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ABSTRACT

The long-term monitoring of long-lived animals often requires individual identification. For cetaceans, this identification may be based on morphological characters observable from a boat such as shape, spots and cuts of the back, fluke and dorsal fins. However, for some species such as the sperm whales (*Physeter macrocephalus*), this approach may be challenging as individuals display a rather uniform skin pigmentation. They also do not very often show their fluke, complicating individual identification from a boat. Immature sperm whales that usually have an unharmed fluke may be excluded from photo-identification catalogues. Within the framework of the Maubydick project, focusing on the long-term monitoring of sperm-whales in Mauritius, passive underwater observation and video recording were used to identify long-lasting body markers (e.g. sex, ventral white markings, cut-outs of fins). A catalogue of 38 individuals (six adult males, 18 adult females and 14 immatures) enabled observers to record some nearly-daily, and yearly resightings.

Advantages and disadvantages of this method are presented here. Such catalogues represent a robust baseline for conducting behavioural, genetic and acoustic studies in social species. Benefits of such newly acquired knowledge are of primary importance to implement relevant conservation plans in the marine realm.

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Introduction

The long-term study of long-lived animal populations often requires individual identification, e.g. for abundance estimation in mark-recapture surveys, social behaviour understanding and for conservation purposes (Hammond et al. 1990; Wursig and Jefferson 1990; Gowans and Whitehead 2001; Möller et al. 2006; Calambokidis et al. 2008; Gero et al. 2014; Cantor et al. 2016; Gero and Whitehead 2016; Augusto et al. 2017; Louis et al. 2017; Huijser et al. 2020; Girardet et al. 2022; Sarano et al. 2021; Sèbe 2021).

This identification may be challenging in the marine environment and cetaceans are no exception, spending only a limited amount of time at the sea surface. The individual identification is then based on a reduced number of morphological characteristics captured on photographs taken from a boat or an unmanned aerial vehicle (Verfuss et al. 2019). The main morphological characteristics that can be observed are the colouration of the back, the shape of the dorsal fin and/or the distinct markings on the trailing edge of the fluke, the latter only being visible when the animal flukes (Arnbom 1987; Sears et al. 1990; Whitehead 1990; Dufault and Whitehead 1995; Gomez-Salazar et al. 2011). Algorithms have been developed to automate the tedious task of visually inspecting photographs for potential resightings (e.g. Whitehead 1990; Huele and Udo de Haes 1998; Huele and Ciano 1999; Beekmans et al. 2005; Hillman et al. 2010; Levenson et al. 2015).

For sperm whales (*Physeter macrocephalus*), many insights have been gained through boat-based observations (e.g. Alessi et al. 2014; Carpinelli et al. 2014; Gero et al. 2014; Cantor et al. 2016; Gero and Whitehead 2016; Cantor et al. 2019; Van der Linde and Eriksson 2020). Individual identification of sperm whales is usually based on mark patterns of the fluke (Arnbom 1987). Body marks on the back can also be used (e.g.

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Alessi et al. 2014; Van der Linde and Eriksson 2020). However, when monitoring sperm whale populations by photo-identification (photo-ID), some individuals may remain unidentifiable from the sea surface because of several factors (Whitehead 2006; Boys et al. 2019; Van der Linde and Eriksson 2020; Kobayashi et al. 2020). First, a significant proportion of individuals have a barely distinctive dorsal fin and a uniformly coloured fluke, unlike humpback whales for example (Mizroch et al. 1990; Van der Linde and Eriksson 2020). The capture probability may also differ between individuals – some spending less time at the surface or having no visible distinctive signs may escape identifications (Whitehead 2006). A particularly important problem concerns the identification of young immature individuals which, on the one hand, do not often show their flukes because they do not participate in deep-water foraging dives, and on the other hand, rarely show distinctive markings on their flukes or on the dorsal region. This makes their identification particularly difficult (Whitehead 2006; Gero et al. 2009). Furthermore, their sexing is impossible from the surface as they do not show any apparent sexual dimorphism (Arnbom and Whitehead 1989; Gero et al. 2013). More, adult females and large immatures have similar sizes and may therefore be difficult to distinguish (Matthews et al. 2001; Gero et al. 2014).

Underwater observation represents a solution to many of these obstacles. Such an approach can be used to make an accurate identification of individuals and collect additional information that cannot be collected from a boat alone. Underwater observation has been used successfully in humpback whales (*Megaptera novaeangliae*) (Glockner-Ferrari and Ferrari 1990), bottlenose dolphins (*Tursiops truncatus*) (Herzing 1997), manta rays (*Mobula* spp.) (Town et al. 2013; Marshall and Holmberg 2018), whale sharks (*Rhincodon typus*) (Pierce et al. 2018) and moray eels (*Gymnothorax* sp.) (Sèbe et al. 2021) to develop catalogues of individuals. Applied to sperm whales, underwater observation may, in some cases, help to identify more individuals as more discriminating markers, e.g. located on the ventral side of the animals, could be observed. This would also allow inferring sex with certainty.

In this study, we wanted to test whether underwater observations could be useful for individual identification of sperm whales, with particular attention to juveniles. We present the results of a study based on an underwater photo-ID and video-identification (video-ID) protocol used to monitor sperm whales in Mauritius since 2015 by the French association Longitude 181, in the framework of the Maubydick programme run by the Mauritian NGO Marine Megafauna Conservation Organization. A unique catalogue of 38 sperm whales displaying long-lasting and reliable morphological markers for each individual was created. Underwater observations and individual-specific identification also allowed for non-invasive sampling and genetic analysis of the group (Girardet et al. 2022; Sarano et al. 2021) as well as acoustics studies (Ferrari et al. 2019). These results, which confirm the relevance of underwater observations for the study of sperm whales, should be of primary interest in terms of data acquisition and conservation of the species in the Indian Ocean, and certainly more widely.

Materials and methods

Field observations

Sperm whales are common off the coast of Mauritius Island (Mascarenes Islands, Indian Ocean). A protocol based on underwater observations through photograph and video recording was implemented in 2011 for the Maubydick project led by the MMCO (Marine Megafauna Conservation Organization, Mauritius Island). In 2015, the protocol was standardized under the scientific lead of Longitude 181 association (France), and the sampling effort has increased over the years since then (Table I).

