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Fish and squid behaviour at the mouth of a drop-chain trawl: factors contributing to capture or escape

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Underwater video recordings in the mouth of a squid trawl were used to evaluate the effectiveness of a trawl configured with drop-chain groundgear to catch longfin inshore squid (*Doryteuthis pealeii*) and reduce bycatch of finfish in the Nantucket Sound squid fishery off Cape Cod, Massachusetts, USA. Entrance through the trawl mouth or escape underneath the fishing line and between drop chains was quantified for targeted squid, and two major bycatch species, summer flounder (*Paralichthys dentatus*) and skates (family Rajidae). Additionally, contact and impingement between animals and groundgear were also quantified. Fish and squid swimming behaviours, positions, orientations, and time in the trawl mouth were quantified and related to capture or escape at the trawl mouth. Squid entered the trawl singly and in schools, and no squid were observed escaping under the fishing line. Most squid entered the trawl in the upper portion of the trawl mouth; mantle orientated away from the trawl and swimming in the same direction, and were gradually overtaken, not actively attempting to escape. Summer flounder and skates were observed to remain on or near the seabed, orientated, and swimming in the same direction as the approaching trawl. The majority (60.5%) of summer flounder entered the trawl above the fishing line. Summer flounder that changed their orientation and turned 180° were significantly more likely to enter the trawl ($p < 0.05$). Most skates (89.7%) avoided trawl entrance and escaped under the fishing line. Neither squid nor summer flounder were observed to make contact or become impinged to the groundgear; however, 35.4% of skates had substantial contact with groundgear, with 12.3% becoming impinged. Video analysis results showed that the drop-chain trawl is effective at retaining targeted squid while allowing skates to escape. However, it is ineffective at avoiding the capture of summer flounder.

Keywords: bycatch reduction devices, flatfish behaviour, groundgear, skate behaviour, squid behaviour, squid trawl, underwater observation.

Introduction

Modifications to groundgear of an otter trawl have been effective at reducing bycatch for many fisheries (He and Winger, 2010). Demersal or less-mobile species have been shown to avoid capture by passing or seeking exit openings underneath the trawl when the fishing line is raised from the groundgear, creating space for escapement. These general designs are used in tropical shrimp trawl fisheries (Eayrs, 2007), US Pacific coast shrimp fisheries (Hannah and Jones, 2000), US Northeast groundfish fisheries (McKiernan *et al.*, 1998), and electric beam trawls targeting shrimp in the North Sea (Polet *et al.*, 2005).

A specific variation of this general design is the raised-footrope trawl, specified in the US Code of Federal Regulations, 50 CFR 648.80(a)(9)(ii)(B) (Federal Register, 2004). The raised-footrope trawl has been developed since the 1990s in the New England small-mesh otter trawl fisheries to reduce the catch of unwanted regulated groundfish species. The raised-footrope trawl has significantly reduced the catch of many demersal species while maintaining commercial capture rates of silver hake (*Merluccius bilinearis*) in the Gulf of Maine and off Cape Cod (McKiernan *et al.*, 1996, 1998; Carr and Milliken, 1998; Schick, 2005). A modified version with the groundgear removed, called a "sweepless trawl", also successfully reduced regulated groundfish species when towing over flat fishing grounds in Cape Cod Bay (Sheppard *et al.*, 2004). Based on the silver hake-directed studies, three raised-footrope trawl exemption areas have been implemented for small-mesh

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trawls targeting silver hake off Cape Cod and the Maine coast [see Bayse *et al.* (2016) for details].

Despite successful sea trials employing a raised-footrope trawl targeting longfin inshore squid (*Doryteuthis pealeii*, hereafter "squid"; Glass *et al.*, 2001), scepticism persists within the fishery about the raised-footrope trawl's capacity to capture squid at a commercial rate, primarily due to the concern of squid escaping underneath the fishing line. Currently, raised-footrope trawl-type gear is being expanded to the southern New England squid and silver hake fisheries (Hasbrouck *et al.*, 2013).

A drop-chain trawl is a demersal otter trawl that is fished with the fishing line "raised" off the seabed (Nguyen *et al.*, 2015). The groundgear is extended by drop chains, placing the groundgear directly underneath or behind the fishing line. This "raised" effect gives demersal species an opportunity to escape underneath the trawl via the increased space between the fishing line and groundgear. The drop-chain trawl is a bycatch reduction design that takes advantage of demersal species' (i.e. flatfish and skates) general association with, and tendency to remain near, the seabed during the capture process (Ryer, 2008; Winger *et al.*, 2010), and the behaviour of species such as Atlantic cod (*Gadus morhua*) that commonly escape under groundgear (Walsh, 1992; Ingólfsson and Jørgensen, 2006).

The impetus to apply a drop-chain trawl in the Nantucket Sound squid fishery was the capture of untargeted species that are incidentally retained in small-mesh (76 mm or less) trawl fisheries, where most fish entering the trawl remain in the codend due to the small mesh used (Bayse, 2015). As a first step to decrease bycatch, a common strategy is to apply larger meshes in the codend. However, this tactic has not been successful due to excessive losses of target species in small-mesh squid fisheries (King *et al.*, 2009; Hendrickson, 2011).

Grids placed in the extension have been successful in separating species and reducing bycatch in the small-mesh trawl fisheries targeting Northern shrimp (*Pandalus borealis*; Richards and Hendrickson, 2006) and silver hake (Halliday and Cooper, 1999), but not as successful for longfin inshore squid (Bayse *et al.*, 2014; Bayse, 2015). Grids alone, however, do not eliminate all bycatch in small-mesh trawls, so additional measures are necessary to further reduce bycatch. Additionally, grids in small-mesh fisheries may exclude larger, more valuable individuals, such as "king" silver hake (McKiernan *et al.*, 1998). Improvements in grid performance by using multiple bycatch reduction devices (BRDs) have been achieved in the Northern shrimp (He and Balzano, 2007, 2011, 2012a, b, 2013; He *et al.*, 2015) and silver hake fisheries (Bayse *et al.*, 2016).

Prior evaluations of a drop-chain trawl applied either the comparative fishing technique (Wileman *et al.*, 1996) to determine how well a drop-chain trawl fished vs. a conventional commercial trawl (Schick, 2005), or a predetermined bycatch threshold for regulated groundfish species bycatch (below 5% of the total catch weight) (McKiernan *et al.*, 1998). The comparative fishing technique is commonly applied; however, its results are determined by what fish actually are retained by the codend, and thus the ability to determine exactly how effective the experimental gear is at retaining or excluding fish at the point of interaction with the BRD is only indirectly assessed—the actual mechanism of exclusion or avoidance can only be inferred from the comparative results. The 5% bycatch threshold removes the commercial gear comparison component entirely, and relies solely on a BRD design to reach a desired management criterion. While each are appropriate methods to determine the effectiveness of new gear types, neither of these methods allows quantifiable counts of species which are or are not excluded, nor the behaviour that led to subsequent capture or escape. Therefore, the effectiveness of the BRD is only indirectly measured, not directly observed.

