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Makoto Tomiyasu
Faculty of Fisheries Science, Hokkaido University, 3–1–1 Minato-cho, Hakodate, Hokkaido, 041–8611, JAPAN, tomiyasu@fish.hokudai.ac.jp

Yoko Tanouchi
Graduate School of Fisheries Science, Hokkaido University, 3–1–1 Minato-cho, Hakodate, Hokkaido, 041–8611, JAPAN

Yasuzumi Fujimori
Faculty of Fisheries Science, Hokkaido University, 3–1–1 Minato-cho, Hakodate, Hokkaido, 041–8611, JAPAN

Minato Kaji
Graduate School of Fisheries Science, Hokkaido University, 3–1–1 Minato-cho, Hakodate, Hokkaido, 041–8611, JAPAN

Takuma Hayashi
Graduate School of Fisheries Science, Hokkaido University, 3–1–1 Minato-cho, Hakodate, Hokkaido, 041–8611, JAPAN

See next page for additional authors

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In situ observations of fish attraction to light-emitting diodes on an undersea observation deck

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Authors

Makoto Tomiyasu, Yoko Tanouchi, Yasuzumi Fujimori, Minato Kaji, Takuma Hayashi, Naoto Matsubara, Hiroki Yasuma, Susumu Shimizu, and Seiji Katakura

RESEARCH ARTICLE

In Situ Observations of Fish Attraction to Light-Emitting Diodes on an Undersea Observation Deck

Makoto Tomiyasu [a,*], Yoko Tanouchi [b], Yasuzumi Fujimori [a], Minato Kaji [b], Takuma Hayashi [b], Naoto Matsubara [c], Hiroki Yasuma [a], Susumu Shimizu [a], Seiji Katakura [a,d]

[a] Faculty of Fisheries Science, Hokkaido University, 3−1−1 Minato-cho, Hakodate, Hokkaido, 041−8611, Japan
[b] Graduate School of Fisheries Science, Hokkaido University, 3−1−1 Minato-cho, Hakodate, Hokkaido, 041−8611, Japan
[c] Fisheries Resources Institute, Japan Fisheries Research and Education Agency, 2−12−4 Fukuura, Kanazawa, Yokohama, Kanagawa, 236−8648, Japan
[d] City of Mombetsu, 1 Kaiyo-koen, Mombetsu, Hokkaido, 094−0031, Japan

Abstract

Many fisheries employ fishing lights to manipulate the behaviors of target fish and to attract them toward the light; however, relatively few long-time observations of fish attraction have been performed in the field. Here, an underwater observation deck was used to examine the differences in the fish-attracting effect of light-emitting diode (LED) lights on the number of attracted fish and on their behavior in the field, using white-edged rockfish as the target species. A total of 604 ± 324, 307 ± 203 and 171 ± 106 white-edged rockfish individuals were attracted to the observation window when it was illuminated with blue, green, and red light, respectively. Under the blue light, fish remained for 133.6 ± 129.8 s around the window, while under the for green and red light, they stayed for 72.5 ± 76.7 s and 45.7 ± 52.2 s, respectively. The longer time spent under the blue light may have result in an increase in the number of fish counted, and this would be related both to the transparency of this wavelength underwater and to the visual sensitivity of white-edged rockfish. Other light environments produced by the blue LED may have been suitable for this species, both in terms of preferred light intensity and optimal feeding environment. The results presented in this study contribute to a better understanding of the ecology of white-edged rockfish and suggest a selective and efficient use of this species in fisheries.

Keywords: Undersea observation deck, Light-emitting diode, Fish attraction, Behavioral response

1. Introduction

In the history of fisheries, light has played a very important role as a tool for attracting fish and obtaining higher catches [1,2]. As many fisheries employ fishing lights to manipulate the behaviors of target species and to attract them, it is essential to understand these behaviors in response to light stimuli [3,4]. It is well known that fish exhibit preferences for, and visual sensitivities to, specific light wavelengths and that they respond differently to different light stimuli [5]. Thus, a considerable amount of research has focused on whether fish are attracted to specific light wavelengths or whether they avoid them. In fact, it is hoped that a deeper understanding of these differences will contribute to the achievement of more efficient fishing practices and to the avoidance of bycatch [6−9].