The study area is located on the west coast of Mauritius Island, up to 15 km off the coast, between 20.465S 57.334E–19.986S 57.605E (Sarano et al. 2021). The boat used for this survey is a 15-metre Mauritian motor vessel, chartered by MMCO and equipped for diving with a low rear platform, from which observers can immerse themselves by gently sliding into the water. All underwater observations were video-recorded, either with a Sony F55 4 K, a Sony EXIR HD, a Nikon D800 Camera in Hugyfot housing or a GoPro camera Hero 4, 7 and 8.

Ethical and legal aspects of the observations

According to Mauritius rules, observations were performed only in the morning (from 6.00 am to 12.00 pm). Out of respect for the cetaceans and their habitats, the observers strictly followed the ethical rules of the official Charter for responsible approach and observation of marine mammals and the Maritime zone regulations (Conduct of Marine Scientific Research/ Notice no. 57 of 2017) promulgated by the Mauritius Government. This study was placed under the policies of the Mauritius Department for continental shelf, maritime zone administration and exploration, with appropriate permits to

Table I. Number of days of fieldwork.

Years	2011–2014 fieldwork 2011	2012	2013	2014	2015–2020 fieldwork 2015	2016	2017	2018	2019	2020	Total numbers of fieldwork days and of observations 2011–2020	2015–2020
Numbers of days of fieldwork	13	5	10	12	36	40	54	70	81	36	357	317
Days with no observations (numbers, percentage)	2	1	0	0	7, 19.4%	6, 15.0%	4, 7.4%	6, 8.6%	13, 16.1%	15, 41.7%	54, 15.1%	51, 16.1%
Days with observation of sperm whales (numbers, percentage)	11	4	10	12	29, 80.6%	34, 85%	50, 92.6%	64, 91.4%	68, 83.9%	21, 58.3%	303, 84.9%	266, 83.9%

The number of days of fieldwork per year is indicated, as well as days with and without observation of sperm whales (in number of days and in percentage of days of fieldwork). The protocol based on underwater observations was implemented in 2011 and standardized in 2015.

conduct underwater videos, underwater observations of sperm whales and marine scientific research.

Underwater observations

The observation protocol was the same as described in Sarano et al. (2021). Briefly, when a group of sperm whales was spotted from the boat, the animals were approached no closer than 100 m and a small group of swimming observers, usually a scuba diver and 4 snorkellers, immerged themselves, upstream considering the movement direction of the sperm whale group. Observers were as passive as possible, typically not swimming towards the whales but waiting for the sperm whales to approach to film them. When sperm whales were static (e.g. socializing or sleeping), observers slowly and quietly approached. The scuba diver recorded videos and observations at a maximum depth of 40 m, while the snorkelers performed observations from the surface and filmed the sperm whales at a maximum depth of 20 m.

The duration of observation varied between 20 s to 10 min when the animals were sleeping or socializing near the observers. The boat always stayed away and picked up the observers once the sperm whale group had moved away.

Video processing

The identification of morphological markers to create the catalogue of individual-cards was based on meticulous analyses of the videos using VLC player (VideoLAN Organization, France). Slow motion mode was used to get the best screenshot for each of the body marks. These pictures were then used to illustrate the morphological markers on the catalogue.

Morphological markers

The morphological markers retained for the catalogue are illustrated in Figure 1. They include: sex, white spots, cuts with removal of material, scars from teeth marks (i.e. rake marks), shape of the fluke. Some of these marks can be observed from a boat (e.g. cuts on the fluke, cuts/callus on the dorsal fin), but the majority are visible only underwater (e.g. sex, cutting of the pectoral fins, pigmentation patterns on the ventral side, on the mandibular area and the cheeks, shape of the jaw, size of the teeth). The pigmentation patterns of the skin in sperm whales result in white areas on the body that can be characterized according to their size (small, medium, large), their shape (spot, stripe, escutcheon) and their position on the body (fluke, genital, ventral, pectoral and mandibular areas, side and back).

Types of cutting pattern of the fins (small nicks, distinct nicks, waves, scallops, missing portions, holes, tooth mark scars and calluses) have already been defined (Arnbom and Whitehead 1989; Whitehead 1990). The features used in this study are (for those previously defined, descriptions are those of Arnbom and Whitehead 1989 when indicated; in the other cases, descriptions have been generalized to fit to underwater observations, Figure 1 and Table II):

- Small nick: small indentation in edge of fin; only distinguished when the fin was relatively close (Arnbom and Whitehead 1989)
- Distinct nick: larger indentation sharply cut away (Arnbom and Whitehead 1989), which can be seen from a longer distance
- Wave: shallow smooth depression, with material removal, the depth of the missing part of the fin is $\leq$20% of its width
- Scallop: deep smooth depression, with material removal, with depth of the missing part of the fin being $\geq$ 20% of its width
- Tip-missing: when only the tip of the fin is missing (fluke and pectoral)
- Missing portion: large part of the fin is sectioned (fluke and pectoral)
- Hole: small perforation of the fins

