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Acoustic Localization Method Applied to the Analysis of Dolphin Calf Acoustical Exploratory Behavior Within its Social Group

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Exploratory behavior includes all the actions that an animal performs to obtain information about a new object, environment, or individual through using its different senses of perception. Here, we studied the development of the exploratory behavior of a bottlenose dolphin (*Tursiops truncatus*) calf aged from 39 to 169 days by investigating its acoustic productions in relation to an immersed object handled by a familiar human without the calf being isolated from the original social group. The study was conducted between July 2015 and January 2016 at Parc Astérix dolphinarium (Plailly, France). Simultaneous audio and video recordings were collected using a waterproof 360° audio-video system named BaBeL, which allows localization of the dolphin that is producing sounds. During 32 recording sessions, for a total duration of 6 hr 55 min of audio-video recordings, 46 click trains were attached to individual dolphins: 18 times to the calf, 11 times to its mother, and 17 times to another dolphin in the pool. When comparing the calf's acoustical production to its mother's, no significant differences were found in their click rate, mean click duration, or mean interclick interval (ICI). However, linear regression showed that calves' click rates increased with age and mean ICI decreased with age, probably due to an increase in its arousal. This nonintrusive methodology allows the description and analysis of acoustic signal parameters and acoustic exploratory behavior of a dolphin calf within its social group.

Keywords: echolocation, laterality, *Tursiops truncatus*, hydrophone array, ontogenesis

Exploratory behavior describes the actions that an animal performs to obtain information about a new object, environment, or individual by using its different senses of perception (Keller, Schneider, & Henderson, 2012). Exploratory behavior is differentiated into extrinsic and intrinsic exploration (Berlyne, 1960). Extrinsic exploration is behavior primarily directed towards an external goal and in response to some specific requirement; intrinsic exploration, also called “novelty seeking” (McReynolds, 1962), “reactive curiosity” (Penney & McCann, 1964), or “stimulus seeking” (Hoyenga & Hoyenga, 1984), facilitates investigation of a stimulus mainly in response to an interest in the stimulus itself (Berlyne, 1960). Intrinsic exploration has been studied in a diverse number of species. For example, in captive jackdaws (*Corvus monedula*), social structure (Katzir, 1982) and heritage (Dingemans, Both, Drent, Van Oers, & Noordwijk, 2002) modulate individuals' novelty seeking behavior. In mammals, intrinsic exploration has been mostly studied in rodents (reviewed in Belzung, 1999) and primates (Miller, Bard, Juno, & Nadler, 1986; Parker et al., 2007; Rubenstein, 1967), and its development in captive species has been shown to depend on multiple factors, including sex (Lynn & Brown, 2009), environmental enrichment (Zimmermann, Stauffacher, Langhans, & Würbel, 2001), and maternal care (Rubenstein, 1967).

Exploratory behavior has been rarely studied in marine mammals. Under human care, environmental enrichment was found to promote exploratory behavior in harbor seals (*Phoca vitulina concolor*) (Vaicekauskaite, Schneide & Delfour, 2018), gray seals (*Halichoerus grypus*) (Hunter, Bay, Martin & Hatfield, 2002), and bottlenose dolphins (*Tursiops truncatus*), with some interindividual variation seen in relation to their different personalities (Birgersson, Birot de la Pommeraye, & Delfour, 2014; Kuczaj, Makecha, Trone, Paulos, & Ramos, 2006), the type of introduced objects (Delfour & Beyer, 2012) and the sex and/or age of the individuals (Eskelinen, Winship, & Borger-Turner, 2015). In wild delphinids, this behavior has been reported <https://doi.org/10.46867/ijcp.2019.32.00.13>

