Contents

1 Abstract

A dolphin’s sonar system is an advanced sense with a highly developed cognitive process which accounts for a large part of the brain activity. A pool constitutes an acoustically poor environment for a dolphin yet an artificial setting (i.e. a pool environment) is the most common mode of display in dolphin facilities around the world and floating toys in acoustically transparent materials are often used as enrichment. For the welfare of these animals it is important to find ways to encourage sonar use in pool environments. In this study environmental enrichment devices were introduced to a pool holding twelve bottlenose dolphins (*Tursiops truncatus)* in order to encourage their use of sonar. The study was conducted at the Kolmården dolphinarium in Sweden. Acoustic enrichment devices included four digital Porpoise Detectors deployed in different parts of the pool complex monitoring the sonar activity, an artificial kelp-alga imitation whose acoustical target strength was increased with air-filled net-floats, and also a hose that was set in motion with high pressure running water in response to sonar. The study showed a low general sonar activity in the pool, however, the sonar activity increased during interactions with devices with good acoustic reflection. The dolphins appeared to use acoustically reflective objects as land marks in otherwise acoustically empty surroundings. An interactive device encouraged sonar use as well as aroused interest and a moving object triggered hunting displays. The dolphins responded positively to tested acoustic enrichment additions indicating that this kind of enrichment should be further exploited.

Keywords: bioacoustics, bottlenose dolphin, dolphinarium, echolocation, environmental enrichment, odontocete, sonar, *Tursiops truncatus*

2 Introduction

A pool constitutes an acoustically poor environment for an echolocating dolphin. This can be improved through environmental enrichment. Because sonar is such an important sense for odontocete species acoustic enrichment should be of high interest and a main priority but this is usually not the case. Floating objects in acoustically transparent materials like rubber, plastic, and fabric are often used as enrichment for practical reasons but this leaves the water column visually and acoustically empty.

In zoos and other animal keeping institutions throughout the world a lot of time, effort, and money are put into designing and building exhibits meeting the requirements of good animal management. There is a growing demand from visitors, international animal welfare organizations, international zoo communities, and other regulatory authorities to see natural exhibits and the implementation of environmental enrichment to improve animal welfare. Dolphin and whale species are popular attractions at these exhibits, the most common species being the bottlenose dolphin (*Tursiops truncatus*).

2.1 The bottlenose dolphin

In the wild, bottlenose dolphins inhabit pelagic as well as coastal habitats and estuaries (Connor et al. 2000). They can migrate long distances over open sea and dive to depths of 600 meter while foraging (Norris 1991). They have good vision (Dawson 1980, Helweg & Mobley 1990, Herman 1990, Ridgway 1990) and along with other odontocete species they have an advanced biosonar system allowing them to navigate in dark and turbid waters. Sonar is frequently used during foraging, hunting and navigation (Ridgway 2000, Gordon & Tyack 2002). The bottlenose dolphin is a skilled hunter and can move at great speeds close to the bottom (Norris 1991). They also act as group hunters and show coordinated and synchronized behavior during hunting sessions (Norris & Dohl 1980, Awbrey & Evans 1988, Bel'kovich et al. 1991, Connor et al. 2000, Gordon & Tyack 2002).

Some odontocete species are known to navigate by bathymetric features when traveling long distances over open sea (Evans 1871, Tyack & Clark 2000). They are able to locate features such as underwater mountain ridges using for example visual and thermal cues as well as sonar (Evans 1971). Bottlenose dolphins have been observed in the wild as well as in captivity to use key structures in the environment as references for orientation (i.e. as land marks) (Evans 1971).

2.2 The sonar system

Odontocete species actively use sonar as one of the main sources of information (Ridgway 2000, Gordon & Tyack 2002). It is an advanced system based on highly developed hearing and cognitive processing accounting for a large part of the brain activity (Ridgway 1990, 2000). The sonar system of the bottlenose dolphin is based on trains of very short, broadband click sounds in which the intensity, power spectrum, and click repetition rate can be considerably varied (Au 1993).

2.2.1 Sound production

In contrast to other mammals, whose main source of sound production is located in the larynx, dolphins produce sound in the nasal cavity area located below the blowhole superior to the skull. Sound is generated by pressurized air in the bony nares being metered up through the main nasal passage which causes the phonic lips and surrounding tissue complexes to vibrate (Cranford & Amundin 2004). In front of the phonic lips and the associated air sacs there is a large, bulbous fat body called the melon. This structure acts as an acoustic lens projecting the sonar forward into a narrow beam with a -3 dB beam width of about 12º and the beam axis pointing approximately 5º above the longitudinal axis of the skull (Au 1993).

Bottlenose dolphins produce short (50-80 μs) pulses or clicks with a power spectrum ranging up to 150 kHz and at sound pressure levels (i.e. intensity) of over 230 dB re 1μPa at 1m (Au 1993). They can control the frequency composition of the clicks and most emissions are around two peak frequencies in the range of 40 – 60 kHz and 110 – 130 kHz (Kamminga 1988, Au 1993, Cranford & Amundin 2004).

2.2.2 Sound perception

The hearing is adapted to the expanded frequency range of the clicks and extends to 150 kHz with greatest sensitivity between about 40 and 100 kHz (Popper 1980, Au 1993, 2000, Ridgway 2000). The inner- and middle-ear are contained in a dense bony structure, i.e. the auditory bulla. Dolphins do not receive sound through the external ear channel as most terrestrial mammals do and they lack external pinnae. Sound enters the head through a thin-walled area of the lower jaw, called the “acoustic window” or pan bone area (Norris 1968, Popper 1980, Brill 1988, Brill et al. 1988, Au 1993, Rigdway 2000). Sound waves are then guided to the inner-ear through the cylinder shaped mandibular fat body, which extends from the pan bone area to the bulla (Norris 1968, Au 1993, Ridgway 2000). The melon and the mandibular fat body consist of a translucent lipid with a unique composition rich in isovaleric acid which gives it a low acoustic absorbance (Gardner & Varanasi 2003).

The inner-ear of the bottlenose dolphin has a more rigid basilar membrane, a longer cochlear channel and about three times as many ganglion cells as the human ear (Wever et al. 1971a, 1971b, Popper 1980, Au 1993, 2000, Ketten 2000, Ridgway 2000). This enables excellent pitch discrimination and perception of high frequency sounds (Wever et al. 1971a, 1971b, Popper 1980, Au 1993, Ketten 2000, Ridgway 2000). In spite of the fact that sound travels nearly five times faster in water than in air, sound perception tests have shown that the bottlenose dolphin has discrimination capabilities in water equivalent to those of humans in air (Au 1993). The bottlenose dolphin is also able to detect and classify a weak signal in a noisy environment better than any other vertebrate tested (Au 1993).

2.2.3 Sonar

When sound hits an object the majority of the reflected sound waves will originate from the front surface of the object creating an echo highlight (Au 1993). However, a large part of the sound waves will pass through the front surface, scatter in the interior structures, and reflect back through other paths with a delay. Circumferential waves will travel around the object. Hence, a target object with complex shape and surface structures will reflect back an echo with many highlights. Such highlights become more distinct and easier to separate if the sound emission is short and has a fast rise time, i.e. like a dolphin sonar click (Au 1993). A dolphin can determine distance, location, size, shape and interior properties of an object by scanning across it or by illuminating it with sonar clicks from different angles (Au1993). They can detect and distinguish details of an object at a distance of over 100 m (Popper 1980, Au 1988, 1990, 1993, 2000, Ridgway 2000). A dolphin can also extract information from the reflected echo of sonar emitted by another individual (Awbrey & Evans 1988, Harley et al. 1995, Gordon & Tyack 2002, Masters & Harley 2004). One or more individuals can passively “eavesdrop” on an echolocating dolphin and obtain the same information as that individual (Gordon & Tyack 2002, Masters & Harley 2004).

Sonar clicks are typically emitted in trains. They are spaced in time so that the reflected echo is received and processed before the next click is emitted (Au 1993). The brief lag between the receipt of the echo from one click and emission of the next click is normally between 20-40 ms (Au 1993). The inter click interval (ICI) in bottlenose dolphin click-trains are typically 10-25 ms when scanning a target at 1 m range, ~50 ms at 20 m range and 175-190 ms for a target at 120 m (Au 1993). In comparison the two-way travel time for a sound pulse is ~1.3 ms at 1 m range and ~160 ms at 120 m. (The speed of sound in water is roughly 1500 m s^{-1}.) At close range during a prey pursuit the ICI is reduced to only 2-3 ms where the echo processing probably is limited to only prey detection. The ICI’s of recorded sonar emissions can tell the approximate distance between the dolphin and the sonar target at the time of emission (Au 1993).

Clicks can also be emitted in social interactions. Such social pulse sounds can be distinguished from sonar by their characteristic frequency spectrum and ICI patterns (Blomqvist 2004).

2.3 A pool environment

An artificial setting (i.e. a pool environment) is the most common mode of display in whale and dolphin facilities around the world. The importance of the acoustic environment in pools was stressed by Stoskopf and Gibbons in 1994 (cited in Couquiaud-Douaze 1999) and later by Couquiaud-Douaze (1999). Animal rights organizations have also expressed concerns in this matter.

For health and safety reasons dolphins in human care are almost always hand fed dead fish as live fish increases the risk of introducing parasites and diseases. Many facilities also use chlorinated water in the pools and therefore making it impossible to offer live fish. This has the effect of reducing the possibility for the dolphins to perform foraging and hunting behavior.