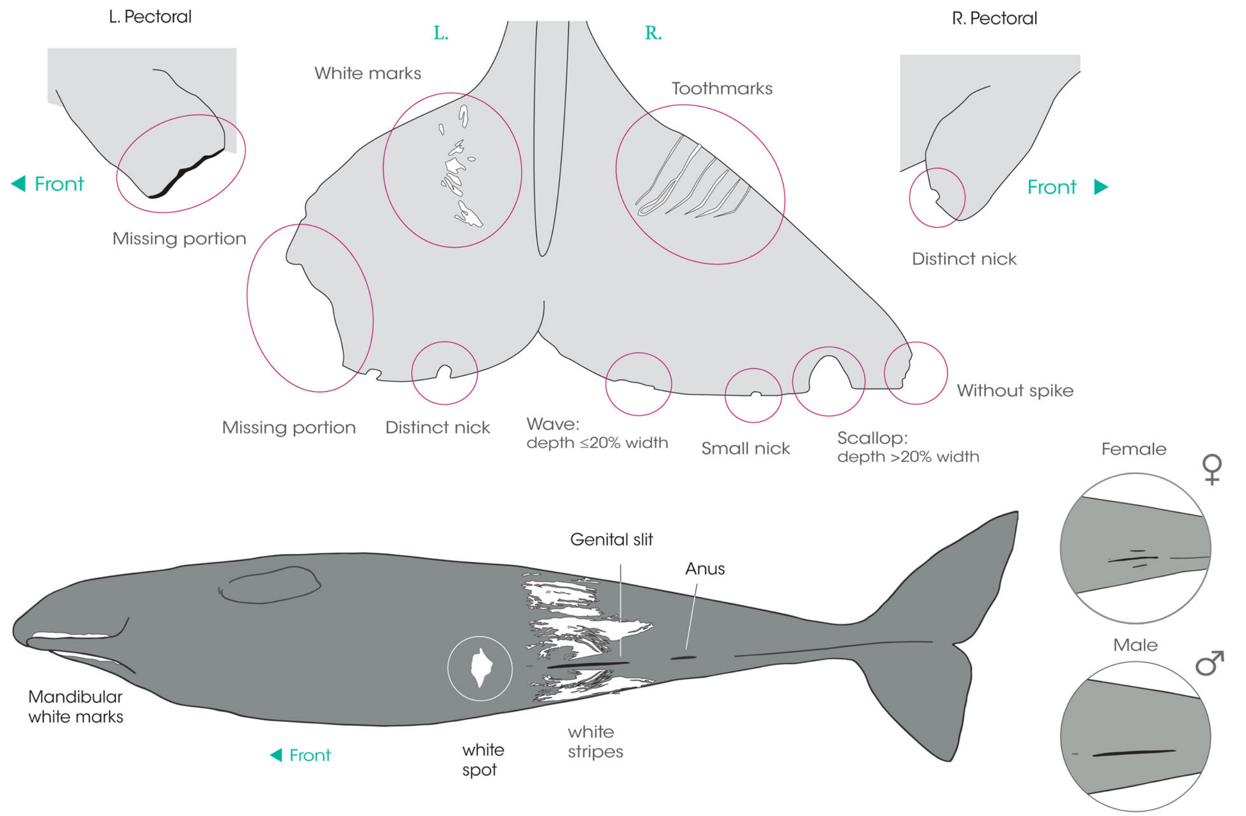

Figure 1. Morphological markers (sex, cutting patterns of the fins and pigmentation patterns) used in this study to identify sperm whales.

- Tooth mark: often seen as parallel permanent scars (made by the teeth of predators such as pilot whales or orcas).
- Curled: tip of the fluke curled
- Callus: greyish or white deformity on the dorsal fin (Arnbom and Whitehead 1989)
- The presence of very discriminating characteristics such as the crooked jaw or the bulge of the neck.

Temporary scratches and peeling spots were used only to help with daily resighting over a field season. These non-permanent markers were therefore, not retained in the catalogue.

Creation of the individual-specific card catalogue

The catalogue developed through the underwater observation protocol consists of a series of individual cards grouping photographs and body marks recorded for each sperm whale (Supplementary Information 1 and 2). For better recognition of individuals in the field and easier use of the catalogue, the cards were designed using simplified standards (see Supplementary Information 1 and 2). For each individual, the distinctive marks were indicated on the card (e.g. on the fluke), and/or detailed on dedicated zoomed photos (of pectoral, spots, mouth, etc.). Additional information was listed at the top of the card such as date of first and last observation and years of successive observations. Each individual was given a name in an alphanumeric reference system to ease its identification in the field. Additional information, such as the availability of DNA samples, or information of kinship relations when known are indicated.

Individual-specific cards were (and are) updated yearly with new elements in order to: (1) add new morphological markers, (2) take into account both the evolution over time of the markers, the growth and the presence of teeth, and (3) include any new information.

The number of resightings for an individual is defined as the number of days that the individual is observed and filmed. Multiple daily resightings were ignored. This number is available for all individuals between 2011 and 2020 (Table III).

Results

Between 2015 and 2020, the team went out in the field on an average of 53 days per year (min 36 days in 2015 and 2020, max 81 days in 2019), mainly between

Table II. Marks used to identify specifically all the individual sperm whales represented in this study.

Name	Sex	Age class	First obs	Last obs	Annual recap. since	Tail Fin					Pectoral fins		Dorsal fin	White marks	Other marks
						Shape	Left tip	Right tip	Left Lobe	Right lobe	Left	Right			
Adélie	F	A	2011-05-20	2020-03-19	2011	Convex	–	–	Wave	Wave	Wave	Scallops	Small nick	Pectoral, medium	–
Aïko	F	A	2008-09-25	2020-03-12	2011	Straight	–	Tip-missing	Wave	Scallops	–	2 Distinct nicks	–	Mandibular, large	–
Caroline	F	A	2012-10-06	2020-02-27	2012	Straight	–	Tip-missing	Scallop	Scallop	2 small nicks	–	Button	–	–
Claire	F	A	2011-05-17	2020-03-12	2014	Straight	–	–	Waves	Waves	Wave	2 Spikes	–	–	Body colour very pale
Déline	F	A	2009-02-25	2019-04-29	2016	Straight	Missing portion	Tip-missing	Wave	Scallop	Tip-missing	–	White callus	–	–
Delphine	F	A	2011-05-11	2020-03-18	2011	Straight	Missing portion	Missing portion	Wave	Wave	Tip-missing	Tip-missing	–	Ventral, small	–
Dos Calleux	F	A	2008-05-12	2020-03-12	2015	Straight	–	–	Small nick	2 distinct nicks	–	2 small nicks	Small nick + Callosity lower part	–	–
Emy	F	A	2007-06-24	2020-03-19	2011	Convex	Missing portion	Tip-missing	Scallop	Waves	Wave	Missing portion	Callus+ scallop	Mandibular, large	–
Germine	F	A	2009-06-13	2020-03-12	2011	Convex	–	–	Scallop	Distinct nicks	Missing portion	–	–	Ventral escutcheon	–
Irène Gueule Tordue	F	A	2009-01-18	2020-03-12	2011	Straight	Tip-missing	–	Distinct nick	Small nick	–	–	Callus	–	Arched-shaped jaw
Issa	F	A	2009-02-25	2020-03-12	2013	Convex	Tip-missing	Tip-missing	Spike	Distinct nick	–	1 Spike	–	Ventral, medium; Genital, small	–
Joue Blanche	F	A	2009-01-27	2015-04-25	2011–2015	Convex	–	Tip-missing	Small nick	Wave + distinct nicks	–	–	–	Left cheek medium	–
Lucy	F	A	2009-06-13	2020-03-12	2011	Straight	–	5 Distinct nicks	Wave	Small nick	Small nick	–	Callus	Mandibular	Body colour very dark
Mina	F	A	2009-06-13	2020-03-12	2011	Concave	–	Distinct nick	–	2 scallops	–	–	–	Mandibular small	–
Mystère	F	A	2011-06-22	2020-02-17	2015	Straight	Tip-missing	–	Wave	Distinct nicks	–	–	2 small nicks	Genital, small	Scar, cheek
Swastee	F	A	2011-03-24	2019-04-26	2016–2019	Straight	Tip-missing	Tip-missing	Wave + spike	Wave + Hole	–	–	Callus	–	Huge bulge on the nape
Vanessa	F	A	2012-01-12	2020-03-18	2014	Straight	Tip-missing	Tip-missing	Scallop	Wave	–	–	White callus	Ventral, medium	–
Yukimi	F	A	2011-03-14	2020-03-10	2015	Convex	Distinct nicks	Distinct nick	Wave	Wave	2 Small nicks	–	–	–	–
Agatha	F	I	2014-03-24	2015-04-17	2014–2015	Straight	Tooth marks	Missing portion	–	–	–	–	–	–	Tooth marks, head
Alexander	M	I	2019-03-05	2020-03-18	2019	Straight	–	–	–	2 Small nicks	–	–	–	–	Scar, mandibular

