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1 **Title**

2 Sound variation and function in captive Commerson's dolphins

3 (*Cephalorhyncus commersonii*)

4

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22

Abstract

Commerson's dolphin (*Cephalorhyncus commersonii*), one of the smallest dolphin species, has been reported to produce only narrow-band high-frequency (NBHF) clicks and no whistles. To clarify their sound repertoire and examine the function of each type, we analysed the sounds and behaviour of captive Commerson's dolphins in Toba Aquarium, Japan. All recorded sounds were NBHF clicks with peak frequency > 110 kHz. The recorded click-trains were categorised into four types based on the changing pattern of their Inter-click intervals (ICI): Decreasing type, with continuously decreasing ICI during the last part of the train; Increasing type, with continuously increasing ICI during the last part; Fluctuating type, with fluctuating ICI; and Burst-pulse type, with very short and constant ICI. The frequency of the Decreasing type increased when approaching an object newly introduced to the tank, suggesting that the sound is used for echolocation on approach. The Burst-pulse type suddenly increased in front of the object and was often oriented toward it, suggesting that it was used for echolocation in close proximity to the object. In contrast, the Increasing type was rarely recorded during approach, but increased when a dolphin approached another dolphin. The Increasing and Burst-pulse types also increased when dolphins began social behaviours. These results suggest that some NBHF clicks have functions other than echolocation, such as communication.

1. Introduction

Commerson's dolphin (family Delphinidae, *Cephalorhyncus commersonii*) is the smallest dolphin inhabiting the inshore waters of Argentina, the Strait of Magellan, and the Falkland and Keruguelen Islands in the Indian Ocean. Like other toothed whales (*Odontoceti*), Commerson's dolphins produce pulse sounds for echolocation (Watkins and Schevill, 1980). However, the species produces only pulse sounds, and no whistle sounds (Dziedzic and De Buffrenil, 1989; Evans et al., 1988; Hatakeyama et al., 1988; Kamminga and Wiersma, 1982, 1981; Shochi et al., 1982; Watkins and Schevill, 1980), while most other delphinids also produce whistles. These species use pulses mainly for echolocation and whistles mainly for intra-specific communication (e.g., *Tursiops truncatus* (Janik and Slater, 1998), *Lagenorhynchus obliquidens* (Caldwell and Caldwell, 1971), and *Sousa chinensis* (Van Parijs and Corkeron, 2001)).

Dolphins in the genus *Cephalorhynchus,* including Commerson's dolphin, two of the genus *Lagenorhynchus* (hourglass dolphin (*L. cruciger*) and Peale's dolphin (*L. australis*)), those of the family Phocoenidae, and the pygmy sperm whale (family Kogiidae, *Kogia breviceps*), all produce short (ca. 130–400 μsec) and narrow-banded (ca. 10–20 kHz) high-frequency (ca. 120–130 kHz) ultrasonic clicks (NBHF clicks) but no whistle sounds (Au, 1993; Au et al., 1999; Dawson, 1988; Kyhn et al., 2010; Madsen et al., 2005; Tougaard and Kyhn, 2010). This may be to avoid predation by killer whales, as the frequency of NBHF clicks exceeds their auditory range (Morisaka and Connor, 2007; Morisaka, 2012).

Although there are no reports of acoustic communication in Commerson's dolphin, acoustic communication using NBHF pulse sounds has been suggested in other NBHF species. Dawson (1991) showed that highly repetitive "click-trains", resulting in a "cry", were often recorded during aggressive behaviour in Hector's dolphin (*C. hectori*). These "cry" sounds were recorded more often in large groups than in small, suggesting a relationship with social interaction. NBHF pulse sounds similar to the cry sound were reported for all *Cephalorhynchus* species, including Commerson's dolphin (*C. commerosonii, C. hectori, C. heavisidii, C. eutropia*)

3

81 (Watkins et al., 1977). Harbour porpoise (*Phocoena phocoena*), which has a
82 body size and shape similar to that of *Cephalorhynchus* dolphins, may also
83 use high-repetition NBHF pulse sounds for communication, as these sounds
84 are frequently recorded during social interactions (e.g. aggressive behaviour,
85 and when approaching other individuals) (Clausen et al., 2010; Nakamura et
86 al., 1998). However, more precise analysis of the relationship between the
87 sounds and behaviour is necessary to conclusively demonstrate that acoustic
88 communication using NBHF pulse sounds occurs in these species.

89   There have been some previous studies on the sounds of
90 Commerson's dolphin in the wild (Dziedzic and De Buffrenil, 1989; Watkins
91 and Schevill, 1980) and in captivity (Hatakeyama et al., 1988; Shochi et al.,
92 1982). Audible sounds similar to the cry sounds of Hector's dolphin were also
93 recorded in some studies (Dziedzic and De Buffrenil, 1989; Hatakeyama et
94 al., 1988; Shochi et al., 1982; Watkins and Schevill, 1980). However, most of
95 these were brief descriptions of the dolphins' behaviours and sounds
96 obtained using a band-limited recording system that recorded only low
97 frequencies < 100 kHz (Dziedzic and De Buffrenil, 1989; Watkins and
98 Schevill, 1980), which does not cover the main frequency of the sound in
99 Commerson's dolphin. Furthermore, most analysed the waveform of a single
100 pulse, though the sounds of Commerson's dolphins consist of click-trains
101 containing from a few dozen to several thousand sequential clicks
102 (Kamminga and Wiersma, 1982). There has been no precise analysis of these
103 click-trains. To examine the possibility of acoustic communication in this
104 species using NBHF clicks, it is necessary to analyse and categorise the
105 click-trains and study the relationships between click-train type and dolphin
106 behaviour.

107   In this study, we analysed the sounds of captive Commerson's
108 dolphins to categorise their click-trains based on changing inter-click
109 interval (ICI) patterns. We also analysed the relationships between
110 click-train type and dolphin behaviours to infer the function of each type of
111 click-train. Finally, we discuss the possible use of clicks for acoustic
112 communication in this species.

113

114

2. Materials and methods

2.1. Study site and subject animals

Video and acoustic recordings of Commerson's dolphins were made at the Toba Aquarium, Mie prefecture, Japan, on July 25 (three animals) and December 27–28 (four animals), 2007. We studied two adult females (Laura: 18 years old, Lala: 16 years old), one adult male (Kai: 10 years old, unrelated to Laura or Lala) and one juvenile male (Peace: 1 year old, son of Laura). All were born in Japanese aquariums: Laura and Lala were born at the Matsushima Aquarium, Miyagi prefecture, Japan in 1989 and 1991, respectively, and have lived in the Toba Aquarium since March 1996. Kai and Peace were born at the Toba Aquarium in 1997 and 2006, respectively. On July 25, 2007, three dolphins, excepting Kai, were housed in the main pool (Fig. 1, 8.4 × 6.8 m and 3.4 m in depth, 194.2 m^3 of water, temperature of 14°C), and Kai was housed in the sub-pool (4.9 × 5.0 m and 1.5 m in depth, 36.75 m^3 of water, temperature of 14°C). On December 27–28, 2007, all four dolphins were housed in the main pool.

2.2. Recording of behaviour and vocalisation

To clarify the vocalisation repertoire and analyse the relationship between sound types and behaviour, we carried out sound recording and video recording of behaviour during the daytime (9:00–17:30) on July 25, 2007, in nine 30-min recording sessions, each starting on the hour. We observed and recorded dolphin behaviour from an underwater observation window (8 × 6 m) in the main pool that enabled observation across almost the entire tank (Fig. 1). Video recordings were made using a Sony (Tokyo, Japan) HDR-HC3 video camera. Sounds were recorded using a hydrophone (Reson, TC4013, Denmark; sensitivity –211 dB re 1V/μPa between 1 Hz to 170 kHz ± 3 dB), an amplifier (Reson, EC6081, Denmark) with 10-kHz high-pass and 250-kHz low-pass filters and 50 dB gain, and one channel of a data recorder (EZ7510, NF corporation, Yokohama, Japan) which consisted of an analogue-to-digital converter (16-bit resolution, 500-kHz sampling rate, 2-V dynamic range) with data stored on a 40-GB hard disk drive (HDD). The hydrophone was placed on a side wall of the main pool at 1-m depth (Fig. 2).

149   To assess reactions to a newly introduced object, we recorded
150 behaviour and vocalisations on December 27 and 28, 2007, from the same
151 observation window and the pool-side floor of the main pool. The object
152 introduced was a handle with two sucker discs affixed to the pool wall, used
153 by aquarium staff for support while cleaning the pool. The object was
154 attached to the wall of the main pool close to the hydrophone (10 cm above
155 the hydrophone, Fig. 2). Video recordings were made using two video
156 cameras (HDR-HC3, Sony, Tokyo, Japan, and DM-IXYDVM5, Canon, Tokyo,
157 Japan). In three 30-min recording sessions, each starting 5 min after
158 introduction of the object, vocalisations were recorded with the same system
159 and settings used in the previous recording of July 25, 2007. In two sessions,
160 we recorded sounds with a custom click detector (Clicker45, Tachibana
161 Electric Co. LTD., Tokyo, Japan), set between the amplifier (Reson EC6081)
162 and video camera (Canon DM-IXYDVM5), using one channel of the video
163 camera (16 bit, 44000-Hz sampling rate). The click detector converted each
164 click to a 500-µs rectangular signal with a voltage corresponding to the peak
165 level of the click.