in rough-toothed dolphins (*Steno bredanensis*) (Kuczaj & Yeater, 2007). The study of exploratory behavior in bottlenose dolphins is of particular interest for two main reasons. First, these cetaceans are social mammals living in a fission-fusion social structure (Connor, Wells, Mann, & Read, 2000; Mann, Connor, Tyack, & Whitehead, 2000) that could influence the development of exploratory behaviors (Katzir, 1982). Second, bottlenose dolphins explore their environment through visual perception (Pack & Herman, 1995) and through echolocation by projecting clicks in order to obtain a sense of their surroundings from the echoes they receive (Au, 1997). Bottlenose dolphins' clicks are directional, forward-projecting, and brief, pulsed sounds of high intensity and broadband frequency (Richardson, Green, Malme, & Thomson, 1995). They use clicks as a sensory tool to navigate or hunt for prey (reviewed in Herzing & dos Santos, 2004), obtaining information from their own returning signals (Au, 1997) and also by eavesdropping on the echoes from other dolphins' sounds (Gregg, Dudzinski, & Smith, 2007; Xitco & Roitblat, 1996).

Studying the ontogenesis of acoustical exploratory behavior in dolphins presents several difficulties. First, following and recording the vocalizations of dolphins from early age in the wild are almost impossible and thus are only feasible with studies in captivity, where the birth of a calf occurs on average every 28 months per female (Cornell et al., 1987). As a consequence, to our knowledge, there are only six studies on the development of dolphins' echolocation, and all were carried out in dolphinaria (Carder & Ridgway, 1983; Favaro, Gnone, & Pessani, 2013; Harder et al., 2016; Linhard, 1988; Manoukian, Azzali, Farchi, & Tizzi, 2002; Reiss, 1988). Second, all these studies focusing on the development of echolocation have faced the difficulty of determining which dolphin emitted a click train and, thus, used several proxy indicators: the production of bubble streams (Reiss, 1988; Favaro et al., 2013), the intensity of the signal and the position of the calves with respect to the hydrophone (Lindhard, 1988), the presence of head scanning behaviors at the same time as click recordings (Favaro et al., 2013), the distraction of mothers in activities with trainers, and the proximity, orientation, and relative position of calves (Harder et al., 2016). All these indicators are subject to uncertainty and only allow accurate analysis of a calf's click trains during specific behavioral circumstances (for instance, mothers distracted by trainers [Harder et al., 2016] or calves clicking with their blowhole outside the water [Favaro et al., 2013]).

In this paper, we applied a 360° acoustic localization method (López-Marulanda et al., 2017) to analyze the acoustic exploratory behavior of a calf aged from 39 to 169 days for the first time. This method involves combining the spatial distribution of hydrophones, the acoustic properties of the acoustic source (propagation speed and spherical propagation model), and the evaluation of the time differences of arrival (TDOA) of acoustic waves from the source to each hydrophone (Alameda-Pineda & Horaud, 2014). The nonintrusive protocol allows recording of the calf's behaviors (here, its acoustical exploratory behavior) and signal productions, allowing analysis of the calf's echolocation while swimming within its social group and regardless of its position with respect to its conspecifics and the hydrophones.

Method

Study Subjects and Facility

The study was conducted between July 2015 and January 2016 at Parc Asterix dolphinarium (Plailly, France) where 9 Atlantic bottlenose dolphins (*T. truncatus*) were housed together in three interconnected pools. In the group, there were 4 females aged 42, 34, 20, and 15 years old, and four males aged 33, 31, 4, and 3 years old. The 15-year-old female gave birth to a female calf on July 3rd, 2015.

Overall, this facility is composed of one outdoor and two indoor pools, which are not acoustically isolated. The outdoor pool has a volume of 3,246 m³ and a depth that varies from 2.5 m at its shallowest point to 4.5 m at its deepest. The indoor part of the complex, divided into two sections, has a total volume of 550 m³ and a depth of 2.5 m. The dolphins have free access between the pools at all times.

Every day, the dolphins took part in at least five training sessions, starting approximately at the same time each day, during which their trainers fed them after they performed several exercises aimed to facilitate the husbandry and medical care procedures and to prepare for presentations to the public.