Video cameras are now commonly used in association with trawl studies (Bublitz, 1996; Chosid *et al.*, 2011; Bayse *et al.*, 2014, 2016; Nguyen *et al.*, 2014). Typically, video observations are made at the early stages of sea trials for new or modified gear designs to determine the correct function of the experimental gear, and make general observations of fish that interact with the new design. Video is often not, or cannot, be used for many hauls, and rarely is behaviour and gear design effectiveness quantified via video recordings due to camera availability, video quality, presence of the camera disrupting fishing gear performance, or the great amount of time required to process video observations of fish and gear interacting. This absence prevents the collection of explicit results, such as quantification of how many fish escape under the fishing line vs. how many fish swim into the trawl.

Video analysis of BRDs also gives the opportunity to partially evaluate potential mortality or injury a BRD may incur on fish (Hannah and Jones, 2012; Nguyen *et al.*, 2014). Fish that interact with a BRD may indeed escape, but, in some cases, fish contact or impingement on the BRD could lead to mortality, injury, or easy predation. To completely evaluate the effectiveness of a BRD, potential causes of injury and mortality must be examined (Hannah and Jones, 2012).

To directly evaluate the effectiveness of a drop-chain trawl, video was collected and analysed of squid and fish reactions to, and interactions with, the fishing line and groundgear during sea trials in the Nantucket Sound longfin inshore squid fishery. This fishery takes place only during daylight hours (when squid are along the seabed) and in relatively shallow and typically clear water. These conditions present a good opportunity for video-based studies. Video observations concentrated on the bosom portion of the trawl mouth. In this location, herding has reached its termination point (Wardle, 1993) and fish behaviours are limited to either entering the trawl or escaping underneath the trawl. Additionally, this location allows focus on what behaviours lead to trawl entrance, escape, or contact with the groundgear. This study aimed to use video observations and behavioural analysis to explicitly determine how effective a drop-chain trawl is as a bycatch reduction design in terms of retention of target species (squid) and escape of bycatch species.

Material and methods

Gear design

A two-panel balloon trawl was rigged as a drop-chain trawl for the experiment (Figure 1). The trawl was spread by a pair of Type 66 Thyborøn doors (2.2 m^2). The bridles were 36.6 m in length, and were made of bare wire on the top and chain on the bottom. The groundgear and fishing line of the drop-chain trawl were both 25.6 m in length. Drop-chains were 30.5 cm long at the centre section of the groundgear, and 20.3 cm at the wingends to allow for the appropriate tapering of the trawl mouth. The groundgear consisted of 30.5 cm diameter rollers and 7.6 cm diameter rubber discs, and had a 60 cm distance between adjacent rollers. One drop chain was installed at the middle of two adjacent rollers along the entire length of the groundgear; thus, the distance between two nearest drop chains was also 60 cm (Figure 2). The fishing line was 49.6 cm above the seabed at the centre of the groundgear, and was 39.4 cm at the wingends. The drop-chains are considered to be vertical and fully extended during towing, as observed via video from cameras placed just ahead of groundgear.

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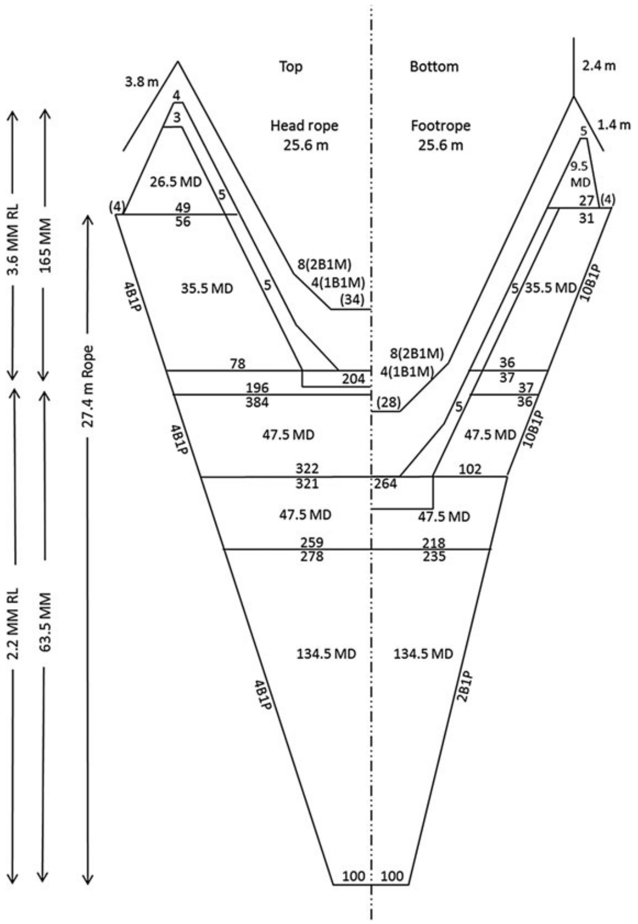

Figure 1. Net plan of trawl used during sea trials. Measurements are in the number of meshes, unless otherwise specified.

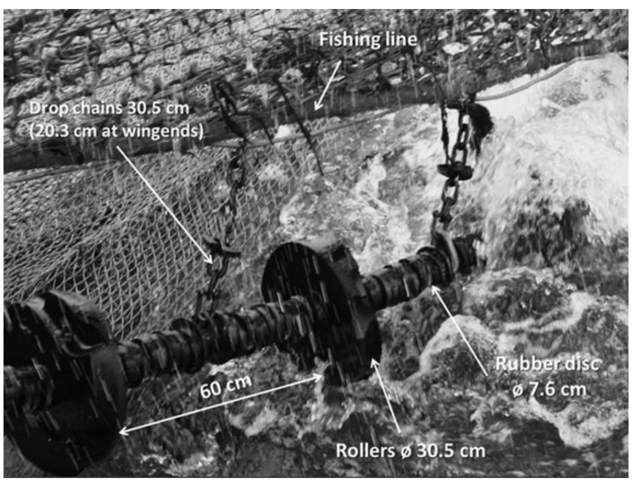

Figure 2. Illustration of the groundgear components of the drop-chain trawl. All measurements were the same for centre and wing sections except drop chains, which were 30.5 cm at the centre and 20.3 cm at the wingends.