Most dolphin pools are built in concrete which has high sonar target strength, but they often lack acoustical challenges. A pool environment is usually static and the animals soon learn all details of it. It is most often sufficiently lighted, have clear water, and few obstacles. Facilities are often illuminated even during dark hours (for example by exit signs), which allows dolphins to navigate solely by vision. A sea area contains numerous shellfish, corals, rocks, algae, fish, and other animals, organisms, and structures which all reflects sonar in various ways. When compared to a barren pool environment a noticeable difference is the severe lack of interesting and challenging acoustic tasks offered to dolphins living in pool environments. Because echolocation is a partially learnt behavior (Awbrey & Evans 1988, Tyack & Clark 2000), the absence of acoustical challenges and therefore stimulation in a pool can result in captive bred dolphins having inferior echolocation skills. Hence, for the welfare of dolphins in human care it is important to find ways to encourage and stimulate sonar use.

Couquiaud-Douaze (1999) addressed several factors to consider when designing and building a pool complex in order to improve the acoustic aspect. In existing pools environmental enrichment can be introduced in order to improve the same. Since the main purpose of environmental enrichment is to stimulate species specific behavior (Shepherdson et.al. 1998, Young 2003), acoustic enrichment should be of high interest and a main priority considering sonar is of such importance for dolphins. Unfortunately, this is usually not the case. Enrichment for dolphins is most often in the form of floating objects in acoustically transparent materials such as rubber, plastic and fabric. However, dolphins can bring air-filled balls underwater to play with. Such balls are strong sonar targets and also may stimulate prey catching behavior if released so they can float towards the surface. Except from this, the water column stays both visually and acoustically empty. (For general information on constructing enrichment devices, see Appendix 1.)

2.4 Objective

The aim of this study was to develop and evaluate environmental enrichment techniques to encourage the use of sonar in dolphins living in a pool environment. Enrichment objects were introduced in a pool in order to encourage activities associated with sonar use (such as navigation and hunting). Objects with good acoustic reflection were introduced to test the potential use of acoustic land marks in an otherwise acoustically bare surrounding. This study was conducted at the Kolmården dolphinarium in Kolmården Animal Park in Sweden.

3 Materials and methods

The dolphin facility at Kolmården held twelve Atlantic bottlenose dolphins during the time of the study. The genetic origin of the group was an inshore population in the Gulf of Mexico near the Mississippi river. Six of the dolphins were born at Kolmården and the age span for the group ranged from 3 to 32 years.

The pool complex of the dolphinarium had a water surface area of approximately 2000 m^2 and contained 6400 m^3 of water. It was divided into two large public display pools connected by a complex of smaller holding pools (Figure 1). The larger of the two display pools was more recently built and was referred to as “the lagoon”. This pool had a surface area of 900 m^2 with water depth varying between 3 and 6 m except for a shallow area in the perimeter of the pool. The water volume was 2500 m^3. The main public display pool was 800 m^2 and had a depth of 4 m. The intermediate holding pool complex had four pools varying in size between 16 and 117 m^2, all with a water depth of 4 m. All pools were interconnected with gates and channels.

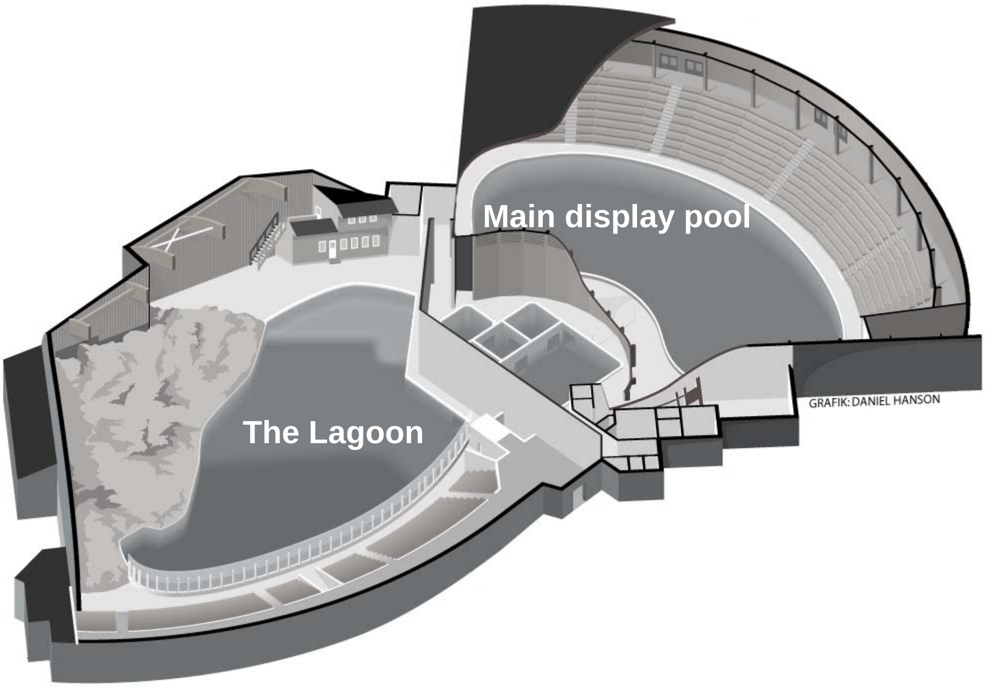

Figure 1. An overview of the dolphinarium in Kolmården.

Three separate experiments were conducted during this study. The first measured the baseline sonar activity using four digital Porpoise Detectors (POD's) deployed in different parts of the pool complex. The second tested the effect of increased sonar target strength of a kelp-algae imitation made of a tough cellulose fabric material. This was done by supplementing it with fabric fire hoses in which ropes with air-filled net-floats were inserted. In the third experiment a hose was introduced into the pool. It could be set in motion by high pressure running water, either started by the experimenter or in response to sonar sound picked up by a hydrophone attached to the end of the hose. The interactions between the dolphins and the devices were documented over time. For definition of documented behavior parameters, see the ethogram presented in Appendix 2.

Observations were conducted during daytime between 7:00 and 17:00, when dolphins were active and trainers present in the facility. The general daily schedule for the dolphins is presented in Appendix 3. The duration of the observation sessions was restricted by daily activities such as feeding, training, and public performances. During the observations no interaction between trainers and animals occurred and no other enrichment objects (i.e. toys) were in the pools. The enrichment devices were not deployed in places the dolphins had particular preference for (for example at feeding stations). Food reinforcements were not used in the experiments. Safety requirements were carefully reviewed and evaluated by the staff for all devices.

3.1 Sonar recording Porpoise Detectors

Four Porpoise Detectors (POD’s) were used to monitor the general sonar activity of the twelve dolphins at the dolphinarium (Figure 2). The POD’s were located so that comparisons of sonar activity could be made between conditions, surroundings and times.

The POD’s were custom made by Aquatec Electronics Ltd. (Highstreet, Hartley Wintney, Hampshire, RG278 NY, UK) for another project (NIPPER; Courtesy of the Fjord&Baelt, Kerteminde, DK, Danish Institute for Fisheries Research; Norwegian Institute of Marine Research and Kolmården Zoo) and recorded the timestamp and the coarse amplitude of high frequency echolocation clicks over a set trigger level.[1]

The POD’s were suspended by ropes from the ceiling of the dolphinarium. Each rope was inserted into a hard plastic tube protruding from the POD to ≥ 1.50 m above the water surface to prevent dolphins from becoming entangled. Extra weight was also added to the POD’s to give them more stability in the water column.

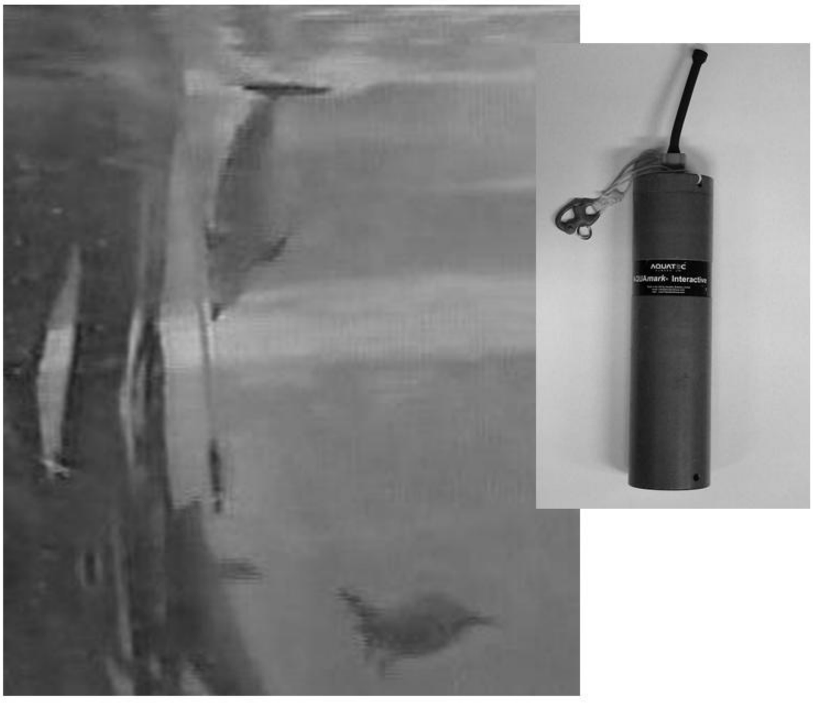

Figure 2. Porpoise detectors (POD’s) were used to monitor the sonar activity in the pool complex.

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[1] At print calibration was pending.

