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Citation for published version:

Southworth, LK, Ratcliffe, FC, Bloor, ISM, Emmerson, J, Watson, D, Beard, D & Kaiser, MJ 2020, 'Artificial light improves escapement of fish from a trawl net', *Journal of the Marine Biological Association of the United Kingdom*, vol. 100, no. 2, pp. 267-275. <https://doi.org/10.1017/S0025315420000028>

Digital Object Identifier (DOI):

[10.1017/S0025315420000028](https://doi.org/10.1017/S0025315420000028)

Link:

[Link to publication record in Heriot-Watt Research Portal](#)

Document Version:

Peer reviewed version

Published In:

Journal of the Marine Biological Association of the United Kingdom

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1 Running head: Influence of LED lights on fish bycatch

2
3 **Artificial light improves escapement of fish from a trawl net**

4
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19 Keywords: bycatch reduction device, haddock, depth, fish behaviour, whiting, flatfish,
20 selectivity, discards

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26

27 ABSTRACT

28 The elimination of unwanted catch in mixed species fisheries is technically challenging given
29 the complexity of fish behaviour within nets. Most approaches to date, have employed
30 technologies that modify the nets themselves or use physical sorting grids within the gear.
31 There is currently increasing interest in the use of artificial light to either deter fish from
32 entering the net, or to enhance their escapement from within the net. Here, we evaluated the
33 differences in catch retained in a standard otter trawl, relative to the same gear fitted with a
34 square mesh panel, or a square mesh panel fitted with LEDs. We found that the selectivity of
35 the gear differed depending on water depth. When using a square mesh panel in shallow depths
36 of 29-40m the unwanted bycatch of whiting and haddock was reduced by 86% and 58%
37 respectively. In deep, darker water (45-95m), the bycatch of haddock increased by 41% in the
38 square-mesh panel treatment, however when LEDs were added to the square-mesh panel,
39 haddock and flatfish catches were reduced by 47% and 25% respectively. These findings
40 demonstrate the potential to improve the performance of bycatch reduction devices through the
41 addition of light devices to enhance selectivity. The results also highlight species-specific and
42 site-specific differences in the performance of bycatch reduction devices, and hence a more
43 adaptive approach to reduce bycatch is probably required to maximise performance.

44

45 INTRODUCTION

46 Bycatch is an important consideration in an ecosystem-based approach to management of
47 fisheries (Gilman *et al.* 2014). Bycatch refers to the accidental capture of non-target marine
48 organisms or undersized target species, which can result in discarding of the unwanted catch
49 that are often dead (Kelleher 2005). Discarding can cause difficulties in estimating fishing
50 mortality, productivity and stock abundance (Catchpole *et al.* 2005). Discarding occurs for

51 various reasons, including; i) regulatory restrictions: quota limitations, minimum landing sizes
52 (MLS) or protected status; ii) quality of catch: damage or contamination; iii) value of catch:
53 species vary in market value, which can result in high-grading ie. strategically discarding low-
54 value species that can be legally landed (Kelleher 2005; Gilman *et al.* 2014).

55 The European Union (EU) have implemented the landings obligation (LO), whereby
56 discarding quota species is banned, instead it is required that all EU quota species are landed
57 and recorded (EC 2013). This legislation requires that fishers either; i) hold sufficient quota to
58 land the bycatch of quota species; ii) prove that discard survivability rates of species is high
59 enough to permit continued discarding (*survivability exemption*); iii) implement bycatch
60 reduction strategies to eliminate or significantly reduce rates of bycatch or; iv) if scientific
61 evidence proves increased selectivity is difficult to achieve, a *de minimis* exemption may
62 permit fishers to discard quota-regulated species that are caught in minor quantities (often 5%
63 of the weight of target catch), these catches will not be counted against the quota but must be
64 documented (EC, 2018) If species are landed surplus to available quota, this could result in the
65 early closure of that fishery (known as *choking*). For these reasons, the reduction of bycatch is
66 of paramount concern for many fisheries in Europe.

