the “Model for size selection” section, we needed to express the probabilities that fish or shrimp of a specific length  $l$  would be observed in each of these three compartments conditioned they were caught. The probability that the fish or shrimp would enter the selection section in one of the test hauls and in one of the control hauls was modelled by the split factor,  $SP$ , as is traditionally done for paired-gear data analysis (Wileman *et al.*, 1996). This means that the probability that a fish or shrimp will enter the test haul is  $SP$ , whereas the probability of them entering the control haul is  $1.0 - SP$ . All fish or shrimp entering the control haul are

retained because both the cover over the grid outlet and the blinded codend retain all potential escapees. For a fish or shrimp entering one of the hauls included in the analysis (test or control), the probability that it will be retained in the cover in front of the Nordmøre grid in one of the test hauls would, based on Equation (4), be  $SP \times e_{\text{grid}}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}})$ . For a fish or shrimp entering one of the hauls included in the analysis, the probability that it will be retained in the codend of a test haul would, based on Equation (6), be  $SP \times r_{\text{combined}}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}, L50_{\text{codend}}, SR_{\text{codend}})$ . Considering this, the probability  $\gamma$  that a fish or shrimp entering one of the test or control hauls will be observed in one of the three compartments (GT, CT, or GC + CC) can be expressed as:

$$\begin{aligned} \gamma(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}, L50_{\text{codend}}, SR_{\text{codend}}, SP) \\ = SP \times e_{\text{grid}}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}) \\ + SP \times r_{\text{combined}}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}, L50_{\text{codend}}, SR_{\text{codend}}) \\ + 1.0 - SP \end{aligned} \quad (7)$$

Based on Equation (7) and the considerations above, the probabilities  $p_{GT}$ ,  $p_{CT}$ , and  $p_{GC+CC}$  that a fish or shrimp observed in the catch will be found in compartment GT, CT, or GC + CC, respectively, can be expressed by:

$$\begin{aligned} p_{GT}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}, L50_{\text{codend}}, SR_{\text{codend}}, SP) \\ = \frac{SP \times e_{\text{grid}}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}})}{\gamma(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}, L50_{\text{codend}}, SR_{\text{codend}}, SP)} \\ p_{CT}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}, L50_{\text{codend}}, SR_{\text{codend}}, SP) \\ = \frac{SP \times r_{\text{combined}}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}, L50_{\text{codend}}, SR_{\text{codend}})}{\gamma(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}, L50_{\text{codend}}, SR_{\text{codend}}, SP)} \\ p_{GC+CC}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}, L50_{\text{codend}}, SR_{\text{codend}}, SP) \\ = \frac{1.0 - SP}{\gamma(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}, L50_{\text{codend}}, SR_{\text{codend}}, SP)} \end{aligned} \quad (8)$$

Using Equation (8), the values for the parameters in the selection model (6) can be estimated from the collected experimental data by minimizing the following function with respect to  $C_{\text{grid}}$ ,  $L50_{\text{grid}}$ ,  $SR_{\text{grid}}$ ,  $L50_{\text{codend}}$ ,  $SR_{\text{codend}}$ , and  $SP$ :

$$\begin{aligned} - \sum_l \left\{ \sum_{i=1}^a \left[ \frac{n_{GTi}}{q_{GTi}} \times \ln(p_{GT}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}, L50_{\text{codend}}, SR_{\text{codend}}, SP)) \right] \right. \\ + \sum_{i=1}^a \left[ \frac{n_{CTi}}{q_{CTi}} \times \ln(p_{CT}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}, L50_{\text{codend}}, SR_{\text{codend}}, SP)) \right] \\ + \sum_{j=1}^b \left[ \left( \frac{n_{GCj}}{q_{GCj}} + \frac{n_{CCj}}{q_{CCj}} \right) \times \ln(p_{GC+CC}(l, C_{\text{grid}}, L50_{\text{grid}}, SR_{\text{grid}}, L50_{\text{codend}}, SR_{\text{codend}}, SP)) \right] \left. \right\} \end{aligned} \quad (9)$$

where the outer summation is over length classes  $l$  in the experimental data and the inner summation is over experimental fishing hauls  $i$  (from 1 to  $a$ ) and  $j$  (from 1 to  $b$ ) with, respectively, the test and control setup.  $n_{GTi}$ ,  $n_{CTi}$ ,  $n_{GCj}$ , and  $n_{CCj}$  are the number of fish or shrimp length measured of length class  $l$  in