The POD's were deployed in different parts of the pool complex (Figure 3). POD A (AQ626-004) was suspended to a depth of 0.60 m in the shallow area of the lagoon and was approximately 1 m from an area 0.50 m in depth. POD B (AQ626-001) was placed in the deeper part of the lagoon (5.50 - 6 m) and was suspended to a depth of 1.45 m. POD C (AQ626-002) was deployed in the largest of the holding pools at a depth of 0.55 m. POD D (AQ626-005) was placed in the middle of the 800 m^2 main public display pool. This POD was suspended approximately 10 m from the nearest pool wall and was at a depth of 1.05 m. Each POD was installed into its respective pool environment three weeks before data collection began in order to allow the dolphins to become habituated to them.

From the data collected around the clock by these POD's the total number of recorded clicks was extracted for one hour long periods each day at the times 06:00 - 07:00, 12:00 - 13:00, 18:00 - 19:00, and 23:00 - 00:00. During these periods there was no interaction between the trainers and the dolphins and no restrictions on the whereabouts of the animals. Click-trains with ICI's shorter than 2 ms were excluded from the data as these emissions are very close range sonar, which are most likely associated with playing with the POD's or social interactions.

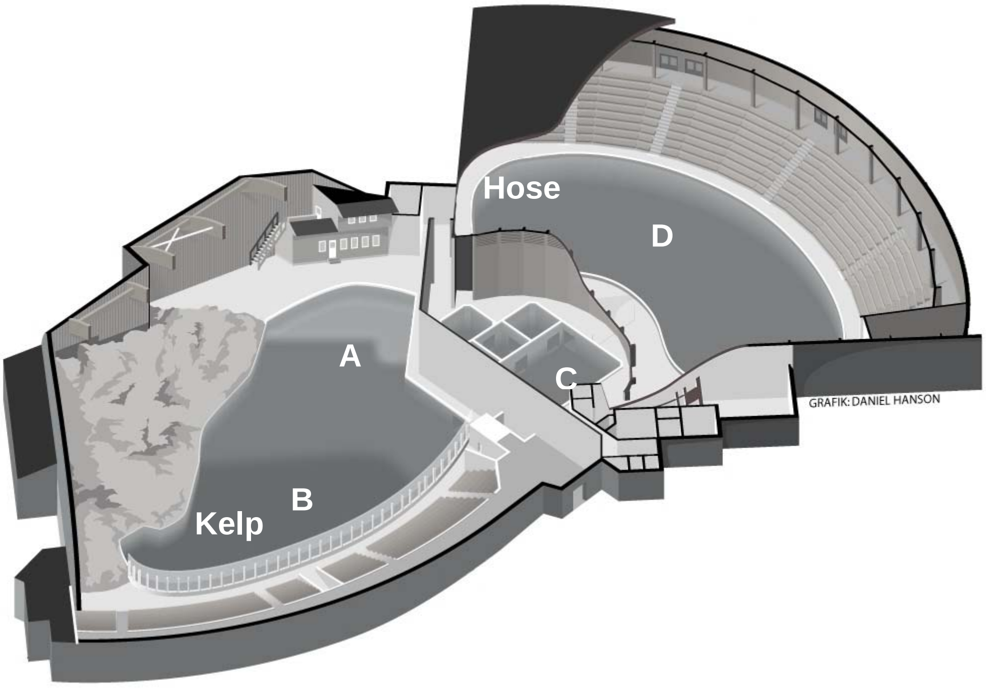

Figure 3. Locations for Porpoise Detectors (A-D) and locations for the artificial kelp and interactive hose in the pool complex.

3.2 The artificial kelp-alga

The artificial kelp-alga simulated kelp found in costal areas. The material of this device was quite acoustically transparent so the acoustic target strength was increased in the device as a means to increase the enrichment value.

The artificial kelp was made from thick Viraduk fabric (from Bravikens Pappersbruk) that was cut into 10 cm by 5 m strips and mounted on a triangular wooden construction with 3 m sides (Figure 4). Viraduk is a very tough fabric that can resist tearing that may occur with weaker fabrics when dolphins chew on it. The wooden construction floated at the surface and the Viraduk strips hung down vertically to the bottom of the 5.5-6 m deep part of the lagoon (Figure 3). This enrichment device was already well known to the dolphins before the experiment was initiated.

To increase the acoustic target strength of the device four 5 m long fire-hoses were attached to the wooden triangle and ropes with twelve P20 fishing-net-floats was inserted inside each of these hoses (Figure 4). The P20 float contains interior airspaces, which gives strong sonar echoes. These floats were fixed at varying distances (1 – 3 dm) on the ropes using a series of knots. In control sessions ropes with no attached floats were used. The dolphins could only determine whether acoustic reflectors were present by biting the hose (which rarely occurred) or by using sonar. The presence of floats in the fire hose was randomized between observation sessions.

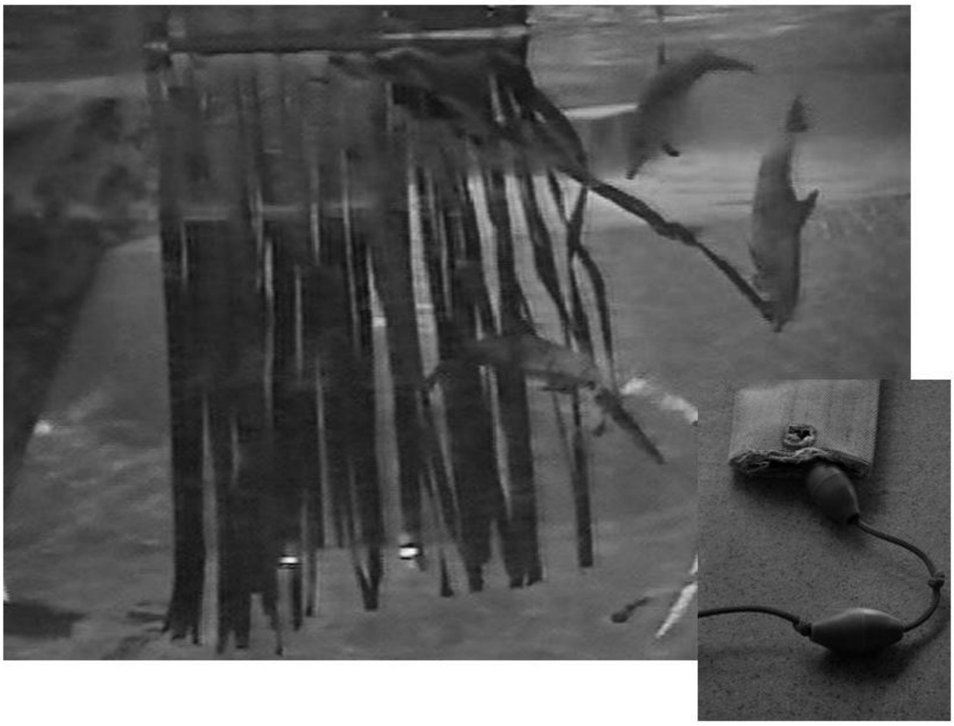

Figure 4. The acoustic target strength was improved in an artificial kelp-algae imitation by inserting floats into firehoses attached to the device.

A hydrophone (Custom made by Prof. Hans W. Persson, LTH, Sweden) was placed approximately 3.5 m below the water surface inside one of the fire hoses and was protected from biting by a thick rubber tube. This hydrophone was connected via two ETEC 1001 preamplifiers (Electronic Technical Engineering and Construction, Industrivaenget 8, DK3300 Frederiksvaerk, DK; www.etec.dk) to an ECD-1 clickdetector (NewLeap Ltd® Ltd, Cardiff, Wales, UK) which made it possible to record sonar emissions directed towards the device on the audio channel of a camcorder (see below). These recordings were later digitized and saved as wav-files.[2]

Observation sessions had a duration of 30 minutes. The artificial kelp was present in the pool daily (both with and without reflectors) for one week before the first observation session and was thereafter deployed at least 30 minutes prior to each subsequent session. The kelp and its immediate surroundings were filmed using a Hi8 mm Canon G10 video recorder supplemented with a Sony 0.7 wide conversion lens.

Four parameters were measured during each observation session: 1) the sonar activity (total number of clicks recorded), 2) the time each

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[2] At print calibration of instruments were pending.

individual spent present in the lagoon, 3) the cumulative time all individuals spent near the device (within a range of 2 m), and 4) the cumulative time all individuals spent chewing on the fabric. In parameter 1 social emissions and noise caused by mechanical or electronic influence were excluded using AdobeAudition1.0 (Adobe Systems®, Incorporated, San Jose, CA 95110-2704, USA). The sound files were then run through a custom made MatLab5.3 (The MathWorks, Inc. Natick, MA 01760-2098, USA) script (courtesy Magnus Wahlberg, Århus University) to calculate the inter click interval and total number of clicks recorded. Parameter 2 was logged directly using Observer 4.0 (Noldus Information Technology, Wageningen, The Netherlands). Parameters 3 and 4 were logged using Observer 4.0 (Noldus Information Technology, Wageningen, The Netherlands) with the plug in VideoPro® and a vertical image time code LTC/VITC generator (AEC-BOX™ 8/18/28, Adriene Electronics Cooperation, Las Vegas, USA).

3.3 The interactive hose device

The hose device was developed with the intention to provoke prey chasing behavior in the dolphins and also to provide an action-response interaction.