Most of the studies conducted on the responses of fish to light stimuli to date have been performed in the laboratory, where environmental variables can be controlled [10,11]. However, in situ experiments are

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* Corresponding author.
E-mail address: tomiyasu@fish.hokudai.ac.jp (M. Tomiyasu).

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better suited to verify phenomena of interest in the field because the fish are exposed to the same environmental factors as those present in the fishing grounds. Previous studies have used waterproof cameras, stereo camera systems, and remotely operated vehicles to count the number of fish and determine their location [12–14]. Furthermore, as light-emitting diodes (LEDs) have a small size, it was possible to attach them to fishing gear, which consequently allowed a greater access to outdoor environments. However, the length and scale of fish observations depend on various factors, such as the movement range, the battery life of underwater camera systems, and the research vessel's operating schedule. Therefore, it is necessary to establish an experimental system to reliably evaluate the response behavior toward specific light wavelengths in the field.

Here, the undersea observation deck of the Okhotsk Tower marine observation center, located in Mombetsu (Hokkaido, Japan), was used to count the number of fish attracted by different LEDs and to observe whether there were any corresponding differences in fish behavior, such as time spent at the window, swimming distance, and swimming speed. The analysis mainly focused on the white-edged rockfish *Sebastes taczanowskii*, which is widely distributed along the coastal area of Hokkaido, including the area around Okhotsk Tower [15]. As this species is dominant in shallow coastal waters, it was possible to evaluate its response to artificial stimuli for a large number of individuals. Within the fishery, this species is targeted by gill nets, set nets, and recreational fishing [16]. This study contributes to a better understanding of the response of white-edged rockfish to light stimuli, and it discusses their selective and efficient use in fisheries, as well as the potential of the in situ experimental system for the evaluation of differences in fish attraction and fish behavior.

2. Materials and methods

2.1. Experimental setup

The experiment was conducted on the undersea observation deck of Okhotsk Tower (Fig. 1). The water depth around the tower is approximately 10 m, and an acrylic window (1.00 m × 1.00 m × 0.09 m) is here installed to permit observations of the seafloor and undersea environment to depths of 6–7 m. The interior of the tower is illuminated during the daytime, but all lights are turned off at night. LED lights were installed at the bottom of the observation window to irradiate the window surface and attract fish at night. During the experiment, the number of attracted fish and their behavior were observed through the observation windows using a video camera (HC-VX985M, Panasonic Inc., Osaka, Japan) (Fig. 2). Underwater turbidity, which affects light transmission, was measured by a CTD logger (ASTD102 RINKO-Profiler, JFE Advantech Inc., Hyogo, Japan) once a day at 9:00 and was representative of the day.

The LED lights (Dotz Par, ADJ Products Inc., CA) used in this study had a beam angle of 60°, and their color could be set to 256 levels (from 0 to 255) for each blue, green, and red LED element. For these colors, the peak wavelengths were 460, 514, and 632 nm, respectively, and the spectral distribution was examined using a spectroradiometer (CL500A, Konica Minolta Inc. Tokyo, Japan) (Fig. 3). The light of each color was unified to the same illumination level, 7.6 lx, corresponding to a distance of 1 m from the light source. The experiment was conducted from July 31 to August 6 in 2019 around the new moon so that the effect of the lunar cycle would not be significant from day to day. It started at 19:30 and ended at 4:00 the next morning. To test differences in fish attraction from day to day, the light color was changed after 1 h of illumination with 30-min intervals which the lights were off between each color (Table 1). The 1-day experiment consisted of six trials, with the experimental time zone defined as the time of each trial.

2.2. Analysis

The number of white-edged rockfish attracted to each color was counted using the video recordings, and the relative effects of each color were compared. White-edged rockfish individuals and those belonging to the related species known as the three-stripe rockfish (*Sebastes trivittatus*) and black rockfish (*Sebastes schlegelii*), which inhabit the same area, were discriminated based on morphological characteristics. Using numerical analysis software (MATLAB, MathWorks Inc., MA), snapshots were extracted from the video recordings of the observation window at 1-m intervals, and the number of white-edged rockfish that could be clearly observed from the tip of the head to the tail fin was manually counted. As it was not possible to identify the same individual in the minute-by-minute snapshots, double counts were included and treated as the number of attracted fish.