166   To assess the relationship between behaviour and sounds when the
167 dolphins approached the introduced object or began to parallel pair-swim
168 with other individuals, the sounds, position, posture, and swimming speed of
169 the approaching dolphin were recorded for 3–5 s until it reached the object or
170 other individual. Parallel pair-swimming is a behaviour in which two
171 dolphins swim side by side in close (< 0.5 m) proximity without body contact
172 (Sakai et al., 2013).

173   Sounds produced at the onset of social behaviour (flipper rubbing)
174 were recorded for 5 s before dolphins engaged in parallel pair-swimming
175 initiated flipper rubbing. Flipper rubbing is a behaviour in which one
176 dolphin rubs the other dolphin with its flipper (Sakai et al., 2006).

177   Although sounds could not be attributed to specific individuals in
178 the July 25 data because the recording was made with a single hydrophone,
179 those recorded December 27–28 were attributed based on the direction and
180 position of all individuals relative to the hydrophone in the video records. In
181 the analysis of sound and behaviour when an object was introduced to the
182 tank, only sounds thought to be produced by the dolphin approaching the

183   object were analysed; i.e. we considered only those recorded when no other

184   dolphins in the tank directed their heads toward the object.

185

186   **2.3. Sound analysis**

187   All sound records on July 25 and December 27–28 were analysed using the

188   Igor Pro ver.6 software (Wave Metrics Incorporated, Oregon, US) and Adobe

189   Audition 3.0 software (Adobe Systems Incorporated, California, US). Sound

190   spectrograms of all sounds with a good signal-to-noise ratio from July 25

191   were generated using the fast Fourier transform (FFT) algorithm, with FFT

192   length of 256, 100% frame size, and a rectangular window. The sound

193   frequency with maximum energy (peak frequency) in each click was

194   analysed using Adobe Audition 3.0. Inter-click interval (ICI) is the interval

195   between the envelope peaks of consecutive clicks. We measured ICI using a

196   program that we made in Igor Pro. In this analysis, we eliminated any ICIs <

197   0.5 ms as they were most likely caused by reflection from the tank walls or

198   water surface. Hatakeyama (1988) reported that the minimum ICI of a

199   captive Commerson's dolphin was 2.9 ms; Kamminga and Wiersma (1981)

200   also reported that the average ICI of a captive Commerson's dolphin was > 2

201   ms (500 pulses/s) and that the minimum ICI of a captive harbour porpoise

202   was 1.0 ms (Clausen et al., 2010). All statistical analyses in this study were

203   conducted using Igor Pro.

204

3. Results

All recorded sounds were ultrasonic pulses (clicks). In all, 114,590 pulses were recorded during 270 min from three individuals on July 25, 2007 and 227,910 pulses during 90 min from four individuals on December 27–28, 2007. Two types of pulse sound with different peak frequencies were recorded. The peak frequencies of each type were 129.4 ± 4.9 kHz (mean $\pm$ SD, $n = 30$, 87.1% of recorded pulses) and 113.0 ± 6.0 kHz ($n = 30$, 11.9% of recorded pulses), respectively.

Figure 3 shows the distribution of ICIs measured for all clicks recorded on July 25, 2007. Ninety-six percent of the measured ICIs were < 100 ms (Fig. 3, mean ICI = 35.16 ± 30.81 ms). Based on this result, we defined a click-train as a group of sequential pulses separated from other pulses by an ICI > 100 ms. Most of the recorded pulses (94.5%) were produced as click-trains, sequences of several clicks (> 5 pulses) with relatively short ICIs, and 5.5% were produced as single pulses or very short click-trains with 2–4 pulses. We removed single pulses or very short click-trains of < 4 pulses from the analysis. A total of 6,449 click-trains were identified on July 25, 2007. The mean values ($\pm$ SD) of pulse number, ICI and duration of the click-trains were 43.9 ± 32.9, 26.5 ± 20.0 ms and 769.2 ± 700.6 ms, respectively.

3.1. Variation of click-trains

We categorised click-trains by focussing on changes in mean ICI pattern, especially in the last part of the train (including > 5 pulses from the last pulse), because it might reflect changes in target distance if the train was used for echolocation. Click-trains were divided into two groups based on mean ICI: those with very short mean ICIs < 4.0 ms, and others with longer mean ICIs. Those with longer mean ICIs were further divided into three groups based on changing ICI pattern in the last part of the train. Thus, click-trains were categorised into the following four types (Fig. 4): Burst-pulse type, with very short (< 4.0 ms mean) and relatively constant ICI (Fig. 4-A); Decreasing type, with longer mean ICIs, in which ICI continuously decreased by > 2.0 ms in the last part of the train (Fig. 4-B); Increasing type, with longer mean ICI, in which ICI continuously increased

239   by > 2.0 ms in the last part of the train (Fig.4-C); and Fluctuating type, with

240   longer mean ICI, in which ICI fluctuated in the train without a definite

241   continuous increase or decrease in the last part (Fig. 4-D).

242   The parameters of each type of click-train are shown in Table 1.

243   Only clear click-trains were used for this analysis because the dolphins often

244   emitted sounds simultaneously, confounding assessment. The mean ICI

245   differed significantly among these types (Kruskal-Wallis test: H = 69.61, $P <$

246   0.001). It was highest in the Increasing type (31.6 ms), followed by the

247   Fluctuating type (29.6 ms), the Decreasing type (25.0 ms), and the

248   Burst-pulse type (3.5 ms).

249   The mean click-train duration was longest in the Fluctuating type

250   (1344.3 ms) and shortest in the Burst-pulse type (458.9 ms), though

251   significant differences were observed only between the Fluctuating type and

252   each of the other types (Kruskal-Wallis test, H = 61.84, $P <$ 0.001). The range

253   and standard deviation of click-train duration were also largest in the

254   Fluctuating type and smallest in the Increasing type.

255   The change in click-train ICI (maximum − minimum) was largest

256   in the Fluctuating type (62.7 ± 19.2 ms) and smallest in the Burst-pulse type.

257   The change in ICI and the duration of continuous ICI change observed

258   during the last part of the train were 25.0 ± 14.3 ms and 409.9 ± 240.2 ms in

259   the Decreasing type and 36.0 ± 18.3 ms and 347.6 ± 201.04 ms in the

260   Increasing type, respectively.

261   Figure 5 shows the frequency (number/min/dolphin) and proportion

262   (percent) of each click-train type in the sounds recorded on July 25, 2007.

263   The Fluctuating (3.7/min/dolphin) and Decreasing (2.7/min/dolphin) types

264   were recorded more frequently than were the other types. The Increasing

265   type was the least common (0.4/min/dolphin, Fig. 5).

266

267   **3.2. Relationship between behaviour and click-train type**

268   Figure 6 shows the change in the frequencies (number/min/dolphin) of each

269   click-train type observed when a dolphin approached and then left a newly

270   introduced object (n = 165, 90 min in total). The dolphins typically swam in a

271   counter-clockwise routine course near the wall, but after the object was

272   introduced, they often changed course to approach it repeatedly (Fig. 1).

Clicks trains were recorded in 156 of 165 approaching-and-leaving episodes (94.5 %; no or few isolated pulses were recorded in the remaining 5.5%). The frequency of the Decreasing type increased during the approach to the object but decreased suddenly as the dolphin passed (Fig. 6). The Burst-pulse type increased suddenly when the dolphin reached a position immediately in front of the object, and was recorded in 50 of 165 episodes. When the Burst-pulse type was recorded, the dolphin often bent its head toward the object (43 of 50 episodes, 86 %) By contrast, when the focal dolphin was approaching the newly introduced target, the frequency of the Fluctuating and Increasing types did not change markedly, though the Fluctuating type seemed to decrease slightly after the dolphin passed.

The frequency of the Decreasing type during approach (14.7/min/dolphin) was significantly higher than normal (2.6/min/dolphin, the mean value of all recording sessions on 25 July, 2007, Fig. 5) (Wilcoxon test, $P = 6.61\mathrm{E}^{-20}$). That of the Burst-pulse type (9.2/min/dolphin) was also significantly higher than the baseline level (1.3/min/dolphin) (Wilcoxon test, $P = 1.25\mathrm{E}^{-13}$). The frequency of the Fluctuating type during the approach (10.7/min/dolphin) was significantly higher than the baseline (3.7/min/dolphin) (Wilcoxon test, $P = 4.93\mathrm{E}^{-09}$), while that of the Increasing type (0.3/min/dolphin) was slightly lower (vs. 0.4/min/dolphin) but not statistically different (Wilcoxon test, $P = 0.53$).

Figure 7 shows the change in the frequency (number/min/dolphin) of each sound type when approaching another individual, and during parallel pair-swimming (n = 44, 220 s in total) thereafter. The frequencies of the Increasing and Decreasing types increased during the approach to the other dolphin, and decreased before the dolphins took up typical positions for parallel pair-swimming. After starting parallel-pair swimming, the frequency of the Increasing type increased again for about 2 s, and then decreased. By contrast, the Decreasing type gradually decreased after the two dolphins started parallel-pair swimming. The frequency of the Fluctuating type decreased gradually during the approach, and increased again gradually after the dolphin reached its partner and began parallel-pair swimming. The Burst-pulse type increased during the approach until

307 parallel pair-swimming commenced, and decreased again thereafter.
308 However, the change of frequency in Fig. 7 was unclear, probably because
309 the sound-emitting dolphin could not be identified and sounds from other
310 dolphins were included in the analysis for Fig. 7.