A 14 m long rubber hose with a diameter of 3 cm and a thickness of 0.50 cm was attached to the wall of the 4 m deep 800 m^2 display pool (Figure 3). It was attached at surface level so that 10 m of it could move freely in the water column (Figure 5). The hose was connected via an electro-magnetic valve (NW20B ND 0.5 – 16 bar Burkert, Germany) to a constantly open water tap with a pressure of 4.5 kPa. A narrow mouthpiece was attached to the tip of the hose to increase the water pressure causing the tip to move with a speed of roughly 2 m s^{-1} when the electro-magnetic valve was open.

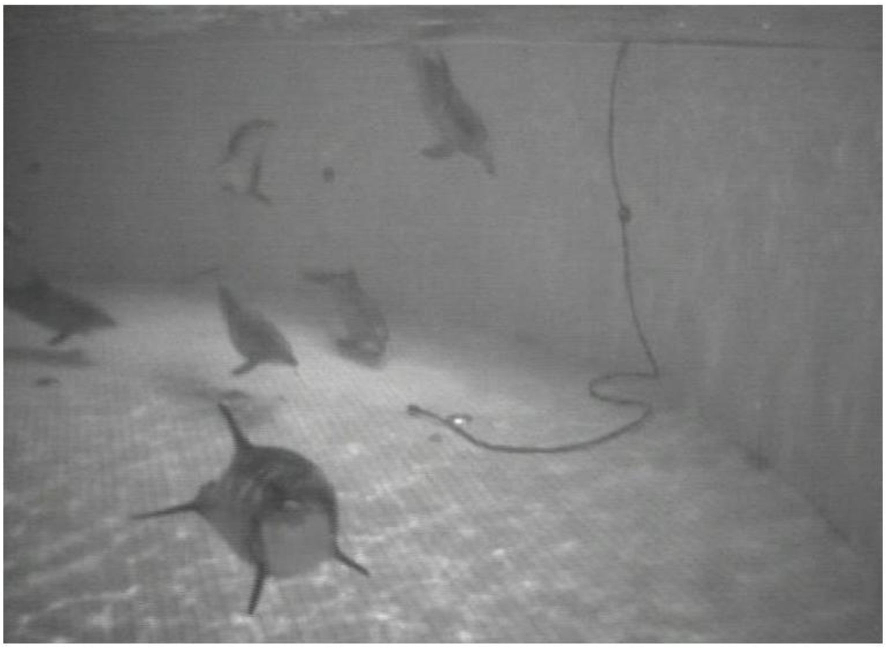

Figure 5. A hose set in motion by high pressure running water in response to sonar sound was introduced to the pool.

An HS/150 hydrophone (Sonar Research & Development Ltd, Grovehill Industrial Estate, Beverley, East Yorkshire, HU17 0LF. U.K. www.srduk.com), protected inside a 10 cm long hard plastic tube was mounted on the tip of the hose using GAFFA tape and self-vulcanizing tape. The hydrophone was connected to two ETEC 1001 preamplifiers (Electronic Technical Engineering and Construction, Industrivaenget 8, DK3300 Frederiksvaerk, DK; www.etec.dk) with a built-in 10 kHz high-pass filter, which was used to reduce water flow noise and mechanical noise. The signal that passed through this filter was received by an ECD-1 click detector (NewLeap Ltd® Ltd, Cardiff, Wales, UK), which extracted the envelope of the dolphins sonar clicks. The ECD output was fed to an acoustic switch (Velleman MK139, ELFA AB, SE-175 80 Järfälla) controlling the electro-magnetic valve. When sonar click-trains were directed towards the hydrophone the acoustic switch opened this magnetic valve allowing high pressure water to pass through the hose, hence the hose was set in motion. The valve was opened for approximately 1 s after the last sonar click. The ECD output was recorded on the audio channel of the Hi8 mm Canon G10 video recorder that was used to film the activities of the dolphins from a position 7 m above the pool. The sound recordings were later digitized and saved as wav-files.[3]

The hose was present in the pool in three different states: 1) an interactive state where the device could be triggered by dolphin sonar, 2) a control state in which the water flow was shut off and the device remained motionless throughout the session, 3) an always on state where water was constantly running causing the hose to be in constant motion regardless of external stimuli. These states were randomized between sessions.

A small number of trial sessions were conducted before the first observation session. After this a ten minute long pre-session period commenced before each observation session with the hose set in the state of the following session. The purpose of these pre-sessions was to allow the dolphins to know the state it was in prior to the commencement of the observation session. If one observation session was followed by another session where the hose device was in the same state, then the hose was removed for 20 minutes before starting a new 10 minute pre-session period.

Three parameters were measured during the observation sessions: 1) the sonar activity (total number of clicks), 2) the cumulative time all individuals spent near the device (within a range of 10 m), 3) the cumulative time all individuals spent using the device (i.e. by following or chasing the device and/or directing sonar towards the device from within a range of 2 m from the tip). Relating to parameter 1, social emissions and noise caused by mechanical or electronic influence were excluded using AdobeAudition1.0 (Adobe Systems®, Incorporated, San Jose, CA 95110-2704, USA). The files were then run through a custom made MatLab5.3 (The MathWorks, Inc. Natick, MA 01760-2098, USA) script (courtesy Magnus Wahlberg, Århus University) to calculate the ICI and total number of clicks. Parameters 2 and 3 were logged using Observer 4.0 (Noldus Information Technology, Wageningen, The Netherlands) with the plug in VideoPro® and a vertical image time code LTC/VITC generator (AEC-BOX™ 8/18/28, Adriene Electronics Cooperation, Las Vegas, USA).

3.4 Statistics

Statistical software used for analysis was Minitab13.0, Excel2003 and Winstat2003.1. Data was tested for deviation from a normal distribution pattern using the Ryan-Joiner test, Anderson-Darling test, and the Kolmogorov-Smirnov tests.

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[3] At print calibration of instruments were pending.

Click data recorded by the POD’s showed significant deviation from normal distribution and did not have a continuous distribution spectrum. This data was evaluated using descriptive statistics.

In the artificial kelp study the datasets for ‘sonar activity’, ‘being near’ and ‘chewing’ were transformed using the common logarithm as data had large variances. No deviation from normal distribution was detected after transformation. Data showed no heterogenic variances when F-test was applied so T-test could be used. The ‘presence’-data for each individual showed a significant deviation from a normal distribution pattern (even in transformed form). This data was discontinuous but had a continuous distribution spectrum; hence the nonparametric Friedman test was applied. Mean values of each group were used in this test.

In the study of the interactive hose the datasets for ‘sonar activity’ and ‘being near’ showed deviation from a normal distribution. As the data showed a continuous distribution pattern the Kruskal-Wallis test was applied. When the Kruskal-Wallis test indicated a significant difference the Mann-Whitney U-test was used to compare specific states. Only a difference at a confidence level of $P<0.01$ was accepted in these comparisons. The dataset for ‘use’ showed no deviation from a normal distribution after log-transformation. It was tested for equal variances using F_{max}-test. One-way ANOVA-test and Tukey´s test could be applied.

Statistical methods accounting for clustering were not used as many individuals moved around independently. Formed groups were constantly changing in constitution and moved independently of each other in the complex. Therefore the distribution pattern was classified as randomized rather than clustered.

4 Results

4.1 The Porpoise Detector recordings

Presented below are graphs showing the sonar activity over two typical 24 hour periods recorded 04-10-01 and 04-10-17 (Figure 6-7). The recordings showed a surprisingly low sonar activity in the pool. At approximately 20:00 hrs the sonar activity dropped and hardly any sonar emissions were recorded during the night. From about 04:00 in the morning there was a higher sonar activity. At 07:30 the trainers arrived and between the hours of 08:00 to 17:00 the recordings were affected by activities such as feeding, training and performances. Between 12:00 and 13:00 the trainers were gone for lunch leaving the dolphins undisturbed.

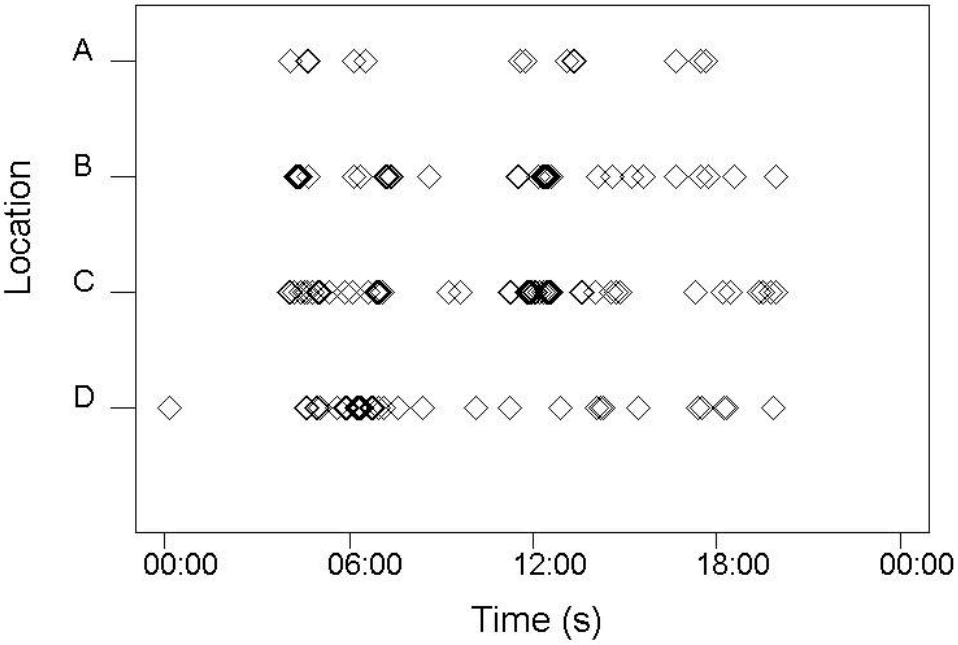

Figure 6. The sonar activity was recorded by POD's at four locations in the pool complex during a 24 hour period 04-10-01. Each diamond represents one sonar emission.