Recording Device

Simultaneous audio and video recordings were collected using a waterproof 360° audio-video system named BaBeL (BioAcoustique, Bien-Être et Langage) (López-Marulanda, Adam & Delfour, 2017). Video data were collected using two Kodak SP360

video cameras (wide angle of 214°), one on each side of BaBeL to allow a 360° view. These cameras were positioned underneath the waterproof housing of a digital audio recorder ZOOM H6 plugged to five calibrated and automatically synchronized Aquarian H2a-XLR hydrophones. The synchronized hydrophones were positioned to obtain the time delay of arrival in order to provide 3D estimations of dolphin positions. Audio recordings were conducted at a 96-kHz sampling frequency and coded on 24 bits. All details about the geometry of the hydrophone array are described in López-Marulanda et al. (2017).

Two successive claps were made at the beginning of the recording session: one in front of each camera in order to manually synchronize videos with audio recordings during the a posteriori analysis with specific video editing software (Final Cut Pro X 10.1.3 © Apple Inc.). A single video file was created from the two Kodak SP360 video cameras in the same window, which was associated with one of the five audio tracks and its corresponding turning spectrogram (FFT size: 1024, overlap 50%, Hanning window) provided by the free software Audacity 2.0.6 (GNU General Public License). We chose to add only one track in the video as a reference.

Recording Sessions

During the first days after the calf's birth, special efforts were made to not disturb the animals in order to protect the mother's and newborn's health and relationship. Mother and calf were never isolated from their social group and could freely move between the three pools. As a person was needed to operate BaBeL, we chose an experienced trainer who was known by all dolphins in the studied group. In order to preserve the mother-calf bonding relationship, we waited 39 days after the calf's birth to conduct recording sessions of maximum 15 min, which were scheduled once a week, two times per day, at 11:30 am and 3:30 pm, after a training session. All the recording sessions took place in the outdoor pool. From July 2015 to January 2016, we conducted a total of 32 recording sessions lasting a total of 6 hr 55 min.

The familiar trainer immersed himself/herself with the BaBeL device below the water surface (≈ 1 m under the surface) and remained floating near the edge of the pool, so the animals could choose the speed and distance with which to approach to the trainer.

Data Analysis

The five audio tracks from each recording were used for the acoustical analysis, conducted by a custom-made program in MATLAB® version 2013a (Mathworks, Natick, MA) (Blanchard, 2015). This custom-made program is based on a geometrical localization method that estimates the position of the vocalizing dolphin. The localization given by the TDOA was linked to the video using a conversion position-pixel (López-Marulanda et al., 2017). The localized dolphin was identified using body size, color, and any particular body marks.

We selected sequences in which the calf was present in the video, a click train was emitted, and our customized program localized the emitter of the vocalization. For these sequences, we used the pulse train analysis function of Avisoft-SASLab Pro version 5.2.07 (Raymond Specht; Berlin, Germany) to measure click rate, mean duration of click, and mean ICI for comparative purposes with previous studies (Favaro et al., 2013; Harder et al., 2016; Lindhard, 1988; Reiss, 1988). A hysteresis of 10 dB and a start/end threshold of -2 dB were the parameters used to analyze all the click sequences. Linear regressions evaluated changes in the calf's click train parameters with age. Mann-Whitney tests were used to compare the calf's click train parameters with its mother's.

Results

Localization Process

During the study, 32 sessions were carried out for a total of 6 hr 55 min of audio-video recordings. Dolphins were present in the videos for 5 hr 7 min and the calf for 27 min 20 s. During this time, the calf swam by the BaBeL device while a click train was recorded 188 times. The localization of the vocalizing dolphin was cataloged as ambiguous because of the proximity of two dolphins on 40 occasions (21.28%). On 9 occasions (4.79%), the dolphin emitting the vocalization was out of the range of vision of BaBeL (in indoor pools). In 37 situations (19.68%), the low signal-to-noise ratio or the overlapping nature of the recorded click trains did not allow the localization of the vocalizing dolphin. For 56 click trains (29.79%), the localization of the source pointed to the wall of the pool, probably due to acoustic reverberation. Finally, in 46 situations (24.46%), the click train was linked to a dolphin present in the video (Figure 1): 18 times to the calf (Table 1), 11 times to its mother (Table 1), and 17 times to another dolphin.

