An echolocation visualization and interface system for dolphin research

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The present study describes the development and testing of a tool for dolphin research. This tool was able to visualize the dolphin echolocation signals as well as function as an acoustically operated "touch screen." The system consisted of a matrix of hydrophones attached to a semitransparent screen, which was lowered in front of an underwater acrylic panel in a dolphin pool. When a dolphin aimed its sonar beam at the screen, the hydrophones measured the received sound pressure levels. These hydrophone signals were then transferred to a computer where they were translated into a video image that corresponds to the dynamic sound pressure variations in the sonar beam and the location of the beam axis. There was a continuous projection of the image back onto the hydrophone matrix screen, giving the dolphin an immediate visual feedback to its sonar output. The system offers a whole new experimental methodology in dolphin research and since it is software-based, many different kinds of scientific questions can be addressed. The results were promising and motivate further development of the system and studies of sonar and cognitive abilities of dolphins. © *2008 Acoustical Society of America.* [DOI: 10.1121/1.2828213]

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I. INTRODUCTION

Dolphins have gone through a long evolution which has resulted in a very advanced active sonar system based on the development of a unique sound generation and detection system (Amundin, 1991; Cranford *et al.* 1996; Au, 2004; Cranford and Amundin, 2004). Their sonar has been extensively studied over several decades, and much of their basic characteristics are already well known (Au, 1993). However, most of these studies have their foundation in an experimental setup where the dolphin has been trained to be voluntarily attached in a test rig, thus permitting its directional sonar beam to be recorded with fixed hydrophones. Although this setup allows for very exact measurements, it has most likely prevented the full dynamic potential of the dolphin's sonar to be revealed. Acoustic tag recordings carried out with free swimming dolphins have indicated that there obviously exists a very precise control of the frequency composition of individual clicks in a sonar click train (Sigurdson, 1997). However, this has not been fully reflected in the rigid setups. The system presented by Thomas *et al.* (2002) measured the sounds from free swimming captive dolphins with eight hydrophones distributed around walls of a 30 m by 45 m pool. The sounds were linked to the phonating dolphins which were also filmed with an overhead camera. Such a system allowed a spontaneous and social interaction between the dolphins while the sounds were recorded. However useful in its specific application, the system design did not enable real-time analysis, had a rather coarse spatial resolution and could not be used in studies of, for instance, dolphin target scanning behavior.

A dolphin's response to scientific questions, e.g., the in-target detection threshold or discrimination trials, has mostly constituted a "go/no go" response, pressing of a yes/no paddle (Au, 1993) or variations of match-to-sample studies. Such trials require trained dolphins, thus limiting the number of animals available for testing. Moreover, the go/no go or paddle responses are very rough indications of a choice, which is difficult to refine, and would thus be unpractical in a multiple-choice paradigm. In match-to-sample studies, multiple-choice paradigms are often required to be able to get clear and concise results. To make these test setups more practical, mostly in studies involving terrestrial animals, variations of symbol interfaces and touch screens have been developed.

In cognitive studies with primates, e.g., the chimpanzee, a computerized symbol interface, based on a finger operated touch screen, has been successfully used (Rumbaugh *et al.*, 1975). This approach has been employed even with birds, such as chickens and doves (Cheng and Spetch, 1995). So far, only two similar interactive tools with dolphins have been reported. Xitco *et al.*, 2001, reported the first use of an interactive keyboard for dolphins. It was designed to enable dolphins to activate symbols. The symbols were three-dimentional (3D) objects housed within circular tubes attached to one of four panels, or keyboards. The dolphins operated the keyboard by breaking an infrared light beam

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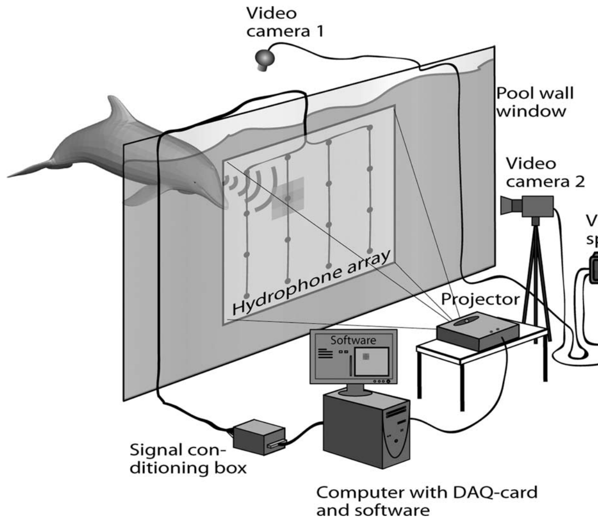