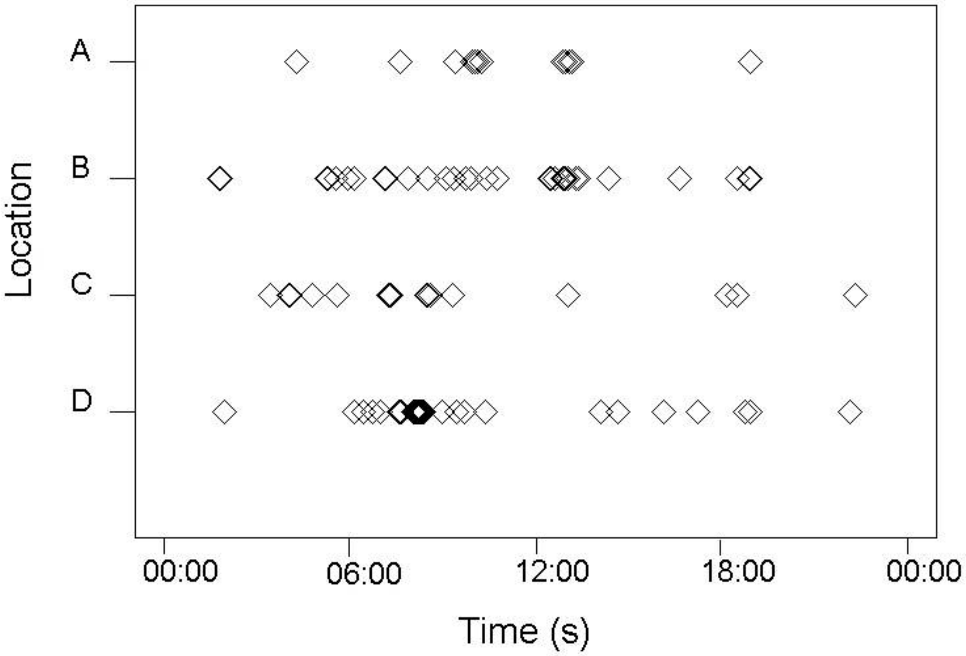

Figure 7. The sonar activity was recorded by POD's at four locations in the pool complex during a 24 hour period 04-10-17. Each diamond represents one emission.

Comparisons of one hour-long recordings made at different times of the day and at different locations within the pool complex showed a higher level of sonar activity in the morning between 06:00 - 07:00 and almost no activity at night between the hours of 23:00 - 00:00 at all locations (Figure 8). The recordings also showed a tendency for lower sonar activity at location A than at other locations. These recordings were made daily over a period of four weeks (from 2004-09-28 to 2004-10-25). No trends in the data were statistically supported but general tendencies could be seen.

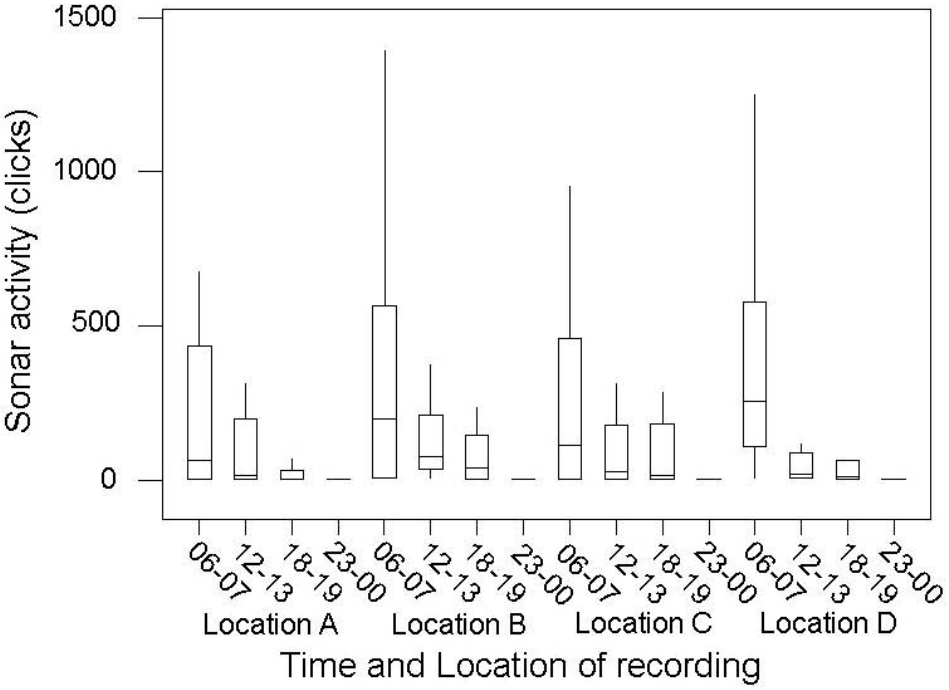

Figure 8. The sonar activity (total number of clicks/hour) was recorded by POD's at four locations in the pool complex. Recordings in 60 min long periods were made daily over a period of four weeks. Each box in the graph shows the interquartile range (IQ range) with the box bottom at the 25th percentile and the box top at the 75th percentile. The centered line indicates the median.

4.2 The artificial kelp recordings

During kelp sessions the dolphins tended to spend a lot of time chewing the fabric while rafting (i.e. hanging in the water) near the surface. They often swam up and down alongside or through the kelp stroking against it. They could also spend time weighing down the wood construction with their snout.

When sonar reflectors were present in the kelp the recorded sonar activity (total number of clicks) was higher compared to the control state ($t_{(17)} = -2.12$; $P = 0.049$) (Figure 9). The individual presence in the lagoon was also higher in sessions with reflectors present ($S_{(1)} = 5.33$; $P = 0.021$), but there was no difference in the frequency of chewing or the time spent near the device between the two states. Conclusions were based on results of 24 observation sessions (a total of 12 hours of observations) recorded over a period of four weeks.

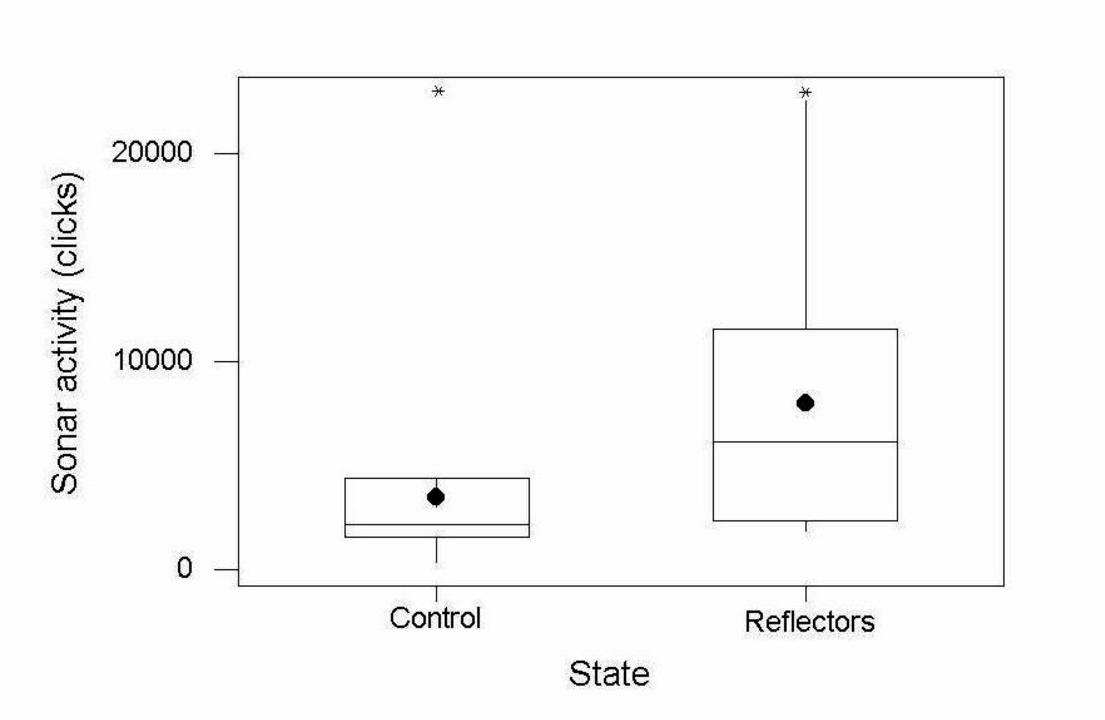

Figure 9. The number of recorded sonar clicks in the artificial kelp was significantly higher during sessions where reflectors were added ($t_{(17)} = -2.12$; $P = 0.049$). Each box shows the IQ range and the median. The mean is indicated by a solid circle. A star marks a state that significantly departs from one or more states.

4.3 The interactive hose recordings

During sessions dolphins being near the hose could pass by, play-fight with each other or watch other individuals interacting with the device. When using the device an individual could produce intense sonar click-trains while following the tip of the hose with their snout, i.e. keeping their sonar beam locked on target. Several individuals could follow behind other individuals without using sonar.