311 The frequencies (number/min/dolphin) of the Increasing and
312 Fluctuating types during the approach were significantly higher than the
313 mean value of the entire recording (Fig. 8, Wilcoxon test, $P = 0.00039$ and $P =$
314 $1.10E^{-10}$); the frequencies of the Increasing (2.3/min/dolphin) and
315 Fluctuating (9.7/min/dolphin) types were 5.7- and 2.6-fold higher than the
316 baseline level (0.4/min/dolphin and 3.7/min/dolphin), respectively.

317

318 Finally, we compared the frequency (number/min/dolphin) of each
319 sound type between the two approach behaviours: approach to a new object
320 (n = 165) and approach to another individual (n = 44) (Fig. 9).

321 The frequencies (number/min/dolphin) of the Decreasing (14.7
322 /min/dolphin) and Burst-pulse (9.2/min/dolphin) types during the approach
323 to the object were significantly higher than those during the approach to the
324 other individual (8.4/min/dolphin and 2.3/min/dolphin; Wilcoxon test, $P =$
325 $3.72E^{-21}$ and $P = 9.04E^{-10}$, respectively), while the frequency of the
326 Increasing type (2.3/min/dolphin) was significantly higher when approaching
327 the other individual than when approaching the object (0.3/min/dolphin;
328 Wilcoxon test, $P = 0.00030$). We observed no significant difference in the
329 Fluctuating type (Wilcoxon test, $P = 0.64$).

330 During parallel-pair swimming before flipper rubbing behaviour (n
331 = 14, 70 s in total), the frequencies (number/min/dolphin) of the Increasing
332 (2.3/min/dolphin) and Fluctuating (8.6/min/dolphin) types were significantly
333 higher than the mean values of the entire recording (0.4/min/dolphin and
334 3.7/min/dolphin, Wilcoxon test, $P = 0.019$ and $P = 6.86E^{-03}$ respectively). We
335 found no significant difference in the frequency of the Decreasing
336 (2.6/min/dolphin) or Burst-pulse (1.4/min/dolphin) types compared with the
337 mean values of the entire recording (3.2/min/dolphin and 1.8/min/dolphin,
338 respectively; Wilcoxon test, $P = 0.91$ and $P = 0.88$).

339

340

4. Discussion

4.1. Variation in recorded sounds

In this study, we recorded only ultrasonic click sounds (ca. 113–130 kHz in peak frequency), with no whistles or audible sounds. In previous studies, low frequency clicks (ca. 1.0–6.0 kHz) were also reported in captive Commerson's dolphins (Dziedzic and De Buffrenil, 1989; Hatakeyama et al., 1988; Shochi et al., 1982; Watkins and Schevill, 1980). Some of these low-frequency clicks were audible to researchers, though not recorded frequently. These click-trains, or cry sounds, include audible low-frequency clicks with very short ICIs, similar to the Burst-pulse type (Shochi et al., 1982). Cry sounds are composed of high (116–133 kHz) and low (1–7 kHz, audible to humans) frequency clicks (Dziedzic and De Buffrenil, 1989; Shochi et al., 1982). Watkins et al (1977) defined the cry sound as a pulse series at a repetition rate rapid enough to produce tonal sounds. Shochi et al. (1982) also reported short clicks in the ultrasonic range superimposed on low-frequency pulses (1–2 kHz) audible to humans only when captive dolphins approached within 20–30 cm of the hydrophone. The two signal components were always synchronous. These reports suggest that the cry sounds were the low-frequency components of clicks caused by high repetition-rate ultrasonic pulses. Therefore, the cry sounds could have been the same sound type as the Burst-pulse type in the present study. The peak frequency of the high-frequency component (116–133 kHz) of the cry sound (Dziedzic and De Buffrenil, 1989; Shochi et al., 1982) was similar to that of the Burst-pulse type (113–130 kHz). Likewise, the peak frequencies of high-frequency clicks recorded in this study (130 kHz) were similar to those reported by previous studies on wild (133 kHz) and captive (116–133 kHz) Commerson's dolphins (Evans et al., 1988; Kamminga and Wiersma, 1981; Kyhn et al., 2010).

4.2. Function of each click-train type

4.2.1 Decreasing type: recognition of a target as it is approached

The ICI pattern of the Decreasing type click-train (Fig. 4), where ICI decreased in the last part of the train, suggests that it is used for echolocation when the dolphin is approaching a target, as the ICI of

375 echolocation clicks may reflect the distance between the dolphin and its
376 target (Au, 1993). Such a rapid decrease in ICI is known as the "approach
377 phase" in the echolocation sounds of harbour porpoise and in bats
378 intercepting a target (Tian and Schnitzler, 1997; Verfuss et al., 2009). The
379 fact that the frequency (number/min/dolphin) of the Decreasing type of click
380 train increased during the approach to an object newly introduced to the
381 tank (a probable target), and when a dolphin approached another individual
382 (Figs. 6, 7), supports this view. However, the change in frequency of the
383 Decreasing type in Fig. 7 was not as clear as that in Fig. 4, probably because
384 the sound-emitting dolphin could not be identified and sounds from other
385 dolphins were included in the analysis for Fig. 7. Shochi et al. (1982) and
386 Watkins and Schevill (1980) also observed that ICI decreased in the
387 click-trains of captive Commerson's dolphins when the dolphins approached
388 a fish or other targets, and suggested that the sounds were used in target
389 echolocation. Similar ICI-decreasing click-trains were reported in wild
390 Hector's dolphins approaching a hydrophone (Dawson, 1991).

391   In captive harbour porpoises, Clausen et al. (2010) reported similar
392 click-trains in a mother-calf pair when they engaged in aggressive or
393 encounter behaviours ("contact call behaviour") in which the dolphins
394 approached each other. These click-trains were characterised by increasing
395 repetition rate (rapid decrease of ICI), changing from 20 to 800 clicks/s (50 to
396 1.2 ms ICI). This is similar to the ICI range of our Decreasing type
397 click-trains (89.5 to 1.1 ms ICI). It is possible that the harbour porpoise
398 click-trains were also used for echolocation, though the results of Clausen et
399 al. (2010) suggest that these sounds were used for communication.

400

401 4.2.2 Burst-pulse type: short-range target recognition
402 The fact that most of the Burst-pulse type click-trains were emitted toward
403 the object newly introduced to the tank from a distance of ~0.5 m suggests
404 that they were used for close proximity echolocation. Moreover, we recorded
405 a significant increase in the Burst-pulse type when an object was newly
406 introduced.

407   However, some "lag time" is thought to be required for the neuronal
408 process of echolocation, and many of the ICIs in the Burst-pulse type (mean

409 3.5 ± 1.1 ms) may have been shorter than the time required. Lag time is
410 defined as the difference in time between the two-way travel time of the
411 sound to the target and the ICI (Au and Cranford, 2000). Although the lag
412 time of Commerson's dolphin is still not known, the minimum lag time
413 estimated for the Atlantic bottlenose dolphin (family Delphinidae, the same
414 as Commerson's dolphin) was reported as 2.5 ms (Au et al., 1974). However,
415 in the harbour porpoise (family Phocoenidae), a small species such as
416 Commerson's dolphin, the minimum lag time was reported as 1.5 ms
417 (Verfuss et al., 1999). Furthermore, the lag time of bottlenose dolphins
418 decreased from 15.4 to 2.5 ms as the distance to the target decreased from
419 1.4 to 0.4 m (Evans and Powell 1967). Assuming that the lag time of
420 Commerson's dolphin was similar to those of the bottlenose dolphin or
421 harbour porpoise, most of the Burst-pulse type ICIs were longer than the lag
422 time. Thus, it is possible that the Burst-pulse type could have an
423 echolocation function in Commerson's dolphin.

424   Kamminga and Wiersma (1981) also recorded a burst of sonar
425 signals (< 2-ms ICI, 500 clicks/s repetition rate, 4-s train duration) similar to
426 the Burst-pulse type when captive Commerson's dolphins approached and
427 inspected newly introduced hydrophones at very short range. The reported
428 mean ICI (< 2 ms) was close to that observed for the Burst-pulse type (3.5 ±
429 1.8 ms), although the mean train duration (4 s) was not (458.9 ± 304.4 ms).
430 Such bursts of sonar signals emitted toward objects in close proximity were
431 also recorded in other dolphin species (e.g. bottlenose dolphin, white whale),
432 and the possibility of their function in echolocation with ICIs less than the
433 lag time has been discussed (Turl and Penner, 1989).