67 Technological modifications to fishing gear can be utilised to improve selectivity and
68 avoid the capture of unwanted catch. Bycatch reduction devices (BRDs) can be designed to; i)
69 select individuals *mechanically*, eliminating or reducing catches of non-target or undersize
70 target organisms by size and shape or; ii) encourage escapement through exploiting differences
71 in *behaviour* between target and bycatch species (Broadhurst 2000). Square mesh panels
72 (SMP) are a form of BRD that incorporates a panel of large square mesh into a traditional
73 diamond mesh net, selecting species mechanically, thereby allowing below MLS individuals
74 to escape or eliminating non-target species by exploiting their behaviour. For example, in otter
75 trawls, gadoid bycatch have the capability to escape through a SMP fitted in the upper panel

76 of a net, as they have a higher motor ability than the target species such as scallops or prawns,
77 which remain in the lower sections of the net (Broadhurst 2000; Courtney *et al.* 2008). The
78 effectiveness of a SMP to select species by size is dependent on the mesh size used, and on
79 seasonal variations affecting fish condition (Brčić *et al.*, 2016; Fryer *et al.*, 2016). Additionally,
80 the effectiveness of SMPs can depend on the panel position, with escapement highest when the
81 distance between the SMP and codline is smallest (Brčić *et al.*, 2016). Selectivity can vary
82 between bycatch species, for example, cod (*Gadus morhua*) and haddock (*Melanogrammus*
83 *aeglefinus*) exhibit different swimming patterns in response to trawls. Cod tend to enter the
84 trawl at the level of the fishing line and remain low in the net, exhibiting low swimming
85 activity, while haddock swim in a more erratic manner, which increases their chances of
86 escapement through BRDs (E. Grimaldo *et al.*, 2007; Ferro *et al.*, 2007; Krag *et al.*, 2009).
87 Subtle changes in environmental parameters can also influence gear selectivity, e.g. water
88 current and temperature can affect the maximum swimming performance of fish (Wardle,
89 1983; Michalsen *et al.*, 1996; Matt K Broadhurst, 2000a). Similarly, depth can also influence
90 selectivity according to species habitat associations, visual capacity, and corresponding ability
91 to avoid gears (Nguyen & Winger, 2019).

92 The use of artificial light to enhance gear selectivity is of increasing interest. However,
93 the behavioural responses to light are species specific (Ben-Yami, 1976; Nguyen & Winger,
94 2019), with light either stimulating a reduction or increase in catches for some species, while
95 having no effect on others (Lomeli & Wakefield, 2012; Larsen *et al.*, 2017, 2018; Lomeli,
96 Wakefield *et al.*, 2018; Melli *et al.*, 2018). Grimaldo *et al.* (2017) placed LEDs within a SMP
97 and found that lights stimulated escape behaviour in haddock but not in cod. Also, when
98 implementing light as a tool to manipulate fish behaviour, technical parameters such as colour,
99 intensity, wavelength and strobing need to be considered (Ben-Yami, 1976; Marchesan *et al.*,
100 2005; O'Neill *et al.*, 2019), which can also vary depending on the fishing environment. For

101 instance fish vision is reduced in deep water due to the lower ambient light levels (Kim &
102 Wardle 1998). Fish behaviour also changes depending on the configuration of the lights within
103 the trawl, lights fitted to the fishing line can either repel fish or increase their awareness of the
104 oncoming trawl (Hannah *et al.*, 2015; Lomeli, Groth *et al.*, 2018; Lomeli, Wakefield *et al.*,
105 2018). In contrast, lights fitted to the escape panel can guide fish towards escape routes (Ben-
106 Yami, 1976; Lomeli & Wakefield, 2014; Elliott & Catchpole, 2015; Eduardo Grimaldo *et al.*,
107 2017). Some fisheries currently use light as a tool to increase catches through attracting species
108 towards fishing gear, notably squid jigs, herring purse seines and snow crab pots (Nguyen &
109 Winger, 2019). Collectively, these studies highlight the considerable variation in the
110 behavioural responses of fish to light, which is both species and environmentally specific.