**Table 1.** Overview of the fish and shrimp length measured in the control hauls carried out during the trials.

Haul Nr	Trawling time (min)	Depth (m)	Day in February	Pos. start		Shrimp		American Plaice		Redfish	
				Lat.	Long.	GC (% measured)	CC (% measured)	GC	CC	GC	CC
1	60	268	20	7604.9 N	03526.9 E	123 (72.31%)	160 (1.63%)	208	177	56	36
2	61	257	20	7605.4 N	03517.8 E	120 (58.14%)	153 (1.95%)	238	182	143	37
3	60	278	21	7605.3 N	03511.1 E	163 (7.47%)	173 (1.16%)	438	187	404	169
4	60	271	21	7605.9 N	03533.8 E	108 (9.60%)	171 (1.20%)	265	156	184	86
5	63	266	21	7605.9 N	03521.9 E	144 (40.54)	160 (1.91%)	321	121	108	20
6	61	271	22	7606.5 N	03531.9 E	169 (100%)	175 (2.02%)	206	150	68	34
7	60	271	22	7606.6 N	03521.9 E	208 (22.74)	169 (1.02%)	391	287	187	94
8	63	272	22	7606.5 N	03531.9 E	189 (21.12)	190 (0.73%)	327	301	164	120

For fish species, all specimens were measured for length. For shrimp, values in brackets represent the proportion of individuals subsampled for length measurements. The catch was collected in the control gear grid cover (GT) and in the gear control gear codend (CT).

haul  $i$  and  $j$  in the respective compartment, with  $qGT_i$ ,  $qCT_i$ ,  $qGC_j$ , and  $qCC_j$  being the corresponding sampling factors (i.e. the fraction of the catch that was length measured). The estimation with (9) is based on the expected total catches and the sampling factors are therefore used to expand the subset of length-specific counts based upon the fractions of the haul measured for lengths. Minimizing (9) with respect to the parameters in it is the same as maximizing the likelihood for the observed experimental data based on a multinomial model, assuming that the formulated model (8) describes the experimental data sufficiently well. The observed experimental length dependent portioning of the catches between the three compartments GT, CT, and GC + CC, which model (8) is expected to describe, are given by:

$$\begin{aligned}
 \widehat{p_{GT}} &= \frac{\frac{n_{GT}}{q_{GT}}}{\frac{n_{GT}}{q_{GT}} + \frac{n_{CT}}{q_{CT}} + \frac{n_{GC}}{q_{GC}} + \frac{n_{CC}}{q_{CC}}} \\
 \widehat{p_{CT}} &= \frac{\frac{n_{CT}}{q_{CT}}}{\frac{n_{GT}}{q_{GT}} + \frac{n_{CT}}{q_{CT}} + \frac{n_{GC}}{q_{GC}} + \frac{n_{CC}}{q_{CC}}} \\
 \widehat{p_{GC+CC}} &= \frac{\frac{n_{GC}}{q_{GC}} + \frac{n_{CC}}{q_{CC}}}{\frac{n_{GT}}{q_{GT}} + \frac{n_{CT}}{q_{CT}} + \frac{n_{GC}}{q_{GC}} + \frac{n_{CC}}{q_{CC}}}
 \end{aligned} \quad (10)$$