Video camera system

A video camera (HD GoPro, Woodman Laboratories, Inc., Half Moon Bay, CA, USA) was placed within a waterproof housing and a steel frame, and attached in the centre and bottom side of the

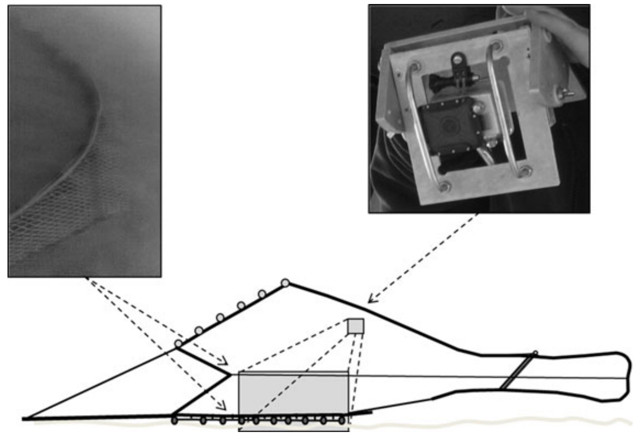

Figure 3. Camera placement and view in the mouth of the trawl. Top left: screen shot of the extent of the trawl mouth viewed and analysed. Top right: the HD GoPro video camera with waterproof housing, and steel frame faced forward. Bottom: illustration of drop-chain trawl; grey square is the area observed by a camera.

square, just aft of the headrope. The camera was placed inside the trawl, on the netting, upside down, with the lens pointing slightly forward towards the entrance of the trawl (Figure 3). Video was recorded in colour under natural light in shallow water, during daylight hours, and in relatively clear water. Video collected was analysed using Adobe Premiere Pro CS5.5 (Adobe Systems, Inc., San Jose, CA, USA) by a single observer.

Sea trials

Video was collected during sea trials carried out in Nantucket Sound, Massachusetts, USA on 16–17 June 2012 aboard the F/V *Atlantic Prince*, a 21 m, 272.2 kW (365 hp) otter trawler. Fishing was carried out at depths between 18.6 and 22.9 m, and the towing speed was maintained at 3.0 knots. Bottom temperature ranged from 13.6 to 15.0°C (TidbiT v2 Water Temperature Data Logger—UTBI-001, Onset Computer Corporation, Bourne, MA, USA). Mean door spread ranged from 39.0 to 41.5 m, wing spread ranged from 9.7 to 12.1 m, and headline height ranged from 1.9 to 2.1 m as measured by the TrawlMaster system (Notus Electronics Ltd, St John's, NF, USA). Gear mensuration was taken on prior hauls without the camera in the trawl mouth. Haul location and duration were determined by the fishers, and were typical for commercial operations. Observations from four tows totalling 257.3 min were analysed.

Analysis of behaviour

Behaviours of individual squid (not in schools), summer flounder, and skate were evaluated at the bosom of the trawl mouth (Table 1 and Figure 3) from first detection to subsequent entrance into the trawl, escape under the fishing line, or unknown (off camera without entering or escaping). Squid in a school (defined as two or more squid within a body length) were evaluated together at the first detection of the leading squid until the last observation of the last squid of the school (Figure 4). Each school was treated as a single subject.

Time was recorded for all summer flounder, skate, and solitary squid individuals from first detection until trawl entrance, escape underneath the fishing line, or unknown.

Squid positions, orientation, and swimming behaviour were characterized for individual squid, and squid schools as defined in Table 1. Squid top vs. bottom position [position (T/B)] was

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Table 1. Detailed description of each variable used to describe animal behaviour and contact at the trawl mouth of a drop-chain trawl.

Squid variables	Description
Position	
Top	Squid that remained higher than the fishing line throughout the entire sequence
Bottom	Squid that remained low, and rose no higher than immediately above (within one body length of) the fishing line upon trawl entrance
Left	Squid to the left (port) of the middle roller at first detection
Right	Squid to the right (starboard) of the middle roller at first detection
Orientation	
Away	Mantle directed away from the trawl
Towards	Mantle directed towards the trawl
Left	Mantle directed to the left (port)
Right	Mantle directed to the right (starboard)
Swimming behaviour	
Swimming	Movement via fin undulation alone
Escape-jet	Movement by jet propulsion alone
Jet-swim	Movement by alternating between jetting and fin undulation
Drift	Squid that did not undulate fins or jet (gradually overtaken by the trawl)
Flounder/skate variables	Description
Position	
Top	Fish above the fishing line at first detection
Bottom	Fish either on or near the bottom at first detection
Left	Fish to the left (port) of the middle roller
Right	Fish to the right (starboard) of the middle roller
Orientation	
Away	Head directed away from the trawl
Towards	Head directed towards the trawl
Left	Head directed to the left (port)
Right	Head directed to the right (starboard)
Swimming behaviour	
With	Fish swimming with the trawl (same direction as trawl is travelling)
Against	Fish swimming against the trawl (opposite direction trawl is travelling)
Passive	Fish remained on the seabed until right before contact with the footrope
Turn	Fish made a change of heading
No turn	Fish did not make a change of heading
Contact variables	Description
Contact—roller	Physical contact with the roller
Contact—rubber discs	Physical contact with rubber discs
Contact—fishing line	Physical contact with the fishing line
Impingement	Pinning or trapping of animal to groundgear

considered. “Bottom” squid were squid or squid schools that remained low, and rose no higher than immediately above (within one body length of) the fishing line upon trawl entrance; the “top” position was squid or squid schools that remained higher than the fishing line throughout the entire sequence. Squid left (port) or right (starboard) position [position (L/R)] was determined by the position of the individual squid, or squid school, at first detection. Left or right position was relative to the middle roller of the groundgear. Squid orientation was defined as the mantle direction relative to the trawl and the groundgear: mantle away (in towing direction), towards [against towing direction (i.e. towards trawl codend)], to the right (starboard), or to the left (port).

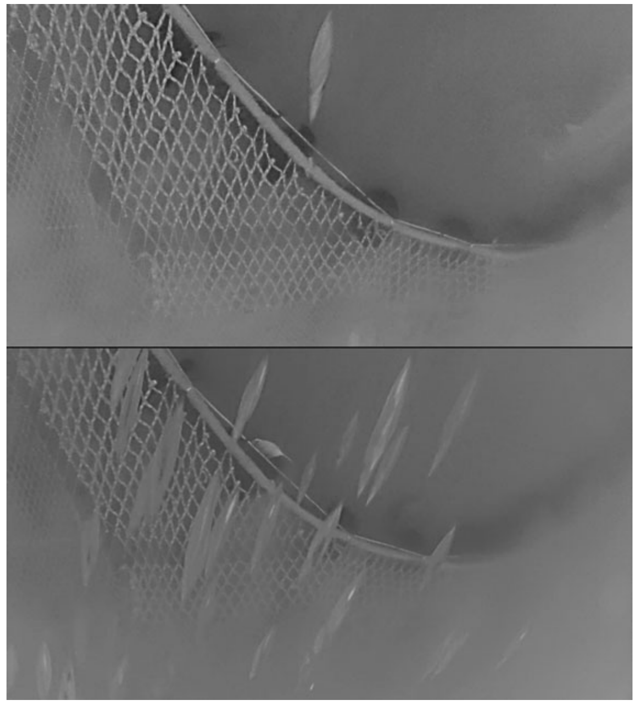

Figure 4. Screen capture of video frames of squid in the “top” position at the mouth area of a drop-chain trawl. Top: an individual squid. Bottom: a school of squid.