111 The present study investigated the effect of using LED lights attached to a SMP
112 designed to reduce the bycatch of gadoids in a Queen scallop (*Aequipecten opercularis*; QSC)
113 trawl fishery in the Irish Sea, UK. Pre 2018 the QSC fishery, was the second most valuable
114 fishery in the Isle of Man (IoM) with ~3,814 tonnes landed from ICES area VIIa (ICES
115 rectangles 36E5, 37E5 and 38E5) worth c. £2.4M annually (MFPO *pers comms.* 2017). The
116 bycatch levels (as a percentage of overall catch) for the fishery, are relatively low at 7.4%
117 (Boyle & Thompson 2012). Nevertheless, at present, the MFPO holds insufficient quota for
118 this fishery to land bycatch species such as whiting (*Merlangius merlangus*), cod and haddock,
119 hence the fishery may become 'choked' prematurely (MFPO *pers comms.* 2017). SMPs are
120 effective at reducing gadoid bycatch and, in some cases large mesh panels can reduce flatfish
121 bycatch (Milliken and DeAlteris 2004) and more recently artificial light reduces both round
122 and flatfish bycatch (Hannah *et al.*, 2015; Nguyen & Winger, 2019).

123 The objectives of the present study were to assess whether the use of LED lights
124 together with a SMP enhanced fish escapement, relative to a SMP without LEDs and in
125 comparison to a standard commercial net without a SMP, or LEDs. The study was replicated

126 in two different environments to understand how differences in environmental conditions
127 affected the selectivity of bycatch species in the modified fishing gear.

128

129 MATERIALS AND METHODS

130 **Experimental design**

131 The study occurred from June - August 2017 during daylight hours. Fishing took place across
132 two commercial fishing grounds in the Isle of Man territorial EEZ, known locally as Targets
133 and Chickens (Fig. 1). The sites vary in terms of bycatch composition, ground type and depth
134 (Boyle *et al.* 2016), and are hereafter referred to as ‘shallow’ (Targets) and ‘deep’ (Chickens).

135 The trials were conducted utilising two commercial fishing vessels of similar size and
136 engine power, “Two Girls” (TG; 13.88m, 216.24 kW) and “Our Sarah Jane” (OSJ; 13.98m,
137 187 kW). The experiment adopted a paired tow design, whereby two nets were towed parallel
138 to one another, one vessel towed the conventional all diamond mesh net (control) and the other
139 vessel towed one of the treatment nets; either the i) SMP alone or, ii) the SMP with LEDs
140 attached (SMP+L) (Fig. 2). Fishing procedures were consistent for both vessels and both nets
141 were identical and new prior to the addition of the SMP to one of the nets. When testing the
142 SMP+L treatment, 6 LEDs were attached to the SMP using cable ties and metal clips (Fig. 2c,
143 d). The SafetyNet Technologies ltd. LED lights were programmed to emit constant white light
144 (luminous intensity 33 cd (candela); voltage 3.1V). The lights were almost neutrally buoyant
145 when in seawater.

146 To minimise environmental and ‘vessel’ effects, the treatment net (SMP/SMP+L) and
147 control net (all diamond mesh) were interchanged between fishing vessels after every second
148 day. The vessels towed their fishing gear in parallel lines but switched their position from port
149 to starboard after every tow. The treatments (SMP/SMP+L) were alternated sequentially every
150 second tow throughout each day. Each vessel towed the nets on the same bearing (into the tide

151 when feasible) at ~2.2 knots (speed over ground) and the warp released was standardised at
152 three times the depth and tow duration was kept constant at 60 minutes.

153

154 **Sampling design and data collection**

155 Once emptied on deck, all fish were identified and counted. Total lengths (TL) of EU quota
156 species were measured to the nearest 0.1mm. The length/weight relationships of fish species
157 were determined to estimate weights of each species caught per tow (Supplementary Table S1).
158 Once the Queen scallops (*Aequipecten opercularis*) had been sorted through the mechanical
159 riddle to eliminate undersized individuals, the number of standard sized bags of marketable
160 catch were recorded per tow and this value was subsequently multiplied by the weight of an
161 average QSC bag (~35kg; MFPO *pers comms*). The towing positions were recorded every
162 minute using GPS loggers. Tow length was standardized to swept area, using a net spread ratio
163 of 0.75 relative to the net headrope length (Fig. 2) (Sterling, 2005).