FIG. 1. The basic design of the EchoLocation Visualization and Interface System, ELVIS. The dolphin transmits a train of sonar pulses, focused in a narrow beam aimed at the hydrophone matrix. The relative sound pressure levels in the sonar beam are converted into light intensity variations on the PC screen. This dynamic image is projected back on the semitransparent hydrophone screen, offering an immediate visual feedback to the dolphin on its sonar output. The relative sound pressure levels can also be coded into, e.g., color variations only visible on the PC screen to the human observer.

projected in front of each symbol with its rostrum. When a symbol was activated the English word for the chosen symbol was played over an underwater speaker. The second tool within the interactive interface genre was reported by Delfour and Marten (2005). They investigated the ability of dolphins to associate sounds with visual stimuli. A custom-made touch screen, based on infrared light beams projected through an underwater viewing panel and guided by mirrors to create a grid in front of the panel, was used as the response interface. A TV screen placed in front of the panel displayed the visual test stimuli as well as various visual reward stimuli. The dolphin indicated its choice by breaking the light beams with its rostrum.

Although dolphins are known for using their rostrum to touch and manipulate objects, it was deemed of more interest to explore and study their main sensory system, i.e., their sonar. The present study thus describes the development of a new tool, called the EchoLocation Visualization and Interface System (ELVIS). An early version of ELVIS was presented by Nilsson (2003) and Nilsson *et al.* (2004). Since then the system has been further developed and tested in marine zoology applications. The aims of the investigation presented here are to demonstrate the basic principle of ELVIS and to test and evaluate the system in two applications: tracing the beam axis during a sonar target detection experiment and using it as an acoustically operated "touch screen" for dolphins.

II. MATERIALS AND METHODS

A. System configuration

The system consisted of a semitransparent screen with a matrix of 16 hydrophones, spaced 20 cm apart (Fig. 1). This screen was lowered into the dolphin pool in front of an underwater acrylic panel, and the system translated the variations of dolphin sound pressure levels in the sonar beam into variations in color and light intensity on the computer screen. Such an approach facilitates for the visually oriented human to observe the dynamics of the dolphin sonar. The computer screen image coded by light intensity was also projected back onto the hydrophone screen, by using a video projector, thereby offering an immediate visual feedback to the dolphins. ELVIS can be programmed to store all available data, such as the values of the measured sound pressure levels (SPLs), and the settings in the touch screen application. This allows for subsequent analyses and renders possible playback at any chosen speed. Two video cameras were used to document the measurement results and to help correlate acoustic and physical behavior (Ball and Buck, 2005). One video camera (video camera 1 in Fig. 1) was mounted directly over the location of the ELVIS screen so that the orientation of the dolphin in relation to the screen could be easily viewed. Also video recordings of the events on the screen were made (video camera 2) during both the testing of the beam axis tracing program and during the training of the dolphins to operate the acoustic touch screen. The obtained video sequences were then synchronized, using a video splitter and stored with a DVD recorder.

The interface was implemented as custom-made software, constituting the core of the interactive features of ELVIS. The maximum SPL in the sonar beam, i.e., the beam axis, was indicated by a round colored spot on the PC screen. The size of the spot was fixed and not related to the actual beam width in these applications. The position where the beam axis hit the screen was derived through interpolation of the signals from the hydrophones in the matrix, and even though the number of hydrophones was rather small, the spatial resolution of the tracing of the beam axis was sufficient for the present applications.

B. Hardware

The maximum sound pressure levels of the sonar pulses were measured by connecting a peak detector to each hydrophone. The block diagram in Fig. 2 shows the signal path through the system.

The hemispherical hydrophones (UD1, Ceram AB, Lund, Sweden) had peak sensitivities around 150 kHz, but were able to detect signals in the whole range where the dolphin echolocation signals have their peak energy, i.e., 40–120 kHz (Au, 1993). The hydrophone sensitivity at 120 kHz corresponds to −220 dB re 1 V/μPa.