Squid are capable of a variety of swimming behaviours (Gosline and DeMont, 1985; Hoar *et al.*, 1994; Anderson and DeMont, 2005; Bayse *et al.*, 2014). Swimming behaviours for squid were defined as swimming (using fin undulations alone; Hoar *et al.*, 1994; Anderson and DeMont, 2005), escape-jet (movement by jet propulsion alone) (Gosline and DeMont, 1985), jet-swim (squid that alternated between fin undulation and jetting; Glass *et al.*, 1999), and drift (squid that were overtaken by the trawl that did not actively undulate their fins or perform a jet).

General morphology of flatfish (size, right- or left-eyed, outline shape, and caudal fin shape) was used to distinguish most flounders typically encountered in this area [fourspot flounder (*Hippoglossina oblonga*), winter flounder (*Pseudopleuronectes americanus*), windowpane flounder (*Scophthalmus aquosus*), and Gulf Stream flounder (*Citharichthys arctifrons*)] from summer flounder. Summer flounder and fourspot flounder have similar body and caudal fin shapes, and are both left-eyed flounders. However, they were easily distinguished based on the conspicuous spots of the fourspot flounder, and based on the size disparity between species: fourspot flounder’s maximum length is 41 cm (Bigelow and Schroeder, 1953; Froese and Pauly, 2011), which was smaller than any summer flounder observed. For skate, species determination was not possible; however, winter skates (*Leucoraja ocellata*) and little skates (*Leucoraja erinacea*) were most common in the catch; barndoor skates (*Dipturus laevis*) were infrequently retained.

Positions, orientation, and swimming behaviour were characterized for each individual summer flounder and skate observed as defined in Table 1. Both top/bottom position [position (T/B)]

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and left/right position [position (L/R)] were defined at first detection. The top position was described as summer flounder/skate above the fishing line, and the bottom position as summer flounder/skate either on or near the bottom. The left or right position was determined by the summer flounder/skate position relative to the middle roller of the groundgear. Orientation was determined as the direction of the head relative to the trawl and the groundgear, either head away (in towing direction), towards [against towing direction (i.e. towards trawl codend)], to the right (starboard), or to the left (port). Swimming behaviour was defined as swimming with the trawl (same direction as trawl is travelling), swimming against the trawl (opposite direction trawl is travelling), or passive (remaining on the seabed until right before contact with the footrope). A "turn" was defined as a change of heading.

Contact and impingement were recorded for all species. Contact was defined as any observed physical contact between an individual and the groundgear that resulted in a change of body motion or contortion. Location (rollers, rubber discs, or fishing line) of the contact was recorded. Impingement was defined as pinning or trapping of an individual to an element of the groundgear (rollers, rubber discs, or fishing line), as a result of contact, for a period longer than 1 s (Bayse *et al.*, 2014). Impingement and duration of impingement were noted.

Observed behaviours were analysed with a generalized linear mixed model (GLMM) with a binomial error using the glmer function of the lme4 package (Bates *et al.*, 2013) in R statistical software (R Development Core Team, 2009; Underwood *et al.*, 2015; Bayse *et al.*, 2016). The dependent variable was capture outcome, which included animals that were observed to enter the trawl (caught) or escape underneath the groundgear (escaped). Independent variables, when appropriate, included "position (T/B)", "position (L/R)", "orientation", "swimming behaviour", "turn", "contact with roller", "contact with fishing line", "impingement", and "time". The random effect was "tow". A maximal model was fitted, which included all independent variables, and was then simplified using stepwise deletion of non-significant variables. Each deletion was tested for a significant increase in deviance with a likelihood ratio test (χ^2, $p < 0.05$). This process was repeated until the minimum adequate model contained only variables that improved the model's fit significantly (Crawley, 2007).

Results

Squid

A total of 2532 individual squid (including those in schools) were observed; none were observed to escape under the fishing line and all entered the trawl (Table 2). A total of 131 squid were observed as solitary, and 209 schools ranging from 2 to 108 squid were observed. Squid that were observed within schools generally maintained the same behaviour as their cohorts while within the bosom of the trawl mouth. The mean observed time to capture for individual squid was 1.5 s (SE $\pm$ 0.7; $n = 131$), and 4.3 s for squid in a school (SE $\pm$ 0.3; $n = 209$ schools).

For individual squid, position (T/B) was similar: 50.4% were observed at the top of the trawl mouth compared with 49.6% at the bottom portion (Table 3). Squid in schools had a larger proportion (59.3%) at the top position than did individual squid (Table 3). Squid position (L/R) differed for individual squid vs. squid in a school; over half (54.2%) of individual squid were observed to the left of the middle roller, while less than half (41.6%) of schooled squid were observed at the left position (Table 3). Orientation was very similar for both individual and squid in schools, with greater than 99.0% observed having a mantle oriented away from the trawl (in towing direction) (Table 3).

Swimming behaviours were similar for both individual squid and squid observed in schools. For both groups, the most squid were observed to "drift", 60.3 and 63.6%, respectively (Table 3). Similarly for the two groups, the second most frequent swimming behaviour was "jet-swim", which made up 38.9% of observed individual squid and 36.4% of squid in schools (Table 3). One squid was observed to perform an escape-jet (individual squid). No squid were observed swimming against the trawl with fins alone. No squid were observed to have contact with the fishing line or the groundgear. GLMM analysis of capture outcome was not possible due to the 100% trawl entrance observed for squid; regardless of squid position, orientation, or swimming behaviour, all squid entered the trawl.

Summer flounder

Of the 87 summer flounder observed at the trawl mouth, 44 had an unknown capture outcome (swam out of camera view) and were removed from analysis. Of the 43 summer flounder with a known capture outcome, 26 were observed to enter the trawl, and 17 were observed to escape underneath the fishing line (Table 2). All summer flounder were observed on or near the bottom, head orientated away from the trawl, and swimming away from the trawl; these behaviours were not further analysed. Summer flounder were observed to the right 65.1% of the time with the remainder to the left (34.9%; Table 2). Many (76.7%) summer flounder changed their heading, turned 180°, and entered the trawl head first. Turning led to a lower percentage of escape compared with not turning (27.3 vs. 76.7%, Table 3), and had a significant effect on trawl entrance ($p = 0.009$, Table 4). Summer flounder that were gradually overtaken by the trawl, and did not perform the 180° turn, did however turn slightly to the left or right as the footrope passed by (Figure 5). Mean time of summer flounder that entered

Table 2. Total numbers and per cent of totals of longfin inshore squid (*Doryteuthis pealeii*), summer flounder (*Paralichthys dentatus*), and skate (family Rajidae) observed to enter or escape at the trawl mouth.

