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Effects of Underwater Sounds on Escape Behavior of Steller Sea Lions

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The reactions of 10 captive Steller sea lions *Eumetopias jubatus*, including one adult male, four adult females and five juvenile animals to underwater sounds, with and without the presence of a baited fishing net, were observed. Two narrow spectrum sounds, an 8 kHz pure tone and a 1 kHz to 4 kHz frequency sweep, three broad spectrum sounds, two mechanically generated impulse sounds, and the recorded vocalization of a killer whale were used. The reactions of Steller sea lions were divided into three categories. Category ○: Both adult and juvenile Steller sea lions landed on a side of their pool during a one-minute period timed from the start of the sound projection. Category △: More than two juvenile Steller sea lions landed. Category ×: A single juvenile Steller sea lion or no animals landed.

Impulsive sounds transmitted at high source level (210 dB re 1 μPa at 1 m) or pure tone sounds (165 dB source level) were found to repel adult Steller sea lions. Broad band spectrum sounds did not repel adult and juvenile Steller sea lions after successive sound projections.

The male Steller sea lion was only deterred from eating the fish entangled in the net by the high source level impulsive sound.

The acoustic characteristics required to repel Steller sea lions are thought to be narrow spectrum within the sensitive range of a Steller sea lion's audible frequency and above 165 dB sound pressure level. However, Steller sea lions appear to acclimatize to repeated sound projections, and a sound pressure level below 165 dB does not appear to be enough to repel Steller sea lions from a fishing net.

Key words: Steller sea lion, acoustic behavior control, bottom-set gill net, fishing gear damage, eared seal

Many types of fishing gear are damaged by Steller sea lions *Eumetopias jubatus* in the coastal area of Hokkaido, Japan. During 1993, fishermen reported 2,173 incidents of Steller sea lion-related damage to fishing gear and the total cost of the damage was estimated to be five hundred million yen (five million dollars). During the year, 1,725 bottom-set gill nets, 307 bottom trap nets, and 141 set nets were damaged. Of these, the damage to bottom-set gill nets are the most serious problem for the fishing industry of Hokkaido.

The Steller sea lions bite holes in the netting in order to eat fish entangled in gill nets. They also attack nets during hauling. Although the damage to the trap net fishing gear by Steller sea lions may be reduced by using stronger twine, the quantity of fish caught may be less.

Calkins and Pitcher[1)] estimated 66,636 Steller sea lions in Alaska Bay, which were counted during the breeding season in 1979. The number of these animals decreased to 47,960 in 1989.[2)] The population of Steller sea lions in the North Pacific Ocean has gradually declined by around 39%–48% over the past thirty years.[2)] The species is in need of protection and it is therefore unacceptable to kill Steller sea lions in order to reduce the damage they cause to the fishing gear and fishing products.

Acoustic signals are thought to be one of the acceptable countermeasures likely to protect the fishing gear from Steller sea lions. Acoustic behavior control methods cause no physical harm to the animals. Although many experiments have been conducted to try to repel dolphins from fishing gear by acoustic signals in Japan,[3-5)] less is known about underwater acoustic signals that may control the behavior of Steller sea lions.

The immature and pregnant female Steller sea lions are more likely to enter the water than are territorial males and females with small pumps producing approaching aircraft sounds.[6)] Maniwa and Hatakeyama[7)] reported that Steller sea lions in a pool stopped swimming and did not approach a sound source which projected pure tone signals at frequencies between 1 and 3 kHz. Unfortunately, neither the source levels of these signals or the animals' distance from the source was defined and the sound pressure levels experienced by the animals are therefore unknown.

It is necessary to determine the source level, the spectrum of an effective sound deterrent, and the range over which this will repel Steller sea lions. It is also necessary to study the effect of acclimatization of the animals to the sounds.

In the present study, we examined the behavior of captive Steller sea lions with five kinds of underwater sounds, and discussed the effect of acclimatization. The sounds tested had various acoustic characteristics, three of the five had a broad band power spectrum and two were narrow band.

Materials and Methods

One adult male Steller sea lion (18 years old, estimated), four adult females (18, 15, 10, 7 years old, estimated) and five juvenile animals (under 2 years old) kept in the Otaru Aquarium were used in this study. The adult male was caught in the wild in 1981 in the waters off Otaru. The four adult females were caught in 1977, 1987, 1989, 1992, respectively in the waters off Shibetsu and Monbetsu on the northern coast of Hokkaido. Three of the juvenile animals were born in Otaru Aquarium, one of them was born in Maruyama Zoo in Sapporo city in Hokkaido, and the other one was caught in 1993 at Monbetsu.

