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Brief Report

Fear of the Light? A Pilot Observational Study of Group Behavioural Responses of Atlantic Salmon (*Salmo salar*) in Commercial Sea Cages to Surface Lights and Human Activity at Night

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Abstract

Artificial lights can be used in sea-caged aquaculture with specific purposes such as to prevent sexual maturation and to manipulate swimming depth for optimisation of parasite control. Previous studies have mostly investigated how continuous underwater lights can influence physiology and behaviour of fish, but little is known about group-level behavioural responses of caged salmon to sudden surface lights related to farm operations such as boat lights and headlamps. Here, we present our observations of behavioural responses of sea-caged Atlantic salmon to sudden light stimuli from boat lights and headlamps in two observational pilot studies. The spatial distribution of post-smolts was monitored by single-beam and multi-beam sonars. In Case-study A, the fish distribution shifted away from the upper water layers after a headlamp was turned on from the cage walkway and subjectively observed jumping behaviour ceased. In Case-study B, boat lights alone were associated with a downward shift in fish distribution, while the most pronounced changes occurred when researchers carrying lights walked along the walkway. Fish initially distributed in the upper 0–5 m rapidly shifted their distribution downwards to a maximum depth of approximately 14 m. The observed changes happened across large parts of the cages and were consistent with avoidance behaviour. Overall, our observational pilot studies suggest that caged salmon can exhibit pronounced group-level behavioural responses to sudden surface lights and human activity at night.

Keywords: hydroacoustics; swimming; sea-caged aquaculture; sonars

Key Contribution: This observational study documents group-level changes in fish distribution and activity following surface light stimuli and researcher activity. The changes were consistent with avoidance behaviour, and point towards the necessity to further investigate the potential influence of operation-related lights on fish behaviour and welfare.

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1. Introduction

In finfish aquaculture, light conditions can affect the behaviour and welfare of reared fish. For Atlantic salmon (*Salmo salar*) reared in sea cages, behaviour such as swimming depth can be affected by natural sunlight [1–3] and artificial underwater lights [2,4–7].

Artificial lights are used for purposes such as stimulating smoltification [8], inhibiting sexual maturation [9], inducing sustained exercise [10], and manipulating swimming depth to optimise parasite treatment [11]. Thus, artificial lights can be used to improve growth and fish welfare, but they can also affect salmon negatively. Sudden changes in light conditions can invoke stress-related behaviour in salmonids [4] and underwater lights can cause group flight responses in farmed salmon [12]. Existing studies mainly focused on continuous underwater artificial lights, and there is little knowledge about the group-level behavioural responses of caged salmon to sudden artificial surface lights, such as lights from boats and workers during operations at night. Although night operations at fish farms are generally less frequent than those during day, many still take place in darkness, especially during winter at high latitude locations where salmon aquaculture is common. Thus, there is a need to investigate how farmed salmon respond to surface lights used in darkness. Here, we present observations of the behavioural responses of cage-farmed Atlantic salmon post-smolts of different body sizes during sudden surface light stimuli in darkness. We focused solely on the observation of fish behaviour, which is among the important indicators of fish welfare in aquaculture [13]. Specifically, we describe the changes in swimming depth which were monitored by multi-beam and single-beam sonars, and changes in swimming activity of the salmon in commercial cages. Observations were made during studies focused on other aspects of salmon group behaviour and based on a limited sample size. This is to our knowledge the first pilot observational study that documents farmed salmon's behavioural changes associated with surface lights at night, which is highly relevant for commercial aquaculture and needs proper investigation. In future studies, it is desirable to include the quantification of stress experienced by fish, for instance by integrating the use of bio-loggers, to understand if observed behavioural changes have any implications for fish welfare.

2. Materials and Methods

One part of the data presented in this study, hereafter referred to as Case-study A, originated from an accidental observation made during the study by Banno et al. [14], which focused on developing monitoring methods for large commercial sea cages. Detailed information about the study site, sonar data collection, data processing, and visualisation methods is provided by [14]. The remaining part, henceforth referred to as Case-study B, was collected in an effort to investigate whether similar observations would be made during the study by Ikegami [15], which focused on the growth and behaviour of farmed fish. Since the latter publication is in Japanese, we provide more details on the methodology of Case-study B below.