Table 1

Acoustic parameters of localized calf's and mother's click trains

Age (days)	Click rate (clicks/s)		Mean duration (ms)		Mean ICI (ms)	
	Calf	Mother	Calf	Mother	Calf	Mother
39	99.13		0.28±0.01		10.08±1.74	
46	57.45	45.94	0.31±0.01	0.31±0.02	17.39±2.74	21.75±10.48
	98.26	86.05	0.32±0.04	2.29±0.97	6.72±3.26	11.59±6.95
	79.71		0.32±0.02		12.53±0.24	
62	91.21	156.6	0.32±0.03	0.36±0.03	10.95±6.80	6.53±2.47
		86.61		0.31±0.04		11.54±4.45
		97.52		0.35±0.04		10.25±4.76
67	85.68	86.99	0.35±0.04	0.31±0.03	10.25±4.76	11.49±1.45
	97.94	80.77	0.29±0.01	0.32±0.06	10.20±1.37	12.37±3.48
81	85.76	124.8	0.30±0.02	0.30±0.01	11.65±10.83	8.00±5.20
138	144.8		0.31±0.05		6.90±5.42	
145	89.96	145.3	0.31±0.06	0.28±0.01	11.11±1.14	6.87±1.03
	72.92		0.32±0.02		13.70±2.81	
	126.5		0.29±0.02		6.38±11.71	
	89.55		0.28±0.01		11.16±9.14	
	186		0.28±0.01		5.37±1.17	
	167.7		0.30±0.03		5.95±2.57	
	111.6		0.29±0.01		8.95±2.15	
166	144.7		0.29±0.01		6.90±2.60	
159		39.7		0.81±0.22		25.17±9.41
166	195		0.288±0.010		5.121±1.156	

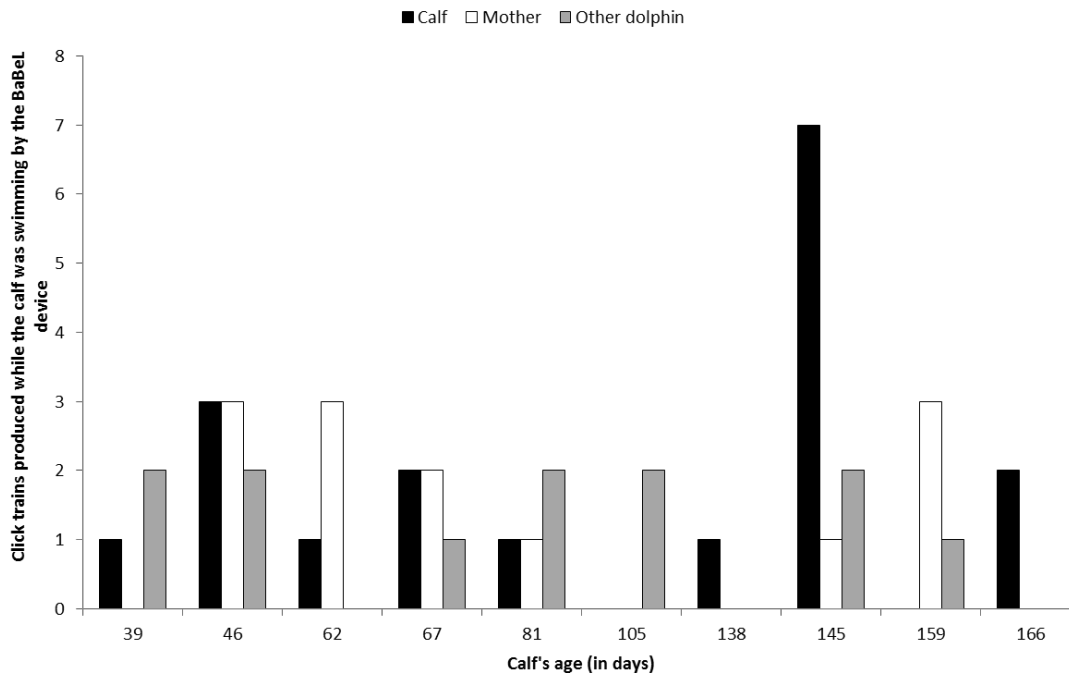


Figure 1. Number of click trains produced per individual, regarding the calf's age (N = 46).