Species	Capture outcome	*n*	% Total	Maximum time	Minimum time	Mean time	SEM
Individual squid	Caught	131	100	6.1	0.3	1.5	0.7
	Escaped	0	0	0.0	0.0	0.0	0.0
Squid in schools	Caught	209	100	25.1	0.7	4.3	0.3
	Escaped	0	0	0.0	0.0	0.0	0.0
Summer flounder	Caught	26	60.5	333.6	2.3	35.9	19.1
	Escaped	17	39.5	87.5	0.8	14.9	4.3
Skate	Caught	20	10.3	4.9	0.1	2.1	0.5
	Escaped	175	89.7	19.3	0.3	1.9	0.2

Time(s) consist of maximum, minimum, mean, and standard error (SEM) of the mean ($\pm$) of observed time from first detection to entrance or escape.

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Table 3. Observed behaviours in relation to trawl entrance or escape for longfin inshore squid (*Doryteuthis pealeii*), summer flounder (*Paralichthys dentatus*), and skate (family Rajidae) at the trawl mouth of a drop-chain trawl. T/B and L/R stand for top/bottom and left/right, respectively.

Species	Variables	*n*	% Total	Caught	Escaped	% Escaped
Squid individual	Position (T/B)					
	Top	66	50.4	66	0	0.0
	Bottom	65	49.6	65	0	0.0
	Position (L/R)					
	Left	71	54.2	71	0	0.0
	Right	60	45.8	60	0	0.0
	Orientation					
	Away	130	99.2	130	0	0.0
	Towards	1	0.8	1	0	0.0
	Left	0	0.0	NA	NA	NA
	Right	0	0.0	NA	NA	NA
	Swimming behaviour					
	Swimming	0	0.0	NA	NA	NA
	Escape-jet	1	0.8	1	0	0.0
	Jet-swim	51	38.9	51	0	0.0
	Drift	79	60.3	79	0	0.0
Squid school	Position (T/B)					
	Top	124	59.3	124	0	0.0
	Bottom	85	40.7	85	0	0.0
	Position (L/R)					
	Left	87	41.6	87	0	0.0
	Right	122	58.4	122	0	0.0
	Orientation					
	Away	208	99.5	208	0	0.0
	Towards	0	0.0	NA	NA	NA
	Left	0	0.0	NA	NA	NA
	Right	1	0.5	1	0	0.0
	Swimming behaviour					
	Swimming	0	0.0	NA	NA	NA
	Escape-jet	0	0.0	NA	NA	NA
	Jet-swim	76	36.4	76	0	0.0
	Drift	133	63.6	133	0	0.0
Summer flounder	Position (T/B)					
	Top	0	0.0	NA	NA	NA
	Bottom	43	100.0	26	17	39.5
	Position (L/R)					
	Left	15	34.9	11	4	26.7
	Right	28	65.1	15	13	46.4
	Orientation					
	Away	43	100.0	26	17	39.5
	Towards	0	0.0	NA	NA	NA
	Left	0	0.0	NA	NA	NA
	Right	0	0.0	NA	NA	NA
	Swimming behaviour					
	With	43	100.0	26	17	39.5
	Against	0	0.0	NA	NA	NA
	Passive	0	0.0	NA	NA	NA
	Turn					
	Yes	33	76.7	24	9	27.3
	No	10	23.3	2	8	80.0
Skate	Position (T/B)					
	Top	0	0.0	NA	NA	NA
	Bottom	195	100.0	175	20	89.7
	Position (L/R)					
	Left	124	63.6	10	114	91.9
	Right	71	36.4	10	61	85.9
	Orientation					
	Away	179	91.8	16	163	91.1
	Towards	16	8.2	4	12	75.0
	Left	0	0.0	NA	NA	NA
	Right	0	0.0	NA	NA	NA

Continued

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Table 3. *Continued*

Species	Variables	*n*	% Total	Caught	Escaped	% Escaped
	Swimming behaviour					
	With	107	54.9	8	99	92.5
	Against	8	4.1	1	7	87.5
	Passive	80	41.0	11	69	86.3
	Turn					
	Yes	5	2.6	2	3	60.0
	No	190	97.4	18	172	90.5
	Contact with the roller					
	Yes	69	35.4	14	55	79.7
	No	126	64.6	6	120	95.2
	Contact with the fishing line					
	Yes	12	6.2	10	2	16.7
	No	183	93.8	10	173	88.7
	Impinge					
	Yes	24	12.3	10	14	58.3
	No	171	87.7	10	161	94.2

Table 4. GLMM of escape at the mouth of a drop-chain trawl for summer flounder (*Paralichthys dentatus*) in the trawl mouth of a drop-chain trawl ($n = 43$).

Retained variables	Estimate	SE	*z*-value	*p* (>z)
Intercept	1.554	0.926	1.679	0.093
Turn	−2.489	0.949	−2.624	0.009*
Removed variables	Order of removal		Δ deviance	$p\ (>\chi^2)$
Time	1		0.315	0.575
Position (L/R)	2		0.577	0.447

Parameters of the retained variables of the minimum adequate model, and the change in deviance caused by the removal of the variable from the preceding model [likelihood ratio test (χ^2) $p < 0.05$].
*Denotes statistical significance at α of 0.05.

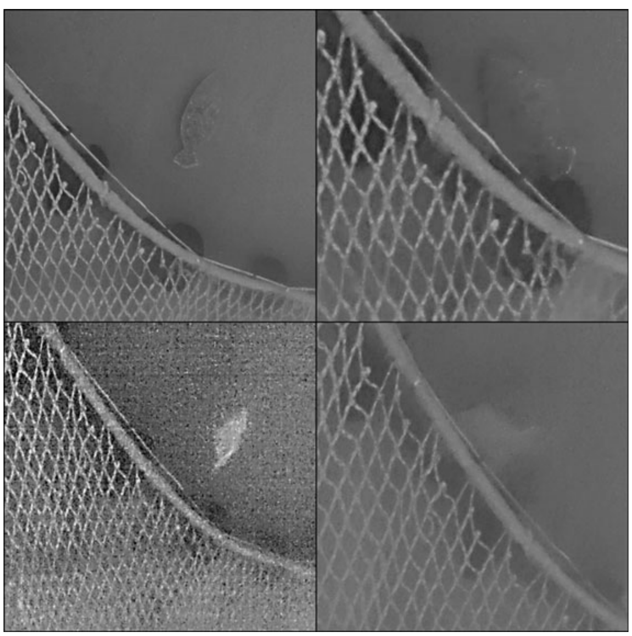

Figure 5. Screen capture of video frames of summer flounder at the mouth of a drop-chain trawl. Top left: summer flounder swimming with trawl. Top right: summer flounder being overtaken by trawl and escaping underneath. Bottom left: summer flounder performing 180° turn and entering the trawl (note the white of the ventral side). Bottom right: summer flounder performing 180° turn and escaping underneath the trawl (note the white of the ventral side).

the trawl was 35.9 s (SEM ± 19.1) vs. 14.9 s (SEM ± 4.3) for those that escaped (Table 2). No summer flounder was observed to have contact with the footrope. Left or right position and time did not significantly affect capture outcome (Table 4).