The experiments were conducted in a pool of 3 m depth, 17.5 m length and 14.5 m width and with a landing space (7.5 m wide) along the longer side (Fig. 1).

A hydrophone (Oki ST 1001) and an underwater speaker (Oki ST2010), which were protected by an iron cage, were set at point A of Fig. 1. A microphone and a video camera were deployed outside the observion shelter B. The sound pressure level in the pool apart from the cage was difficult to measure because of the Steller sea lions attack. The estimated reduction of sound pressure level in the pool by the sound propagation model in the shallow water[8] are shown in Fig. 1. The underwater and aerial sounds and the behavior of Steller sea lions were recorded on a video tape recorder (Sony EV-S55) in the observation shelter.

The underwater speaker was driven by signals controlled from the observation shelter. Test signals were amplified by a pre-amplifier (Victor JS-A77) and a power amplifier (Yamaha PC2002). The source levels of all the sounds, except for the 'Boomer', could be controlled by an attenuator (Tokyo Ko-on-denpa STA-113). The underwater speaker could transmit a maximum source level of 170 dB re 1 μPa at 1 m, (rms value).

Steller sea lions are thought to be sensitive at 2 kHz.*4 California sea lions and Steller sea lions are from the same family Otariidae. Shusterman *et al.*[9] found the California sea lion *Zalophus californianus* to be sensitive to pure tone sounds at frequencies up to 28 kHz. Below 1 kHz the hear-

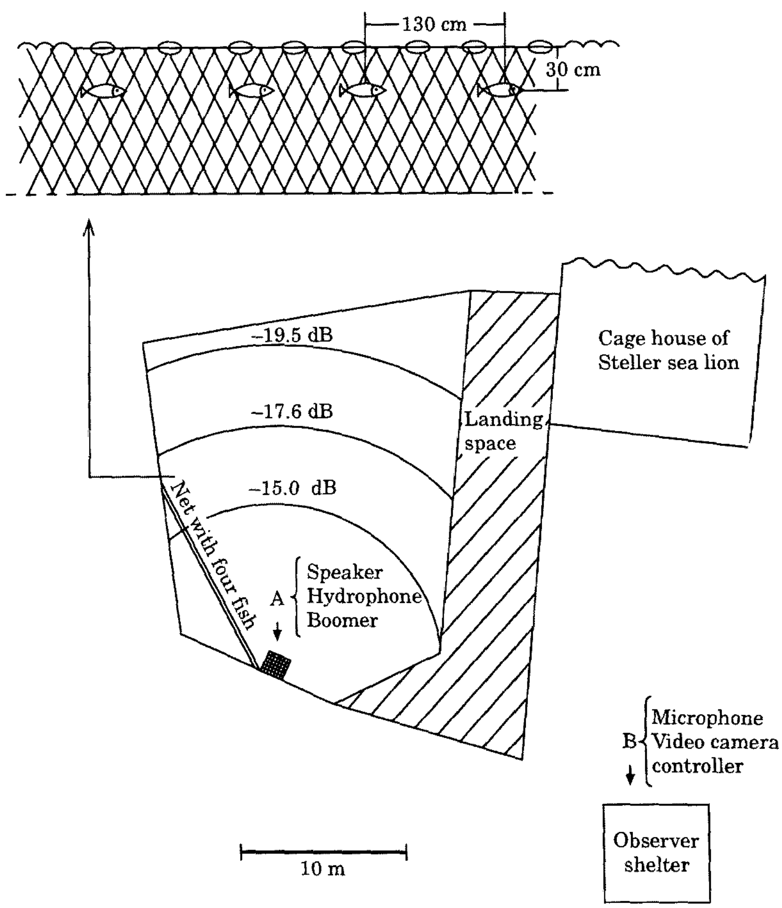

Fig. 1. Top view of the pool.
A: an iron cage protects a hydrophone and an underwater speaker, B: observion shelter.
The estimated reduction of sound pressure levels from the sound source are indicated.

*4 H. Shimura, T. Akamatsu, and M. Takeda: Auditory characteristics of a Steller sea lion with masking noise, Journal of Japanese Association of Zoological Gardens and Aquariums (1996), to be submitted.

ing sensitivity of the California sea lion fell rapidly, and was measured to be about 30 dB less sensitive at 100 Hz that at 1 kHz.[10] The frequencies of underwater sounds used to control the behavior of Steller sea lions were therefore chosen within the range of 1 to 28 kHz.