434   Burst-pulse sounds have been observed during aggressive social
435 interactions as well as approaching behaviour in NBHF species and other
436 odontocetes, and their function in both communication and echolocation in
437 these species is suspected. Harbour porpoise also emits a cry sound with a
438 mean ICI of 3.7 ms. Harbour porpoises use this cry sound during aggressive
439 behaviour toward other dolphins (Clausen et al., 2010; Nakamura et al.,
440 1998). However, we did not observe such behaviour or any remarkable
441 responses of other dolphins to the Burst-pulse type in Commerson's dolphin,
442 though Watkins and Schevill (1980) reported that cry sounds of captive

443 Commerson's dolphins seemed to elicit responses from others in the same
444 tank.

445　　　　The Burst-pulse type was recorded not only when the dolphins
446 faced a newly introduced object in close proximity but also when no obvious
447 echolocation targets were present, other than the tank walls and other
448 dolphins. However, we observed no notable behaviours oriented to those
449 targets (e.g. head bending toward the objects) (Fig. 10). The Burst-pulse type
450 also increased immediately after a dolphin approached another dolphin and
451 initiated parallel-pair swimming, though we could not identify the dolphin
452 emitting the sound. These facts suggest that some of the Burst-pulse type
453 click-trains were used for other functions, such as calls to swim together.
454 However, this increase may also have been due to increased short-range
455 echolocation of the partner when pair swimming. Although Burst-pulse type
456 click-trains aimed at the newly introduced object might also have been alarm
457 calls, we did not observe any obvious reactions in other dolphins when they
458 were emitted. Thus, our results suggest that the Burst-pulse type sounds of
459 Commerson's dolphin in captivity were used as short-range sonar rather
460 than for communication. The fact that the reported cry sounds of
461 Commerson's dolphins were recorded for only a few days after the dolphins
462 were moved to a new tank (a novel environment with many targets for them
463 to inspect) also supports this view, as a prominent increase in the
464 Burst-pulse type was recorded when an object was newly introduced.
465
466 4.2.3 Fluctuating type: sensing targets at various ranges
467 In the Fluctuating type click-trains, ICI fluctuates irregularly over a wide
468 range. If this type of click-train were used for echolocation, the target
469 distance would also change irregularly and widely, because ICI reflects the
470 distance between the dolphin and the target, including the lag time (Au,
471 1993). Thus, the irregular change of ICI suggests that the Fluctuating type
472 was used for scanning a wide range of space in front of the dolphin rather
473 than for echolocating a particular target. Hatakeyama et al. (1988), who
474 studied captive Commerson's dolphins in a Japanese aquarium, reported
475 that clicks with widely varying ICI (similar to the Fluctuating type)
476 increased when the aquarium lights were turned off, suggesting that they

477   were used for echolocation.

478   The Fluctuating type was the most frequently recorded sound type,
479 accounting for about half of all recorded click-trains. The Fluctuating type
480 became significantly more frequent than the baseline level when
481 approaching both the introduced object and other dolphins prior to
482 parallel-pair swimming. This suggests that the Fluctuating type increased
483 during active behaviours, though it decreased as other sound types increased
484 just before and after dolphins started parallel-pair swimming (Fig. 7). Shochi
485 et al. (1982), who studied captive Commerson's dolphins, reported that the
486 repetition rate of clicks varied widely (like the Fluctuating type) when the
487 dolphin was resting in the water, motionless, or swimming slowly, though
488 they did not provide precise data. This observation suggests that the
489 dolphins produce Fluctuating-type click-trains even when inactive. The
490 frequent use of this sound type, in both active and inactive states, suggests
491 that it is used for forward scanning; e.g. to avoid collision, to find fish, or to
492 investigate the surroundings (Akamatsu et al., 2010).

493   Akamatsu et al. (1998) compared the clicks of Baiji, Finless
494 porpoise, and Bottlenose dolphin between captive and wild individuals. They
495 reported that in all studied species, most of the click-trains from the wild
496 dolphins showed irregular ICI change without monotonous increment or
497 decrement, like the Fluctuating type, while those from captive dolphins often
498 showed monotonous ICI decrement, similar to the Decreasing type.
499 Furthermore, these latter sounds were used for echolocation by dolphins
500 approaching targets such as tank walls. Although Akamatsu et al. (1998) did
501 not discuss the function of click-trains with irregular ICIs, their results
502 suggest that the Fluctuating type is not used for echolocating a particular
503 target, as there are fewer target objects in open water than in aquarium
504 tanks. Dolphins in open water may scan their surroundings more frequently
505 than those in aquarium tanks. If so, the frequent use of this sound type in
506 open water also supports our view.

507

508 4.2.4 Increasing type: possibly for social communication
509 The changing pattern of ICI in the Increasing type, in which ICI increased in
510 the last part of the train, suggests that the target distance increased during

511   the train if it was used for echolocating a particular target object. Such an
512   echolocation target (to which the distance from the emitting dolphin
513   increased with time) was largely absent from our study, with the potential
514   exception of other dolphins and the tank walls, because dolphins did not
515   swim backwards. The target distance could increase if the targeted dolphin
516   swam away from the emitting dolphin. It could also increase as the angle
517   between emitted clicks and the targeted tank wall changed as the dolphin
518   changed course at the tank corners.

519   The frequency (number/min/dolphin) of Increasing-type click-trains
520   increased when a dolphin approached another dolphin and began
521   parallel-pair swimming, while they were rarely emitted when approaching a
522   newly introduced object. They also increased during parallel-pair swimming
523   just before flipper rubbing. These facts suggest that the Increasing type is
524   not used for echolocation. It is difficult to explain these results if we assume
525   that the Increasing-type click-trains were used for echolocating the tank
526   walls, as we observed no obvious change in the emitting dolphin's swimming
527   course. Rather, these facts suggest that the Increasing type was used for
528   initiating social behaviour in which the cooperative movements of two
529   dolphins are required.

530   There are no previous reports on click trains corresponding to the
531   Increasing type in Commerson's dolphin. In Hector's dolphin, however,
532   Dawson (1991) recorded click trains similar to the Increasing type. He
533   compared the sound types between social and non-social contexts to examine
534   the possibility that the dynamics of the click rate (increasing, constant, and
535   decreasing) carry social meaning, but detected no significant differences.
536   Click-trains similar to the Increasing type were also found in a report on
537   harbour porpoises (Clausen et al., 2010), although it did not describe these
538   click-trains precisely.

539   We examined the potential functions of each click-train type based
540   on the results of rather preliminary observations in which identification of
541   the sound-emitting dolphin was difficult. More precise studies on the
542   relationship between these click-train types and behaviour are needed to
543   clarify the functions of the various click-train types.

544

551

552 **Figure Titles (Captions) & Legends**

553 Fig. 1

554 Title: Recording setting.

555 Legend: Two video cameras and one hydrophone set in the main pool. All

556 dolphins usually swam the course indicated by the grey line. Dotted lines are

557 examples of swimming courses when approaching and leaving the object.

558

559 Fig. 2

560 Title: Example of approaching dolphin to the introduced object, and the

561 hydrophone.

562 Legend: Frame from video camera A (Fig.1). The sounds of the dolphin were

563 recorded by the hydrophone underneath the object.

564

565 Fig. 3

566 Title: Histogram of all recorded Inter-click-intervals (ICI) on July 25, 2007.

567 Legend: The right axis shows the ICI value and the left axis the

568 accumulation rate of all recorded ICIs. Ninety-six percent of measured ICIs

569 were < 100 ms (mean ICI ± SD = 35.16 ± 30.81 ms). The grey line indicates

570 the ICI cumulative frequency curve.

571

572 Fig. 4

573 Title: Click-train of each sound type.

574 Legend: X-axis: time line, Y-axis: ICI; Inter-Click-Interval (ms), SPL: Sound

575 Pressure Level (dB).

576

577 Fig. 5

578 Title: The frequency and percentage of each click-train type.

579 Legend: The numbers in the upper right are the percentages of all observed

580 trains.

581

582 Fig. 6

583 Title: Change in frequency of each click-train type when the dolphin was

584 approaching and leaving the object.

585 Legend: The frequency of the Decreasing type increased while approaching

586 the object, and the Burst-pulse type increased suddenly when the dolphin

587 reached a position immediately in front of the object.

588

589 Fig. 7

590 Title: Change in frequency of each click-train type while approaching

591 another individual.

592 Legend: The right y-axis indicates the number of Fluctuating type sounds.

593 The left y-axis indicates the number of other types.

594

595 Fig. 8

596 Title: Frequency of each sound type while approaching another individual.

597 Legend: The frequencies of the Increasing (2.3/min/dolphin) and Fluctuating

598 (9.7/min/dolphin) types were 5.7- and 2.6-fold higher than the baseline level

599 (0.4/min/dolphin and 3.7/min/dolphin), respectively.

600

601 Fig. 9

602 Title: Frequency of each click-train type during the approach to two different

603 targets.