Click Parameters of the Mother and Calf

No significant differences were found when comparing the calf's click rate (Mann-Whitney U-test, $U = 73$, $p = 0.26$), mean duration of click (Mann-Whitney U-test, $U = 142.5$, $p = 0.05$), and mean ICI (Mann-Whitney U-test, $U = 133.5$, $p = 0.13$) with those of its mother.

Calf's Echolocation Production According to Its Age

Linear regressions showed that calf's click rates increased with age ($R^2 = 0.79$, $p < 0.01$) (Figure 2a), that mean ICI decreased with age ($R^2 = 0.72$, $p = 0.01$), and that mean duration of clicks showed no significant changes ($R^2 = 0.20$, $p = 0.26$) (Figure 2b).

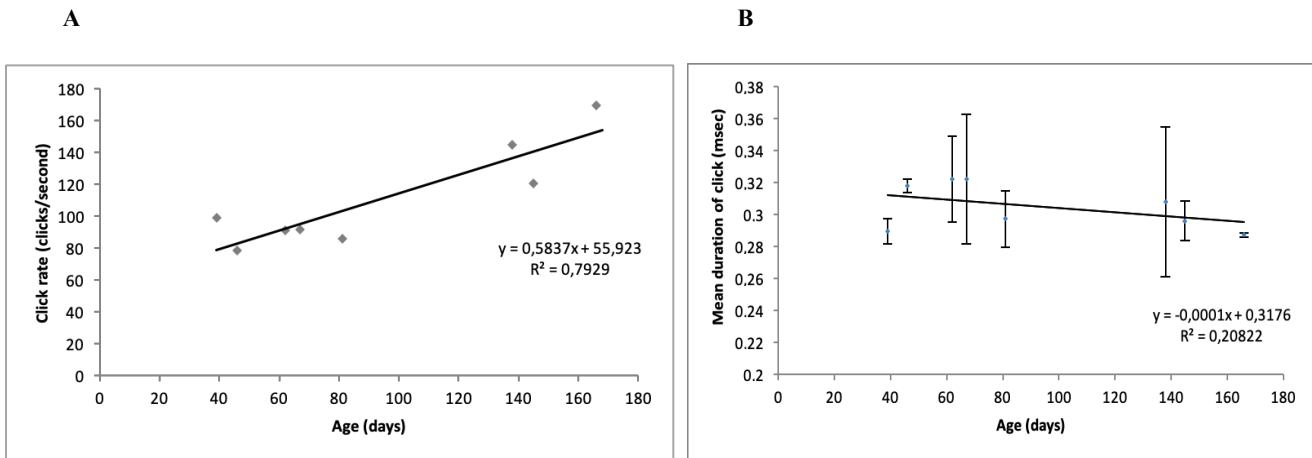


Figure 2. Linear regressions of acoustic parameters of calf's click trains: A: click rate, and B: mean duration of click.

Discussion

The localization process allowed us to identify the dolphin producing a click train in 24.46% of cases. The click train parameters of the calf during the time of the study did not significantly differ from its mother's, but we did find that the calf's click rate increased with age.

The study of the ontogenesis of acoustical exploratory behavior in dolphins presents several difficulties (e.g., regular, long term observations of individuals almost impossible; birth rate quite low, Cornell et al., 1987; the difficulty of determining which dolphin is emitting a click train), and, as a result, only six studies, conducted on dolphins under human care, have taken on this challenge (Carder & Ridgway, 1983; Favaro et al., 2013; Harder et al., 2016; Linhard, 1988; Manoukian et al., 2002; Reiss, 1988). In this study, we presented the BaBeL system and a geometrical localization methodology that allowed analysis of a dolphin's click trains, which occurred in varied circumstances, with the presence of other dolphins around and regardless of its position in relation to the recording device. For the first time, we were able to analyze the ontogenesis of a calf's acoustical exploratory behavior while it remained in its social group.