Five kinds of sounds were used. The first sound was generated by a 'Boomer' (formerly called Bikkura in Akamatsu *et al.*[5]) which had a 210 dB source level. This radiates a sound pulse with a spectral energy peak around 1.5 kHz (Fig. 2). The sound is generated by an underwater iron drum, which is struck by a solenoid-driven piston. The piston strikes a circular iron plate and can generate repeated sound impulses at a 2 Hz rate. It is not possible to alter the source level of this device.

The second sound tested was a tape recording of the Boomer's sound, hereafter called 'Boomer-T'. This sound had a maximum source level adjusted to be 165 dB to match that of the other signals tested.

The third signal was a tape recording of a killer whale (*Orcinus orca*) vocalization indicated as 'Orca'. This sound was composed of three parts, 13 seconds (Orca 1), 3 seconds (Orca 2), and 2 seconds of silence. Orca 1 had a spectrum peak around 2.8 kHz and Orca 2 peaked at 2.4 kHz as shown in Fig. 2. The three parts were recorded on an audio tape repeatedly.

The fourth signal was also a tape recording sound in which the frequency was swept from 1 to 4 kHz during one second and repeated. This is called 'Sweep'.

The fifth signal was a tape recording of an 8 kHz pure tone, which was transmitted for 5 seconds with a 5 second interval and repeated continuously. This is referred to as 'Pure tone'.

Boomer, Boomer-T and Orca exhibited a broad band spectrum and the Sweep and Pure tone signals were narrow band. The duration of Boomer and Boomer-T impulsive sounds were 1 ms and the other sounds were continuous for a few seconds.

Each sound tested was projected for a two minutes followed by a 28 minute rest interval. The five sounds were transmitted randomly in 98 sessions (Table 1). The source level of these sounds remained fixed (165 dB) during sessions 1 to 30 to compare the effectiveness of each sound. The source levels were selected at random from 165, 155, 145 dB between sessions 31 to 82, with the exception of the Boomer signal as the source level of this device could not be changed. From sessions 83 to 98, the Boomer, Sweep, and Pure tone of 165 dB were projected (since the Boomer-T and Orca were judged to have been ineffective).

All of the Steller sea lions hauled out of the water after sunset at about 17:00 and rested on the landing space until