Skates

A total of 197 skates were observed at the trawl mouth. Of the 197 skates observed, 20 entered the trawl and 175 escaped under the footrope; two had an unknown capture outcome (impinged until the end of the tow) and were removed from analysis ($p = 0.447$, Table 2).

Like summer flounder, skates were observed only on or near the bottom, and position (T/B) was not further analysed. Skates on the left side were observed 63.6% of the time vs. the right side (Table 3). Many skates (91.8%) were orientated in the same direction as the trawl, 8.2% in the opposite direction, and zero to the left or to the right of the trawl mouth (Table 3). Skates that were orientated towards the trawl had a lower escape percentage (75.0%, Table 3), and this skate orientation significantly affected trawl entrance ($p = 0.039$, Table 5). A little over half (54.9%) of skates were observed swimming with the trawl, 4.1% were swimming against the trawl, and 41.0% were considered passive (Table 3). Few skates turned (2.6%); however, those that did had a relatively low escape percentage (60.0%), and this behaviour had a significant effect on trawl entrance ($p = 0.029$, Table 5). Skates that entered the trawl had a mean time of 2.1 s (SEM ± 0.5) vs. 1.9 s (SEM ± 0.2) for skates that escaped under the footrope. Left or right position, swimming behaviour, and time did not significantly affect capture outcome ($p > 0.50$, Table 5).

Overall, 69 skates (35.4%) with a known capture outcome came into contact with some part of the groundgear. Of these skates, all 69 were observed to have contact with the rollers, 12 additionally came in contact with the fishing line, and no skate had any substantial contact with the rubber discs between the rollers (Table 3). Skates that had contact with the fishing line had a very low escape percentage (16.7%, Table 3), and this contact had a significant effect on trawl entrance ($p < 0.001$, Table 5). Contact with the rollers did not significantly affect skate capture outcome ($p = 0.436$, Table 5).

A total of 24 skates with a known capture outcome became impinged to the groundgear (Table 3 and Figure 6). Of these skates, 10 entered the trawl, and 14 escaped under the footrope; impingement did not have a significant effect on capture outcome

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Table 5. GLMM of escape at the mouth of a drop-chain trawl for skate (family Rajidae) in the trawl mouth of a drop-chain trawl ($n = 195$).

Retained variables	Estimate	SE	z-value	p (>z)
Intercept	−3.2848	0.6003	−5.472	<0.001*
Orientation	1.6786	0.8127	2.065	0.039*
Turn	2.3815	1.0874	2.19	0.029*
Contact with the fishing line	4.918	0.9481	5.187	<0.001*
Removed variables	Order of removal		Δ deviance	$p (>\chi^2)$
Swimming behaviour	1		0.006	0.997
Position (L/R)	2		0.010	0.921
Time	3		0.367	0.545
Impinge	4		0.206	0.650
Contact with the roller	5		0.607	0.436

Parameters of the retained variables of the minimum adequate model, and the change in deviance caused by the removal of the variable from the preceding model [likelihood ratio test (χ^2) $p < 0.05$].
*Denotes statistical significance at α of 0.05.

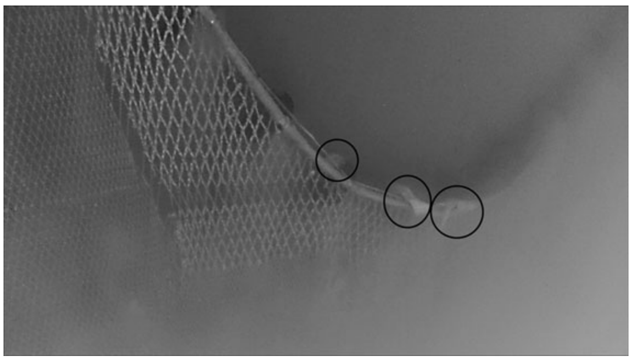

Figure 6. Screen captures of three skates (circled) impinged to the groundgear and/or fishing line of the drop-chain trawl.

($p = 0.650$, Table 5). The mean time that skates were impinged was 100.2 s (SEM ± 60.4), with a maximum time of 1217.2 s and a minimum time of 3.2 s. The two unknown skates were impinged until the end of the tow, and determination of trawl entrance or escape was unknown; however, they were observed impinged to the footrope for 668.5 and 3650.6 s, respectively.

Discussion

Through video analysis, we demonstrated that a drop-chain trawl is extremely effective at capturing squid, the target species, with no squid observed escaping underneath the fishing line, and also effective at avoiding the vast majority (89.7%) of skates. However, the design was less effective at releasing summer flounder (39.5% escaped). The bycatch reduction approach of "raising" the fishing line above the seabed to allow demersal species to escape underneath has been tested, proved successful, and mandated in certain regions and fisheries in New England (DeAlteris *et al.*, 1996; McKiernan *et al.*, 1996, 1998; Carr and Milliken, 1998; Glass *et al.*, 2001; Sheppard *et al.*, 2004; Schick, 2005; Hasbrouck *et al.*, 2013). However, none of these studies quantified target or bycatch species behaviour to the experimental groundgear, nor did they quantify results of species that entered or exited underneath the gear. While catch comparison studies often can glean similar results by comparing mean catch rates, the results from this study explicitly showed how well the catch is actually separated at the trawl mouth and what behaviours, initial positions, and orientations led to either capture or escape.

These results were determined from 209 individual schools of squid, 131 individual squid, 43 individual summer flounder, and 195 individual skates. Each of these individuals were considered to be experimental subjects, and to be independent. Animals with an unknown capture outcome were excluded from analysis. Pseudoreplication can be a problem in behavioural studies when data are considered independent when they are not (Hurlbert, 1984). During our study, both summer flounder and skates entered the trawl mouth at a low rate (average 1 individual for every 6.0 and 1.3 min, respectively) and can be considered as independent. Squid entered the trawl mouth both as individuals and in schools. Each squid school was analysed as a single experimental subject to avoid pseudoreplication that can arise from assuming individuals within a school are independent of each other (Millar and Anderson, 2004). Additionally, an increase in tows and individuals observed would increase statistical power. Regardless, the described behaviours in this study provide a convincing, valuable insight into the effectiveness of a drop-chain trawl to capture squid and release summer flounder and skates.

The camera was placed to view the centre of the trawl mouth. This camera placement, at times, made the wingends difficult to see. Therefore, some animals may have been missed at the extreme ends of the wingends, potentially effecting left/right proportions. However, as is typical with trawl gear, the vast majority of species entered or escaped close to the trawl's centre point. Additionally, video was of high quality due to fishing taking place during daylight hours, shallow depths, and low turbidity. While these conditions can be typical of the Nantucket Sound fishery (particularly daylight and shallow depths), it is not the case generally for temperate latitude trawl fisheries. Observations of fisheries in lowlight or turbid waters may have different results.