2.1. Study Site

Both case studies were conducted at the salmon aquaculture research and farming site Gudmundset (62.353 N, 6.601 E) located at the west coast of Norway. The sea cages consisted of cylindrical nets up to 15 m in depth, with conical nets attached to their lower edge. The cages were 39.2 m in diameter, 27 m in total depth, and 18,850 m^3 in volume. For Case-study A, the data were collected on 19th November 2022 in a cage which contained approximately 130,000 Atlantic salmon with an average weight of 2.2 kg, corresponding to a fish density of ca. 15 kg/m^3. For Case-study B, the data was collected on 23rd September 2025 in a cage which contained approximately 60,000 Atlantic salmon with an average weight of 3.6 kg, corresponding to a fish density of ca. 11 kg/m^3.

2.2. Environmental Data

During Case-study A, water temperature, oxygen saturation, salinity, water current speed and direction, cage deformation, and ambient light were monitored as described

in [14]. During Case-study B, water temperature, oxygen saturation, and salinity were monitored by wireless sensors (aquaMeasure, Innovasea, Boston, MA, USA) every 10 min. Two oxygen sensors were positioned at 3 m and 10 m depth ca. 75 m away from the sea cage and one salinity sensor was positioned at 9 m depth inside the cage. All three sensors measured water temperature as well. Water current speed between 3 m and 31 m depths were monitored by a Doppler current profiler (Seaguard II, Aanderaa Data Instruments AS, Bergen, Norway) positioned approximately 100 m away from the cage, which logged the data at 20 min intervals. Ambient light was monitored by light loggers (HOBO Pendant MX 2202, Onset Computer Corporation, Bourne, MA, USA) placed facing upwards underwater at 2 m depth, ca. 1 m from the inside cage wall, and in air at the handrail of the cage.

2.3. Salmon Distribution and Behaviour

In Case-study A, the spatial distribution of salmon in the cage was monitored by a multi-beam sonar WASSP (F3 model, Electronic Navigation Ltd., A Furuno company, Auckland, New Zealand). "Snapshots" of salmon distribution (i.e., distribution of salmon in the whole cage at a time) were captured by manually triggering an automatic rotation of the sonar transducer placed near the side wall of the cage [14]. Eight snapshots of salmon distribution pattern were obtained between 03:04 and 03:10. The first four snapshots were obtained under natural night conditions with a few second intervals between each snapshot. After obtaining the fourth snapshot, there was a 2 min operational pause. A researcher standing on the walkway of the cage near the transducer's location then turned on a headlamp (Petzl MYO XP, Petzl, Crolles, France) directed parallel to the water surface, but its wide beam also illuminated part of the water surface. The fifth snapshot was obtained immediately after the headlamp was turned on, and the remaining snapshots were obtained consecutively with only a few seconds' pause between each. The researcher did not move during the collection of the snapshots.

In Case-study B, the spatial distribution of salmon was monitored by two single-beam sonars (FFS-600, Furuno Electric, Co., Ltd., Nishinomiya, Japan) ca. 12 m apart, which were fixed inside the cage at 0.5 m depth at ca. 7 m away from the cage wall. The sonars had a beaming angle of 10° and beamed straight downwards. In addition, a multi-beam sonar (FCS-500, Furuno Electric Co., Ltd., Japan) with a beam opening angle of 120° was installed just below the water surface with 30° tilt, in the centre of the cage and oriented towards one side net. The spatial distribution of salmon was first monitored continuously under natural night conditions. Then, the cabin and deck lights of a small boat (Ardea 820 Combi) moored to the sea cage were turned on at 22:11. Since a behavioural response similar to the one in Case-study A was not apparent after the boat lights were turned on, we conducted multiple trials in which handheld lights were turned on and researchers moved along the cage. When switched on, the lights were directed parallel to the water surface, but as the researchers moved along the cage, the lights were generally directed towards the walkway. Each trial was followed by several min of natural darkness (Table 1). The trials represented repeated observations within the same fish population and should not be considered independent replicates. In both case-studies, subjective visual and auditory observations of the salmon's jumping behaviour were made. Due to the moonlight, it was possible to observe the behaviour of salmon at the water surface even without any artificial light in Case-study A. In Case-study B, surface activity was assessed from audible jumping.

Table 1. An overview of the light trials in Case-study B.