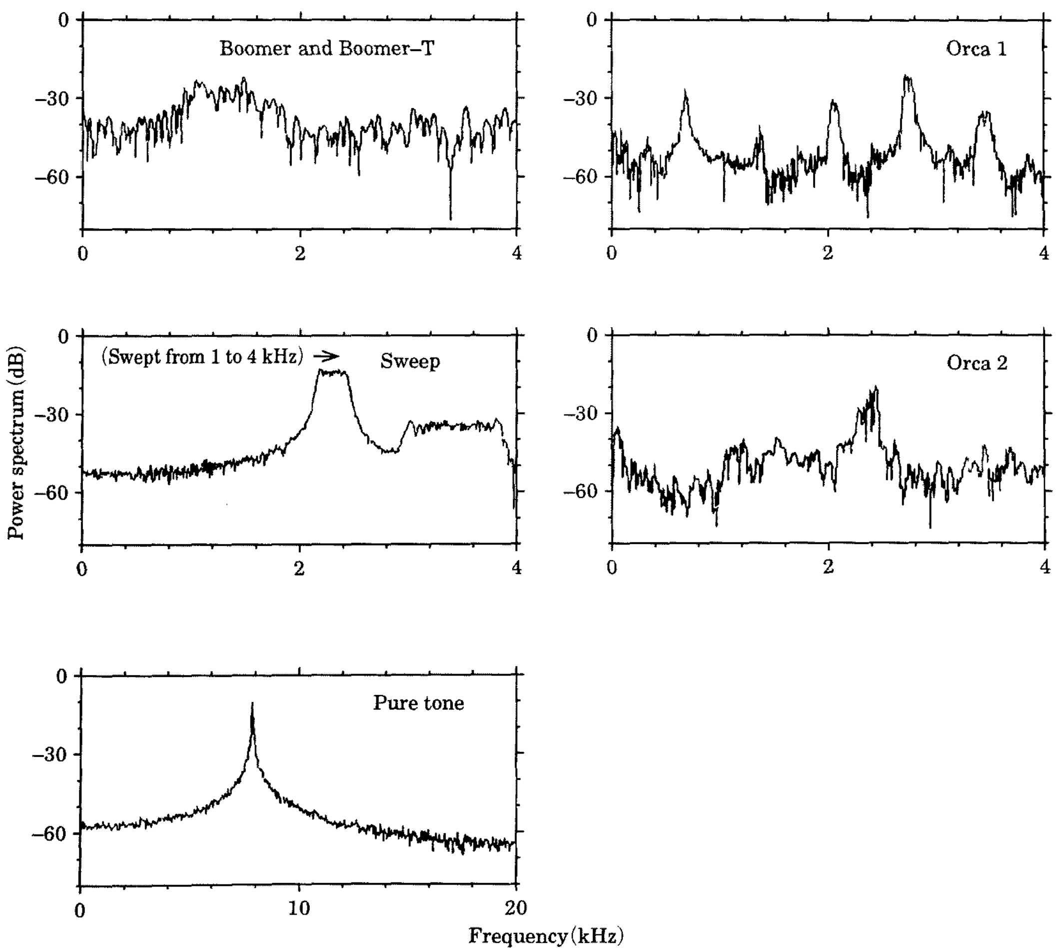

Fig. 2. Power spectrum of projected sounds.

Table 1. Transmitted sounds and reactions of Steller sea lions

n	Sound	SL	R	Feeding	n	Sound	SL	R	Feeding
1	Boomer	210	○		50	Sweep	165	△	
2	Orca	164	×		51	Boomer	210	○	
3	Orca	164	×		52	Pure tone	165	○	
4	Boomer-T	167	△		53	Boomer	210	○	
5	Pure tone	167	○		54	Orca	145	△	
6	Boomer-T	166	×		55	Orca	165	×	
7	Pure tone	162	×		56	Sweep	165	△	
8	Sweep	167	△		57	Boomer-T	145	×	
9	Pure tone	170	○		58	Pure tone	145	×	
10	Boomer	210	○		59	Orca	165	×	
11	Boomer-T	167	×		60	Pure tone	155	×	
12	Orca	165	○		61	Pure tone	145	△	
13	Pure tone	168	○		62	Sweep	155	×	
14	Sweep	168	△		63	Boomer-T	165	×	
15	Sweep	168	△		64	Sweep	165	×	
16	Boomer	210	○		65	Boomer	210	○	
17	Pure tone	156	×		66	Pure tone	155	×	
18	Boomer	210	○	Net	67	Boomer	210	○	
19	Boomer-T	164	△		68	Pure tone	145	×	
20	Orca	160	×	Net	69	Boomer	210	○	
21	Orca	158	×		70	Boomer-T	145	×	
22	Boomer-T	163	×		71	Sweep	155	×	
23	Boomer	210	△		72	Boomer-T	165	×	
24	Sweep	165	△		73	Pure tone	155	×	
25	Boomer-T	161	△		74	Orca	165	×	Net
26	Pure tone	165	△	Net	75	Orca	155	×	
27	Sweep	166	△		76	Boomer-T	165	△	Net
28	Orca	164	×	Net	77	Boomer	210	○	Net
29	Pure tone	161	△		78	Pure tone	165	×	Net
30	Boomer-T	166	×	Net	79	Orca	145	×	
31	Sweep	165	×	Net	80	Sweep	165	×	Net
32	Boomer	210	△	Net	81	Sweep	155	×	
33	Sweep	165	△		82	Boomer-T	155	×	
34	Orca	155	×		83	Pure tone	165	×	
35	Sweep	155	△		84	Boomer	210	○	
36	Boomer	210	○		85	Sweep	165	×	
37	Pure tone	165	△		86	Pure tone	165	×	Throwing
38	Orca	155	×		87	Sweep	165	×	Throwing
39	Sweep	145	×		88	Boomer	210	△	Throwing
40	Boomer-T	155	×		89	Sweep	165	×	
41	Sweep	165	△		90	Boomer	210	○	
42	Pure tone	155	△		91	Sweep	165	×	
43	Orca	165	×		92	Boomer	210	○	Throwing
44	Sweep	155	×		93	Pure tone	165	○	
45	Pure tone	165	○		94	Pure tone	165	○	
46	Sweep	145	△		95	Sweep	165	×	
47	Pure tone	145	△		96	Boomer	210	○	Throwing
48	Boomer-T	165	×		97	Boomer	210	○	Net
49	Boomer-T	145	×		98	Boomer	210	○	Net

n: session number, SL: source level (dB), R: reactions, ○: Both adult and juvenile Steller sea lions landed after sound projection, △: Two or more juvenile Steler sea lions landed, ×: Only one juvenile or no Steller sea lion landed.

the next morning. The underwater sound projections were therefore confined to the period between 08:30 and 16:30. It took 6 days to conduct all 98 sessions.