In the interactive state as well as in the always on state hunting and foraging behavior were often seen. Displays such as “razor buzzes”, “echolocation runs”, open-mouth scanning, up-side-down swimming, “log” jumps and synchronized group formations (Figure 10 - 13) were observed. “Razor buzzes” are high intensive click-trains with a frequency range of 2.0 to 6.0 kHz and a click repetition rate up to 200 clicks per second (i.e.

the ICI is about 5 ms). These are typical for bottlenose dolphins during hunting and foraging (Herzing 2000). "Echolocation runs" are click-trains in which a dolphin approaches an object of interest. As the two-way-travel time decreases, the click repetition rate increases. These are high frequency emissions used to detect small objects (such as smaller fish) and are typical during hunting activities (Gordon & Tyack 2002). Open-mouth scanning is used during hunting and foraging (Herzing 2000) and swimming up-side-down is a display commonly seen during fish chase near the bottom (Awbrey & Evans 1988, Bel'kovich et al. 1991, Herzing 2004). This is believed to give the dolphin a better acoustical view of the target and the bottom topography (Awbrey & Evans 1988, Herzing 2000). A "log" jump or "breach" in which the dolphin turns over in the air and lands on the side is used to drive fish during a social hunt (Bel'kovich et al. 1991). Group formations such as the front formation (where dolphins swim parallel to each other), diagonal formation (where one or more dolphins place themselves in a diagonal line behind the first individual), and fork formation (in which several dolphins surround a school of fish by bracketing it) are associated with social hunting according to observations made by Bel'kovich et al. (1991) in wild dolphin schools.

Figure 10. Open mouth scanning is typically used during foraging and hunting. This was frequently seen in the interactions with the hose device.

Figure 11. In the interactions with of the hose device the dolphins were often seen swimming up-side-down while chasing the tip of the hose. This is commonly seen in wild dolphins chasing fish near the bottom.

Figure 12a-f. During interactions with the hose device dolphins were often observed to perform “log” jumps. This is a behavior believed to be used to drive fish during hunting.

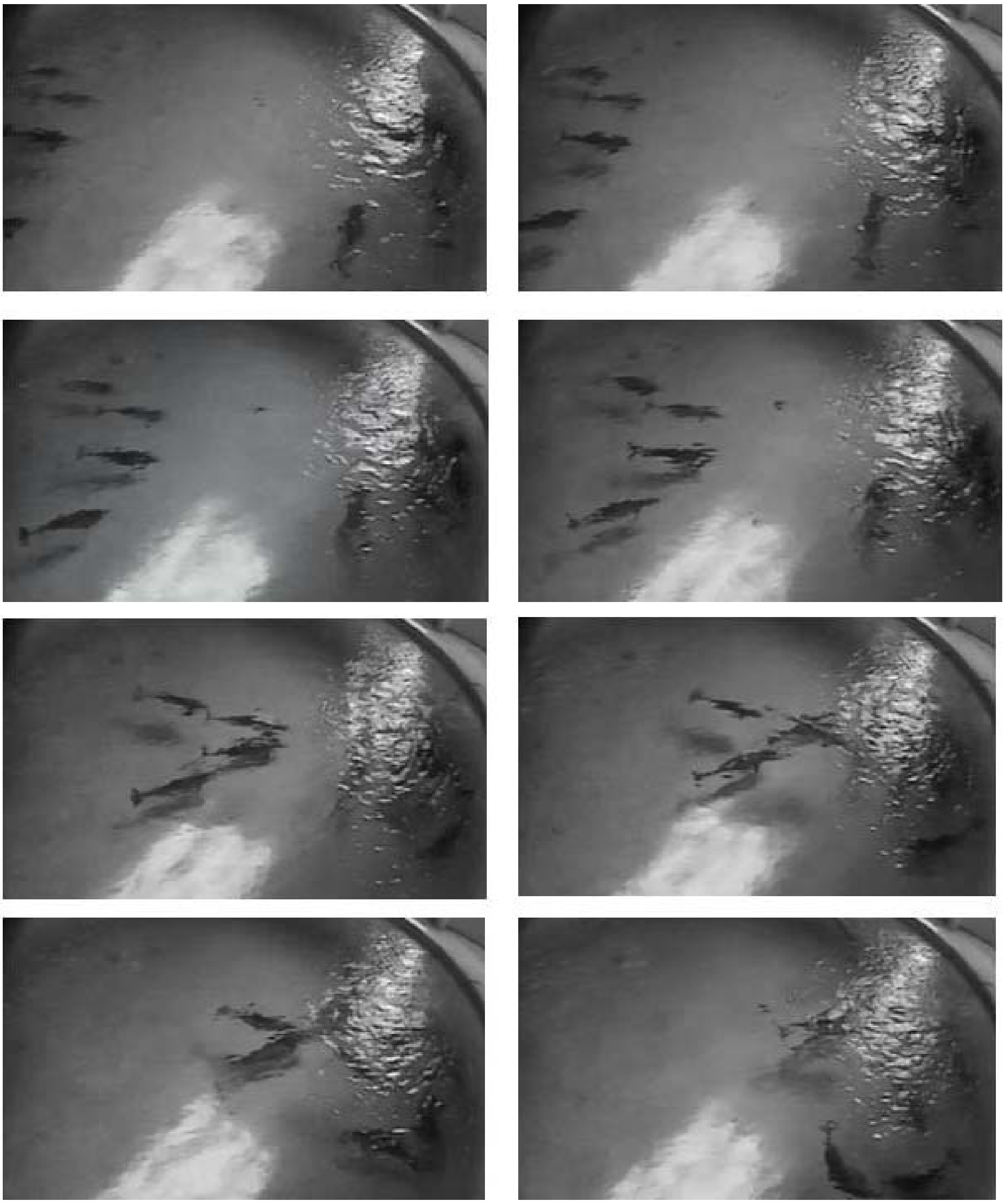

Figure 13a-h. Group formation patterns, such as the fork formation associated with social hunt were seen in sessions with the hose device.

In sessions when the hose was in an interactive state a higher sonar activity was recorded, and the dolphins spent more time near the device compared to the control state ($W_{(12,15)} = 245.0$; $P = 0.0002$ and $W_{(13,16)} = 271.0$; $P = 0.0009$ respectively) (Figure 14 - 15). There was more usage of the device in both the interactive state and the always on state compared to the control state ($T_{12} = 0.562$; $P < 0.05$ and $T_{23} = 0.613$; $P < 0.05$ respectively) (Figure 16). Analyses were based on the results of 40 observation sessions (20 hours) recorded over a period of eight weeks.

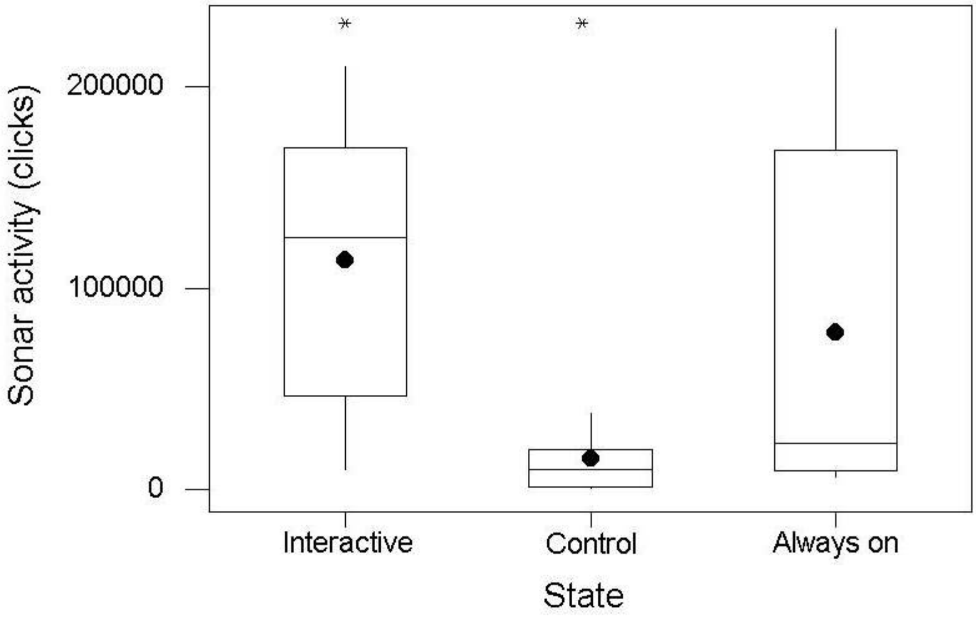

Figure 14. The number of sonar clicks directed towards the hose device was significantly higher in sessions where the device was in the interactive state compared to the control state ($W_{(12,15)} = 245.0$; $P = 0.0002$). Each box shows the IQ range and the median. The mean is indicated by a solid circle. A star marks a state that significantly departs from one or more states.