Due to the experimental procedure followed, there was no obvious way to pair the data from the individual test and control hauls. Hence, to estimate the mean selectivity parameters for the experimental gear, the length dependent expected total catches for the test hauls were combined and compared with the combined expected total catches for the control hauls as formulated in function (9). The confidence limits for the parameters and curves for the size selection model were estimated using a double bootstrapping method that accounts for the uncertainty resulting from this unpaired nature of the data collection. For this, we adopted and further generalized the method for estimating uncertainty in size selectivity based on unpaired trawl data described by Sistiaga *et al.* (2016). This procedure accounts for uncertainty caused by between-haul variation in size selection processes (Fryer, 1991) and by the unpaired data collection method with groups of test and control hauls by selecting

independently  $a$  hauls with replacement from the test hauls and  $b$  hauls with replacement from the control hauls during each bootstrap loop. Uncertainty caused by finite sample sizes on haul level (within-haul variability) is accounted for by randomly selecting fish with replacement from each of the selected hauls for each compartment separately, where the number selected from each compartment in each haul is the same as the number sampled in that compartment in that haul. These data are then raised and combined as described above, and the selectivity parameters are again estimated. The additional uncertainty in the estimation caused by subsampling is automatically accounted for by raising the data after the re-sampling (Eigaard *et al.*, 2012). We performed 1000 bootstrap repetitions to calculate the 95% percentile confidence limits (Efron, 1982; Chernick, 2007) for the selection parameters and curves.

The model's ability to describe the experimental data sufficiently well was evaluated based on the  $p$ -value, model deviance versus degrees of freedom (DOF) and inspection of how the model curve reflects the length-based trend in the data (Wileman *et al.*, 1996). The  $p$ -value expresses the likelihood to obtain at least as big a discrepancy between the fitted model and the observed experimental data by coincidence. In case of a poor fit statistics ( $p$ -value being  $< 0.05$ ; deviance being  $\gg$  DOF), the model curve plots were inspected to determine whether the poor result was due to structural problems when describing the experimental data using the model or if it was due to over-dispersion in the data (Wileman *et al.*, 1996). The analysis was carried out using the software SELNET (Herrmann *et al.*, 2012, 2013a,b), which implements the models and the bootstrap method described above.

## Results

### Collected data

We conducted eight control hauls (Table 1) and eight test hauls (Table 2). To ensure that the group of test and control hauls were fishing a similar size and species compositions all hauls were conducted within 5 days in February 2016 at same fish ground within a small area, at similar depth and with similar towing time (Tables 1 and 2). In all hauls, a subsample of the shrimp catch was length measured whereas catches of every American plaice (*Hippoglossoides platessoides*) and redfish (*Sebastes* spp.) were length measured. The total number of shrimp, American plaice and redfish length measured during the data collection were respectively 4405, 8773, and 4439 individuals.