We also observed the behavior of Steller sea lions against a net with fish 14 times during the series of 98 sessions. This experiment is referred to as "Net" in Table 1. Four dead atka mackerels (*Pleurogrammus azonus*) with a body length of 20 cm were entangled in the blue net below 30 cm from the float line. This net had a 70 mm stretched mesh size, 1.5 mm diameter twine, and was rigged to be 4.3 m in height and 10 m in length. The four fish were spaced 130 cm apart from each other. The sound signals were projected in the water as the net with the fish was inserted into the pool. The reactions of the Steller sea lions, including underwater and aerial sounds, were monitored in the same manner as the experiments without the net.

One-kilogram atka mackerel were thrown five times near the underwater speaker with the transmitting sound initiated as these were thrown, ("Throwing" in Table 1). This situation was the most attractive one for the Steller sea lions as it replicated their normal aquarium feeding which was carried out from the same position.

Results

During sound projection, the most typical escape behavior exhibited by the Steller sea lions was to haul-out on the landing space.

In a few days preliminary observation conducted in 1993 and just before the present experiment, the Steller sea lions usually swam in the center of their pool where there was a deep area. Also, during many silent intervals of 28 minutes between the sound projection (total 440 minutes observation), the adult male and females hauled-out only seventeen times. Ten of these were adult females landing to nurse juveniles, four of them were for ordinary feeding and three of them for no obvious reason. There were few male or female landings without a behavioral context.

The experiments were not conducted at ordinary feeding times or during any other disturbance caused by human ac-

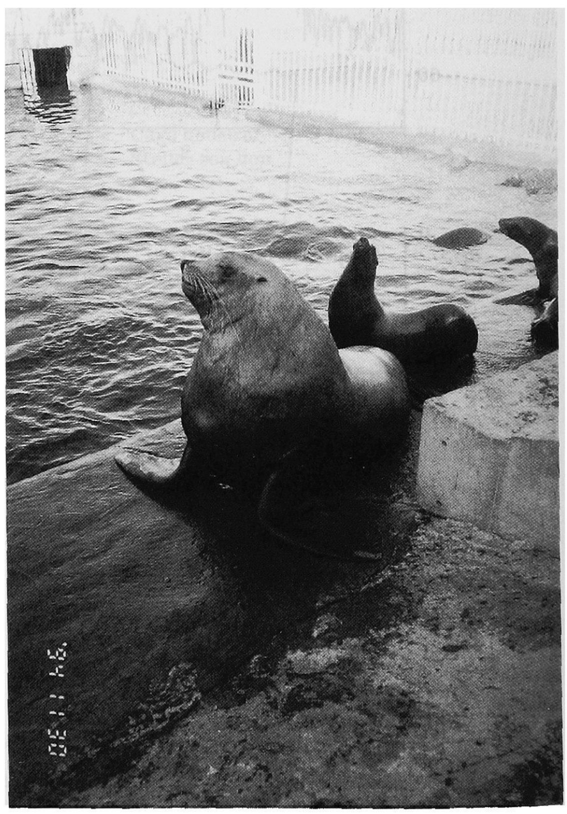

Fig. 3. Reaction ○.
One adult male and juvenile sea lions landed due to the sound projection.

Table 2. Comparison between devices at maximum source levels until 30th session except for the net feeding

	SL (dB)	Reaction ○	Reaction △	Reaction ×	Total
Boomer	210	3	1	0	4
Pure tone	165	3	1	2	6
Sweep	165	0	5	0	5
Boomer-T	165	0	3	3	6
Orca	165	1	0	3	4

○: Both adult and juvenile Steller sea lions landed after sound projection.
△: Two or more juvenile Steller sea lions landed.
×: Only one juvenile or no Steller sea lion landed.

tivity around the pool in order to clearly distinguish reactions due to the projected sounds from those due to other landing behavior. Unexpected adult hauling-out behavior (independent of sound projection) rarely occurred just after the sound projection.

On the other hand, for the juvenile Steller sea lions, it proved difficult to distinguish hauling-out for play from escape behavior induced by sound. During 440 minutes without sound projection, a single juvenile landed 32 times. However, eleven of these landings were initiated by the need to feed or be nursed, but 21 landings occurred during playing. More than two juvenile Steller sea lions landed together 34 times and 24 of these occurred during play. In total 45 landings occurred during the 440 minute period without sound projection during juvenile play, so about 10 percent of the juvenile hauling-out behavior just after the sound projection seems to be caused by play.

The reactions of the Steller sea lions were divided into three categories. Category ○ was defined as both adult and juvenile sea lions landing within one minute after the start of the sound projection depicted in Fig. 3. Category △ was defined as more than two juvenile sea lions landing. By neglecting the single juvenile landings, half of the errors induced by landing to play could be eliminated. This definition is possibly conservative. Category × was defined as only one juvenile sea lion or no animals landing.