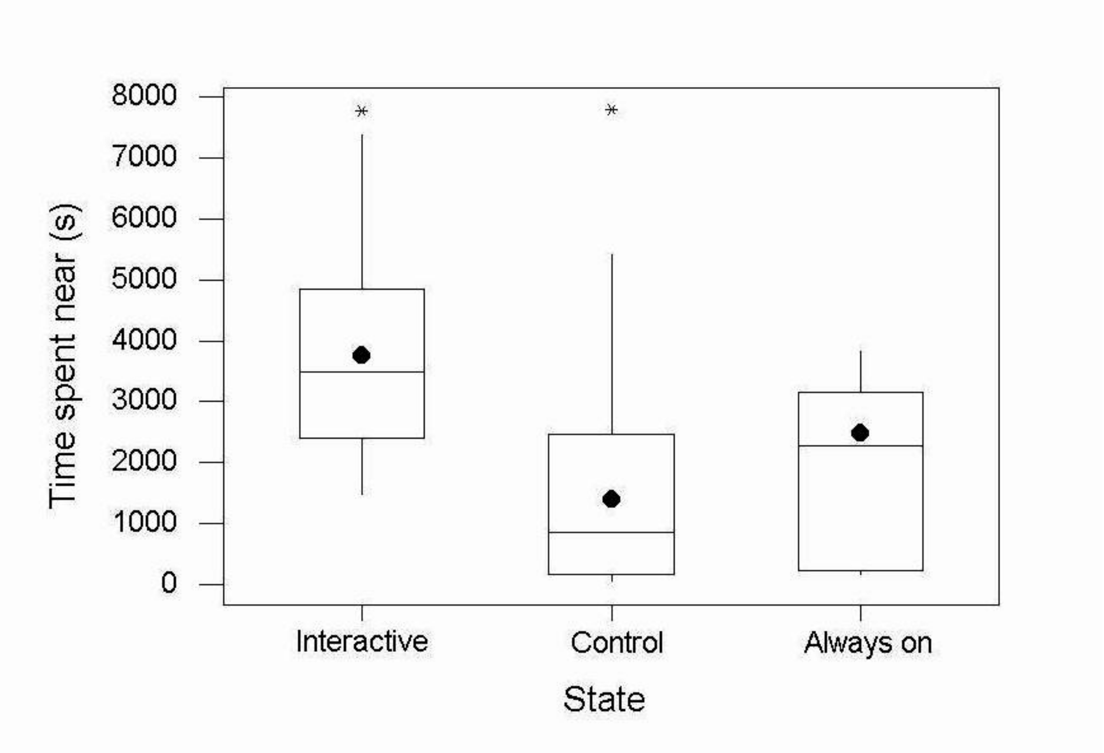

Figure 15. The dolphins spent significantly more time near the hose device (within 10 m) during sessions in the interactive state compared to the control state ($W_{(13,16)} = 271.0$; $P = 0.0009$). Each box shows the IQ range and the median. The mean is indicated by a solid circle. A star marks a state that significantly departs from one or more states.

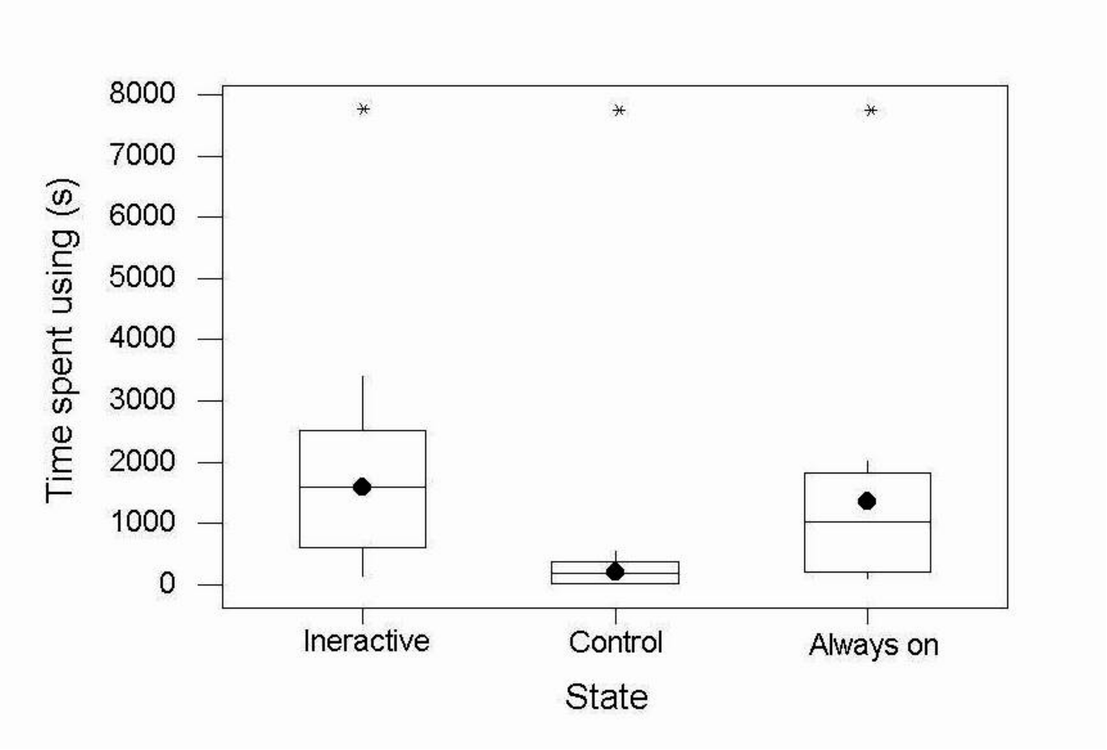

Figure 16. The dolphins spent significantly more time using the hose device during sessions in the interactive state ($T_{12} = 0.562$; $P < 0.05$) and always on

state ($T_{23} = 0.613$; $P < 0.05$) compared to the control state. Each box shows the IQ range and the median. The mean is indicated by a solid circle. A star marks a state that significantly departs from one or more states.

5 Discussion

5.1 Sonar recording Porpoise Detectors

Recorded sonar emissions included close range emissions and long distance emissions. Emissions with ICI's shorter than 2 ms were excluded in order to exclude social and play emissions.

The sonar activity was surprisingly low in the pools. However, dolphins in the wild have also been observed to stay silent for long periods in familiar waters in order to decrease the risk of being detected by predators (Almada & dos Santos 2004, Blomqvist 2004). In the absence of predators it is not likely that this is the reason for the low sonar activity in the dolphinarium.

Almost no sonar clicks were recorded during night time (between 20:00 and 04:00 hrs). This is likely attributed to low levels of activity i.e. resting. Dolphins are able to lower the activity in one brain hemisphere while the other is active to control the breathing during resting stages (Ridgway 1990). According to observations based on EEG activity by Ridgway (1990) bottlenose dolphins spend an average of 33.4% of each day asleep, i.e. approximately eight hours. This is in agreement with the observed time duration of lower sonar activity in the dolphinarium.

According to observations made by Bel'kovich et al. (1991) schools of bottlenose dolphins observed over three years were usually spotted at various times during daylight hours from 05:00 until 20:30 hrs. Most often the animals were observed in the morning hours from 05:00 until 09:00 hrs and only one-tenth of all the recordings were made after 17:00 hrs (Bel'kovich et al. 1991). The sonar activity in the pool complex was high between 04:00 to 08:00 hrs which closely matches the findings of Bel'kovich et al. (1991). Sunrise occurred at approximately 08:00 hrs, which coincided with the daily arrival of the trainers. Sunset occurred at approximately 18:00 hrs.

An increase in activity pattern at dusk and dawn has been observed in other dolphin species (Evans 1971). It could be suggested that the sonar activity was correlated to dusk and dawn or to the absence of light, and that an increase in sonar activity might be expected at or after sunset. However, no increase in sonar activity was observed at this hour and also the lighting in the dolphinarium during dark hours could be compared to a moonlit night, which should be enough for the dolphins to orientate themselves by eyesight just as well as during daylight in this well known surrounding. It is possible that the anticipation of trainers arrival and feeding might increase the sonar activity in the morning hours.

The sonar activity at location A, which was a shallow and more closed in space was lower than that of other locations (Figure 8). Possible reasons for this are that the dolphins may not have frequented this location as often as other locations due to its smaller size, or perhaps sonar was not needed here to the same extent as the risk of colliding with this POD was lower than with other POD's when it was located so close to a wall.

Locations B and D were open spaces with greater depths than location A and the recorded sonar activity in these areas was higher (Figure 8). The dolphins might have spent more time at these locations which would explain the higher sonar activity. The risk of colliding with the POD's was likely higher in these locations, making it necessary to use sonar to avoid it.

Location C was situated in the passage between the two large pools and the dolphins often passed through here. The POD could have constituted an obstacle which had to be checked when passing to avoid collision.

From both a close range and long range it was not difficult for the dolphins to locate the objects solely by using vision, since the water was clear and the illumination was sufficient. It appeared, however, that the dolphins preferred to use sonar to locate the objects (which had good acoustic reflection) as a supplement to vision.

Because the POD's were present for a long time before sonar activity recordings commenced, the dolphins were habituated to them. For this reason the dolphins should have been able to avoid collisions with the POD's without locating them by sonar unless they were traveling very close to them. Therefore it is more likely that the frequent use of a POD was due to the fact that it functioned as a land mark. Consequently the POD's in open surroundings (locations B and D) were most likely more frequently hit by sonar as no other potential land marks existed in the open water column. In a smaller space, such as location A, several alternative land marks were available in close vicinity of the POD, e.g. the water outlets on the pool floor, the pool walls and an underwater sloping ramp.

For an acoustic land mark to be useful, it must have enough sonar target strength to provide audible echoes from a distance. The optimal target strength for such a land mark is yet to be defined, but apparently the POD's, with their air-filled electronics compartments, and molded ceramic transducers, was easy for the dolphins to detect.

5.2 The artificial kelp-alga

The recorded sonar emissions included short range emissions and long range emissions. Social emissions were excluded from the data, whereas play emissions were not as these also reflected the use of sonar towards the device.

The sonar activity increased when the alga was present compared to the daily sonar activity in the pool (Figure 8 and 9).[4] It appeared that the artificial kelp encouraged sonar activity even when no strong sonar target was added.