Nevertheless, our methodology presents several limitations. First, the recording device was maintained in close proximity of the wall so that reverberations of the sounds caused our custom-made program to identify the wall as the source of sound in 29.79% of the analyzed sequences. Second, the identification of the vocalizing dolphin is only possible if the animal is in the range of vision of the video camera (López Marulanda et al., 2017). When dolphins were vocalizing from the inside pools, they were no longer visible and this did not allow identification of the emitter. Third, because of the dolphins' interest in the device, sometimes our recordings showed a general cacophony of clicks in which click trains mostly overlapped, making it impossible to determine the initial start and end time of click trains and, thus, compare the click train duration with results of previous studies (Favaro et al., 2013; Harder et al., 2016).

Our results revealed that the calf showed an increase in click rate and a decrease in ICI with age. The minimum value for the click rate was found at 46 days old (57.45 Hz) and the maximum value at 166 days old (195 Hz). This could be explained by a decrease in its passive echolocation and an increase in its active echolocation due to an ongoing mastering of the production of acoustical signals and/or an increased interest/curiosity in its

surroundings. This contrasts with a previous study (Harder et al., 2016) that analyzed click train production in six calves during their first six months of life and found that mean click rate increased during the first month, decreased during the second month, and remained constant between the third and sixth month. With respect to ICIs, the values for the six calves remained consistent with a mean value of 25.32 ms (SD = 10.35) (Harder et al., 2016). In our study, ICI values from the calf's click trains varied from a mean value of 17.39 ms (SD = 2.74) at 46 days old to a mean value of 5.12 ms (SD = 1.15) at 166 days old. The calf in our study showed higher click rates and lower ICIs than the six calves analyzed by Harder et al. (2016). These differences might be explained by the nature of the object explored. Contrary to Harder et al. (2016), in which the calves were in the presence of a simple object (a single hydrophone), in our study, the calf was exposed to a complex object consisting of five arms with attached hydrophones and two video cameras that were handled by a familiar person in water. The physical parameters of the object offered various densities and shapes. Moreover, the presence of a trainer in the water could have generated an increased interest by the calf and its mother. The calf might have increased its click production per second for two reasons: As a response to the complexity of the device, which is known to arouse curiosity (Berlyne, Borsa, Craw, Gelman & Mandell, 1965), and/or due to the presence of a human in water, which can modify the behavioral response of animals (Akiyama & Ohta, 2007; Breusing, Linke, Busch, Matthes, & van der Woude, 2005).

The lack of difference between click rate, mean duration of click, and mean ICI of the calf and its mother supports the finding that infant and adult pulses are indistinguishable at 40 days old (Reiss, 1988). As our recordings started at 39 days old, it is possible that the calf was already able to produce click trains similar to those of an adult, at least with respect to the measured acoustic parameters in this study. This does not exclude the possibility that other acoustical parameters of the calf's click train not measured here could differ from those of an adult.

To conclude, at the age of 39 days, a bottlenose dolphin calf's acoustic parameters regarding its click trains did not differ from those of an adult. However, click rate was shown to increase with the age of the calf. This study used a new methodology that allowed us to describe not only the acoustic parameters of the subjects' click trains but also the position of the calf during exploratory behavior with respect to the object explored. Compared to other methods of localization (i.e., Dudzinski, Clark, & Würsig, 1995), our method allows an acoustic localization in the vertical axis, regardless of the observer's position, thanks to the 360° video system. The BaBeL method is nonintrusive and allows the study of social behaviors as well as the dynamic of vocal production at an individual level. As communication is crucial for dolphin social behaviors (Janik, 2009), our method offers an opportunity to better understand how vocal communication develops and is organized within a group. For example, further studies using the same technology and methodology would reveal how the exploratory behavior of dolphin calves changes over time and how the mother and other conspecifics influence this learning process. The BaBeL system has the potential to uncover unknown aspects of the dolphins' perception of their world and allows scientists to build new paradigms, as, for the first time, it is possible to identify and spatially localize the clicks emitters and, hopefully very soon, any sound productions. This technology and applied methodology will give new insights on dolphins' communication dynamics.

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