(*Continued*)

Table II. Continued.

Name	Sex	Age class	First obs	Last obs	Annual recap. since	Tail Fin					Pectoral fins		Dorsal fin	White marks	Other marks
						Shape	Left tip	Right tip	Left Lobe	Right lobe	Left	Right			
Ali	M	I	2018-02-02	2020-03-12	2018	Straight	–	Tooth marks	–	–	–	–	–	Mandibular, white mark black mottled. Caudal, white marks	–
Arthur	M	I	2013-04-05	2020-03-12	2013	Straight	Missing portion	–	Distinct nick	Scallop	–	Distinct nick	Bear ear shaped	Ventral escutcheon	–
Baptiste	M	I	2017-03-11	2017-03-24	2017–2017	Straight	–	–	–	–	–	–	–	Back, medium	–
Chesna	F	I	2018-03-02	2020-03-18	2018	Straight	–	Missing portion	–	Tooth marks	–	Distinct nick	Furrow left side	–	–
Daren	M	I	2018-04-18	2020-03-12	2018	Straight	–	–	Hole	–	–	–	Furrow left side	–	–
Eliot	M	I	2011-03-14	2020-03-19	2011	Straight	Small nick	Tooth marks	–	Small nick + thooth marks	–	–	–	Ventral, escutcheon	–
Lana	F	I	2019-02-21	2020-03-12	2019	Straight	–	–	–	–	–	–	Bear ear shaped	–	Hole head
Maurice	M	I	2011-03–	2016-02-24	2011–2016	Concave	–	–	Small nick	Wave	–	–	–	Genital, small	–
Miss Tautou	F	I	2016-02-24	2020-03-12	2016	Straight	Missing portion	–	–	–	–	Scallop	Tooth marks	Ventral, stripes	–
Roméo	M	I	2013-03-13	2020-03-12	2013	Straight	–	–	Small nick	Scallop	–	–	High + callus	–	–
Tache Blanche	M	I	2011-06–	2020-03-19	2011	Concave	–	–	Small nick	–	–	Small nick	–	Genital, medium	–
Zoé	F	I	2013-12-16	2020-03-18	2013	Concave	–	–	–	Hole	Distinct nick	2 distinct nicks	–	–	–
Aman	M	A	2018-07-18	2018-07-18	1 obs	Straight	Curled	Curled	Wave	Curled + waves	–	–	–	Genital, Escutcheon	Back, stripes
Anjhin	M	A	2017-04-17	2017-05-05	2017–2017	Straight	Curled	Curled + Distinct nick	Waves	Scallop	–	–	White marks	Pectoral, stripes; Ventral, stripes; Escutcheon (ventral, genital, sides) large	–
Jonas	M	A	2018-07-18	2019-06-07	2018–2019	Straight	–	–	Wave	Waves	Waves	Waves	–	Pectoral, Large. Escutcheon (ventral, genital, sides) large	–
Noé	M	A	2018-04-16	2018-04-18	2018–2018	Straight	Curled	–	Wave + distinct nick	–	Small nick	–	–	Genital, medium	–
Reza	M	A	2019-03-14	2019-03-28	2019–2019	Straight	–	–	–	Distinct nicks	–	Waves	–	Genital, large. Caudal, small	–
Vasilily	M	A	2018-07-02	2018-07-02	1 obs	Straight	Missing portion	Missing portion	Distinct nick	Waves	–	–	–	Escutcheon pectoral, large	–

A: Adult. I: Immature.

Table III. Numbers of days of observation per individual and percentage of days of observation per individual and per number of days of fieldwork with sperm whale observation.