Time (Light Trial ID)	Type of Event	Peak Light Intensity (lux) [1]
22:11–22:16 (L1)	Boat cabin and deck lights on. No researcher movement.	1.9
22:23–22:25 (L2)	A researcher with a headlamp walks around the cage.	9.1
22:40–22:43 (L3)	Two researchers with headlamps and a handheld light walk around the cage.	88.9
22:58–23:01 (L4)	Same as above.	20.4
23:15–23:17 (L5)	Same as above but with one more handheld light.	21.6
23:25–23:32 (L6)	Boat cabin and deck lights on, and the researchers leave the cage with a small outboard boat.	1.9

[1] measured by a light logger placed on the handrail of the cage. Darkness = 0 lux. The angle and distance of the logger relative to lights were not constant within and among the trials. Therefore, the measured light intensity was to some extent influenced by the changing distance and angles relative to the lights.

2.4. Data Processing and Visualisation

In Case-study A, post-processing of the multi-beam sonar data was done as outlined in [14] in Echoview v.13.0.392 (Echoview Software Pty Ltd., Hobart, Australia), and the numerical data of the detected targets within the scanned area was exported to R v.4.3.0 [16] for visualisation. Depth distribution of the detected targets was plotted as histograms for each snapshot. In Case-study B, vertical profiles of volume backscattering strength (Sv) were derived from single-beam sonar measurements at depths ranging from 0.5 to 15 m. Sv represents the intensity of acoustic energy backscattered by fish within a given sampling volume and is expressed in decibels (dB). The Sv data were aggregated at 1-min intervals and visualised as a depth–time heatmap to illustrate temporal variations in fish distribution across the water column. Supplementary, the echogram derived from the multi-beam sonar showing the real-time movement of fish within the 120° beaming angle was saved as a video and assessed visually to check the influence of the light trials on fish behaviour.

3. Results

3.1. Case-Study A

The environmental conditions were stable during data collection, with weak water current (0–10 cm/s), little cage deformation (net lifting below 1 m), high oxygen level (above 90%), and little fluctuations in the vertical profiles of water temperature (10–12 °C) and salinity (30–33) (see more details in [14]). It was estimated that more than 80% of the cage volume was scanned by the sonar, while the calculation of the precise volume of the scanned cage area was impossible due to the influence of cage deformation which could not be measured accurately. After sudden light stimuli from the headlamp, the vertical distribution of salmon changed. In the four snapshots obtained during natural night conditions, 40%, 38%, 40%, and 35% of the detected targets were distributed above 4 m depth (Figure 1, first row). When the headlamp was on, 19%, 23%, 30%, and 30% of the detected targets were distributed above 4 m depth (Figure 1, second row). The underlying data for Figure 1 is shown in Table S1. Based on subjective visual and auditory observations, salmon showed jumping behaviour at the water surface under natural night conditions,

but these activities were no longer observed when the headlamp was turned on. When the light was turned on, the researcher standing on the walkway felt vibrations which were interpreted as being caused by salmon swimming into the cage wall.