Squid

Previously successful raised-footrope trawl sea trials in the Nantucket Sound squid fishery resulted in no significant squid loss compared with a commercial trawl (Glass *et al.*, 2001). However, scepticism remained among the industry of the ability to capture squid without a ticker chain or rubber disc groundgear, and that too many squid would be lost underneath the fishing line. Direct observations in this study showed that no squid exited underneath the fishing line, and 100% of squid observed ($n = 2532$) entered the trawl above the fishing line. This result shows that a "raised" footrope design with a fishing line 50 cm above the seabed can be very effective and efficient at capturing squid, and that traditional groundgears made of chains and rubber discs used in the squid fishery are not the only effective groundgears used in conjunction with a drop-chain trawl for the Nantucket Sound squid fishery. While concerns might be raised

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regarding behaviours outside the centre of the footrope, our results can be used to alleviate concerns from fishing industry members.

These results provide additional insights into squid behaviour compared with prior studies. Squid behaviour at the trawl mouth was previously described by Glass *et al.* (1999). That study described squid behaviour in the trawl mouth qualitatively, reporting squid showing herding behaviour and "considerable swimming endurance" (Glass *et al.*, 1999). Squid were observed to swim with their mantle away from the trawl, then, after tiring, rising in the water column, with a portion changing orientation to mantle towards the trawl. Glass *et al.* (1999) reported squid to enter the trawl very high in the trawl mouth and to swim with the trawl for a long period, gradually rising then often turning. Squid were only observed in schools, with long periods of time between schools. For the most part, squid behaviours were generally described, without quantitative description. The exception was one squid school, estimated to be in the hundreds, that was described as swimming with the trawl for 3 min, and to be alternating between jetting and fin undulation.

Squid in this study exhibited behaviour differing from those observations in several ways. First, many squid ($n = 131$) were observed swimming individually and not in schools. The maximum time observed for squid in the trawl mouth was 25.1 s for a school of 32 squid, and school size ranged from 2 to 108. No squid were observed to equal the 3-min observation made by Glass *et al.* (1999). Many squid did appear already herded at first observation, and all but six squid were orientated with their mantle away from the trawl, as was described by Glass *et al.* (1999). For the six squid, their orientations appeared to be a reaction to a predator, summer flounder. As the summer flounder moved in front of the trawl, these squid changed their orientation, and some inked—the only squid observed to ink in this study.

Squid tended to maintain their depth in the water column, either much higher than the groundgear or low, approximately even with the groundgear, and rose only briefly. Some squid raised just enough to cross the fishing line and enter the trawl. Dramatic rises described by Glass *et al.* (1999) were not observed.

Furthermore, no squid were observed to change their mantle direction and enter the trawl as described by Glass *et al.* (1999). To investigate this further, we gradually moved cameras further back in the trawl (towards the codend), and squid (when no predators were present in trawl) were not observed to change orientation throughout the length of the belly, conversely orientation changes were common for squid in an experimental extension with a grid and escape window (Bayse *et al.*, 2014).

In this study, squid swimming behaviour was a mixture of jet-swimming and drifting. Drifting squid rarely used their fins, apparently only to maintain position in the water column and to conserve energy. When not in proximity to predators, squid generally allowed the trawl to overtake them and did not employ any of the escape behaviours described by Bayse *et al.* (2014) in the extension in the presence of a separator grid and escape window.

Some of the differences between this study and Glass *et al.* (1999) are likely explained by differences in study design, including different groundgears and camera placement. Additionally, this study used an HD camera, technology unavailable in 1999. Environmental conditions could also cause a difference (such as amount of light, temperature, etc.), although the effect of these conditions on squid is unknown. Both studies took place in the same area and the same season, but inadequate detail is available to more fully compare the two studies.

We observed most squid in schools (58.4%) on the right side of the trawl, and most individual squid (54.2%) on the left side, no difference in summer flounder right to the left position, and a majority of the skates (63.6%) on the left side of the trawl. The reasons for these distributions are unclear. Our perception of location of fish and squid is sensitive to the normality of the camera orientation to the footrope, although we strove to keep the camera perspective in a normal direction. However, the conflicting tendencies of squid and skates and the similarity of summer flounder suggest that camera orientation is not creating a false impression since the observed differences were not all in the same direction. Other causes could include tow direction relative to tide (cross-current seems more likely to produce this effect than towing with or against tide), or an unrecorded vessel turn. Furthermore, perhaps the gear itself was not square to the tow direction. Regardless, these results had no effect on trawl entrance as tested by the GLMM.

Time in the trawl mouth was different for individual squid vs. squid in a school. Differences in densities of finfish affect behaviour and catch rates in the trawl mouth (Godø *et al.*, 1999). Squid turnover rate (rate entering the trawl) appears similarly affected by density based on our results, and similarly, individual squid entered the trawl sooner (higher turnover rate) as was shown for "loner" fish species described in Godø *et al.* (1999). These differences may suggest that squid seek out conspecifics and prefer to be in schools, or that squid exhibit separate behaviours based on individual tendencies and tolerances for risk. Furthermore, fish swimming in schools are believed to have an energetic advantage, thus allowing for longer swimming endurance (Weihs, 1975). The linkage between squid behaviour and density may have implications for designing fishing gear based on behavioural differences—catch by a gear may differ depending on the density of squid.

Summer flounder

Flatfish reactions to groundgear and trawl entrance have been described quantitatively by others (Bublitz, 1996; Albert *et al.*, 2003; Winger *et al.*, 2004; Underwood *et al.*, 2015) and reviewed by Ryer (2008), but this is the first study to quantify summer flounder behaviour to fishing gear. All individual summer flounder were orientated with their head away from the groundgear and swimming with the trawl. Since observations were taken in the bosom portion of the trawl mouth, all summer flounder were likely herded before entering camera view. Summer flounder entered the trawl by one of two ways, rising off the bottom and rapidly turning 180° to head towards the trawl, and by rising off the bottom and gradually being overtaken by the trawl. These reactions to the groundgear were similar to those described by Bublitz (1996) for North Pacific flatfish in reaction to roller gear; our study observed a greater proportion of summer flounder turning and heading towards the trawl (76.7%), compared with Bublitz (1996), who observed 20% of flatfish turn at the trawl mouth. Of the summer flounder that were gradually overtaken by the trawl (23.3%) in our study, only two rose above the fishing line and entered the trawl, whereas the other eight escaped underneath.