The presence of the artificial kelp may have limited the visibility and therefore encouraged the dolphins to depend more on sonar. It may have also acted as an obstacle in the environment, which the dolphins checked by sonar. Even though the clear water made it possible for the dolphins to interact with the device only guided by vision, sonar (unlike vision) gives exact distance measurement. It is likely that the sonar target strength of the kelp fabric may have been enough to give interesting echoes in itself, although much lower than the P20 net-floats.

However, the amount of sonar directed towards the kelp increased significantly when its acoustic target strength was improved. This suggests that the floats constituted a stimulating and rewarding acoustic addition. Since the dolphins were well acquainted with the device and attached floats, investigative and play emissions does not alone explain the increase in sonar activity. The device most likely constituted a visual land mark and as acoustic target strength improved the dolphins were provided with an acoustic land mark as well. The increase in sonar activity would then imply that dolphins used sonar as a supplement to vision when the device had improved acoustic target strength. They might have used sonar in order to locate the object as well as use it as a reference for orientation.

The individual presence in the lagoon (the pool in which the kelp was situated) also increased significantly when reflectors were present in the kelp. Except for the implication that the adding of acoustic reflective floats was a positive and interesting addition to the device, the increase in presence of dolphins might also imply that the dolphins preferred a pool environment in which an acoustic land mark was available as opposed to an environment with a visual land mark alone. This suggests that enrichment of the pool environment by acoustic land marks is preferred by the dolphins as opposed to an acoustically barren environment.

In conclusion the artificial kelp increased the sonar activity in the pool and acted as an excellent enrichment device. By increasing the acoustic

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[4] There might have been a difference in sound pressure trigger level between instruments used. The instruments used in the kelp study could have had a slightly higher sensitivity than the POD's.

reflection properties of the kelp a dramatic increase of sonar activity and an increase of dolphins numbers within the environment was observed. This strongly suggests that enrichment by the addition of acoustically reflective objects provides a stimulating and beneficial environment for dolphins.

5.3 The interactive hose device

Unlike recordings made by POD's and during kelp sessions the sonar activity in hose sessions was mainly short range emissions with short ICI's. Social emissions were excluded from the data but not play associated emissions.

The hose device dramatically increased the sonar activity in the pool (Figure 8, 9 and 10).[5] The fact that all observed parameters (i.e. the sonar activity, time spent near and time spent using the device) increased when the hose was set in the interactive state as opposed to the control state indicates that an interactive device offering a direct action-response was stimulating and rewarding for the dolphins. The hose appeared to stimulate hunting behavior in the dolphins and sonar use is associated with this activity.

When the device was set in the always on state the dolphins used the device significantly more frequent compared to the control state. The fact that usage was not accompanied with an increased sonar activity could be explained by the dolphins following the tip of the hose without emitting sonar. This occurred in the interactive state as well when individuals stayed in the vicinity of an active individual apparently silently eavesdropping. Although the usage of the hose increased, the time spent near it did not significantly increase. This suggests that the dolphins used the device more frequently when being near it in the always on state compared to the interactive state. The dolphins possibly disliked being near the hose without using it (perhaps they felt threatened or disturbed in its presence) or the device was more effective in inducing usage when constantly in motion. Although the general activity during the always on state was high it appeared that the presence of dolphins dropped when the hose was present very frequently in this particular state. This suggests that the dolphins became bored with its presence. However, this tendency was not observed during the interactive state.

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[5] There might have been a difference in sound pressure trigger levels between instruments used. The instruments used in the kelp study and the instruments used in the hose study could have had a slightly higher sensitivity than the POD's.

In conclusion it can be said that the hose device indeed encouraged hunting behavior as well as sonar use and had a stimulating and beneficial effect upon the dolphins.

5.4 Conclusion

A concrete pool constitutes an acoustically poor environment for a dolphin. The using of toys made of acoustically transparent materials such as rubber, plastic and fabric leaves the open water column acoustically empty. If toys are floating the water column stays also visually empty. This leaves the dolphins with a barren habitat far from the richness of the sea.

Odontocetes use active sonar as one of their main sources of information (Gordon & Tyack 2002). The sonar system of dolphins is highly advanced with a well developed cognitive processing, which takes up a large part of the brain activity (Ridgway 1990, 2000). For the welfare of dolphins in human care it is important to find ways to encourage and stimulate sonar use.

The general sonar activity measured with passive porpoise detectors (POD's) in the Kolmården dolphin colony was surprisingly low and almost no sonar emissions were recorded during night hours when the dolphins were most likely resting. An increased sonar activity was seen in the morning hours before the trainers arrived.

The artificial kelp stimulated some sonar activity but it increased even further when the kelp was supplemented with a number of net-floats with high sonar target strength.

Objects with good sonar target strength, such as the POD's and the net-floats in the kelp, appeared to be used by the dolphins as acoustic land marks in otherwise acoustically empty surroundings.

The interactive hose device encouraged intense sonar use as well as roused general interest. The moving hose tip triggered prey chasing behavior with which sonar is associated.

The dolphins responded positively to all the tested acoustic enrichment additions, which should encourage further exploration of this kind of enrichment.

5.5 Recommendations

When designing pool facilities, the possibilities for dolphins to use their sonar should be of high consideration. This includes pool shape, wall and floor materials, structures in the water column and interchangeable objects. Appropriate enrichment devices and structures can be developed and implemented in existing traditional pools to improve the acoustic properties of the environment.

Submerged obstacles, objects limiting the visibility, and moving objects can be added to pools in order to challenge the dolphins and provide a changing and stimulating environment. Objects offering a good and acoustically interesting sonar echo can be further added to the environment as can devices constructed for the open water column. In this way the habitat created will be closer to resembling a natural coastal area.

The positive response to objects used as acoustical key references or land marks in this study motivates the adding of objects with high sonar target strength in open or acoustically empty areas.

As seen in this study the interactive device seemed to be a very positive addition. Other acoustically interactive concepts can be explored, e.g. ways for the dolphins to interact acoustically with trainers or visitors. Even if live fish cannot be offered, opportunities to perform hunting behavior should be and can be provided.

5.6 Further research

The ways in which a pool environment inhibits or stimulates the use of sonar should be more thoroughly researched in order to develop and implement appropriate enrichment to improve the acoustic aspect. Possible factors that may improve this could be the availability of total darkness, murky water or sound damping materials such as sand bottoms or sound damping panels.

The usage of land marks is an area that should be further researched for the benefit of captive dolphins. One way of doing this is to examine the ICI’s of the sonar emissions recorded during this project. The ICI’s would offer an approximate measure of the distance from where a sound was emitted (as described in Au 1993). Emissions from a short range would most likely imply that the dolphins located an object to avoid collision. If the emissions were from a longer distance it is more likely that they used the object as a land mark.

Ways of providing live fish or artificial hunting opportunities should be further explored as well as ways for dolphins to interact acoustically with for example trainers.

6 Acknowledgements

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Appendix 1

Environmental enrichment design

When designing an enrichment device one should have a clear understanding of the reason for introduction of the device and the goals it aims to achieve (Young 2003). The device should promote species-specific behavior which requires a good knowledge and understanding of a species' behavioral biology and natural history (Shepherdson et.al. 1998, Young 2003). A study is planned and conducted in a way so the specific question is answered. To evaluate the enrichment device it is important to document animal-device interaction over time (Barber 2003). Time, intensity and manner in which a device is used (i.e. if used in species-appropriate manner) are documented (Barber 2003). Safety considerations are of outmost importance. (For further information, see Shepherdson et al. 1998 and Young 2003).

A common design fault is the use of food reinforcement for devices not associated with species-specific foraging behavior. The risk of teaching the animal new behaviors instead of encouraging species-specific ones is high and it makes the device attractive as a food source rather than as an enrichment (Young 2003). Internally stimulated behaviors are motivated with or without the presence of external stimulus (Young 2003).

Appendix 2

Ethogram

Sonar recording Porpoise Detectors (POD's)

Recorded Parameters:

The sonar activity

- Definition: The total amount of sonar clicks recorded during a session.

The artificial kelp-alga

Recorded Parameters:

The sonar activity

- Definition: The total amount of sonar clicks recorded during a session.

The presence (recorded for each individual)

- Definition: The time (s) an individual were present in the pool in which the enrichment device was situated (i.e. the lagoon).

Time spent near the device

- Definition: The cumulative time (s) (for all individuals) the dolphins were within the range of 2 m from the device.

Time spent chewing on the device

- Definition: The cumulative time (s) (for all individuals) the dolphins were chewing on the device.

Time spent not near

- Definition: Default state

The interactive hose device

Recorded Parameters:

The sonar activity

- Definition: The total amount of sonar clicks recorded during a session.

Time spent near the device

- Definition: The cumulative time (s) (for all individuals) the dolphins were within the range of 10 m from the device.

Time spent using the device

- Definition: The cumulative time (s) (for all individuals) the dolphins followed or chased the device and/or directed sonar towards the device from within a range of 2 m from the tip of the hose. This was visually indicated by the individual arching the head in attempt to keep the sonar beam locked on target.

Time spent not near

- Definition: Default state

Appendix 3

Daily schedule for the dolphins

At 07:30 the caretakers arrived and at around 9:00 and 11:00 the dolphins were fed, usually in combination with some form of training or performance. Between 12:00 and 13:00 the caretakers went to lunch and many observation sessions were conducted during this time. A close-encounter-program usually ran between 13:00 and 15:00. The dolphins received food again at 15:00 and 16:30 often in combination with training or show, before the caretakers went home for the day at 17:00. There were often toys available to the dolphins at night and at periods during daytime.