The relationships between the number of attracted fish and experimental setup were investigated using a generalized linear model (GLM). The response variable was the total number of attracted

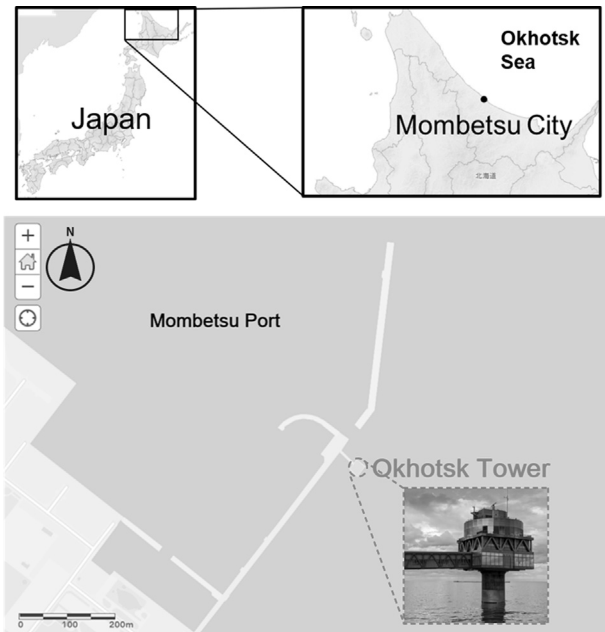

Fig. 1. Map of the Okhotsk tower.

fish per hour and the explanatory variables were the peak wavelength of LEDs (ω_C [nm]), water turbidity (ω_{Tur} [mg/l]), and experimental time zone (ω_{Time}). Given that data overdispersion was expected, the following model with negative binominal distribution was selected to estimate the probability distribution of errors:

$$\log(y) = a_0 + a_C\omega_C + a_{Tur}\omega_{Tur} + a_{Time}\omega_{Time} \quad (1)$$

where a_C, a_{Tur} and a_{Time} indicate the coefficient of each variable, and a_0 indicates the intercept. The

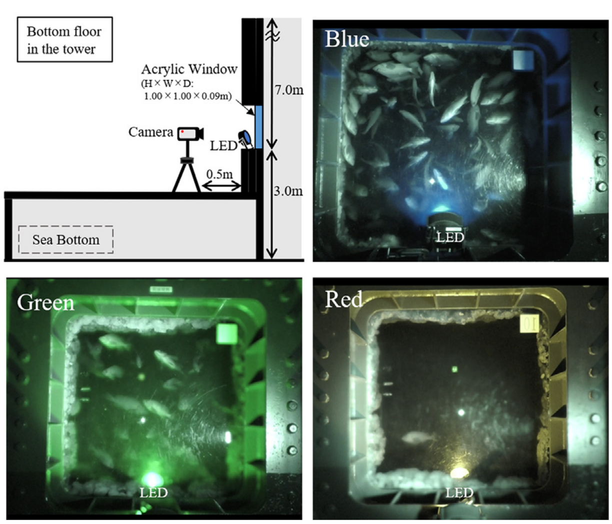

Fig. 2. Illustration depicting the observation system and snapshots of the fish aggregating in response to illumination with LED lights of different colors.

experimental time zone was used as a dummy variable because it is a factor data type. For optimal model selection, Akaike's information criterion (AIC) was used to compare all models. When the number of parameters estimated by maximum likelihood is k, the AIC of the model is expressed as follows

$$\mathrm{AIC} = -2\ln L + 2k \quad (2)$$

where L indicates the likelihood. The AIC of each model was compared by increasing the number of explanatory variables from the null model, and the model with the smallest AIC was selected as the optimal one. The MASS package in R (version 3.6.3) was used for statistical analysis.