Most of the landed adult and juvenile steller sea lions

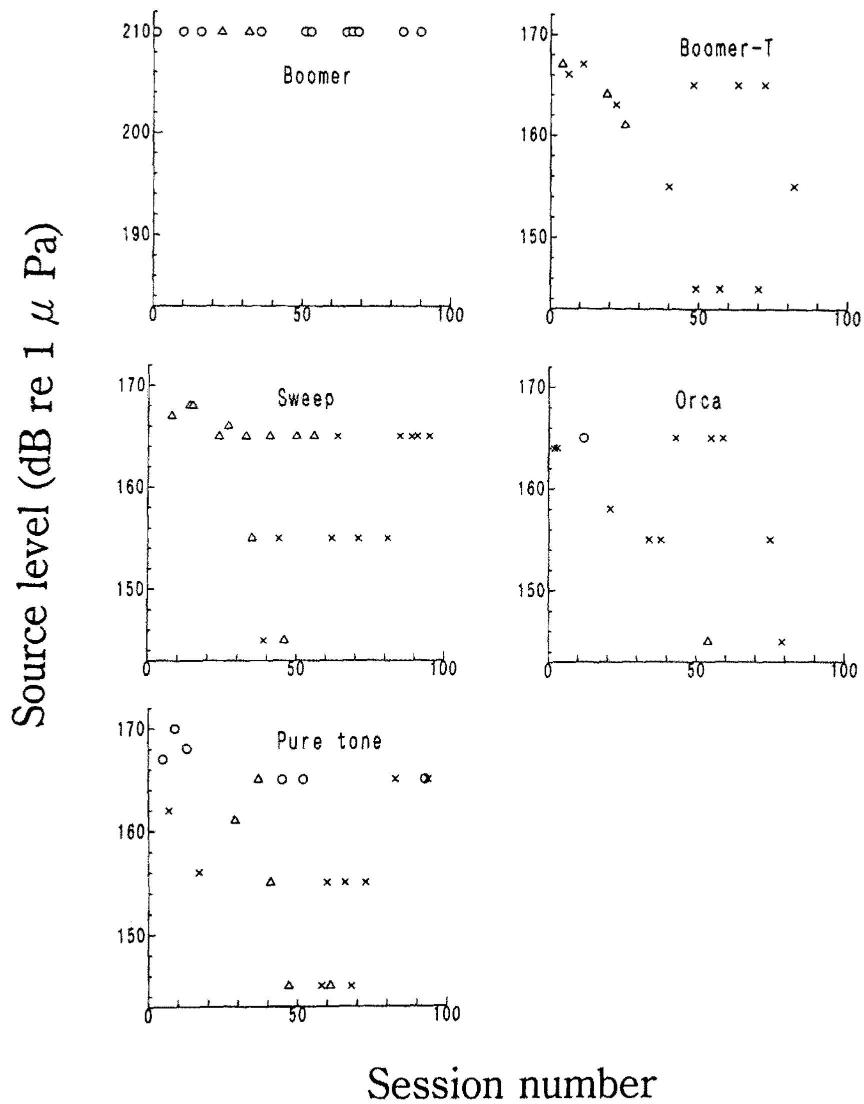

Fig. 4. Reactions of Steller sea lions in the serial sessions.

returned to the pool during the 28 minute interval after each sound projection.

Table 1 shows all the reactions of Steller sea lions with serial session number and the source level of sounds. If there were some landed individuals before the projection, the increment of the landed number is used for the judgment of reaction category. During the first 30 sessions, all five juveniles landed frequently, but in the last 16 sessions, few ○ reactions were observed except for the Boomer.

Table 2 shows the reactions to a source level of approximately 165 dB for without net or feeding sessions until the 30th session. Experiments were conducted for four to six sessions at each device. The ○ reaction that was observed to the sounds of Boomer, Pure tone, and Orca was not observed to the sounds of Sweep and Boomer-T. The × reaction was not observed by Boomer. On the other hand, the Orca sound had three × reactions in four trials. Sweep and Boomer-T affected the landing behavior of only juvenile Steller sea lions.

The reactions of Steller sea lions for each sound with various sound pressure levels except the feeding sessions are depicted in Fig. 4. The abscissa represents the number of experiments shown in Table 1 and the ordinate represents the source level. During sessions 31 to 82, the source levels were altered randomly among 145, 155 and 165 dB. The ○ and △ reactions changed to the reaction × in all kinds of sounds, except to Boomer as the session number increased. Although there were eleven ○ or △ reactions to the Pure tone and Sweep signals in total, the Orca sound caused only one ○ and × reaction during 13 sessions, similarly, there were only three △ reactions to Boomer-T.