	1st OBS	2011	2012	2013	2014	2015		2016		2017		2018		2019		2020		Total	Total
Adult females		N	N	N	N	N	%	N	%	N	%	N	%	N	%	N	%	2015–2020	2011–2020
Adélie	2011	4	0	4	3	11	0.38	13	0.38	22	0.44	20	0.31	24	0.35	5	0.24	**95**	**106**
Aïko	2008	3	1	4	2	13	0.45	14	0.41	12	0.24	16	0.25	26	0.38	8	0.38	**89**	**99**
Caroline	2012	0	1	3	1	3	0.10	12	0.35	18	0.36	18	0.28	18	0.26	4	0.19	**73**	**78**
Claire	2011	1	1	0	1	6	0.21	13	0.38	12	0.24	15	0.23	15	0.22	5	0.24	**66**	**69**
Déline	2009	3	0	1	1	3	0.10	8	0.24	8	0.16	6	0.09	1	0.01	0	0.00	**26**	**31**
Delphine	2011	3	1	4	4	9	0.31	18	0.53	29	0.58	35	0.55	19	0.28	4	0.19	**114**	**126**
Dos Calleux	2008	1	0	0	0	2	0.07	7	0.21	20	0.40	14	0.22	15	0.22	8	0.38	**66**	**67**
Emy	2007	5	2	1	1	7	0.24	16	0.47	21	0.42	22	0.34	19	0.28	3	0.14	**88**	**97**
Germine	2009	10	5	4	4	23	0.79	21	0.62	31	0.62	32	0.50	36	0.53	11	0.52	**154**	**177**
Irène	2009	9	3	3	5	9	0.31	24	0.71	30	0.60	26	0.41	38	0.56	9	0.43	**136**	**156**
Issa	2009	1	0	1	3	3	0.10	13	0.38	10	0.20	14	0.22	14	0.21	5	0.24	**59**	**64**
Lucy	2009	4	1	3	3	11	0.38	23	0.68	18	0.36	27	0.42	21	0.31	4	0.19	**104**	**115**
Mina	2009	2	0	1	3	5	0.17	13	0.38	16	0.32	31	0.48	18	0.26	3	0.14	**86**	**92**
Mystère	2011	3	1	0	2	6	0.21	8	0.24	11	0.22	21	0.33	17	0.25	2	0.10	**65**	**71**
Swastee	2011	1	0	0	1	3	0.10	2	0.06	6	0.12	4	0.06	6	0.09	0	0.00	**21**	**23**
Vanessa	2012	0	1	1	4	5	0.17	11	0.32	26	0.52	33	0.52	14	0.21	3	0.14	**92**	**98**
Yukimi	2011	3	0	1	1	1	0.03	12	0.35	5	0.10	17	0.27	30	0.44	3	0.14	**68**	**73**
Averages							**0.24**		**0.39**		**0.35**		**0.32**		**0.29**		**0.22**	**0.30**	
Immatures	1st OBS	N	N	N	N	N	%	N	%	N	%	N	%	N	%	N	%		
Alexander	2019													38	0.56	7	0.33	**45**	**45**
Ali	2018											47	0.73	45	0.66	11	0.52	**103**	**103**
Arthur	2013			3	6	21	0.72	29	0.85	30	0.60	41	0.64	43	0.63	11	0.52	**175**	**184**
Chesna	2018											39	0.61	31	0.46	6	0.29	**76**	**76**
Daren	2018											14	0.22	46	0.68	11	0.52	**71**	**71**
Eliot	2011	6	4	5	6	16	0.55	21	0.62	30	0.60	41	0.64	32	0.47	6	0.29	**146**	**167**
Lana	2019													43	0.63	6	0.29	**49**	**49**
Miss Tautou	2016							25	0.74	34	0.68	35	0.55	44	0.65	11	0.52	**149**	**149**
Roméo	2013			2	5	19	0.66	28	0.82	24	0.48	35	0.55	41	0.60	8	0.38	**155**	**162**
Tache Blanche	2011	3	3	5	5	11	0.38	15	0.44	25	0.50	41	0.64	32	0.47	7	0.33	**131**	**147**
Zoé	2013			1	4	12	0.41	21	0.62	23	0.46	31	0.48	27	0.40	6	0.29	**120**	**125**
Averages							**0.54**		**0.68**		**0.55**		**0.56**		**0.56**		**0.39**	**0.55**	
Missing individuals	1st OBS	N	N	N	N	N	%	N	%	N	%	Last Obs							
Joue Blanche	2009	0	2	0	3	3	0.10	–	–	–	–	2015-04-25						**3**	**8**
Agatha (Juv)	2014				5	13	0.45	–	–	–	–	2015-04-17						**13**	**18**
Baptiste (Juv)	2017									9	0.18	2017-03-24						**9**	**9**
Maurice (Juv)	2011	1	4	3	6	15	0.52	1	0.03	–	–	2016-02-24						**16**	**29**

1st obs: date of the first observation of each individual; **N**: number of days of observation of each individual per year; **%**: number of days of observation of each individual per number of days of fieldwork with sperm whale observation; **Total 11–20**: total number of observations of the individual during 2011–2020 period; **Total 15–20**: total number of observations of the individual during 2015–2020 period. **Average**: average of % of observation per categories. For the missing individuals, days of last observations are indicated.

February and May (Table I). In 2020, the fieldwork season was shortened due to bad weather and the Covid19 pandemic. The catalogue was created from about 250 h of underwater video recording between 2015 and 2020, for a total number of 317 days of observation (Table I). Sperm whales were observed in 83.9% of the field trips.

Catalogue of individual-specific cards

A total of 38 identified individuals are presented in this study: 18 adult females, 14 immatures (9 males, 5 females) and 6 adult males (Table II and Supplementary Information 1 and 2). All morphological markers identified for each of these 38 individuals were recorded (Table II). They are classified according to their position on the body (e.g. sex, fluke, pectoral, dorsal, back, head) and, for white marks, according to their location on the ventral parts of the animal.

Gender was the first identification criterion used in the field to identify the individuals. Then the individual-specific body marks were used to narrow down the identification at the individual level. The number of body marks typically increased with age, young individuals displaying very few (e.g. Ali, Alexander, Daren, Lana) to more than 10 marks in older individuals (e.g. up to 14 marks for the adult male Anjhin, Table II). Some of these body marks were unique enough to enable direct identification of the individuals: e.g. distinct missing portions on the fluke (e.g. Arthur, Chesna, Miss Tautou, Agatha) or on the pectoral fin (e.g. Germine), white marks (e.g. Adélie, Tache Blanche, Issa, Joue Blanche) or arched-shaped jaw (e.g. Irène's twisted jaw). For other individuals, the observation of several body marks was required to make the identification. Overall, the body marks presented in Table II enabled field observers to unambiguously identify these 38 individuals.

Marker persistence over time

All individuals had persistent markers over time and only those markers were used as individual-specific marks, i.e. no body mark disappeared during the present nine-years study. White skin pigmentations appeared stable over time as well as marks resulting from a wound with flesh removal: e.g. Eliot's clear ventral escutcheon (Figure 2), the white spot of Tache Blanche, the sectioned pectoral of Germine or Irène's twisted jaw were resighted on the videos, either from birth (for immature: Eliot and Tache Blanche), or since their first observations in 2011 (for adult females: Germine and Irène).

Resighting rate of females and immatures

The primary aim of the catalogue was to enable underwater field identification of individual whales from 2015 to 2020. The catalogue was also used to analyse field videos recorded between 2011 and 2014, as well as some older underwater photographs taken in 2007 and 2009, in order to identify the individuals. The observation effort was therefore divided in two periods, one until 2014 and the second starting in 2015 (Tables I and III).