A gain of 50 dB was used to amplify the received sonar signal levels up to a couple of volts, which is the optimal level for the DAQ-card (Data acquisition) (12 bit Adlink NuDaq PCI-9112, Adlink Technology Inc, Taipei, Taiwan). In order to keep a maximum amount of signal bandwidth, the gain was separated into two steps, i.e., first 20 dB and then 30 dB. After amplification, the signal was filtered with a 160 kHz first order low-pass filter followed by a 40 −130 kHz second order Butterworth band-pass filter.

The monolithic analog peak detectors with reset-and-hold mode (PKD01, Analog Devices, Norwood, MA, USA)

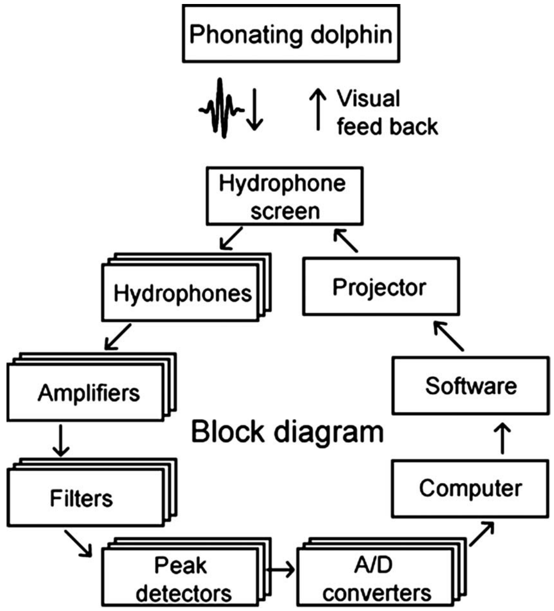

FIG. 2. Block diagram displaying the signal path through the system. The five blocks, labeled hydrophones, amplifiers, filters, peak detectors and A/D converters, represent 16 independent channels.

monitored the click amplitudes as detected by each hydrophone and retained the highest value until they were read and reset by a control signal from the DAQ card.

The small gray circles in Fig. 3 (marked by three arrows) on the peak detector output signal indicate the acquired amplitude readings that are stored by the computer software. According to the manufacturer, the sampling rate of the DAQ card is restricted by the hardware to a maximum of 110 kS/s. The Adlink DAQ card has 16 analog input channels and two analog output channels. Multiplexing the channels (i.e., acquiring data from one channel at a time) with an auto scanning function simplifies the design of the software. One of the analog output channels was used for resetting the peak detectors after reading.

The actual sampling rate was set by the software, and it turned out to be necessary to limit it to a total maximum rate of 70 kS/s, so as to eliminate the risk of overloading the hardware. This provided a sampling rate of 4.4 kS/s for each transducer, which was enough to catch every click even at very high click repetition rates. The normal click rate in a close distance sonar "buzz" is <500 clicks/s (Au, 1993). In Fig. 3 the theoretical maximum dolphin click rate of approximately 1000 clicks/s is used to illustrate the resulting sampling of the click amplitude.

C. Software

A software program was developed to control all the core functions of the system as well as the data acquisition via the DAQ card. Its function was to configure the card and sequentially read data from each of the peak detectors. The peak detectors were reset after each reading before a new series of data could be acquired.

Two main application programs were designed in order to render the system interactive to the dolphins, and both were extensions of the basic program. The first program (referred to as the "Beam axis tracing program") could be set to show either a light intensity graph on the screen as in Fig. 1 or a color light intensity spot at the location of the sonar beam sound pressure level maxima on the screen. It was possible to set the persistence time for the color spot, causing it to stay longer on the screen, thus also making it possible for the dolphins to "paint" on the screen by moving the beam axis over the hydrophone matrix. This also facilitated for the human eye to follow the trace of the sonar beam axis. The size of the spot was fixed, but its light intensity depended linearly on the sound pressure level of the click. A beam axis replay function, based on the amplitude measurements stored in a log file on the computer hard disk, was added to the program to facilitate the analysis of the dolphins' sonar behavior. From these log files the beam axis trace could be reconstructed on the computer screen in fast as well as slow motion.