A drop-chain trawl was not as effective at releasing summer flounder as it was at releasing the other demersal species (skates) examined. Previous studies of a drop-chain trawl were successful at decreasing the catches of flatfish, but most of the flatfish encountered in these trials were American plaice (*Hippoglossoides platessoides*), which was not observed in these sea trials, and winter flounder, which was observed infrequently (McKiernan *et al.*, 1998). Summer flounder is a much larger species, in terms of both size and

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musculature, and its behaviour to a drop-chain trawl is likely different from that of smaller flatfish, such as American plaice and winter flounder, and likely similar to Pacific halibut (*Hippoglossus stenolepis*), which Rose (1995) observed to swim with a footrope for considerable amounts of time, up to 8 min. Furthermore, Ryer (2008) suggested that this behaviour of Pacific halibut was more similar to that of roundfish than flatfish, due to this increased swimming endurance. Therefore, summer flounder behaviour should perhaps be discussed in terms more similar to Pacific halibut than to the other flatfish species commonly found in New England.

Drop-chain trawls can have different configurations of groundgear (McKiernan *et al.*, 1996; Sheppard *et al.*, 2004; Nguyen *et al.*, 2015). Groundgear in previous studies (McKiernan *et al.*, 1996), and mandated by regulation (raised-footrope trawl; Federal Register, 2004), are made of chains. These chains were connected to longer drop chains as well, at least 107 cm, where drop chains in this study, in the centre of the footrope, were 30.5 cm. The different groundgear configurations could have led to the different results for flatfish catch and behaviour between previous studies (McKiernan *et al.*, 1996, 1998) and this one. We used roller gear on our drop-chain trawl, as opposed to chain groundgear, because chain groundgear, with the increased drop chain length, can become hung up on the seabed and in derelict gear. This problem has made the raised-footrope trawl unfishable in Maine (Bayse *et al.*, 2016), and can be a concern elsewhere.

All summer flounder observed were actively swimming away from the approaching trawl, and zero were observed to lay on the substrate. Possibly, summer flounder could have been buried in the substrate, missed by our analysis, and not quantified. However, there was high visibility during our recorded tows, an HD camera was used, and skates were easily observed on the substrate.

Most of the summer flounder observed turned and entered the trawl; this behaviour was defined by Bublitz (1996) as an escape behaviour, as opposed to the gradual overtaking of the trawl as an avoidance behaviour. Less reduction in summer flounder catch by a drop-chain trawl, compared with other flatfish, could be due to this effect, caused by the fishing line being higher above the seabed (up to 50 cm) than typical groundgear that is maintained on the bottom. Perhaps, the fishing line being maintained at a higher level elicits this escape response, which unintentionally results in more summer flounder entering the trawl than desired. More work should be done on summer flounder behaviour to trawl groundgear and to a drop-chain trawl, focusing on possible length or species effects, and if any gear modification could decrease summer flounder turning towards the trawl.

Skates

The skate behaviour we observed has not previously been documented. Skates appeared already herded at first detection, 91.8% head away from the oncoming trawl, and similar patterns were observed for skates at trawl bridles in another study (PH and MVP, unpublished data). Generally, skates remained on the bottom until contact with the trawl was imminent, at which point the skate would either swim in the direction of their heading while remaining low, near the bottom, or stay on the bottom and undulate their wings with little or no forward movement until interaction with the trawl. Skate orientation (and likely herding) was generally similar to summer flounder; however, skates were more inclined to remain on the seabed, and less likely to be swimming with the trawl, when compared with summer flounder. It is conceivable but unlikely that other, unobserved and randomly orientated skates were present but not observed because they remained motionless or buried in the sediment. Nevertheless, the observation of this orientation in two separate studies suggests the possibility that skates have already orientated their body in reaction to the trawl well before the trawl is in proximity. The possibility of orientation based on non-visual stimuli (e.g. orientation by underwater radiated noise before trawl components are within the visual range) should be investigated, perhaps, by observing skate orientation when not pursued.

Skates had a low mean time in the trawl mouth (2.4 s) and were unable to hold station for long periods. DeAlteris *et al.* (1992) observed similar times (3–4 s) for skates in the trawl mouth. Few skates turned in our study, and most were observed to maintain their original heading throughout the interaction with the trawl. Generally, skates did not respond until the gear was very close, and the vast majority (89.7%) escaped underneath the gear; therefore, a drop-chain trawl appears an effective design to avoid capture of skates.

Contact and impingement

An effective BRD should avoid both capture of and damage to unwanted organisms. Previous studies have described contact between the groundgear of a trawl and crabs (Rose, 1999; Rose *et al.*, 2013; Nguyen *et al.*, 2014). In our study, no contact was observed between squid and the groundgear. No substantial contact was observed between summer flounder and the groundgear, as summer flounder that escaped avoided the rollers, and exited between them, above the rubber discs. Perhaps, there was some small amount of contact between summer flounder and the cookies, as the fish crossed over, but none was observed and summer flounder showed no reaction while crossing.

Sixty-nine skates made substantial contact with the groundgear, and 24 of those became impinged. While it has not been quantified, this type of contact may result in increased, unaccounted mortality and therefore reduce the drop-chain trawl's effectiveness as a BRD. Skates are considered one of the more hardy species in terms of surviving the trawl capture process (Benoît *et al.*, 2013), and the two species most commonly observed in this study, winter and little skate, were shown to have relatively low levels of post-release discard mortality with minor and moderate injuries (Mandelman *et al.*, 2013). However, post-release discard mortality greatly increased for extensively injured skates, and the only immediate point of capture mortalities observed in Mandelman *et al.* (2013) was for specimens that were impinged in the netting or ropes when the net was brought on board.

Post-contact mortality of skates in this study can only be speculated upon, since skates were not investigated for physical injury or physiological trauma. However, skates were impinged for long periods of time, had substantial contact with the gear, and in some cases became wedged between the footrope and seabed, and were dragged against the seabed. This contact likely contributes to unobserved escapee mortality (Suuronen and Erickson, 2010), and may be a concern if this or similar BRDs are considered for implementation. Skates were not observed to become impinged or have substantial contact with the rubber discs of the groundgear, likely due to their relatively small size compared with other groundgear components. If minimization of injuries to skates is a consideration when fishing a drop-chain trawl, rubber disc groundgear may be a better choice than roller gear.

Conclusions

This study validated a drop-chain trawl as a BRD by quantifying behaviour at the trawl mouth via video analysis. Explicit results for

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three primary species, including percentage entering the trawl vs. escape underneath, were obtained. The drop-chain trawl design was highly effective at retaining squid and excluding skates. While some summer flounder were not caught, many summer flounder turned and entered the trawl in front of the groundgear significantly affecting trawl entrance, and this unexpected result is a matter that needs further research to improve upon summer flounder release. No squid or summer flounder were observed to have contact with the groundgear, while 35.4% of observed skates had contact, and 12.3% became impinged. All contact with the gear occurred either at a roller or the fishing line, and contact with the fishing line increased skate capture. To reduce this contact, either a rubber disc groundgear should be employed or the fishing line could be raised further from the seabed. While no BRD solves all bycatch issues, the results of this study strongly suggest that employing a drop-chain trawl in squid trawl fisheries would maintain squid catch rates, while decreasing the catch of demersal species, with minimal damage to non-skate species. This study showed that video recordings can be employed to quantify BRD effectiveness.

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