604

605

606 Fig. 10

607 Title: A dolphin bending its head toward the introduced object.

608 Legend: Frame from video camera B (Fig. 1).

609

610 Table 1

611 Title: Characteristics of each click-train type

612

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700

Fig.1

8.4 m

6.8 m

Video Camera B

Hydrophone and the newly introduced object

Out of the frame of Video Camera A

The frame of Video Camera B

Usual swimming course

Examples of swimming course in approaching –and- leaving behavior

Starting area of approach and leaving（4 to 6 m from the object）

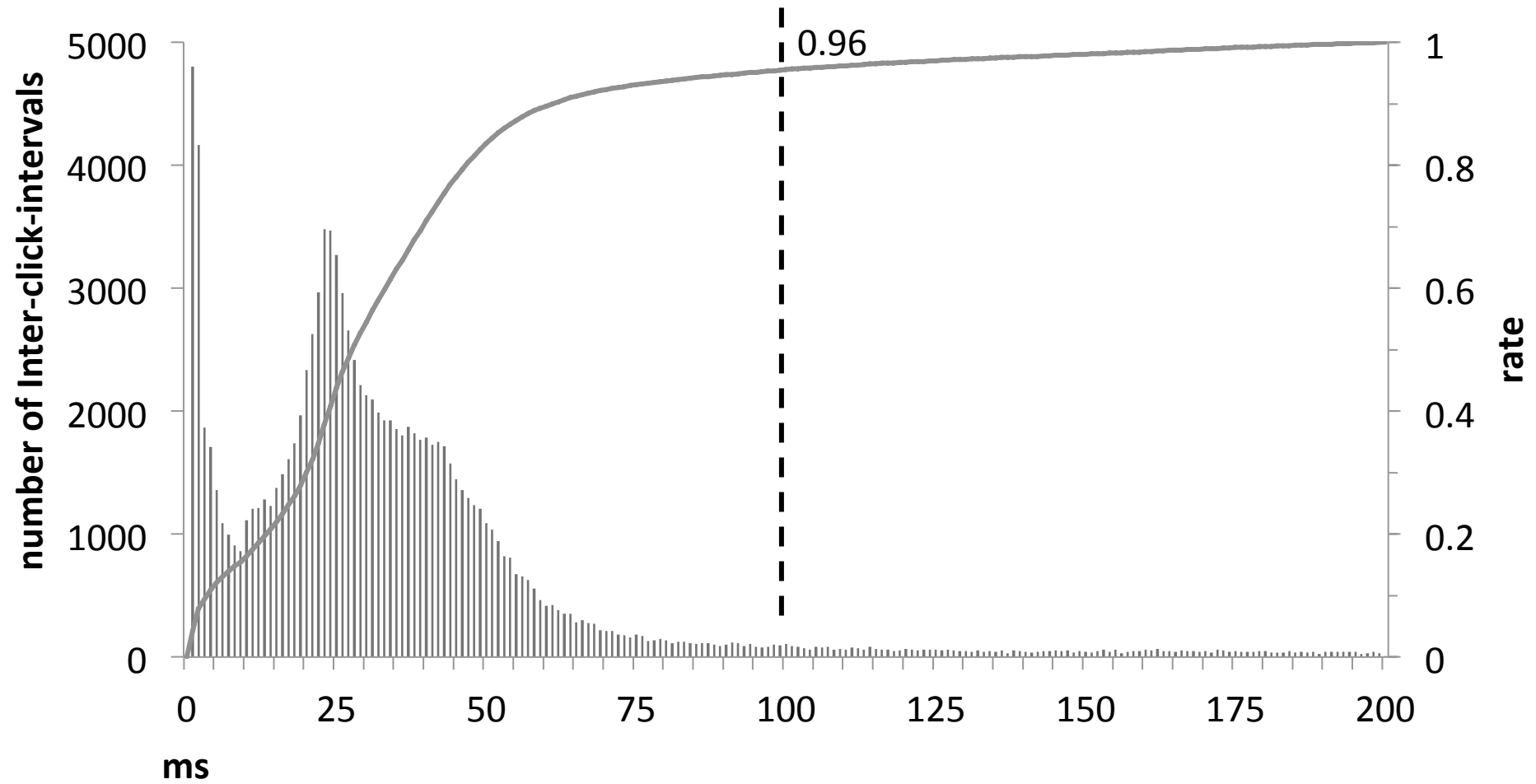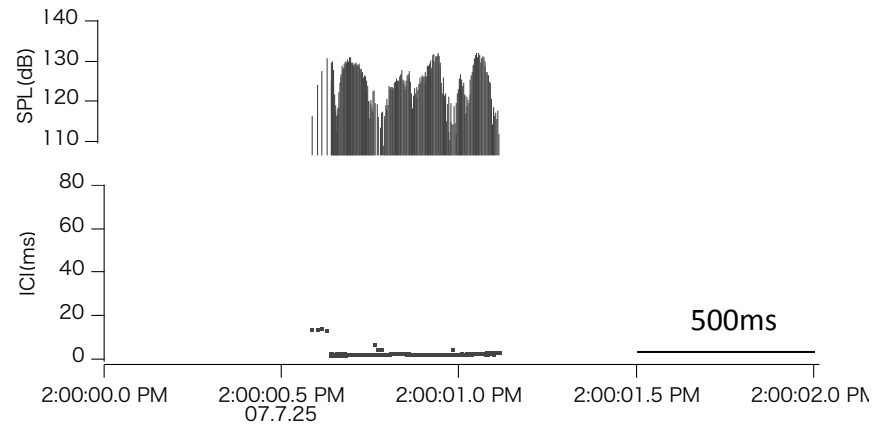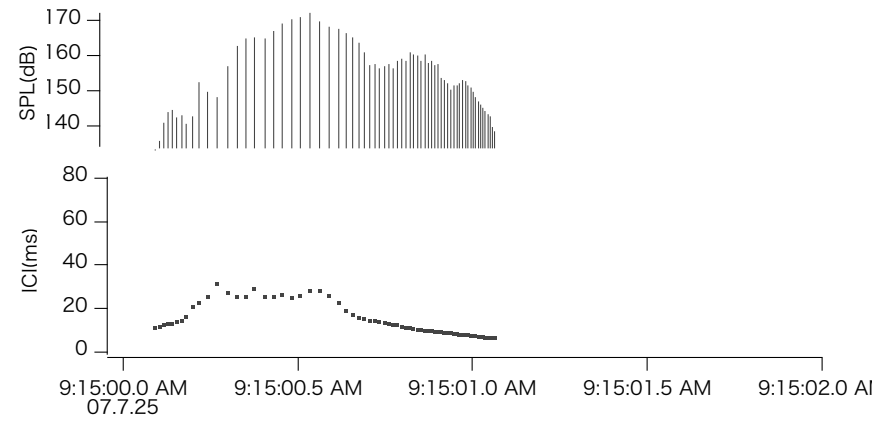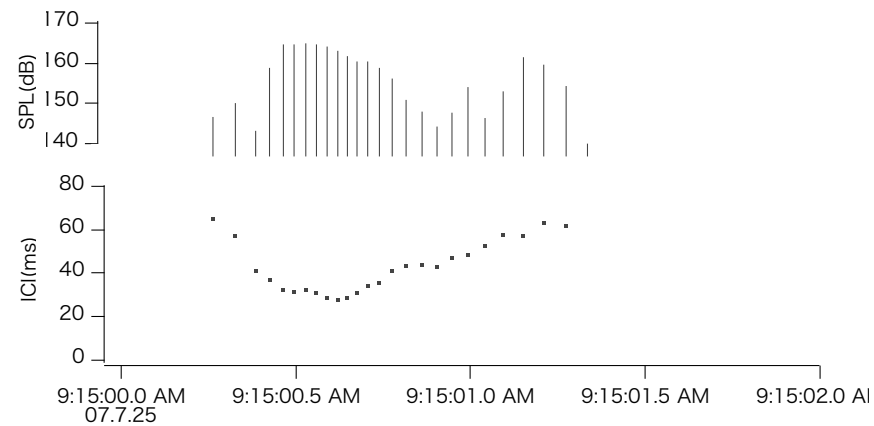Observation window （7 m width）