## Size selectivity for shrimp

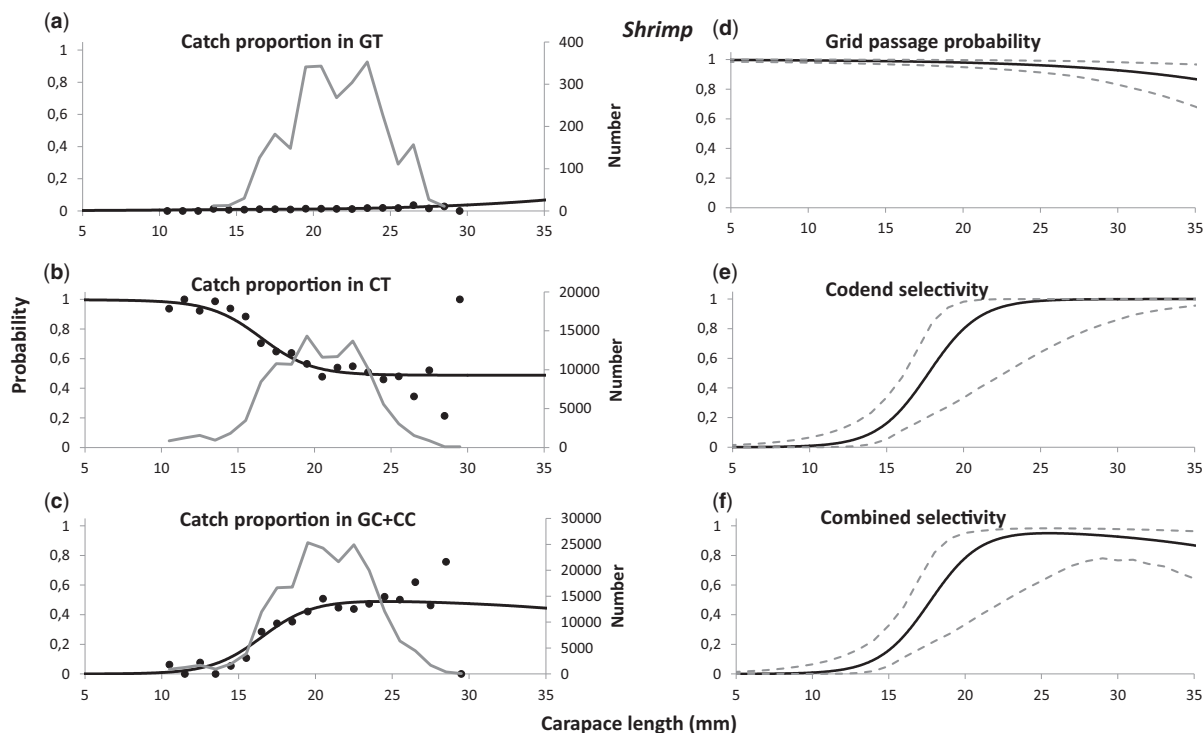
The model used reflected the pattern observed in the experimental data well (Figure 2a–c). Thus, although the  $p$ -value (Table 3) observed in the fit statistics was low, we are confident that the model used represents the data adequately. We considered the low  $p$ -value to be a consequence of over-dispersion in the

experimental catch portioning data that resulted from working with pooled and subsampled data with low sampling rates (Tables 1 and 2). Such cases have led to low  $p$ -values and high dispersion (Brčić *et al.*, 2015; Alzorriz *et al.*, 2016; Notti *et al.*, 2016) especially for length classes with relative low frequency, such as our shrimp data for individuals with carapace length above 25 mm (Figure 2a–c). All shrimp were estimated to make

**Table 2.** Overview of the fish and shrimp length measured in the test hauls carried out during the trials.

Haul Nr	Trawling time (min)	Depth (m)	Day in February	Pos. start		Shrimp		American Plaice		Redfish	
				Lat.	Long.	GT (% measured)	CT (% measured)	GT	CT	GT	CT
9	60	268	22	7606.1 N	03522.3 E	150 (63.13%)	150 (1.34%)	391	283	211	42
10	62	265	23	7605.4 N	03523.2 E	123 (31.72%)	146 (0.94%)	444	347	392	65
11	64	268	23	7605.8 N	03525.1 E	98 (66.77%)	134 (1.05%)	482	402	494	108
12	62	265	23	7605.7 N	03522.1 E	7 (100%)	121 (2.10%)	283	309	211	47
13	63	274	23	7605.9 N	03523.4 E	21 (100%)	141 (1.76%)	239	212	354	91
14	60	256	24	7604.7 N	03516.8 E	50 (100%)	161 (2.67%)	256	202	98	33
15	63	252	24	7604.0 N	03512.9 E	75 (80.61%)	146 (1.08%)	230	320	135	82
16	66	269	24	7606.1 N	03517.2 E	140 (8.18%)	167 (1.78%)	298	120	142	24

For fish species, all specimens were measured for length. For shrimp, values in brackets represent the proportion of individuals subsampled for length measurements. The catch was collected in the test grid cover (GT) and in the test codend (CT).