Comparing the number of landed animals by the sounds in the same conditions, Fig. 5 shows the component of landed individuals during the 165 dB sessions (source level of Boomer was 210 dB) until session 83, except during feed-

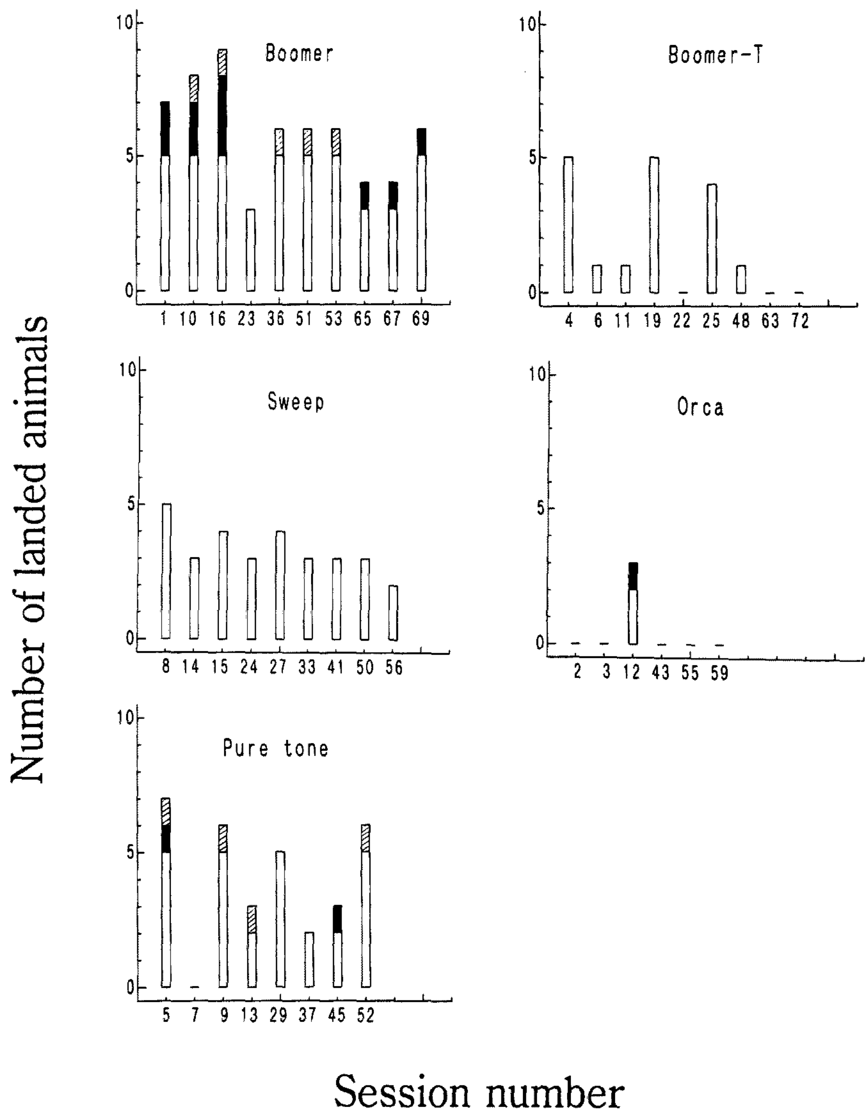

Fig. 5. Landed number of adult and juvenile sea lions at maximum sound pressure level.
The abscissa is the session number and the white bars indicate the number of juvenile Steller sea lions landed. The black and oblique line bars indicate the number of adult females and male landed, respectively.

Table 3. Statistical tests of landed number of Steller sea lions

	Boomer	Pure tone	Sweep	Boomer-T	Orca	Reactions
Boomer	—	—	**	**	**	Adult animals landed
Pure tone	—	—	—	*	**	Adult animals landed
Sweep	**	—	—	—	**	Juvenile animals landed
Boomer-T	**	*	—	—	*	Juvenile animals landed
Orca	**	**	**	*	—	Few animals landed

**: within 1%, *: within 5%, —: no significant difference.

Table 4. Reaction at the presense of a net with four fish

	SL (dB)	Reaction ○	Reaction △	Reaction ×	Total
Boomer	210	4	1	0	5
Pure tone	165	0	1	1	2
Sweep	165	0	0	2	2
Boomer-T	165	0	1	1	2
Orca	165	0	0	3	3

○: Both adult and juvenile Steller sea lions landed after sound projection.
△: Two or more juvenile Steller sea lions landed.
×: Only one juvenile or no Steller sea lion landed.

ing sessions. Data after 84 sessions were neglected since the Boomer-T and Orca sounds were discontinued.