Fish movement was tracked using the video analysis software Kinovea (version. 0.8.26, www.kinovea.org). A target white-edged rockfish individual was selected in the video and was tracked from the time it appeared at the window until it left the frame. The fish were tracked every 30 min from the beginning of the experiment; specifically, 2 individuals per trial and 24 fish per light color were tracked in all 36 trials. The video frame rate during tracking was approximately 60 fps and the resolution was approximately 6.7×10^{-2} cm. The time spent (s) at the window, the horizontal and vertical coordinates of the fish, and the total swimming distance (cm) and swimming speed (cm/s) were measured based on the swimming trajectories of fish.

3. Results

3.1. Number of attracted fish

The fish species that was most attracted to the lights was white-edged rockfish. Other species included the three-stripe rockfish *S. trivittatus*, the

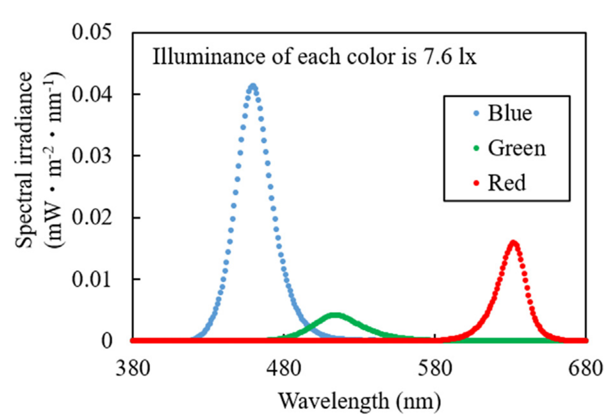

Fig. 3. Spectral distribution of the LED lights. The peak wavelengths were 460, 514, and 632, for blue, green, and red light, respectively.

Table 1. Experimental conditions separated by time zone and total number of attracted white-edged rockfish to each light color: R, red; G, green; and B, blue. TZ indicates the time zone for single trials.

	19:30–20:30 (TZ1)	21:00–22:00 (TZ2)	22:30–23:30 (TZ3)	0:00–1:00 (TZ4)	1:30–2:30 (TZ5)	3:00–4:00 (TZ6)
31 Jul	R 51	G 220	B 752	R 134	G 815	B 1359
1 Aug	G 205	B 255	R 148	G 307	B 631	R 201
2 Aug	B 283	R 223	G 119	B 254	R 239	G 286
3 Aug	R 34	G 99	B 416	R 81	G 365	B 977
5 Aug	G 439	B 529	R 233	G 208	B 541	R 75
6 Aug	B 741	R 408	G 498	B 510	R 232	G 131

surfsmelt *Hypomesus japonicus*, and greenling species belonging to the *Hexagrammidae* family; however, these appeared in extremely lower numbers compared to white-edged rockfish.

For this species, 604 ± 324 (average ± SD), 307 ± 203, and 171 ± 106 individuals/hour were attracted under blue, green, and red light conditions, respectively, in each time zone (Table 1, Fig. 2). Fish numbers were ordered as blue > green > red (Steel–Dwass test: $t = 14.71$, $p < 0.01$, $t = 22.55$, $p < 0.01$, $t = 9.91$, $p < 0.01$ for the blue-green, blue-red, and green-red light pairs, respectively).

The model with the smallest AIC was defined as Model 5 as follows:

$$\log(y) = -0.007\omega_c + 9.511 \tag{3}$$

where ω_C indicates the peak LED wavelength (Table 2), as the peak wavelength is significant at the 1% significance level and the coefficient is negative. The experimental time zone and turbidity, which

Table 2. Estimated parameters for the number of attracted fish for the selected models through GLM analysis.