**Figure 2.** Size selectivity plots for shrimps. The left column shows the fit of the selection model [Equation (8)] to the experimental catch portioning rates. Plot “a” shows the length dependent portioning of shrimps found in the grid cover of the test gear, plot “b” shows the length dependent portioning of shrimps observed in the codend of the test gear and plot “c” shows the length dependent portioning of shrimps found in the control gear. The points in plots “a”–“c” represent the observed experimental length dependent portioning of the catches between the three compartments GT, CT, and GC + CC [Equation (10)]. The grey curves in plots “a”–“c” represent the total catches in number of individuals (right y-axis) in the three compartments GT, CT, and GC + CC. The plots in the right column show the selectivity curves for the test gear with plot “d” showing the length dependent grid passage probability [Equation (4)], plot “e” showing the length dependent codend selectivity in the test gear [Equation (5)], and plot “f” showing the combined size selectivity of the Nordmøre grid and the codend for the test gear [Equation (6)]. The stippled curves in plots “d”–“f” represent 95% confidence bands.

contact with the Nordmøre grid, and most of them passed through it. However, the grid passage probability was estimated to decrease slightly with increasing shrimp size. The codend selectivity showed size-dependent release for shrimp with carapace length  $< 23$  mm, with only about 20% of the shrimp with carapace length of 15 mm being retained by the codend.  $L50_{\text{codend}}$  was estimated to be 17.72 mm, and  $SR_{\text{codend}}$  was estimated to be 3.63 mm (Table 3).  $L50_{\text{grid}}$  was 49.2 mm, which at first glance could seem meaningless because it is above the size range for this species of shrimp (Table 3). However, this value is expected to be

**Table 3.** Size selectivity parameters and fit statistics results for shrimps, American plaice and redfish based on fitting the model (8) to the experimental data.

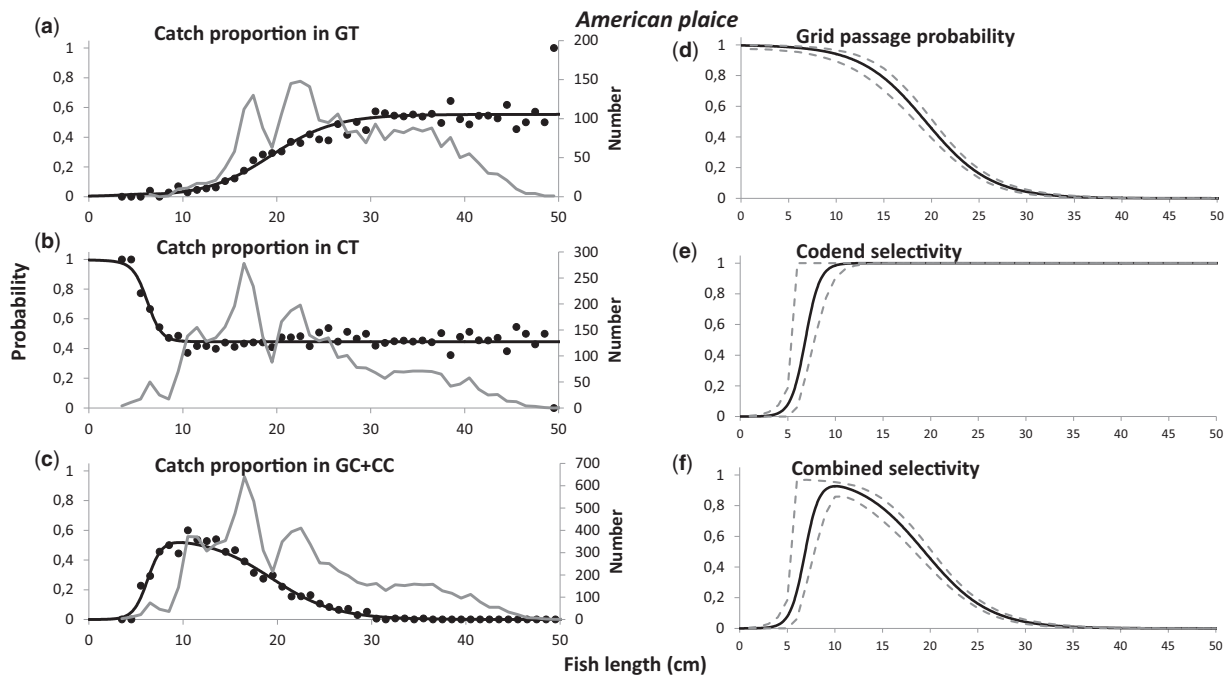
	Shrimps	American Plaice	Redfish
$C_{\text{grid}}$	1.00 (0.98–1.00)	1.00 (0.97–1.00)	0.90 (0.75–0.99)
$L50_{\text{grid}}$	49.17 (37.16–68.57)	19.40 (18.41–20.20)	13.61 (13.06–14.28)
$SR_{\text{grid}}$	16.52 (8.02–27.82)	7.47 (6.44–8.61)	3.46 (2.93–3.97)
$L50_{\text{codend}}$	17.72 (16.10–22.59)	6.84 (5.46–7.68)	9.78 (8.85–10.45)
$SR_{\text{codend}}$	3.63 (1.79–9.45)	1.66 (0.10–2.66)	1.74 (1.33–2.60)
SP	0.51 (0.42–0.70)	0.55 (0.49–0.61)	0.63 (0.51–0.74)
DOF	34	90	54
Deviance	175.66	118.38	101.91
$p$ -value	$< 0.0001$	0.0241	0.0001