This figure shows that both adult and juvenile animals were landed by the Boomer and Pure tone signals. The total number of Steller sea lions landed by Boomer was significantly different from that by Sweep, Boomer-T and Orca (Mann-Whitney U test, $p<0.01$), but was not significant from that by Pure tone ($p=0.057$) as shown in Table 3. The total landing number by Orca was significantly different from that by Boomer, Pure tone, and Sweep ($p<0.01$) and also different from Boomer-T ($p<0.05$). Sweep and Boomer-T were not significantly different.

Table 4 shows the reactions of Steller sea lions to the sounds when the net with four atka mackerel was put in the pool. Four ○ reactions were observed to Boomer, but after 80, 34, 33, 40 seconds from the end of the projection, the male came to the net and ate fish. Other sounds could not repel the adult sea lions onto the landing space.

When the fish were thrown into the pool, adult and juvenile Steller sea lions did not land and eat fish during projection of the Pure tone and Sweep sounds. During the throwing fish experiment, the Boomer-T and Orca sounds were not transmitted. Boomer kept both juveniles and adult females away from the fish just after the projection, but on one occasion the adult male took and ate a fish when only 1.5 m away from the cage during sound projection.

Discussion

The sound pressure levels experienced by the sea lions in a center of the pool are thought to be reduced by about 17 dB from the indicated source levels, due to spreading loss. On the opposite side of the pool, the sound pressure level will be reduced by about 22 dB. (Note for narrow band sources these sound pressure levels may be expected to vary locally by up to +/− 6 dB due to standing wave interference effects.) When the source level was 165 dB, a swimming Steller sea lion in the middle of the pool should have experienced a sound pressure level of about 150 dB. However, as the sound pressure levels actually experienced by the Steller sea lions could not determined precisely, the source level values are used in the following discussions.

Among the tape recorded sounds transmitted at the 165 dB source level, Pure tone sounds were relatively more effective than other sounds. Pure tone sounds repelled the adult sea lions. The sweep sound also repelled juvenile sea lions, and the number of landed animals did not decrease so much as the session number increased (Fig. 5). This suggests that narrow band spectrum sound is more effective in changing the behavior of Steller sea lions than broader band spectrum sound.

The Boomer sound source was different from the other test signals because it had a higher source level. The number of landed individuals was more than half of the group in the pool when these were exposed to the Boomer. Although the spectrum of Boomer was broad and identical to that of Boomer-T, the Boomer sound impulses repelled both adult male and female sea lions which did not land when exposed to Boomer-T. The sound pressure level is therefore thought to be one of the dominant factors controlling the behavior of Steller sea lions.

The Steller sea lions did not react at the 165 dB level during the last part of the experiment especially to Boomer-T and Orca sounds, which seems to indicate acclimatization to these sounds. The number of sound projections is thought to be another dominant factor. The 165 dB narrow band signals (Pure tone and Sweep) seem to be relatively difficult to acclimatize to since the landed number was not noticeably affected by the increase in session number.

Only the Boomer impulses actually stopped the male Steller sea lion from trying to eat the fish in the net. However, the juvenile Steller sea lions did not approach the net with fish at △ reaction during the projection of the Boomer, Boomer-T and Pure tone sounds. The protection of fishing nets from Steller sea lions seems to need high sound pressure level signals, and the 165 dB source level sounds (narrow or broad band) are thought to be inadequate to protect fishing gear containing fish from adult male Steller sea lions.

Desirable acoustic characteristics to repel Steller sea lions are thought to be narrow band spectrum with operating frequencies selected within the sensitive part of the sea lion's audible frequency range. These signals need to be projected at sound pressure levels above 165 dB in the net zone requiring protection. The Steller sea lions can acclimatize to such sound projections and a 165 dB source level is not enough to repel sea lions from fishing nets. The commercial underwater speaker used in these tests could not project source levels significantly greater than 170 dB in the audible frequency range of the Steller sea lion.

The efficient generation of high sound pressure levels with a narrow band spectrum appears to require an impulsive (mechanical impact) mechanism. Such a mechanism driving a resonant structure, designed to ring at around certain frequency, would appear to be optimized to the hearing sensitivity of the Steller sea lion and is thought to be suitable to alter their behavior.

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