164 Environmental variables that may have influenced catch per unit area (CPUA) were
165 recorded per tow including: sea state (Beaufort scale), turbidity (Secchi disk; m), cloud cover
166 (%). Ambient light levels in the net (lux) were recorded with HOBO UA-002-64 64K Pendant
167 Temp/Light Logger (Tempcon Ltd.). Although the logger was incapable of detecting low
168 natural ambient light levels, it was deployed on the treatment net (30cm anterior of the square
169 mesh panel) to record variations in natural and artificial light. The mean daily tidal coefficient
170 was recorded (tides4fishing.com) and the average depth (m) data per tow were extracted from
171 bathymetry data (*EMODnet.EU*) in ArcGIS (ESRI,v10.3).

172 **Length frequency distributions**

173 Length frequency distributions were visually inspected per site for each bycatch group,
174 comparing the treatment with the corresponding control net. All tows within each site were

175 pooled to represent the approximate size distribution of each treatment. These data were
176 visualised but not statistically analysed because of low numbers of fish caught per tow, with
177 each group falling below the recommended 375 individuals per sample for the purposes of size
178 frequency analysis (Miranda, 2007) (median n for whiting = 2, haddock = 4 , flatfish = 14).
179 Low numbers of bycatch fish species are a characteristic of this fishery, but nevertheless,
180 sufficient to choke the fishery due to the small size of the quota held by the Producer
181 Organization.

182 **Statistical analysis**

183 Initially, the standardized abundance of all species caught in the control tows (count/tow,
184 square root), was analysed to assess differences in species community assemblages between
185 fishing grounds using analysis of similarity (ANOSIM) pairwise testing, in PRIMER v.7
186 (Clarke and Warwick 1994).

187 All subsequent analyses were conducted using ‘R’ (Version 3.5.2). The abundance data
188 for each species was converted to catch (count) (CPUA) and weight (WPUA) per unit area,
189 using an estimated weight (g or kg) per swept area (ha):

$$190 \quad WPUA (kg ha^{-1}) = \frac{\text{Estimated weight (kg)}}{\text{Swept Area (ha)}}$$

191

192 WPUA and CPUA were strongly positively correlated for commercial species caught
193 ($r = 0.92$) (Supplementary Table S3), therefore only WPUA was analysed as weights are more
194 directly relevant to the landings obligation. The treatment WPUA was divided by the control
195 WPUA, per paired tow, to create a relative response ratio. The response ratio (RR) was then
196 transformed by a natural logarithm (ln), hereafter referred to as the ‘relative WPUA’ (lnRR) in
197 the equation below:

198
$$LnRR_{Weight} = Ln\left(\frac{WPUA_{Treatment} + \frac{1}{2} \text{minimum non-zero}}{WPUA_{Control} + \frac{1}{2} \text{minimum non-zero}}\right)$$

199

200 As a single value, the relative WPUA (lnRR) quantifies the relative change in WPUA
 201 due to the modifications to the net, for each treatment tow relative to the ‘paired’ controlled
 202 tow (Lajeunesse 2011; Sciberras *et al.* 2013).

203 To ensure there was no vessel bias, the average CPUA of the *quota gadoids* (haddock
 204 *Melanogrammus aeglefinus*, cod *Gadus morhua*, whiting *Merlangius merlangus*), *all bycatch*
 205 *species* recorded and *marketable QSC* caught in the control nets were compared between the
 206 two fishing vessels (TG and OSJ) in a two-way analysis of variance (ANOVA), which included
 207 both site and vessel as explanatory factors.

208 Analysis of the performance of the BRDs was only undertaken for the sites where
 209 species were caught in sufficient abundance for adequate statistical power to be achieved. To
 210 test whether the WPUA in the treatment nets differed from the control, intercept only linear
 211 regression models were conducted on the relative WPUA (lnRR) of the following species:
 212 marketable QSC, haddock, whiting, and flatfish species (lemon sole (*Microstomus kitt*), dab
 213 (*Limanda limanda*) and plaice (*Pleuronectes platessa*)). To analyse the influence of the BRDs
 214 collectively on marketable QSC catches compared to the control net, the SMP and SMP+L
 215 treatments were aggregated. In addition, to uncover any variation in selectivity between
 216 treatments, catches in the SMP and SMP+L net were also analysed separately at both sites.
 217 ANOVA were then used to compare the relative WPUA (lnRR) of the two treatments (SMP
 218 and SMP+L), to test whether the effectiveness of the gear significantly differed from one
 219 another.