Video Camera A

Fig.2

Object

Hydrophone
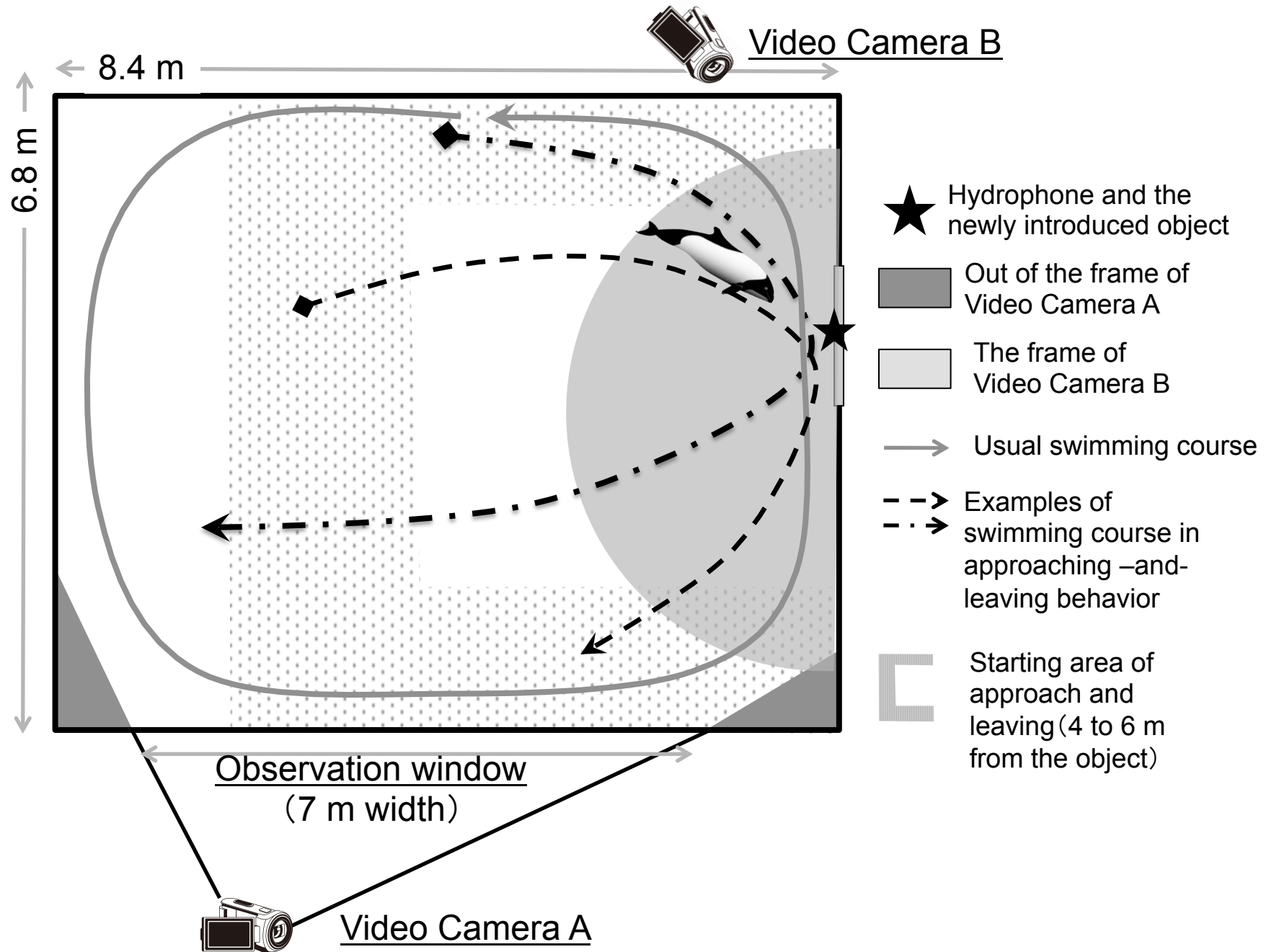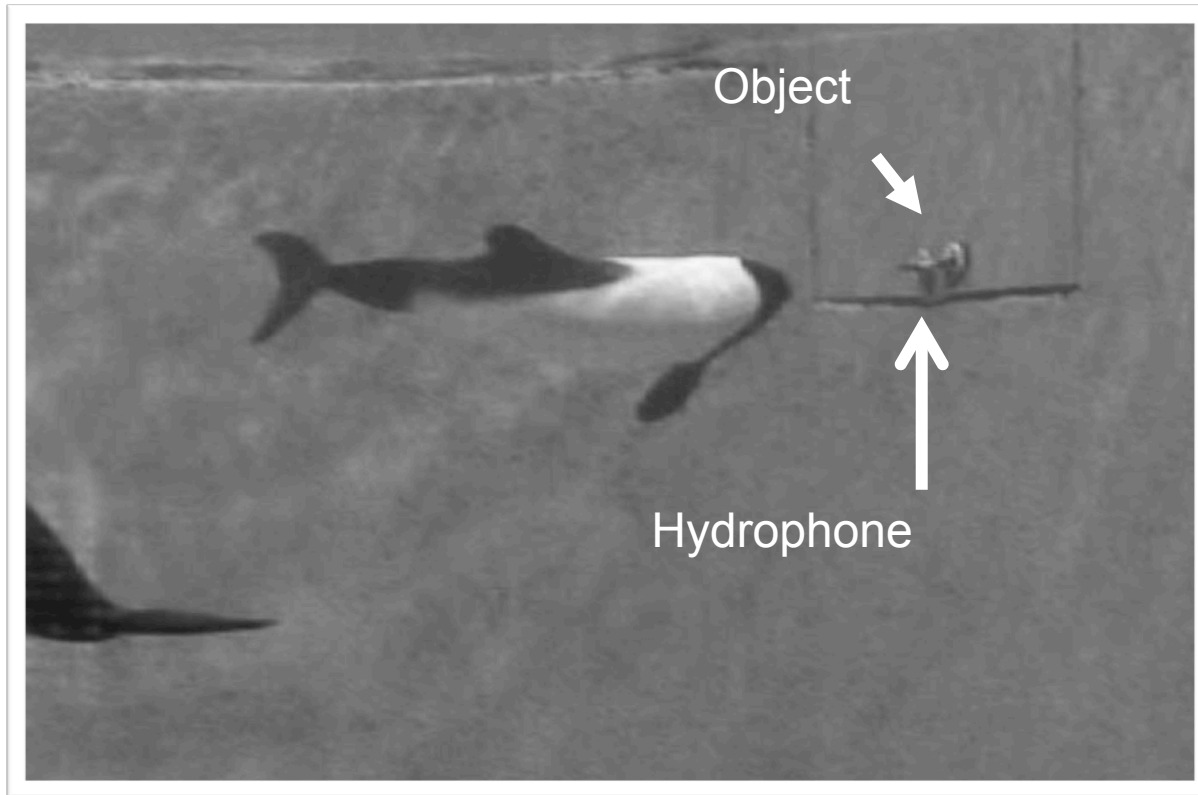
Fig.3