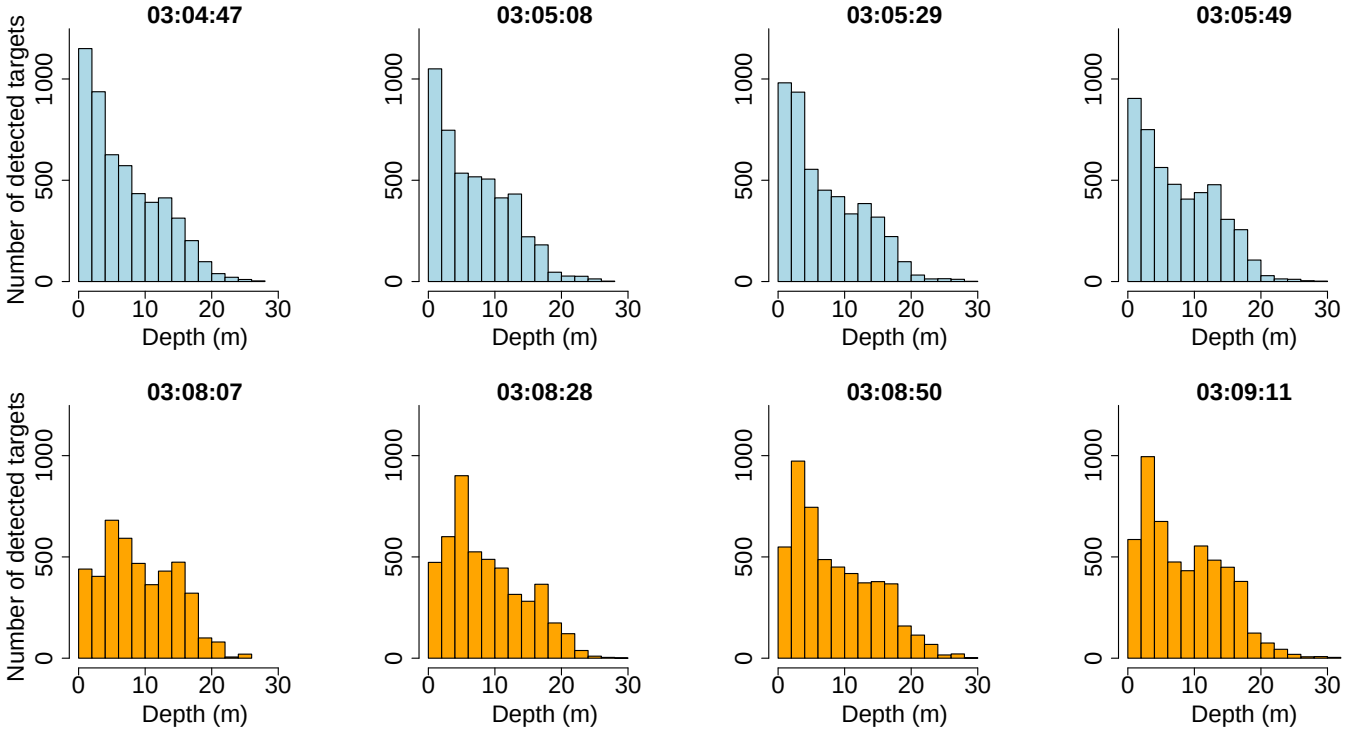


Figure 1. Depth distribution of the detected targets in the sea cage of Case-study A under natural night conditions (above four figures in blue) and when the headlamp was on (below four figures in orange). The interval for the bars in the histograms is 2 m.

3.2. Case-Study B

The environmental conditions during Case-study B were stable with weak water current (0–10 cm/s), little fluctuation in water temperature (12.6–12.9 °C), salinity (22.6–27.0), and dissolved oxygen (103–105%) measured between 22:00 and 23:30. The light logger underwater did not record the light stimuli (0 lux). The logger at the handrail recorded up to 88.9 lux when the headlamps were on. After sudden light stimuli and activity from the researchers, the depth distribution of fish changed. In darkness, fish were mainly distributed near the water surface between 0 and 5 m depth. During light trials, the fish distribution rapidly shifted towards deeper depths, reaching a maximum of approximately 14 m. The two single-beam sonars captured similar profiles of the volume backscattering strength (Figure 2). The most pronounced response was observed when the two researchers with the headlamps walked along the walkway of the cage. There were ca. 1–3 min gaps between the time these people started walking with the headlamps, and the time when the most pronounced reaction of salmon moving deeper was observed in the Sv echogram (Figure 2). The echogram from the multi-beam sonar showed changes in fish distribution during all of the light trials (Figure S1, Video S1). Based on subjective visual and auditory observations, no apparent changes in jumping behaviour were noticed when the lights were turned on, although changes in fish distribution were recorded by the sonars. A decrease in surface activities was noticeable after the researchers started walking along the walkway, but no vibrations similar to those in Case-study A were noticed.