220 Generalised linear models (GLMs) were implemented to assess whether environmental
 221 parameters influenced the relative WPUA (lnRR) of target and bycatch species in both

222 treatment nets. The models were fitted to subsets of relative WPUA (lnRR) per species so that
223 each treatment (SMP and SMP+L) could be investigated independently. Multi-model inference
224 techniques were used to compile all possible subsets from a global model in order to extract
225 the best set of models that could explain the response in relative WPUA (lnRR) with the
226 explanatory (environmental) variables. Multi-model averaging techniques include the
227 inference of numerous models, reducing the chance of biases in parameter estimations, which
228 may occur when using stepwise multiple regression approaches, which rely on the
229 inappropriate need to select a single best-fit model (Burnham & Anderson, 2002; Whittingham
230 *et al.*, 2006).

231 Initially, global models were fitted as Gaussian distributed (ie. normally distributed)
232 GLMs which incorporated all environmental variables that we assumed may affect the
233 selectivity of certain species, the parameters $\beta_0 - \beta_n$ were estimated and the unexplained
234 variation in the model was represented by ε :

235 i) marketable QSC;

$$236 \quad \text{WPUA} = \beta_0 + \beta_1 * \text{tidal strength} + \beta_2 * \text{depth} + \beta_3 * \text{sea state} + \beta_4 * \text{site} + \varepsilon$$

237 ii) fish species, (haddock, whiting, flatfish);

$$238 \quad \text{WPUA} = \beta_0 + \beta_1 * \text{cloud cover} + \beta_2 * \text{tidal strength} + \beta_3 * \text{ambient light} + \beta_4 * \text{depth} + \\ 239 \quad \beta_5 * \text{turbidity} + \beta_6 * \text{sea state} + \varepsilon.$$

240 All combinations of the explanatory variables were tested and compared, and then
241 ranked by the Akaike information criterion corrected for small sample sizes (AICc) value. The
242 best ranked model, and all models within 2 AICc values, were selected as the best-fit models
243 (Burnham & Anderson, 2002). Each set of models were then averaged, using the R packages

244 “arm” and “MuMIn”. Model suitability was assessed by plotting the model fit on the respective
245 data.

246 All models were inspected for normality of residuals using the Kolmogorov –Smirnov
247 test and a Q-Q plot. Cook’s distance plot was used to check for outliers. Heteroscedasticity was
248 tested using the Levene’s test and scatter plots of the standardized residuals, fitted values and
249 all covariates were assessed.

250

251 RESULTS

252 **Sampling effort and environmental context per site**

253 A total of 116 tows (58 paired) were conducted across the two sites (an overview of the towing
254 criteria is given in Supplementary Table S2). The environmental context differed for each site,
255 the shallow site consisted of depths from 29-40m with the highest ambient light levels,
256 compared to 45-95m in the deep site with the lowest light levels (Supplementary Table 2). The
257 majority of fishing occurred on spring tides, with only two days of neap tides.

258 Overall a total of 9,293 bycatch individuals were caught, including flatfish, rays,
259 gadoids, crustaceans and shark species. Of these, 4,218 (c. 45%) were EU quota species. Across
260 both sites for *all bycatch species* an average of 13.40 (± 8.20 standard deviation) individuals
261 per hectare were caught in the control, compared to 13.37 (± 9.82) in the SMP and 10.10 (± 4.98)
262 in the SMP+L net. In the shallow site for *all bycatch species* recorded an average of 9.86
263 (± 4.21) individuals per hectare were caught in the control, compared to 7.95 (± 3.91) in the
264 SMP and 8.12 (± 2.61) in the SMP+L nets. In contrast in the deep site the control net caught an
265 average of 21.24 (± 9.50) bycatch species, the SMP net caught 24.80 (± 8.62), while the SMP+L
266 net caught 14.75 (± 6.17) individuals. Bycatch species composition (abundance) differed
267 significantly between sites (ANOSIM $P < 0.001$, $R = 0.56$).

268 There was no vessel or observer bias detected between the two fishing vessels in terms
269 of the count (CPUA) of all bycatch species (ANOVA d.f= 54, F= 0.81, P= 0.37) and quota
270 gadoids (haddock *Melanogrammus aeglefinus*, cod *Gadus morhua* and whiting *Merlangius*
271 *merlangus*) caught in both sites (ANOVA d.f=54, F= 0.22, P=0.64). Similarly, there was no
272 difference in biomass (WPUA) of marketable Queen scallop (*Aequipecten opercularis*) caught
273 between vessels in either site (ANOVA d.f =50, F=0.16 P=0.69).