Over the period 2011–2020, 17 adult females identified were resighted 1542 times with an average rate of 91 resightings per individual (min = 23, max = 177). One adult female, Joue Blanche, was seen only eight times, and no more since 2015 (Table III). Among the adult females, two had few resightings (Déline $n = 31$ and Swastee $n = 23$) although they were easily identified thanks to their distinct marks (for Swastee, a huge bulge on the nape; for Déline, a big cut on the fluke – see Supplementary Information 1 and 2). The most resighted females were Germine ($n = 177$) and Irène ($n = 156$), observed during more than 50% of the days of fieldwork.

Immatures were more often resighted, even those presenting limited distinctive marks such as Roméo, Ali or Daren (between 39% to 68% of the days of observation depending on the individual, 55% on average) than adult females (between 22% to 39%, 30% of the days of observation on average). The most resighted immature was Arthur ($n = 184$).

During the 2015–2020 period, some individuals disappeared. They have been collated at the bottom of Table III, i.e. two immature males (Maurice, 5 years old and Baptiste, 3 weeks old), probably dead, and an immature female (Agatha, 1 year old) with her assigned mother Joue Blanche (observed since 2009) who both disappeared (or left the group) in April 2015.

Discussion

In the Indian Ocean, sperm whales have been little studied compared with other regions. Kirkwood et al. (1980) estimated a global abundance of about 30,000 sperm whales, but no more recent estimates are available. Sperm whales have been studied, for example, off Sri Lanka, the Seychelles and around Mauritius (Gordon 1987; Whitehead and Kahn 1992; Sarano et al. 2021; Girardet et al. 2022). Photoidentification campaigns and satellite tracking have confirmed that sperm whales are common near Mauritius and La Reunion Islands (Huijser et al.

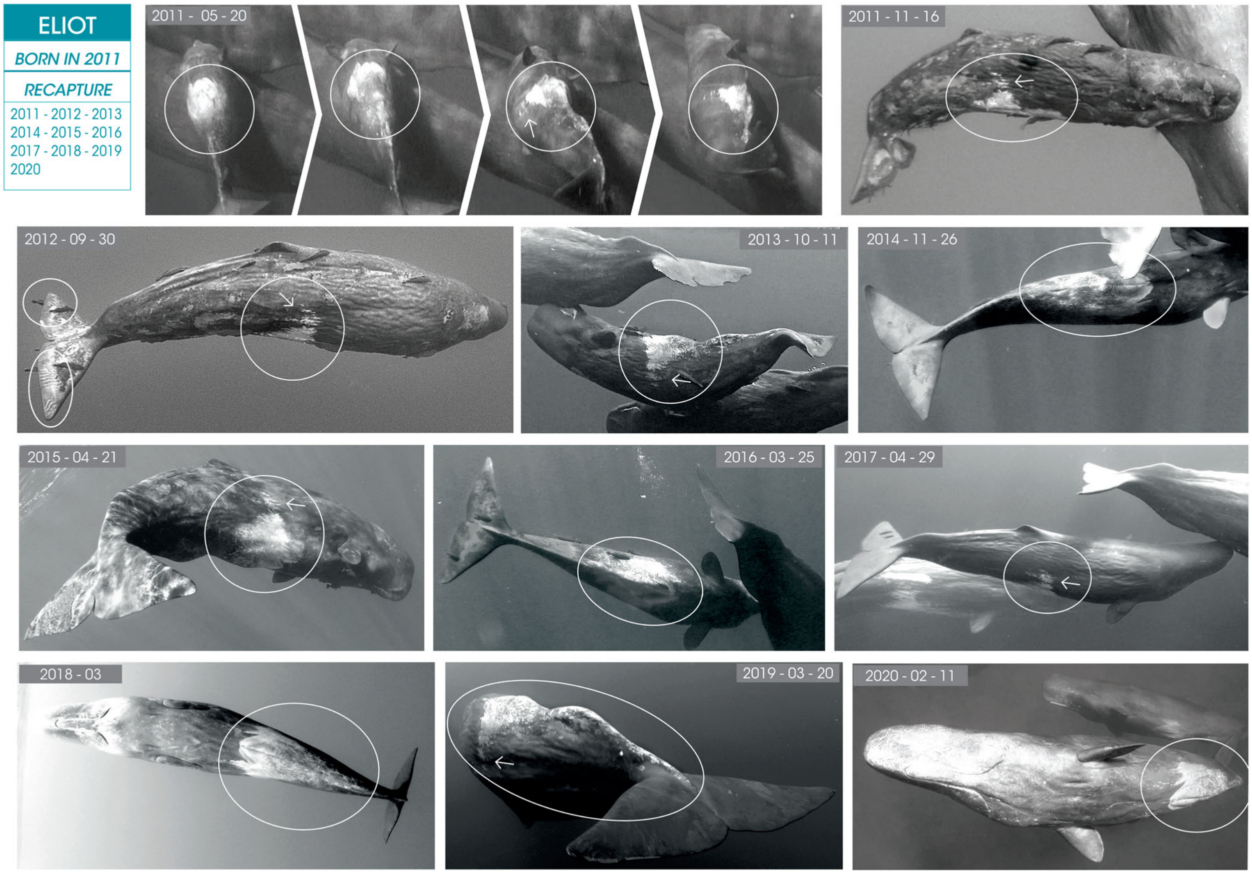

Figure 2. Example of resighting of a body mark over nine years: the first four photos (taken from a sequence where the newborn Eliot turns around) show the shape of the escutcheon captured at different angles. The other photos were taken every year from its birth in 2011 until 2020. The escutcheon being unique, it allows the direct identification of this immature, while its fluke shows only traces of teeth and tiny notches almost indistinguishable.

2020; Chambault et al. 2021). Here, we present a long-term study of sperm whales off Mauritius, based on an underwater observation protocol allowing individual identification using morphological body marks. The study led to the development of a robust catalogue enabling the unique identification and monitoring of 38 sperm whales. A particular social group composed of 28 individuals, 'Irene's group', has been characterized and extensively studied thanks to non-invasive sampling (Girardet et al. 2022; Sarano et al. 2021).