Fig.4

(A) Burst pulse type

(B) Decreasing type

(C) Increasing type

(D) Fluctuating type
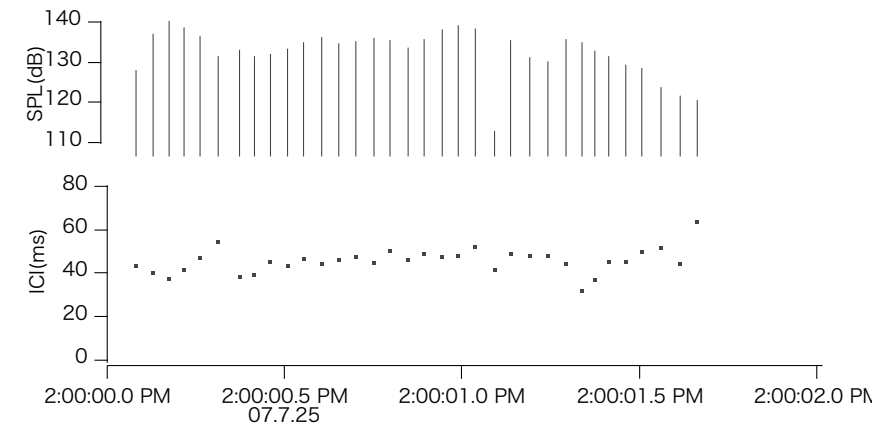
Fig.5
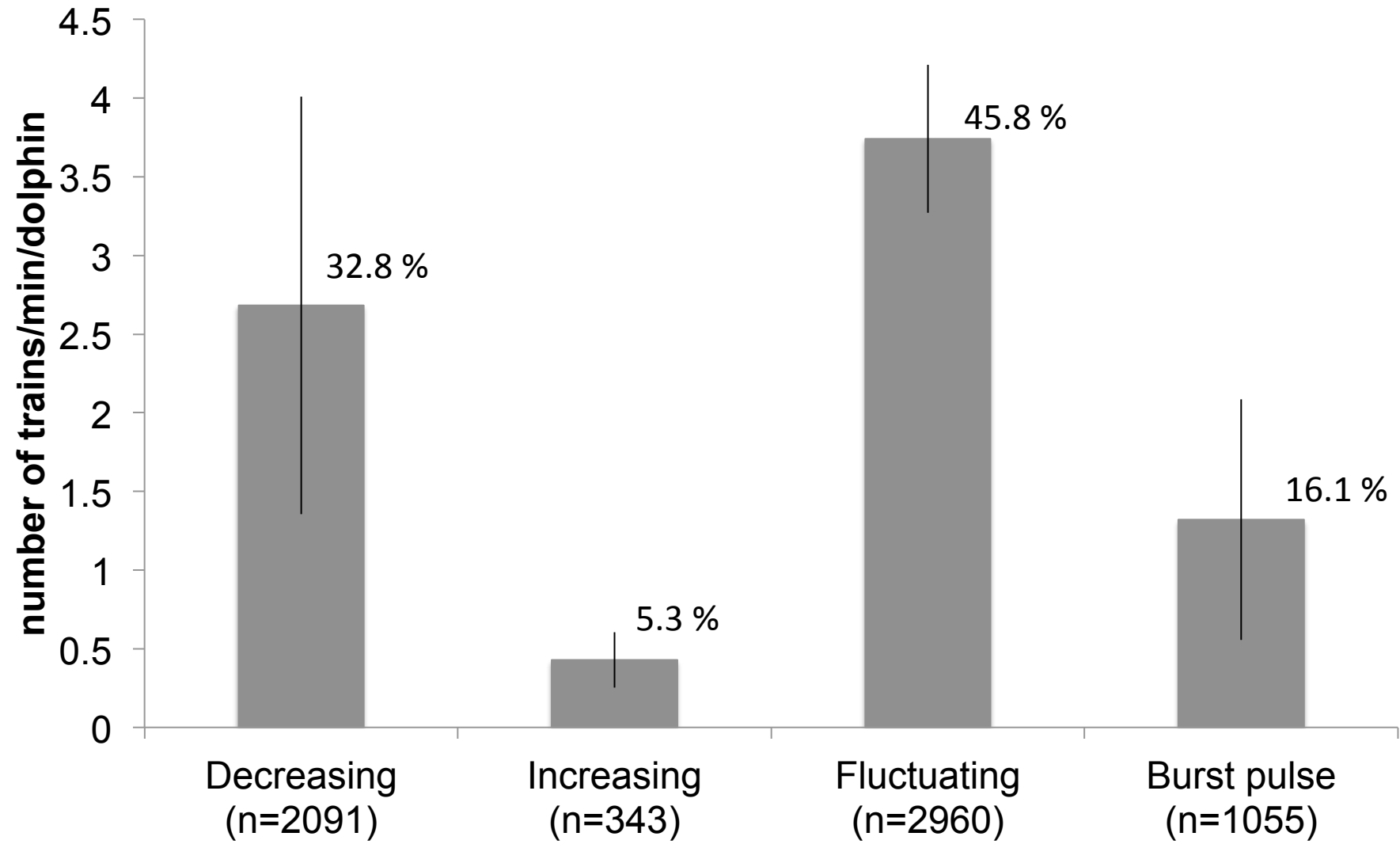
Fig.6
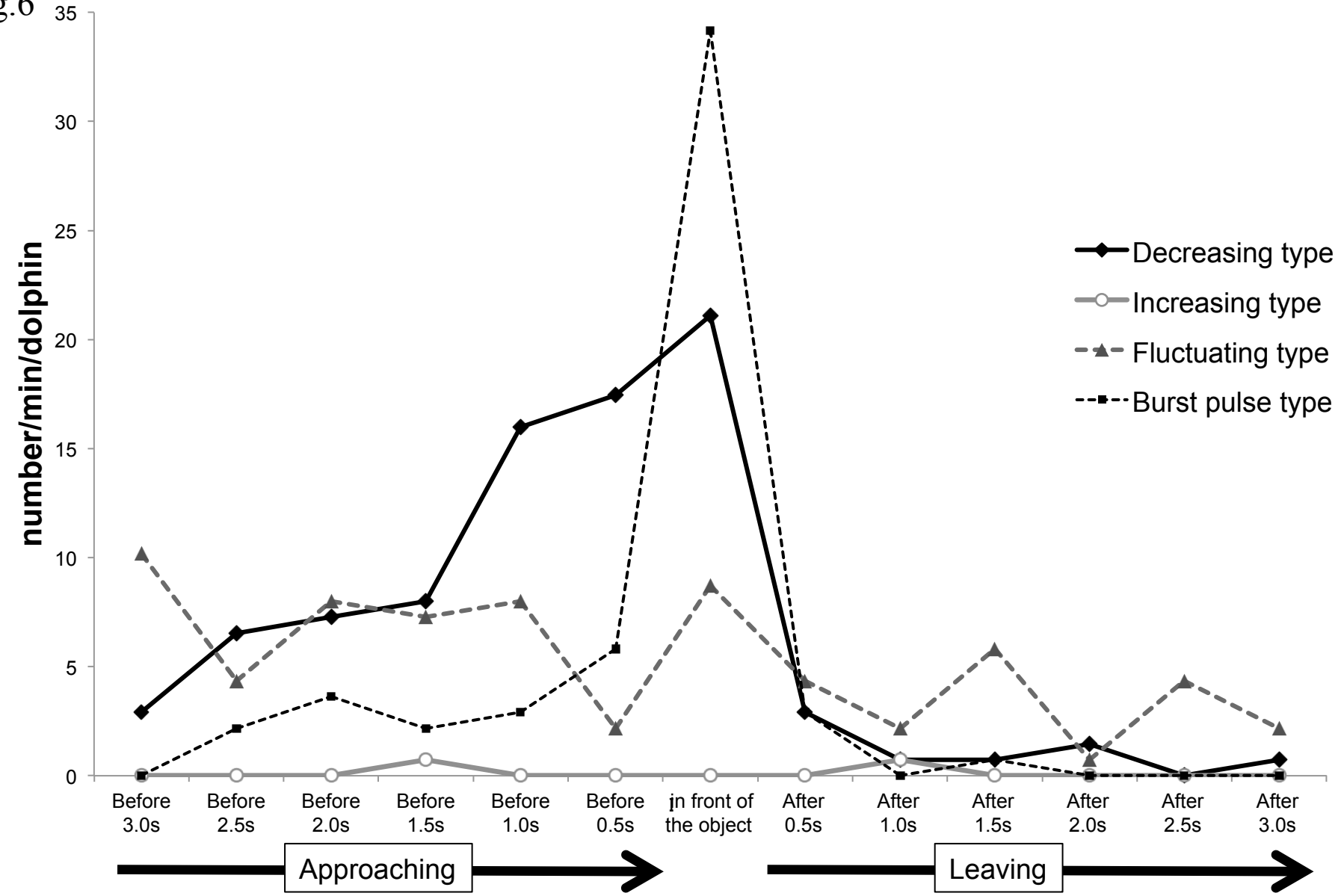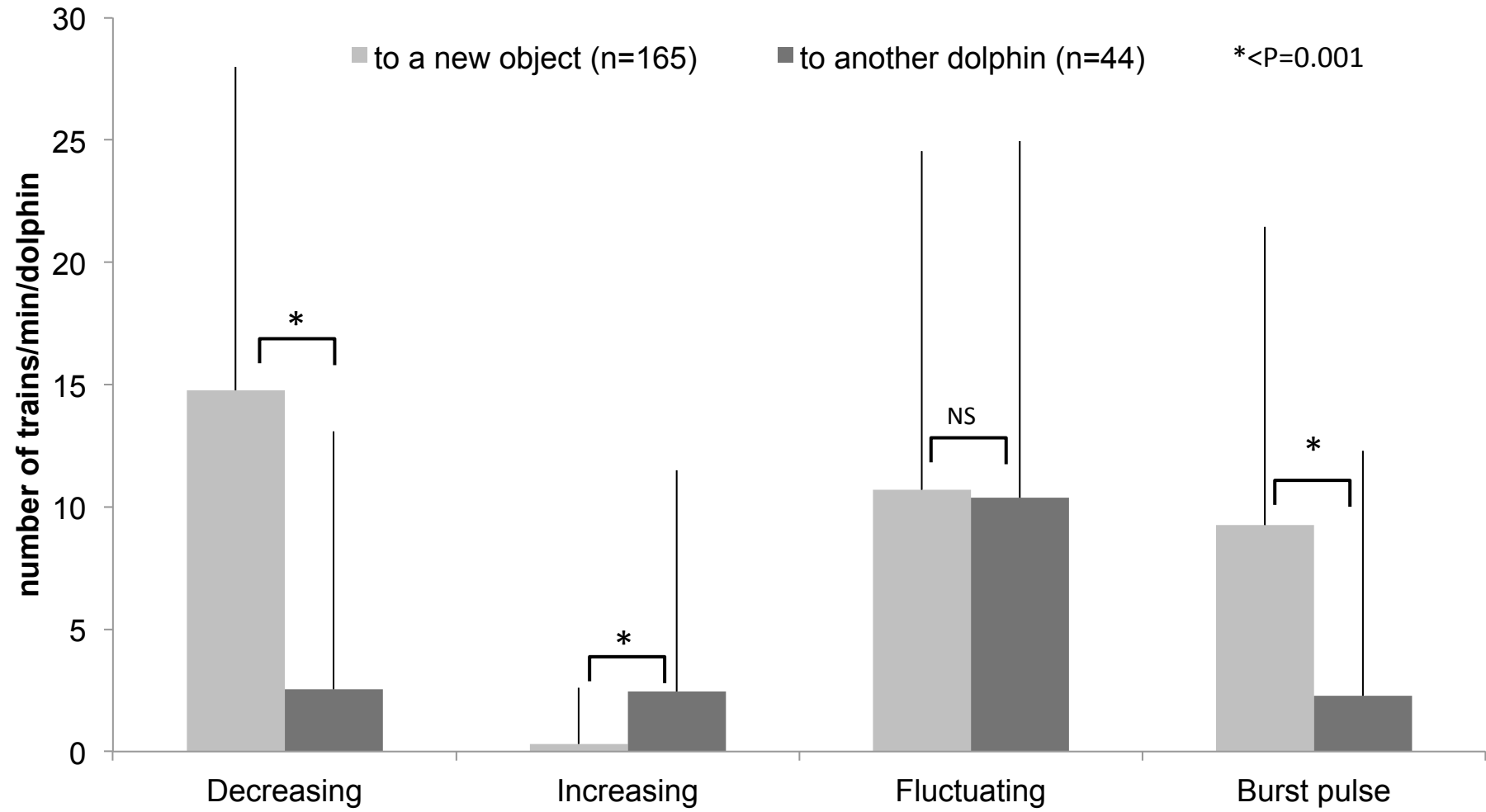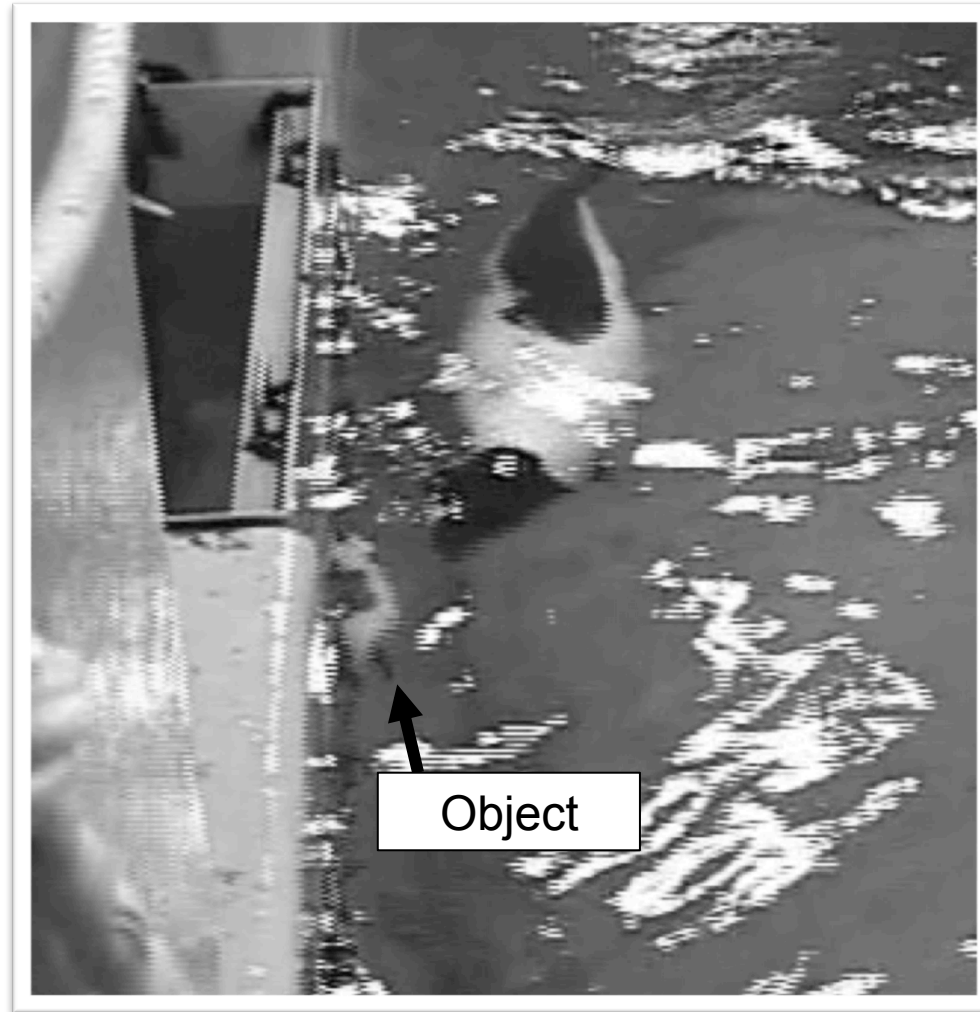
Fig.7