	Parameters								DF	Model Deviance	AIC
	b_C	b_{Tur}	b_{Time2}	b_{Time3}	b_{Time4}	b_{Time5}	b_{Time6}	ε			
Model 1(C + Tur + Time)									28	37.64	480.33
Estimate	−0.00729	−0.1305	0.4193	0.4099	0.0146	0.7172	0.5719	9.37017			
SE	0.001239	0.3178	0.3073	0.3073	0.3077	0.307	0.3071	0.729421			
Z value	−5.888	−0.411	1.365	1.334	0.047	2.336	1.862	12.846			
p value	3.90E-09 ***	0.6814	0.1724	0.1822	0.9623	0.0195 *	0.0626 .	<2.0E-16 ***			
Model 2(C + Tur)									33	38.02	478.00
Estimate	−0.00698	0.0406						9.474264			
SE	0.001363	0.3499						0.772525			
Z value	−5.119	0.116						12.264			
p value	3.07E-07 ***	0.908						<2.0E-16 ***			
Model 3(C + Time)									29	37.65	478.50
Estimate	−0.00728		0.4117	0.3981	−0.0027	0.6921	0.5393	9.290042			
SE	0.001241		0.3079	0.3079	0.3083	0.3076	0.3077	0.698452			
Z value	−5.864		1.337	1.293	−0.009	2.25	1.752	13.301			
p value	4.53E-09 ***		0.1811	0.1959	0.9931	0.0245 *	0.0797 .	<2.0E-16 ***			
Model 4(Tur + Time)									29	38.86	501.09
Estimate		−0.0951	−0.0045	0.2298	−0.1508	0.4963	0.5768	5.727432			
SE		0.4212	0.4071	0.4069	0.4072	0.4068	0.4068	0.405074			
Z value		−0.226	−0.011	0.565	−0.37	1.22	1.418	14.139			
p value		0.821	0.991	0.572	0.711	0.223	0.156	<2.0E-16 ***			
Model 5(C)									34	38.02	476.01
Estimate	−0.007							9.511029			
SE	0.001363							0.735691			
Z value	−5.131							12.928			
p value	2.89E-07 ***							<2.0E-16 ***			
Model 6(Tur)									30	38.86	499.14
Estimate		0.1876						5.7606			
SE		0.4447						0.3255			
Z value		0.422						17.697			
p value		0.673						<2.0E-16 ***			
Model 7(Time)									34	39.17	495.65
Estimate			−0.0109	0.2115	−0.1599	0.4765	0.5469	5.6773			
SE			0.4073	0.4072	0.4074	0.407	0.407	0.288			
Z value			−0.027	0.52	−0.392	1.171	1.344	19.712			
p value			0.979	0.603	0.695	0.242	0.179	<2.0E-16 ***			

Signif. codes: 0‘***’ 0.001‘**’ 0.01‘*’ 0.05‘.’ 0.1‘ ’ 1.

fluctuated from 0.32 to 1.09 mg/l in the experimental period, were not selected as explanatory variables.

When considering the relationship with the elapsed time, the number of attracted fish per minute to both the blue and green lights was low level within red light until experiment up to 11 and 14 min after the start, respectively (Fig. 4). In particular, in the trial conducted in the 0:00–1:00 time zone, the low levels lasted longer for both lights. After this phase of low attraction, the number of attracted fish to the blue light per minute tended to gradually increase, while those attracted to the green and red lights changed only slightly.

3.2. Fish behavior

The fish (n = 72) remained at the window for a longer time and swam longer distances when exposed to blue light than when exposed to red light, i.e., 133.6 ± 129.8 s and 458.1 ± 397.3 cm for the former and 45.7 ± 52.2 s and 211.8 ± 147.6 cm for the latter (Table 3, Fig. 5). The swimming speed of fish attracted to the blue light was lower (4.0 ± 2.0 cm/s) than that of those attracted to red light (5.6 ± 2.1 cm/s). The fish attracted to the green light remained for a longer time (72.5 ± 76.7 s) compared to those attracted to the red light. However, the swimming speed and distance