$L50$  and  $SR$  values are given in mm for shrimps and in cm for American plaice and redfish. Values in brackets are 95% confidence limits.

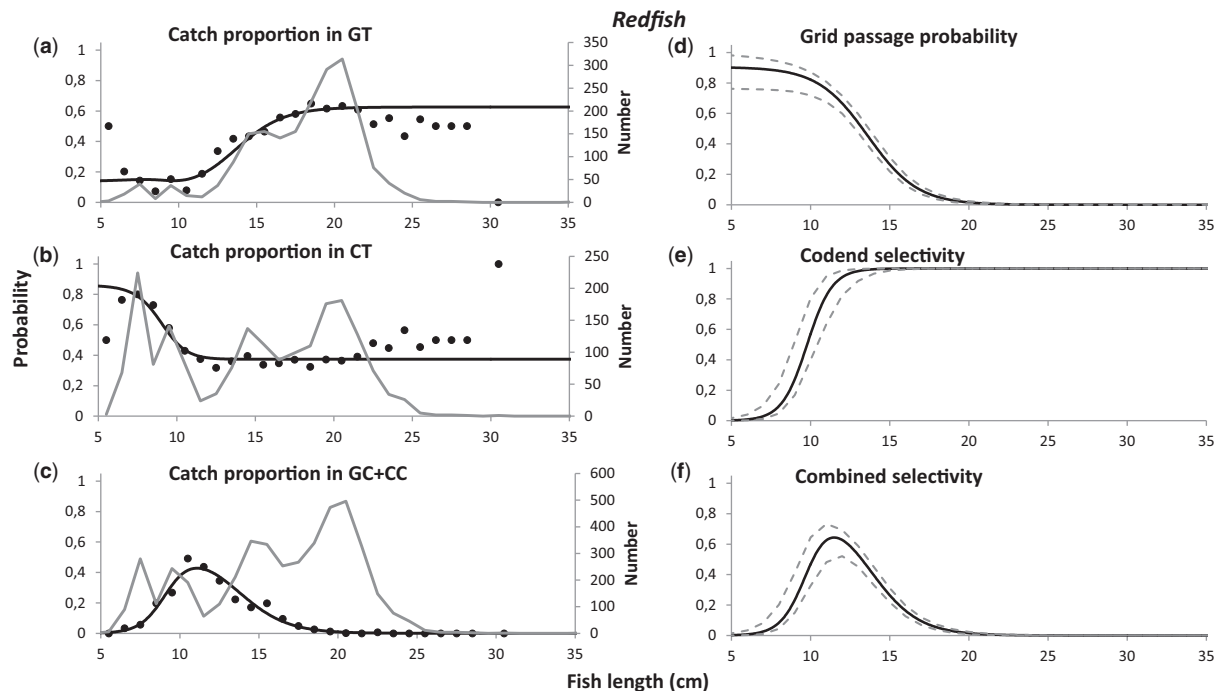
above a biologically meaningful value and confirms that most of the shrimp can pass through the grid except for the slight decrease for large shrimp. The combined selectivity for the grid and codend exhibited a slightly bell-shaped signature, with few shrimp  $< 15$  mm being retained, a maximum retention rate for shrimp with carapace length of 25 mm, and a slight decrease for shrimp above this size.