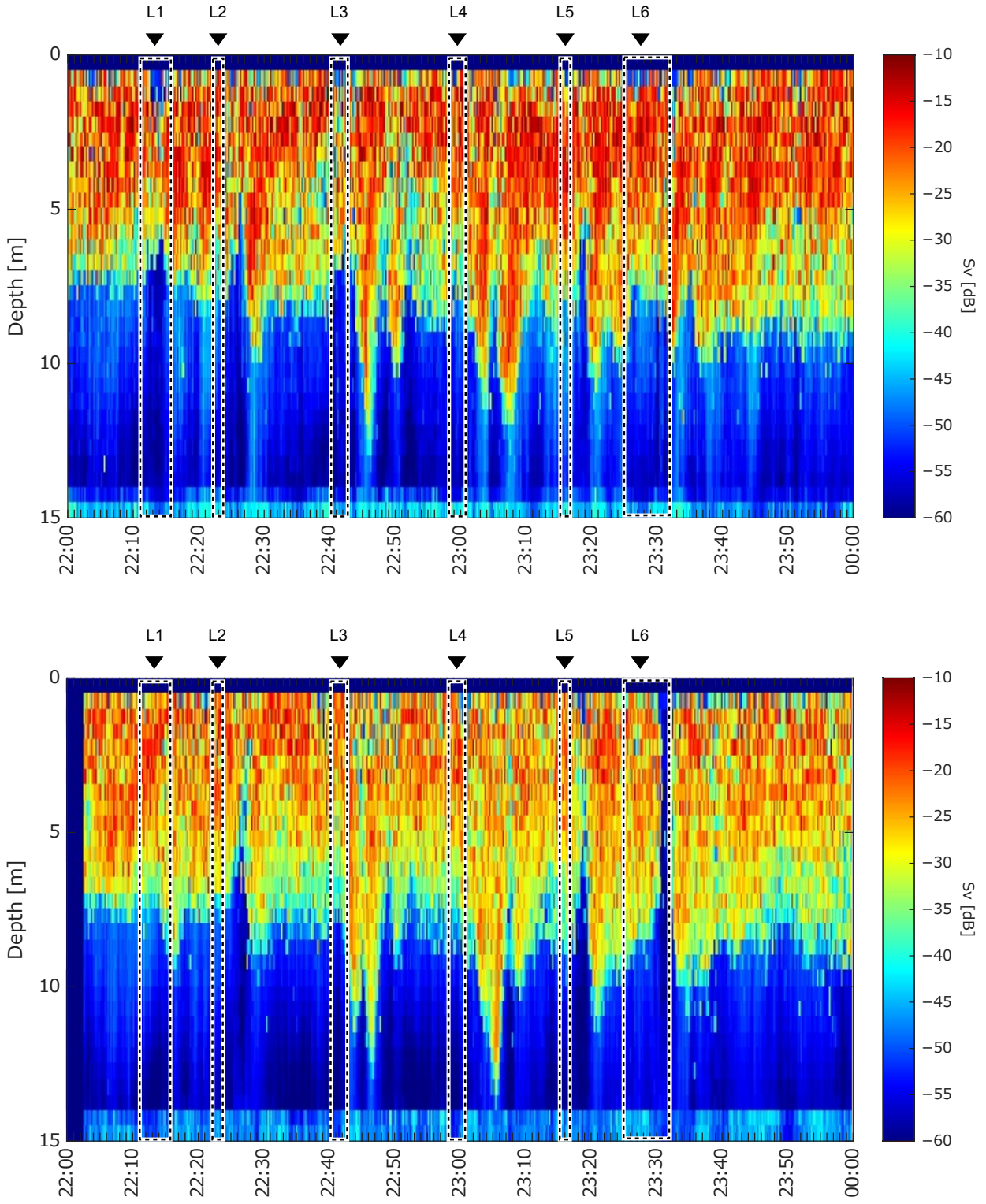


Figure 2. Depth profile of the volume backscattering strength (Sv) measured in decibel (dB) by the two single-beam sonars during Case-study B. Higher Sv values (towards red colour) indicates higher fish density. White and black dotted boxes indicate the six light trials outlined in Table 1.

4. Discussion

In Case-study A, group-level shifts towards deeper swimming depths and changes in swimming depth and activity occurred immediately after the headlamp was turned on and were consistent with avoidance behaviour following exposure to the surface light.

In Case-study B, a similar behavioural pattern was observed, although the independent effects of surface lights and human movement on the walkway could not be distinguished in most trials. However, turning on the boat lights without researcher movement in trial L1 was followed by a change in fish distribution observed by the sonars, suggesting that light alone might have influenced fish behaviour. This is to our knowledge the first study which documents changes in the group behaviour of farmed Atlantic salmon post-smolts, associated with relatively weak surface light stimuli at night. However, given the observational nature of our study, these finding should be considered preliminary until confirmed through controlled experiments.

Salmon can show avoidance behaviour induced by turning-on of underwater lights [12], and even the weak light stimuli from our headlamps or boat lights were followed by apparently similar changes in swimming activity and vertical distribution. In both case studies the behavioural changes extended across large portions of the cages, rather than being restricted to only the fish near the light source. One possible explanation is that some fish behaving irregularly could change the behaviour of fish around them, leading to behavioural changes in the large fish group [17]. The small time lags between the time when the lights were turned on, and the time when the single-beam sonars recorded the changes in the salmon's vertical distribution, may indicate that the light stimuli first changed the behaviour of fish directly near the lights and then gradually influenced fish in the surroundings.