274

275 **Queen scallop**

276 The total catch of Queen Scallop (*Aequipecten opercularis*) throughout the trial was 125 bags
277 weighing ~4375 kg (shallow site: 82, and deep site: 43). No significant change in the relative
278 WPUA of marketable QSC caught in the treatment nets was detected, at both sites compared
279 to the control net (Fig. 3; Shallow site (29-40m): **Estimate**= -0.29, P=0.22; Deep site (45-95m):
280 Estimate=-0.15, P=0.57, Supplementary Tables S3, S4). The relative WPUA of QSC did not
281 differ between the SMP and SMP+L net in either site, indicating there is no difference in the
282 effectiveness of the treatment nets to retain QSC, with neither treatment significantly reducing
283 target catch (ANOVA Shallow site (29-40m): P=0.85; Deep site (45-95m): P=0.89;
284 Supplementary Table S5).

285 There was no effect of variation in the environmental parameters on relative WPUA of
286 QSC caught in the aggregated SMP and SMP+L nets (GLM; Supplementary Table S6.)

287

288 **Bycatch species**

289 Haddock were caught most frequently out of the three quota gadoid species (695 individuals).
290 Whiting were encountered less frequently (172 individuals), with largest catches at the shallow
291 site (25-40m). Flatfish (dab *Limanada limanada*, plaice *Pleuronectes platessa*, lemon sole
292 *Microstomus kitt*; 3018 total) were consistently caught across both sites. Very few cod were

293 caught (53 individuals), which meant no formal analyses could be conducted. However, the
294 data suggests there were no reductions in catch of cod in the shallow site where they were
295 encountered most frequently (Supplementary Table S3).

296 Overall the SMP+L net reduced haddock, whiting and flatfish catches across the
297 majority of size-classes upon inspection of the raw data, with the exception of flatfish in the
298 shallow site, where little change in size frequencies was apparent (Fig. 4). The SMP net
299 incurred varied results, with reductions across most sizes in the shallow site for haddock and
300 whiting. While, haddock catches in the deep site (45-95m) incurred increases across all sizes
301 (Fig. 4). However, no change was observed in size frequencies of flatfish caught by the SMP
302 net at the deep site.

303 At the shallow site (29-40m), whiting catch per hectare was significantly reduced in
304 both the SMP and SMP +L nets by 85% and 75% (both $P=0.01$; Supplementary Tables S3, S4)
305 However, the addition of lights to the panel at these depths had no additional influence on the
306 selectivity of whiting, with no difference in relative WPUA detected between the two treatment
307 nets (ANOVA $P=0.76$; Supplementary Table S5). Haddock catches were also reduced in both
308 treatment nets, although, the average reduction of 0.07 kg per hectare (58.33%) for both the
309 SMP net and SMP+L were non-significant (Supplementary Tables S3, S4; SMP: $P= 0.05$;
310 SMP+L: $P=0.21$). Similarly to whiting, the relative WPUA of haddock caught in the SMP net
311 did not differ to that caught in the SMP+L nets in shallow depths (ANOVA $P=0.47$;
312 Supplementary Table S5). In shallow water there was no change in relative WPUA of flatfish
313 in either of the treatment nets compared to their paired control tows and the selectivity of the
314 treatment nets did not differ (SMP Estimate=-0.03, $P=0.84$; SMP+L Estimate=-0.01, $P=0.98$;
315 ANOVA $P=0.91$ Supplementary Tables S3-S5).

316 While fishing in the deep site (45-95m), the treatment nets produced mixed results.
317 There was no change in WPUA for flatfish in the SMP net relative to the control net (Fig. 3;

318 Estimate= -0.06, P=0.79; Supplementary Tables S3, S4). The SMP net had a non-significant
319 increase (c 42%) in the retention of haddock relative to the standard net in terms of WPUA
320 (Fig. 3; Estimate = 0.47 P= 0.06; Supplementary Tables S3, S4). Conversely, the SMP + L net
321 significantly reduced the WPUA of flatfish by c. 26% (Fig. 3; Estimate = -0.34, P= 0.01) and
322 haddock by c. 47 % (Estimate= -0.94, P=0.004; Supplementary Tables S3, S4). The relative
323 catch of haddock WPUA in the SMP net differed significantly to the SMP+L (ANOVA
324 P<0.001), while there was no difference when comparing the relative WPUA of flatfish
325 between treatments (ANOVA P=0.13; Supplementary Table S5). These results indicate that
326 adding light to the SMP reduced the retention of haddock in deep water.