### Size selectivity for American plaice

The model used reflected the pattern observed in the experimental data well (Figure 3a–c). Despite the  $p$ -value being  $< 0.05$  (Table 3), the model represented the data adequately and we are confident about the performance of the model. All American plaice were estimated to make contact with the Nordmøre grid, and most of them passed through it. The grid passage probability was very high for American plaice up to 12 cm long, followed by a decrease and then very low passage probability for fish  $> 30$  cm long. The codend only showed low size selectivity for American plaice with an  $L50_{\text{codend}}$  value of 6.84 cm, thus all American plaice  $> 10$  cm long that entered the codend were retained (Table 3). The combined selectivity for the grid and codend showed a clear bell-shaped signature, with a high retention probability for American plaice  $\sim 10$  cm long (ca. 90% retention). Retention of individuals  $< 5$  cm long was practically 0 and retention of fish in the range of 10–30 cm decreased, with really low retention rates for fish  $> 30$  cm long. In the range of 6–23 cm, retention



**Figure 3.** Size selectivity plots for American plaice. The left column shows the fit of the selection model [Equation (8)] to the experimental catch portioning rates. Plot “a” shows the length dependent portioning of American plaice found in the grid cover of the test gear, plot “b” shows the length dependent portioning of American plaice observed in the codend of the test gear (left y-axis) and plot “c” shows the length dependent portioning of American plaice found in the control gear. The points in plots “a”–“c” represent the observed experimental length dependent portioning of the catches between the three compartments GT, CT, and GC + CC [Equation (10)]. The grey curves in plots “a”–“c” represent the total catches in number of individuals (right y-axis) in the three compartments GT, CT, and GC + CC. The plots in the right column show the selectivity curves for the test gear with plot “d” showing the length dependent grid passage probability [Equation (4)], plot “e” showing the length dependent codend selectivity in the test gear [Equation (5)], and plot “f” showing the combined size selectivity of the Nordmøre grid and the codend for the test gear [Equation (6)]. The stippled curves in plots “d”–“f” represent 95% confidence bands.



**Figure 4.** Size selectivity plots for redfish. The left column shows the fit of the selection model [Equation (8)] to the experimental catch portioning rates. Plot “a” shows the length dependent portioning of redfish found in the grid cover of the test gear, plot “b” shows the length dependent portioning of redfish observed in the codend of the test gear (left y-axis) and plot “c” shows the length dependent portioning of redfish found in the control gear. The points in plots “a”–“c” represent the observed experimental length dependent portioning of the catches between the three compartments GT, CT, and GC + CC (Equation 10). The grey curves in plots “a”–“c” represent the total catches in number of individuals (right y-axis) in the three compartments GT, CT, and GC + CC. The plots in the right column show the selectivity curves for the test gear with plot “d” showing the length dependent grid passage probability [Equation (4)], plot “e” showing the length dependent codend selectivity in the test gear [Equation (5)], and plot “f” showing the combined size selectivity of the Nordmøre grid and the codend for the test gear [Equation (6)]. The stippled curves in plots “d”–“f” represent 95% confidence bands.

probability for American plaice for the gear was >25%, meaning that this gear would not be adequate in areas where the numbers of American plaice within this range are high.