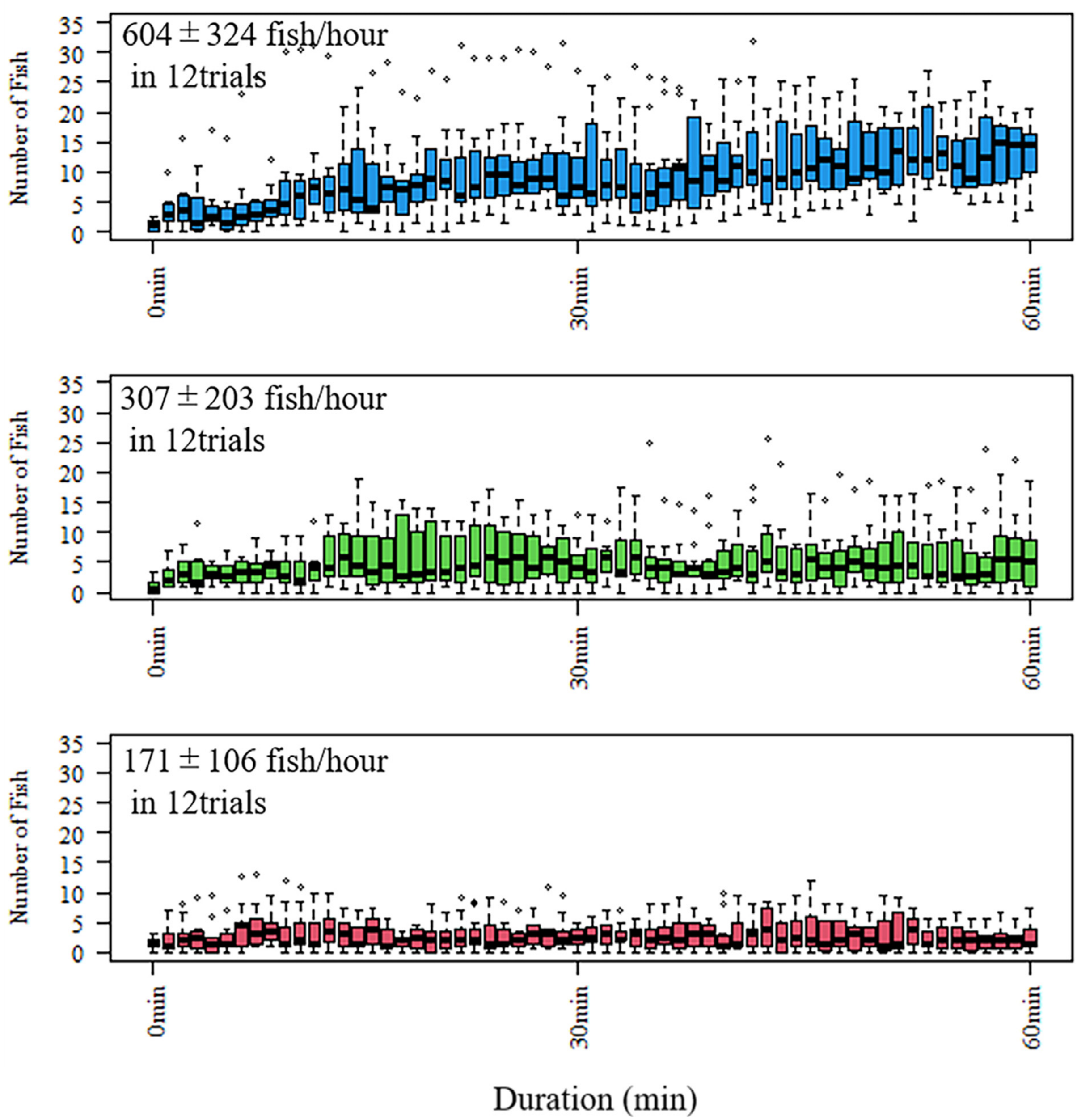

Fig. 4. Time series box plots of the number of attracted fish per minute in a 60 min trial with LED lights of different colors. The values included above each graph indicate the number of fish per hour and trial (average ± SD).

Table 3. Statistical test results for each fish behavior.

Contents	Test	Pair	Statistical value	*p* value
Distance	Steel–Dwass Test	Blue-green	$t = 1.53$	0.28
		Blue- red	$t = 2.68$	0.02
		Green-red	$t = 1.15$	0.48
Duration	Steel–Dwass Test	Blue-green	$t = 2.68$	0.02
		Blue-red	$t = 4.02$	1.7E-04
		Green-red	$t = 1.51$	0.29
Speed	Tukey's test	Blue-green	$diff = 0.77$	0.38
		Blue-red	$diff = 1.64$	0.01
		Green-red	$diff = 0.87$	0.28

values (i.e., 4.8 ± 5.1 cm/s and 277.8 ± 184.0 cm, respectively) were not significantly different from those under other illuminated conditions.