The second program converted the system to a truly interactive, acoustically operated touch screen. This program (referred to as the "Acoustic touch screen" program) dis-

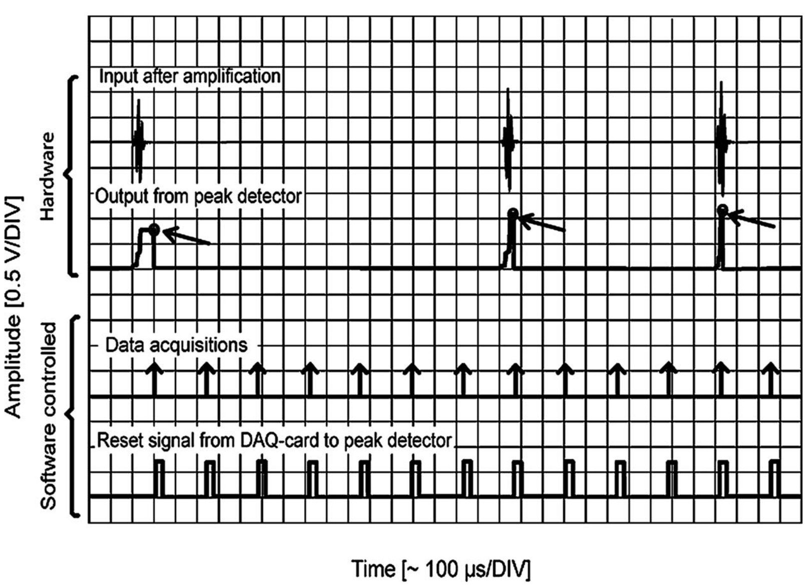

FIG. 3. The peak-hold detector output as it monitors the maximum amplitude of the input signal (dolphin click) from a hydrophone. After software-controlled storage to a hard drive, the detector is reset by a control signal from an output on the acquisition board.

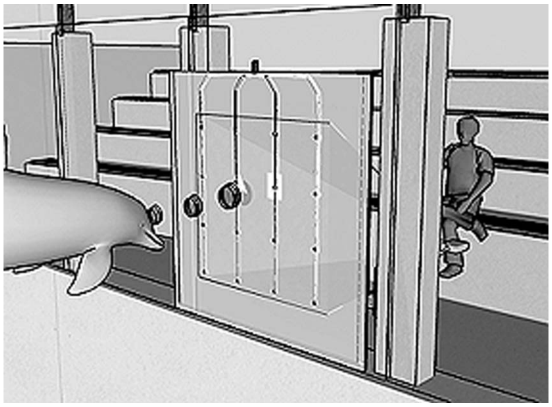

FIG. 4. The ELVIS, as seen from the dolphin's point of view, while being used as an acoustic "touch screen." The dolphin can "click" on the two white symbols by aiming its sonar beam axis at them. The symbols correspond to active buttons on a normal touch screen. The active area as well as the trig level can be set by the operator to adjust accordingly to the training level of the dolphin.

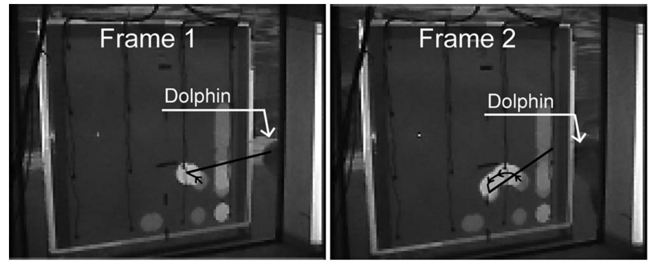

FIG. 5. These video frames span over a total time of 0.2 s. The picture shows the beam axis trace on the screen and a dolphin echolocating as it swims up to the right side of the screen. The video recordings were made with camera 2. The black line was added to indicate the beam axis orientation. The small black arrows illustrate the motion path of the beam axis across the screen.

played a variety of white symbols at either random or fixed locations on the screen. These symbols functioned as active buttons to be "clicked" on by the dolphin. Figure 4 shows a dolphin operating the acoustic touch screen by pointing its sonar beam axis at one of the projected symbols.

Depending on the application, the buttons can be associated with, for instance, various actions of the program and/or a number of objects that can be chosen by the dolphin. In one study, the symbols represented different species of reward fish. A symbol was activated when the sound pressure level in the beam axis of a detected sonar click reached above a preset trigger level. This led to the symbol flashing shortly and a reward whistle (the bridging stimulus) to be played to the dolphin through speakers connected to the computer. The dolphin then returned to the trainer at the pool side to receive a fish of the species represented by the chosen symbol.