In conjunction with boat-based observation, allowing the identification of a high number of individuals (Huijser et al. 2020), the underwater approach presented in this study will greatly help to determine the trends of the studied sperm whale populations. First, by increasing the accuracy and the frequency of individual identification, and the number of individual resightings. Second, by bringing the opportunity to differentiate calves from one another. Calves and juveniles are in fact particularly important to study, as only their precise count allows the determination of the real rate of increase of the population (e.g. Gero and Whitehead 2016). Demographic parameters concerning young individuals (e.g. birth, survival, sex ratio) are crucial to understand population health and, in the case of sperm whales, cannot be properly determined from boat observations (Whitehead 2006; Gero et al. 2009). All juveniles of Irene's group were identified and sexed during our study, proving that underwater observation represents a very relevant approach to study sperm whale populations.

Sex assignation, individual-identification of immatures, high rates of resighting are, among others, several benefits of underwater monitoring of sperm whales.

Except for adult male sperm whales which are easily identifiable (Arnbom and Whitehead 1989), skin biopsies or sloughed skin samples and molecular sexing are necessary to determine gender (Gero et al. 2008, 2009, 2014). Underwater observation allows for observation of the genital slit, and thus to distinguish between males and females, even before they reach

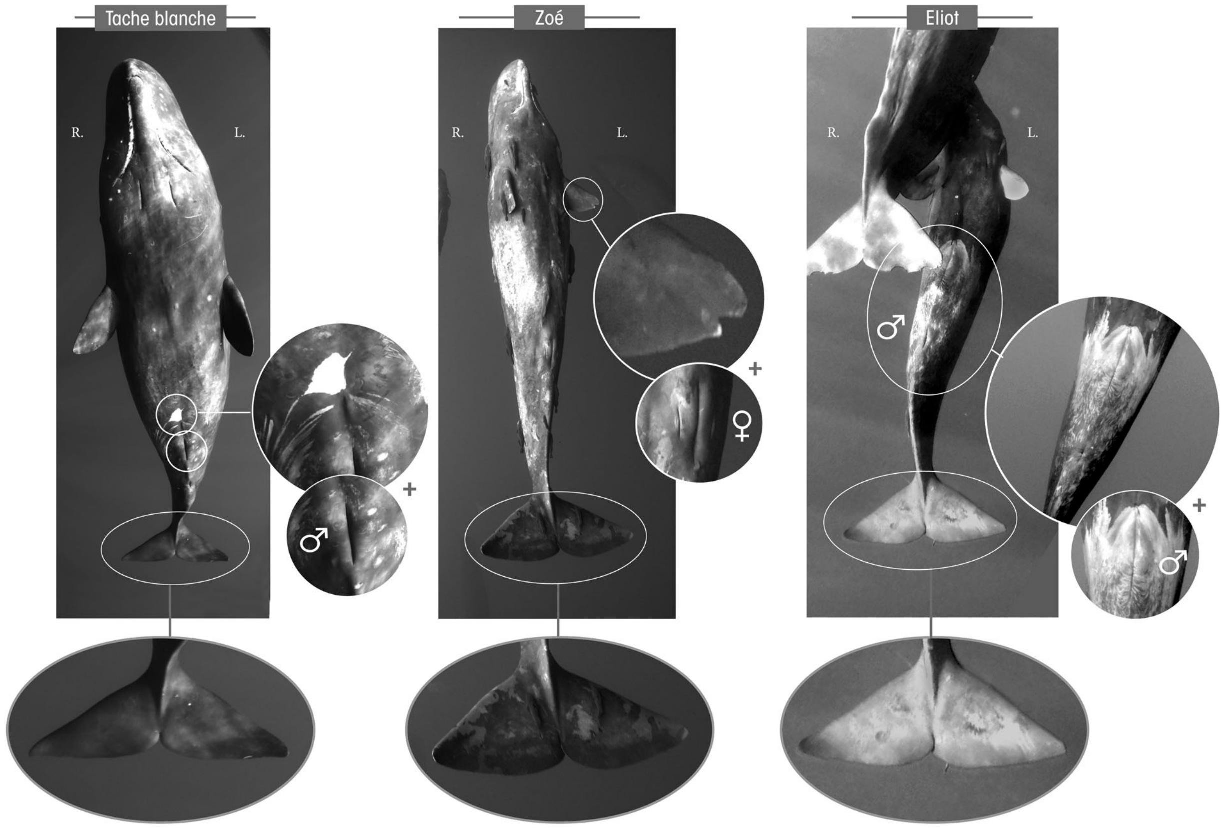

Figure 3. Differences between three immatures with intact fluke (from left to right): Tache Blanche has a white spot on the belly, a small nick on the right pectoral and is a male; Zoé has a nick on each pectoral and is a female; Eliot has a white ventral escutcheon and is a male.

sexual maturity. Here gender assignment was possible for 14 immatures (five females, nine males), some of them from the day they were born (Supplementary material 1).

Underwater observation provides access to a range of body markers that are, in particular, relevant for individuals without any distinctive marks on the fluke (Figure 3) and for the very young individuals that seldom fluke. These markers are, for instance, the indentations on the pectoral fins, the shape of the jaw or the pigmentation patterns on the ventral side, the flanks and the mandibular area. The presence/pattern of coloured markings is often used for humpback whales (Glockner-Ferrari and Ferrari 1990) or for dolphins (Herzing 1997). Three immatures with an intact fluke and therefore impossible to identify from a boat were identified this way: Zoé, Tache Blanche and Eliot (Figure 3).

The resighting rates allowed by underwater observation are high: over a period of nine years, the method presented here has resulted in numerous resightings for all the individuals identified (mean rate for adult females = 91, Table III). As a comparison, another sperm whale study off Mauritius, based on boat-observations, identified 101 different sperm whales among which 32 were sighted more than once over five years (Huijser et al. 2020). Another 28-year study in the West Indies identified 419 individuals, of which 175 individuals were resighted 2–14 times (Gero et al. 2014).

In addition, underwater studies enable researchers to observe and capture several behaviours and social interactions that may be difficult to record from a boat, such as underwater gathering (playing, socializing, swimming together), suckling (Johnson et al. 2010) or sleeping behaviour (Figure 4).

It should be noted that, as the sperm whales can be identified in the field, skin samples can be taken in an individual-specific manner by the snorkellers, allowing individual-specific genotype determination, of primary use for kin relationship determination for instance (Sarano et al. 2021).