327 Only depth explained any change in the catch WPUA of haddock, and none of the other
328 species were affected by variation in the environmental variables (GLM Estimate= -1.49,
329 P=0.01; Supplementary Table S6).

330

331 DISCUSSION

332 The weight per unit area of all bycatch species caught in the modified nets was lower compared
333 to the traditional control nets, with no significant losses of the marketable Queen scallop
334 (*Aequipecten opercularis*). Reductions were observed for the numbers of haddock
335 (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*) and flatfish (dab *Limanda*
336 *limanda*, plaice *Pleuronectes platessa*, lemon sole *Microstomus kitt*) retained in the modified
337 nets. However, the results demonstrated that the effectiveness of the BRDs was context
338 specific. For instance, the SMP+L net only reduced haddock and flatfish bycatch in deeper
339 water, which may be related to associated lower levels of ambient light affecting fish
340 swimming behaviour (Ferro *et al.*, 2007). The addition of lights in deep water presumably
341 either guided the haddock towards the SMP or encouraged them to escape through it for another
342 reason (e.g. fright stimulus).

343 Vision is thought to be the primary sense that fish use to detect oncoming nets. When
344 light levels are low, gadoids are incapable of both swimming in an ordered pattern in front of
345 a trawl and locating the gear to avoid collisions, in contrast to behaviour observed at higher
346 light levels (Glass and Wardle 1989). This presumably explains why there was no reduction in
347 the WPUA of haddock caught in deeper water >45m with the SMP treatment (Fig. 3).

348 Low haddock and whiting catches may have reduced the statistical power to detect
349 reductions of haddock catch in the SMP in the shallow site, despite our paired control-treatment
350 design. In addition, the low abundance of fish may have inhibited gadoid escape, as schooling
351 behaviour is induced when lots of fish aggregate in the codend, stimulating an escape response
352 (Broadhurst & Kennelly 1996; Broadhurst *et al.* 2002). The swimming behaviour of cod
353 (*Gadus morhua*) may have inhibited their escapement. Previous studies have found that
354 whereas whiting and haddock rise up in the net and actively locate escape gaps, cod tend to
355 remain low in the net and tend to drift past escape panels located in the upper panel of nets
356 (Krag *et al.* 2009; Herrmann *et al.* 2015).

357 Additional net modifications could help to reduce bycatch further because the
358 escapement of fish (cod, haddock and whiting) increases as the distance between the SMP and
359 the aft of the codend decreases (Broadhurst *et al.*, 2002; Graham *et al.*, 2003; Herrmann *et al.*,
360 2015). Positioning of the SMP was limited in the QSC trawls due to the large SMP relative to
361 net size (~3.5m from aft of the codend; Fig. 2). However, if the SMP was reduced in size and
362 placed as close as possible to the codend without the risk of losing QSC, both water flow and
363 distance from the SMP to the codend would be reduced (Broadhurst *et al.* 2002; Campbell *et al.*
364 *et al.* 2010;). Furthermore, aids such as mechanical guiding devices (ie. float ropes) require
365 further investigation, as they may also help increase escapement of species that remain low in
366 the net ie. cod (Eduardo Grimaldo *et al.*, 2017; Melli *et al.*, 2018)

367 The reductions of fish bycatch did not appear to be size-dependant, which implies that
368 both large and small individuals were capable of escape. Such similar size distributions may
369 arise because the SMP in this study was designed to allow escapement of a range of individual
370 sizes, which here spanned 100-450 mm. Although bycatch size frequencies were not
371 statistically analysed due to low sample sizes of individual tows, other fisheries use SMPs
372 which are size selective (Brčić *et al.*, 2016; Fryer *et al.*, 2016). Therefore, BRDs and artificial
373 lights affect on size selectivity is important to consider in future research. Such studies may be
374 particularly important for fisheries with higher bycatch levels, and where catches must adhere
375 to MLS whilst maintaining commercially-sized individuals.