It was also possible to set a time criteria in the program, forcing the dolphin to echolocate on the symbol a fixed number of seconds before the trigger level was accepted. However, in the initial study, only one click above the trig level was required to indicate a choice. The purpose of this first application was to test the acoustic touch screen and to introduce the dolphins to this concept. Initial results of this study are presented in Starkhammar *et al.* (2007) and Olsén (2007).

To help evaluate the functionality of the touch screen, a tracing function of the beam axis was built into the program of the acoustic touch screen. This rendered it possible to continuously monitor the beam axis as the dolphin selected a symbol to click on, and consequently to study how the dolphins, through trial and error, learned how to handle the program. The beam axis spot was displayed in dark red to make it inconspicuous to the dolphins (Madsen and Herman, 1980) and thus not distract them while operating the touch screen. Moreover, a click detector (ECD-1, NewLeap Ltd, UK) with a speaker was connected to one of the hydrophones in the center of the screen, making it possible to hear the echolocation during the trials. This was done to provide additional feedback to the operator. Seen from the pool side of the screen the click detector was connected to the second hydrophone from the left in the second row from the top.

Several different settings were possible in the acoustic touch screen program. The active area around the symbols could be increased so as to comply with the level of training of a specific dolphin. For instance, an inexperienced dolphin could be aided by being provided with a larger active area around the symbol, hence making it easier for it to "hit" it with its sonar beam axis.

III. RESULTS AND DISCUSSION

The beam axis tracing program was found to perform according to the objective of the design and visualized the location and sound pressure levels of the beam axis as intended. When the screen was first presented to the dolphins, showing all sound pressure level variations within their sonar beam, they spontaneously and deliberately explored it with their echolocation. Their reactions were interpreted as them being intrigued and stimulated by the visual feedback of their sonar beams. With the inter-hydrophone distance set to 20 cm, the system was found to operate best when the dolphins were at a minimum of 1 m distance from the screen. If the dolphins were too close, the entire sonar beam might fall in between the hydrophones and hence not be registered at all. Such a scenario resulted in gaps in the tracing of the beam axis. Furthermore, if only one hydrophone was hit by the sonar beam, the interpolation function might result in a positioning error of a maximum of half an inter-hydrophone distance. An array of 64 elements, i.e., an inter-hydrophone distance of 10 cm, should make the interpolation operate properly for a dolphin at a distance as short as 0.5 m from the screen.

The software was developed under the assumption that only one dolphin at a time would echolocate towards the screen. Thus, if two dolphins were aiming their sonar beam at the screen simultaneously, the resulting maximum point, i.e., the beam axis, might appear on an incorrect location on the screen. However, the relatively fast scanning rate of the hydrophones made this a minor problem and even with several dolphins spontaneously echolocating at the screen at the same time, the system was able to monitor the beam axis. Figures 5 and 6 were created from a video sequence filmed

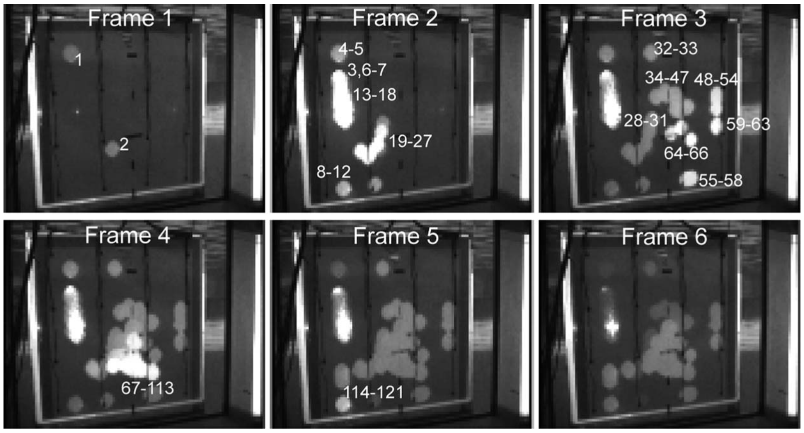

FIG. 6. These six frames show the beam axis tracing program while one dolphin is exploring the system for the first time. The frames are captured from a sequence filmed with video camera 2. The time between each frame is 1 s. All spots drawn by the system were numbered according to the order of which they appeared on the screen. The text and numbers in the pictures were added after the filming.