### Size selectivity for redfish

For redfish, the model used represented the experimental data well up to  $l = 22$  cm (Figure 4a–c). Because fish above this size are outside the selective range of the gear, the model adequately describes the size selection process in the gear. The discrepancy between model and experimental data above the selective range of the gear is regarded as a consequence of unequal entry of bigger redfish into the test and control gears. The combined size selection showed a clear bell-shaped signature, with >60% of redfish around 12 cm long being retained by the gear but <25% of redfish <9 cm and >15 cm long being retained. The grid passage probability was high (>80%) for redfish <12 cm long, and it decreased monotonously, with no redfish >20 cm entering the codend. The codend size selection showed that none of the redfish >14 cm would be released by the codend and that  $L_{50_2}$  and  $SR_2$  were 9.8 and 1.7 cm, respectively (Table 3).

### Discussion

The size selection data resulting from the grid and codend configuration used in this study were based on a new model and estimation method that is an extension of the unpaired method

described in Sistiaga *et al.* (2016). This new approach models the observed data summed over hauls for a group of test and controls hauls, and it combines a structural dual sequenced size selection model with unpaired data collection for groups of test and control hauls. This model effectively described the length-dependent portioning of the observed catch between the test codend, the test grid cover, and the control gear for all species investigated. In addition to enabling estimation of the combined size selection for the Nordmøre grid followed by the diamond mesh codend, this method enabled estimation of the size selection for each of the selection devices individually because the structural model explicitly described the selectivity processes in each of the devices. Structural size selection models have previously been developed and applied to describe size selection in other trawl fisheries. This includes models for fish sorting grids in combination with codends in finfish fisheries (Sistiaga *et al.*, 2010; Herrmann *et al.*, 2013a), square mesh panels in combination with selective codends (Zuur *et al.*, 2001; O'Neill *et al.*, 2006; Alzoriz *et al.*, 2016), double grid sorting devices (Larsen *et al.*, 2016; Sistiaga *et al.*, 2016), and excluding grids combined with a selective codend (Brčić *et al.*, 2015; Stepputtis *et al.*, 2015; Lövgren *et al.*, 2016). Excluding grids combined with a selective codend result in the same bell-shaped selection pattern as the Nordmøre grid followed by a size selective codend. However, our study is the first time such a modelling process has been applied to a shrimp trawl fishery and the first time that a sequential model with two



compartment data collection in test and control gears have been used. Our gear configuration was more complex than the methods previously applied, but it is necessary due to the practical problems that potentially could have resulted from using a small mesh cover over the test codend.

The method and model presented herein offer new possibilities for studying size selectivity in other shrimp fisheries. In particular, our approach enables detailed mapping of which sizes of bycatch species would have especially high risk of being caught if they are abundant in the shrimp fishing grounds.

In this study, we demonstrated the ability of the new model to represent bell-shaped selectivity data in detail for shrimp and two fish bycatch species: American plaice and redfish. For the juvenile bycatch species, our results demonstrated very high and length-dependent grid passage probability. Thus, in conjunction with the small-meshed diamond mesh codend used in the shrimp fishery, the gear has high catch risk for certain size ranges of these bycatch species. The use of the combined bycatch reducing and size selective system consisting of the Nordmøre grid and 35 mm codend mesh is well established in the Northeast Atlantic shrimp fishery. However, the data from our study clearly show that fish within a limited size range and undersized shrimps retained in the 35-mm codend will continue to be a problem for the northern shrimp fleet.

Some precaution is required since our fishing trial was based on only 16 hauls and the number of shrimp, American Plaice and redfish length measured was respectively limited to 4405, 8773, and 4439 individuals (Tables 1 and 2). This leads to a degree of uncertainty in the estimated size selection curves (Figures 2–4) and needs to be considered when interpreting the results. However, this uncertainty is reflected in the selectivity parameters (Table 3) and confidence bands around the size selection curves. A recent study by Herrmann *et al.* (2016) has shown that estimating trawl size selectivity to a specific level of precision based on a paired gear method will require around 10 times as many fish as needs to be measured using a covered method. Based on that claim we had concerns whether it would be possible to estimate size selectivity with an acceptable level of precision as our gear configuration uses a combination of a paired and covered sampling design. However, the relative narrow confidence bands around the size selection curves in our study demonstrates the practicality and appropriateness of our method.

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