376 Square mesh has previously shown little change in the selectivity of flatfish (Marlen,
377 2003; Krag *et al.*, 2009). However, this study demonstrated that the addition of LEDs fitted to
378 the SMP has the potential to reduce fish capture of various shapes and sizes, including haddock
379 and unexpectedly, flatfish. When considering avenues for future gear trials incorporating
380 artificial light, expanding our understanding of the behavioural stimulus lights have on marine
381 species is required for future fisheries applications (Melli *et al.*, 2018). It is suggested that
382 LEDs attached to the mouth of the net (to deter species from entering or enable species to detect
383 the approaching net), could potentially reduce the capture of various species, including
384 individuals that are unlikely to escape through the SMP, which has previously been a successful
385 strategy for reducing fish bycatch in ocean shrimp trawls (Hannah *et al.*, 2015; Lomeli, Groth
386 *et al.*, 2018). Using LEDs alone would be a simple, cheap solution, involving minimal
387 alterations to fishing gear. LEDs can be implemented in small and large scale fisheries and are
388 not restricted to certain gear types, and could prove beneficial in reducing multi-taxa bycatch
389 in fisheries operating at night or in dark waters (Hannah *et al.*, 2015; Ortiz *et al.*, 2016; Mangel
390 *et al.*, 2018). A video capturing bycatch escapement through the SMP+L net is available to
391 view online (Supplementary video S7).

392 To conclude, for BRDs, one size does not fit all; this study demonstrates the importance
393 of assessing and implementing BRDs on a site-by-site basis within a fishery, as environmental
394 parameters change over small spatial scales, which may influence the ability of the devices to
395 reduce bycatch.

396

397 ACKNOWLEDGEMENTS

398 We are grateful to the skippers and crew of FVs Our Sarah Jane and Two Girls for their
399 assistance on-board the vessels. We especially thank our colleagues Sian Morgan and Claire
400 Lambden for their valuable help at sea, our sponsors at SafetyNetTechnologies Ltd. and the
401 Manx Fish Producer's Organisation for their technical support and insight during the gear trials.

402

403 FUNDING SUPPORT

404 This study was supported by the Manx Fish Producer's Organisation and Department for
405 Environment, Forestry and Agriculture, Isle of Man Government.

406

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544

545

546 FIGURE CAPTIONS

547

548 **Fig. 1** Areas fished within the commercial fishing grounds Targets (shallow) and Chickens
549 (deep), during the gear trials (data sourced from GPS loggers used on board the vessels).
550 Bathymetry data is also shown as Depth (m) (Sourced from EMODnet.EU).

551

552 **Fig. 2** The dimensions of a) the control net, a conventional diamond mesh QSC otter trawl; b)
553 the treatment net, identical to the control, with the addition of a square mesh panel inserted aft
554 of the fishing circle and; c) a schematic of the placement of the 6 LED lights within the SMP.
555 The SMP began 1.8m aft of the centre of the headrope and ends 0.5m from the anterior section
556 of the codend. Note that the IoM QSC net differs to conventional fish or prawn bottom trawls,
557 as the diamond mesh near to the mouth of the net are held open due to the wider spaced meshes
558 (ie. 60 mesh into 3.35m) SM = Square mesh. DM= Diamond mesh. d) The SafetyNet LED
559 light inserted within the SMP.

560

561 **Fig. 3** The relative catch (lnRR of WPUA, kg/ha) of QSC, haddock, whiting and flatfish caught
562 in both treatments (SMP and SMP+L) paired tows per site. The horizontal line (0), represents
563 equal catches by weight per unit area between control and treatment nets (ie. no effect). The
564 median WPUA (lnRR) is indicated by the horizontal line on the boxplot and error bars indicate
565 the 1.5 times inter-quartile range, the dots represent outliers.

566

567 **Fig. 4** Length frequency of catch distributions of haddock, whiting and flatfish plotted per site
568 for both treatments, SMP (left) and SMP+L (right). The blue solid line represents the control
569 net, the green dashed line the SMP and the yellow dashed line the SMP+L net.

570

571