4. Discussion

4.1. Effect of different LED colors on white-edged rockfish

Blue and green LED lights attracted greater numbers of white-edged rockfish than the red light did; however, this result was largely expected based on the lights' physical properties and the visual properties of the fish. The blue (459 nm) and green (514 nm) lights used in this study had high transmittance in the water column. The wavelength sensitivity of species belonging to the genus *Sebastes* generally peaks in the green region; for example, in the black rockfish *S. schlegelii*, visual sensitivity is reported to peak at 522 nm [17]. Previous studies have indicated that the red light does not elicit any response in *Sebastes* spp [14]. In this study, neither the length of stay nor the swimming speed at the observation window changed in response to the red light. White-edged rockfish are found at various depths, include very shallow waters where red light is still present. However, as they gradually reach greater depths as they growth [15,16,18], the need to preferentially identify red in the space they regularly use is expected to diminish.

The GLM including only wavelength had the lowest AIC. In general, the effect of light on fish attraction is influenced by the lunar cycle, time of day related to sunset and sunrise times, and turbidity; however, in this study, the changes in LED light wavelength seemed to be the dominant factor. The lunar cycle is an important element of illuminance affecting fish behavior in the field; however, this effect was not verified because the experimental period in this study was concentrated around new moon cycle. During the experiment, sunrise was at 4:04–4:10 and sunset was at 18:36–18:41. Although these times generally affect underwater illumination, in this experiment, where the wavelength changed every hour, there seemed to be no effects on the number of attracted fish. Although the turbidity values varied from day to day, this parameter has probably a small effect on light diffusion or fish ecology.

In terms of the relationship between time elapse and the number of attracted fish in a single trial, both blue and green lights were attracted a low number of fish at the beginning of the experiment, and this was also the case with red light, suggesting that this initial period is the time necessary for white-edged rockfish to adapt to blue and green lights. Its duration (10–13 min) was the same for all light colors; however, the period tended to last longer around midnight. A past study has shown that [19]. In the GLM, the time of the day had no effect on the total number of attracted fish; however, it may influence the time in which the fish began to be attracted to the lights.

After the initial period in which a low number of fish were attracted, the average number of fish per minute gradually increased for the blue light, while it remained stable for the green light. The reason is probably that the mean length of time spent at the window when it was illuminated with blue light was 1.84 times longer than when it was illuminated with

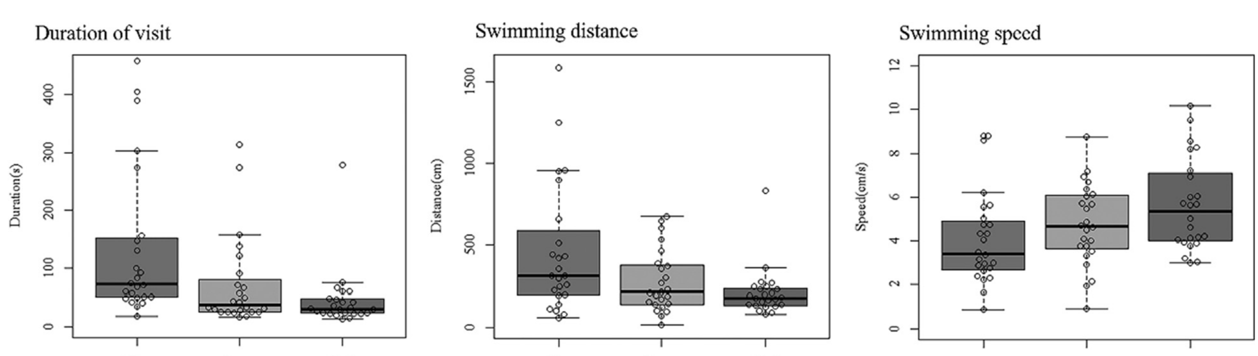

Fig. 5. Box plots and swarm diagrams of fish behavior at the window, duration of visit, swimming distance and swimming speed for LED lights of different colors. White dots indicate limited data.