with camera 2 during the first time the dolphins encountered the full version of the beam axis tracing software. Unfortunately camera 1 was not used at the time of this initial testing of the newly developed software. The whole group of nine dolphins was allowed to swim freely in the pool and investigate the screen. In Fig. 5 an echolocating dolphin swims up to the screen from the lower right corner. The beam axis is visualized to both the dolphin and the human observer. The vertical trace at the very right side of the screen came from echolocation clicks a few seconds earlier, possibly from another dolphin. To help the readers to perceive the orientation of the dolphin in the pictures, a black line representing the beam axis was added in both frames. This shows that the beam axis tracing program visualizes the beam core location with acceptable accuracy. Small black arrows indicate the movement of the beam axis as it hits the screen.

During the screen shot sequence in Fig. 6, one dolphin (not visible to camera 2) explores the screen by echolocating at it. The time between each frame is 1 s. The dots drawn by the system, indicating the trace of the beam axis, are numbered according to the order of which they appeared on the screen. Note that the light intensity of the trace represents the maximum peak sound pressure levels of the measured click. If there are multiple clicks at the same location the light intensity sums up until it reaches a maximum level (white). The fade-out time was set to 6 s. A possible way of making the time for each spot more intuitively clear to the operator would be to let the diameter of the dots decrease over time, instead of letting the dots' intensity fade out and then number them afterwards.

The beam axis tracing program has been employed in a study of benthic foraging in bottlenose dolphins, carried out at Dolphin Encounters, in the Bahamas (Dahl, 2007). Here, the hydrophone matrix was buried under coral sand and the sonar beam axis was traced while trained dolphins searched the sea floor for buried sonar targets. In this application the dolphins received no visual feedback; this was restricted to the human observer operating the computer. The replay function proved to be a very useful tool in the analysis process, and Fig. 7 shows a screen dump from such a replay sequence.

ELVIS fulfilled all our expectations as a visualization tool for tracing the dolphin sonar beam axis. It also proved that the acoustic touch screen concept can be operated by the dolphins and thus function as a computerized interface between man and dolphin. The acoustic touch screen software rendered it possible for the dolphins to activate the buttons (the projected symbols) by pointing their sonar beam axis at them.

Figure 8(A) shows the position of the dolphin relative to the acoustic touch screen while operating it. The orientation and position of the screen is marked in white. Figure 8(B) displays the white projected symbols and the tracing of the dolphin's beam axis. In order to make the shapes in B clearer to the reader, the boundaries of the symbols have been enhanced with a white line. The round dots represent the beam axis of individual clicks and are numbered in the order they appeared on the screen. All edits were made in the analysis process after the session. The time difference between echolocation click No. 1 and No. 4 in the figure was less than 0.4 s.

Sixteen dolphin training sessions, each lasting approx. 10 min, were carried out in which three dolphins were subjected to the task of "clicking" on the buttons of the screen with their sonar beams (Olsén, 2007). All three dolphins

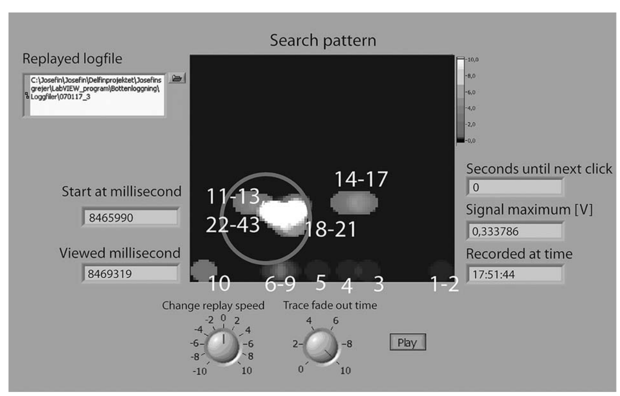

FIG. 7. A screen shot from running the replay program interface with a short sequence of a sonar beam axis trace of a dolphin searching for an object partially buried in coral sand over the hydrophone matrix. The object's position within the "Search pattern" area is indicated by the painted gray circle. The light intensity of the spots indicates the sound pressure levels of the clicks. It spans from dark red for weak clicks to white for strong clicks in a linear scale. The fade-out time of the trace can be set during replay. The intensity of each click hitting the same location was summed in this particular visualization mode. This figure has been converted into grayscale, thus representing dark red as dark gray. Consecutive clicks are numbered from 1 to 43 and were recorded during 3.5 s.