Fig.8

Fig.9

Fig.10

Object
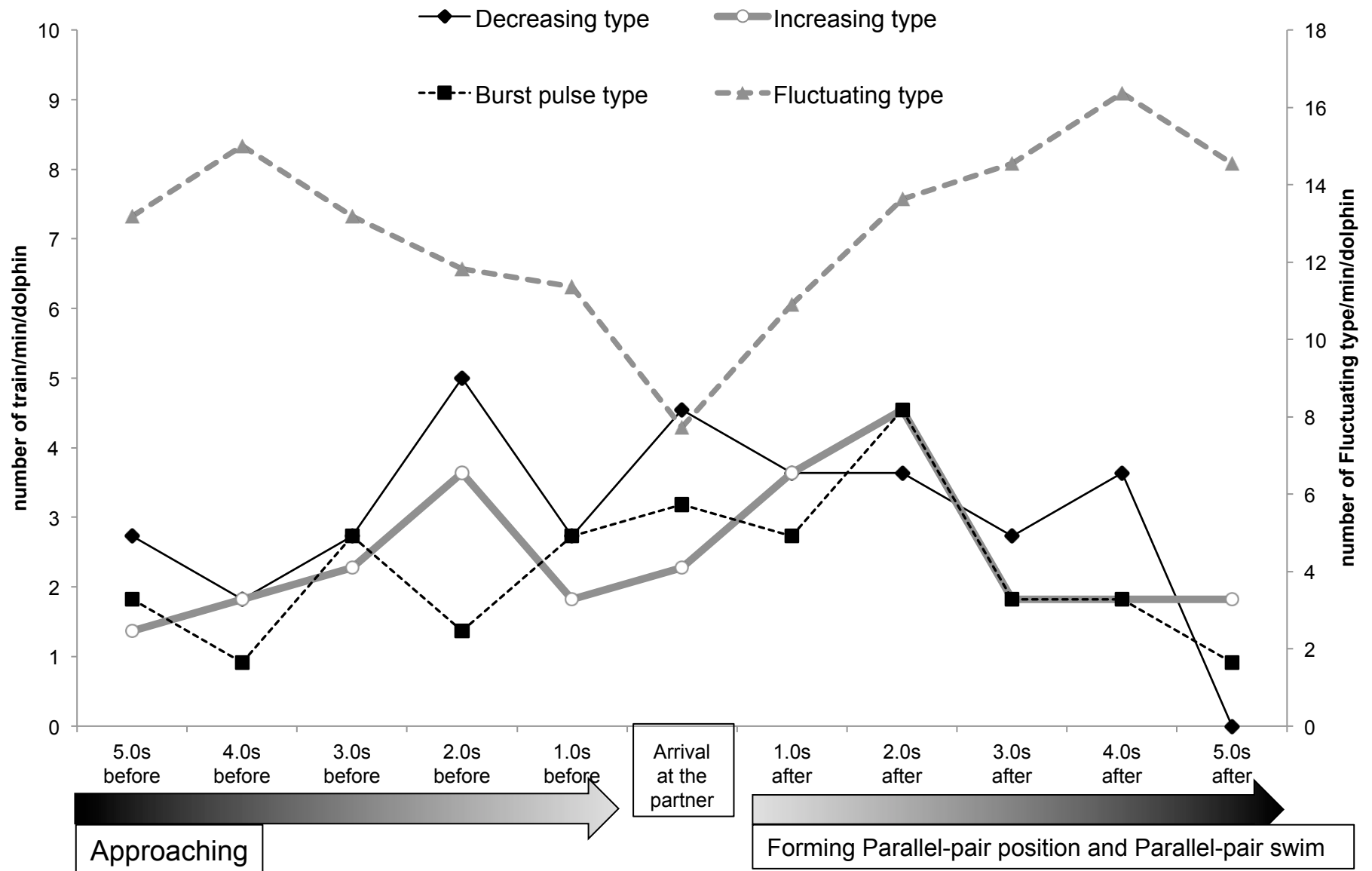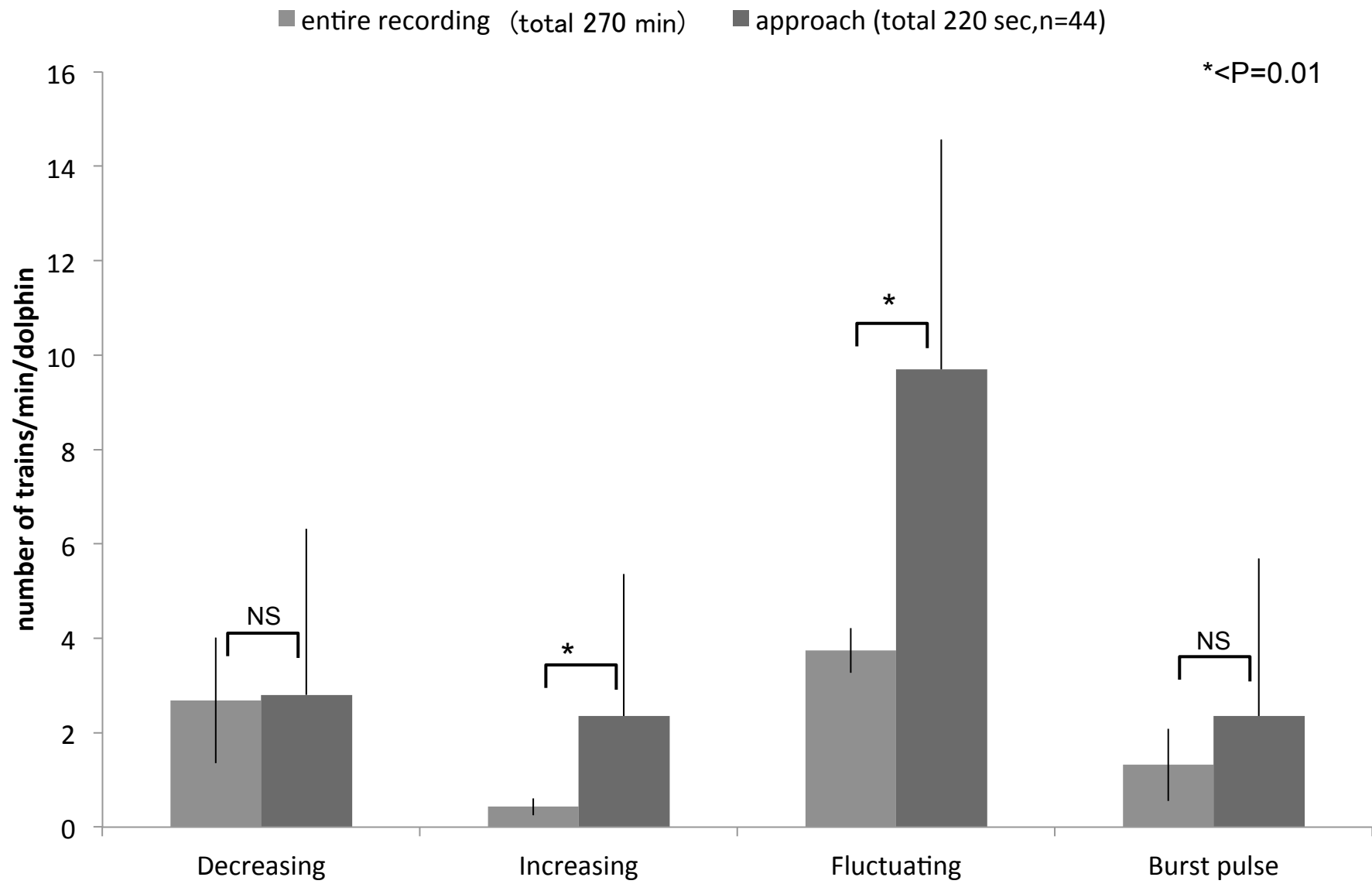
Table.1

Click-train type (n)	Inter-click interval (ICI) (ms)		Duration of the train (ms)		Change in ICI (ms)	
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
Decreasing (42)	25.0 ± 12.4	1.1 - 89.5	571.3 ± 324.6	81.2 - 1557.9	25.0 ± 14.3	3.2 - 69.1
Increasing (48)	31.6 ± 13.4	0.5 - 99.5	541.4 ± 264.8	167.9 - 1399.3	36.0 ± 18.4	11.2 - 86.5
Fluctuating (107)	29.6 ± 8.2	10.9 - 99.3	1344.3 ± 751.5	392.1 - 3977.5	62.7 ± 19.2	13.8 - 96.3
Burst Pulse (65)	3.5 ± 1.8	1.8 - 10.7	458.9 ± 304.4	73.1 - 1141.3	19.1 ± 23.2	0.1 - 75.0