green light. Considering the time spent at the window by one individual, it is expected that the visible fish are being replaced. However, the longer time spent under the blue light may mean that a less frequent replacement occurs, resulting in an increase in the number of fish counted. Among the reasons explaining why fish are attracted to, and remain in the vicinity of, light sources, the hypotheses of preferred light intensity and forced locomotion have long been considered [20]. The first implies that the preferred light intensity varies depending on the species and on the density of individuals, while the second suggests that the strong artificial light stimulus disorients fish and affects their ability to select their preferred light intensity. Furthermore, it has been reported that these disoriented fish exhibit specific behaviors such as contact with the light source, lunging, and body bending [20]. In this study, white-edged rockfish individuals appeared to move slowly around the window when it was illuminated by light of any color and did not exhibit any behavior that was considered to be typical of disorientation. The observation of fish appearing to remain in the area for a longer time in the presence of blue LED light is attributed to the fact that the environment was favorable and the light intensity was preferred by the fish.

On the other hand, the mechanism of fish attraction should be examined, not only in terms of the direct relationship between the target fish and light intensity but also in terms of the indirect relationship between predatory fish and their prey, which are attracted to the light. It has long been believed that the response to light stimuli is influenced by the enhancement of the feeding environment [21]. For example, in the Atlantic cod cage fishery, increased yields were reported for cage nets fitted with green LED lights [6]. However, Atlantic cod avoided this type of light in indoor experiments, while their prey, the Antarctic krill *Euphausia superba* aggregated around the light source, indicating that Atlantic cod might be attracted to green light in response to the aggregations of their prey [11]. In the case of white-edged rockfish, an ambush feeding species, it is possible that individuals stayed near the light source for longer and swam slowly enough in order to feed. To verify this, it will be necessary to determine whether small fish and plankton, the prey of white-edged rockfish, are attracted to the LEDs of each color in the vicinity of the tower.

4.2. Potential of the in situ experimental system

The observed differences in the number of attracted fish and their behavior around light sources could be applied to the artificial management of white-edged rockfish fisheries. Attempts to install small LEDs on fishing gear to increase fishing efficiency and reduce bycatch rates have been made for many species, including *Sebastes* spp [7,9]. In this study, the tendency of white-edged rockfish to stay for a longer period under the blue light would lead to an increase in the catch efficiency of gill nets and set nets. On the other hand, as white-edged rockfish is not a primary target species for coastal fishery, and is often a bycatch, behavioral manipulation using the blue color may be effective particularly to avoid this unintended catch. Similarly to the strategies employed to split bycatch species at the cod end of trawls, there is hope that LED lights installed on the gill nets and set nets can be used to direct the fish away from fishing gear and allow them to escape. White-edged rockfish is a unique ovoviviparous species, and its mating season around Hokkaido begins after September [22]. To control the catch efficiency, it would be effective to target the reproductive period using blue light. In Korea, the aquaculture production of *Sebastes* spp. has been made [23]. Even for white-edged rockfish in captivity, the use of blue light would allow fish to be gathered in specific areas for efficient feeding, length measurements and fish counting using cameras and sonar.

In this study, an observation system was used at an underwater observation deck to examine the differences in the fish attraction effect in the field, using white-edged rockfish as target species. The differences in the number of fish attracted by different light colors, and their behavior, were quantified. The results obtained provide a better understanding of the behavioral ecology of white-edged rockfish and suggest a selective and efficient use of this species in fisheries. These findings could introduce new possibilities for the utilization of similar environments and structures. The main species used in this study was white-edged rockfish; however, it would be possible to examine species-specific and species-common responses to light stimuli in an environment where multiple species coexist.

However, a limitation of this study was that the observations of the fish-attracting effect of LED lights were limited to a single undersea window. As fishing grounds are tridimensional, the number of attracted fish and their behavior should be assessed in a three-dimensional context. Observations obtained using an echo sounder would provide a better understanding of the differences in the fish-attracting effects of different light wavelengths. In combination with the tracking of individuals through acoustic tags, it would also be possible to accurately verify the replacement of individuals attracted to each light color. Another issue associated with this observation system is that it does not consider the light reflection on the window surface. Although in this study the attraction effect of each color did not change depending on the irradiance and illumination level, it will be necessary to investigate the spectral distribution and illumination in the surrounding seawater as a function of the distance from the light source, because the acrylic window surface is a strong reflector of electromagnetic waves.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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