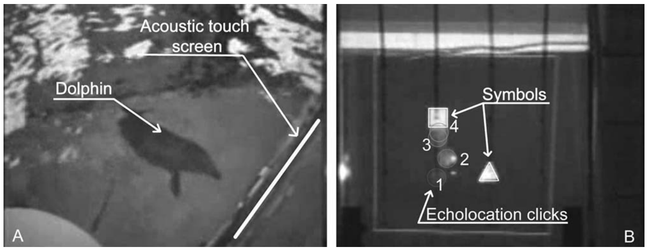

FIG. 8. Time synchronized video frames of a dolphin operating the acoustic touch screen, where A shows the dolphin from above, and B shows the acoustic touch screen from the dry side of the pool, with the trace of the dolphin's sonar beam axis as it hits the square symbol.

were previously trained to echolocate on a 3D sonar target lowered into the pool. During the very first training session all three dolphins learned the task of echolocating on a white square, in each run appearing at the same position on the screen. This was accomplished by holding the sonar target in front of the projected symbol for three runs. Then the target was removed. During the following 13 sessions, the dolphins learned to deliberately "click" on a symbol when up to three symbols were simultaneously projected onto the screen on random locations. Only one dolphin at a time was sent to the screen to perform the task. The dolphins were rewarded for clicking on any of the symbols on the screen. Each dolphin learned the task in its individual pace. The youngest subject (born 2001) learned the task quickest and clicked on a symbol with sufficient accuracy and sound pressure level within 10 s in 100% of the trials after the first session with the sonar target. The oldest subject (born 1973) seemed to be the slowest learner and clicked on a symbol within 10 s in 75% of all trials. All three dolphins required a mean time of less than 4 s to perform the task correctly, calculated using data from all trials during the 13 sessions.

Since sound and sonar dominate the lives of dolphins, it was assumed that they might intuitively understand and adopt the acoustic touch screen without extensive training. This assumption was supported by the obtained results. With the present system, a whole range of unexplored research areas regarding dolphin cognition and sonar skills can be studied. One cognitive study can be to investigate the ability to understand and interpret contents in pictures and videos. Regarding dolphin sonar skills the hypothesized internal beam forming ability in dolphins can be further explored with this system. The promising results of the tests highly motivate a further development of the system in order to render it even more potent. In addition to improving the resolution by increasing the number of hydrophones, the system should be expanded from merely measuring the peak sound pressure levels of the clicks to high frequency digital sampling of the clicks in each hydrophone position. Such a development would allow for the full frequency bandwidth of the sonar clicks and its dynamic frequency variations to be studied on-line. It would push the limits of fast data streaming to the hard drives but should nevertheless be realistic considering the fast development of DAQ cards and PC buses.

The flexibility of the software-based system makes it possible to match each application in an optimal way to the task. If one application requires only, e.g., the variations of peak frequency and not sound pressure levels to be visualized, this can easily be implemented to be set on line by the operator. In some applications, only some parameters would be presented to the dolphins and others only available to the operator. If more than one property at a time are to be shown (peak frequency, click interval, sound pressure level, beam width, etc.), the operator must have the possibility to control the presentation of these parameters. As an example, the change in peak frequency and sound pressure levels can be visualized by a variation of shape and light intensity, respectively. Click interval can, e.g., be visualized by a change in fade out time of the projected color spot, e.g., a long click interval giving a long fade out time and a short click interval a fast fade out time. This would make it easier to see each new click even in a fast click train. It should be emphasized that these are only suggestions to how the system can be set up to match a number of future applications.

IV. CONCLUSIONS

The preliminary tests of ELVIS described herein displayed that the system functioned as intended both as a tool for visualizing the sound pressure level dynamics in the dolphin sonar beam and as an interactive acoustic "touch screen" operated by the dolphins' sonar. The promising results motivate additional studies of dolphin behavior, echolocation and cognition, as well as a further development of the system. As a result of the system being software based, numerous types of ethological and cognitive studies (e.g., pictorial competence) can be implemented.

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