Subjective observations made from the walkway of the cages, particularly the vibrations interpreted as salmon swimming into the cage wall in Case-study A, suggest that the behavioural response was more pronounced in Case-study A than in Case-study B. However, the extent of the vertical distribution changes could not be quantitatively compared due to the difference in monitoring equipment and set-up. Similarly, the reason for the more pronounced response in Case-study A can only be speculated upon. For instance, smaller Atlantic salmon are more responsive to stimuli [18] and mature salmon generally show reduced primary stress responses compared to immature individuals [19]. The fish of Case-study A were smaller, but the maturation status was unknown in both case studies. Differences in stocking densities and environmental conditions between the case-studies were relatively small, although their possible influence on the behavioural responses cannot be ruled out. For instance, even small differences may influence salmon behaviour, as temperatures around 10 °C can trigger juvenile salmon to become more nocturnal [20]. Likewise, differences in season, time of night and ambient light conditions might have influenced the observed behavioural patterns. Given the preliminary nature of our observations, the possible sources of variation discussed above should be investigated in future studies.

Salmonid fish can show behavioural response to lights as weak as 0.005 lux [21], which is considerably lower than the minimum measurable strength of the light loggers (which was 0.2 lux, based on our study). Lux is a unit based on the human visual perception of light. Our observations emphasised the need for a standardised metrology for the characterisation of the light perceived by fish, which was also suggested by Noble et al. [22]. As responses may depend on the characteristics of the light source [7], future research should adopt the use of a spectroradiometer to characterise the spectral composition and spectral irradiance of the light above and below the water surface.

This study was based on spontaneous observations, therefore it did not include independent replicates or controls to statistically analyse the behavioural response of salmon, nor could natural variation in fish distribution be separated from responses associated with the light trials. Also, in Case-study B, the respective influences of light and researchers movement on the walkway could not be disentangled due to the absence of control trials. Although the results from Case-study A show that fish spatial distribution changed fol-

lowing the turning-on of surface lights without movement of the researcher, it remains unclear whether the surface lights or the researchers' movement in Case-study B have more relative influence.

The main contribution of this pilot study is the first documentation of fish group-level behaviour changes consistent with avoidance and associated with weak surface lights under commercial sea-cage conditions. The sonars revealed changes in fish distribution in large parts of the cages, while their extent was not apparent to the researchers on the walkway. Our findings show the need to gather more data in well-designed experiments to understand how operation-related lights might influence the behaviour and welfare of farmed salmon. Specifically, we should conduct controlled experiments with standardised light conditions, defined treatments and controls and adequate replication, allowing the behavioural responses to be analysed quantitatively and statistically. Such experiments will allow us to investigate the conditions under which salmon show behavioural responses consistent with avoidance of surface lights and whether these behavioural changes are associated with physiological stress or have any implications for fish welfare. In salmon, behavioural responses to artificial light are not necessarily associated with increased stress levels [23]. Physiological stress responses and their potential welfare implications could therefore be assessed at the individual level by bio-loggers [24–27]. Most importantly, in future studies about fish behaviour, researchers should account for the fact that even a weak light stimulus or human movement on the cage might influence the group behaviour of fish, which potentially can interfere with the responses under investigation.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/fishes11110670/s1, Table S1: Underlying data for Figure 1, including the number and percentage distribution of detected targets by depth in each scan. Figure S1: Description of the video echogram in Video S1. Video S1: Video echogram showing the changes in fish movement during the light trials.

Author Contributions: K.B., A.I. and C.S. contributed to conceptualisation, methodology, software, validation, formal analysis, investigation, resources, data curation, visualisation, and project administration. The original draft of the manuscript was written by K.B., A.I. and C.S. reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: This study does not require approval from the Ethics Committee or Institutional Review Board since this study only involved the deployment of sonars and the use of standard lights (headlamps and boat lights), which are part of routine management procedures at fish farms. The fish farm where the study was conducted produces Atlantic salmon according to Norwegian legislation, i.e., according to the Animal Welfare Act (LOV-2009-06-19-97).

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting the findings of this study are available within the paper and as Supplementary Materials, while additional details may be provided from the corresponding author upon reasonable request.

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