Moreover, this visual identification of each individual may allow for the collection of individual-specific recordings, which is key for research on individual acoustic signatures (Ferrari et al. 2019).

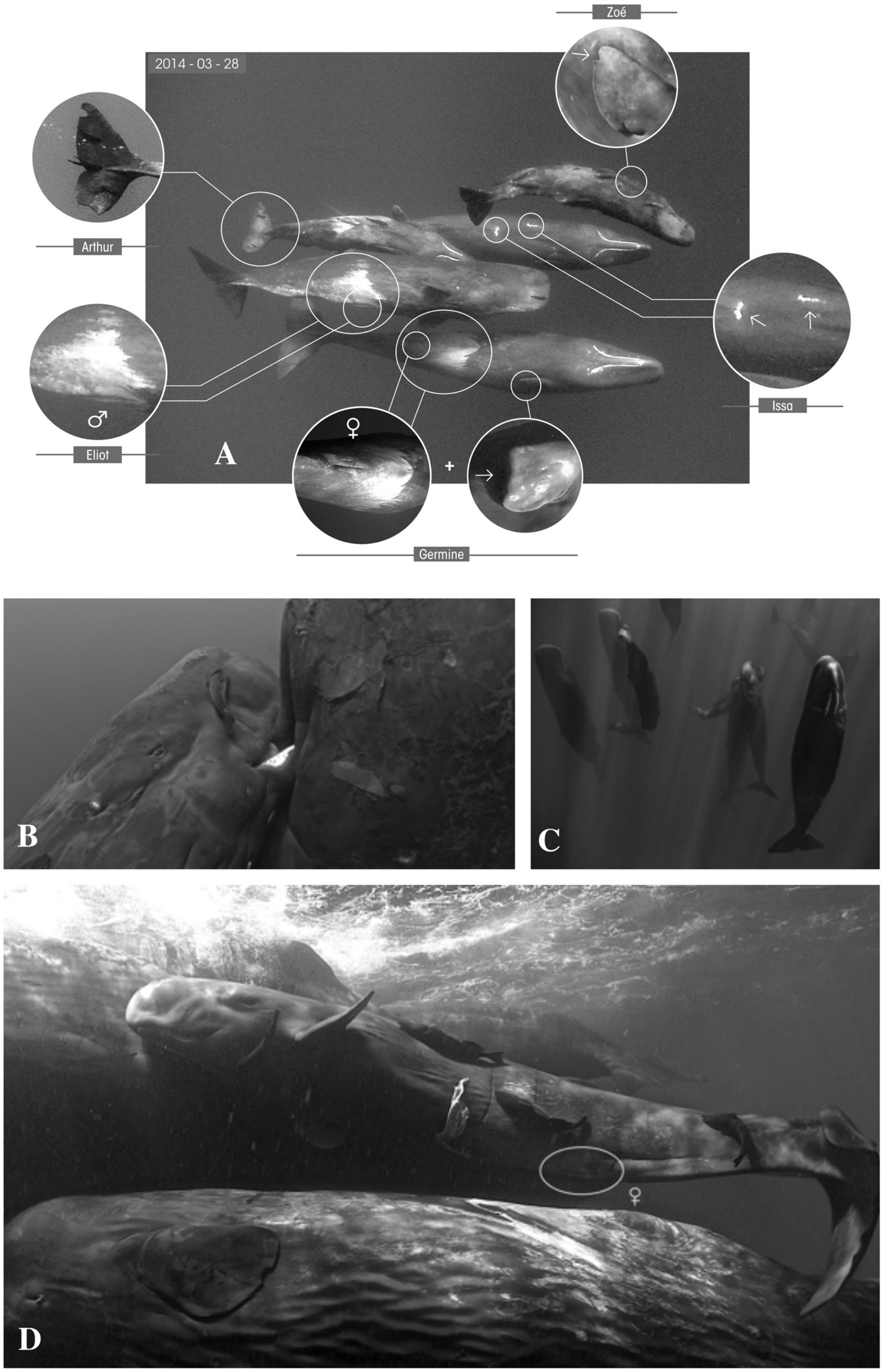

Figure 4. Different examples of behaviours and social interactions recorded underwater: **A**: gathering (note that all the individuals are recognized through body marks), **B**: suckling by the mouth (Johnson et al. 2010), **C**: sleeping, **D**: sex identification of a newborn.

Disadvantages and limits of the underwater approach

In this study, the underwater visibility (around 20 m) enabled easy identification of morphological marks and white spot patterns on the body. But in terms of logistics linked to climatic conditions, it is clear that this underwater method cannot be implemented everywhere, e.g. it is much more complicated to perform underwater observations in polar waters for example, which are relatively dark and where the temperature may be near 0°C. Additional equipment adapted to these conditions would then be necessary. High turbidity can also reduce the visibility to a few metres (due to high primary production or turbid rainwater coming from inland). In those cases, this underwater method cannot be implemented, and only well-marked sperm whales (i.e. with white spots or large missing portions on the fins) are identifiable.

The underwater approach also has legal constraints, and can only be used in areas where swim-with activities are legally allowed, ethically acceptable, and with appropriate permits from the authorities. Our protocol implies that, once the snorkellers and scuba divers are in the water, the boat goes away. This also helps to reduce human presence: other protocols, using boat observations, involve the boat following the sperm whales (Arnbom 1987), which can be very disruptive. However, swimming regularly with marine mammals might impact their behaviour with a possible habituation or sensitization in the long term (Bejder et al. 2009): targeted animals tend to increase their avoidance behaviours (Constantine 2001; Delfour 2007; Filby et al. 2014), to change their activity budget and aerial behaviours (Peters et al. 2013) and to modify their sound productions (Scarpaci et al. 2000). However recent studies showed that the animals' responses might be species-specific (Pagel et al. 2017; Cecchetti et al. 2019). Richter et al. (2006) showed an impact of whale-watching tour boats on sperm whales' ventilation, vocalization patterns and swimming direction changes. The potential impacts of swim-with activities on sperm whales' behaviours will have to be analysed in the next years. In areas where swim-with activities are not possible or permitted, AUVs (autonomous underwater vehicles) could be an excellent alternative. By recording underwater footage, this technology has successfully been used to study underwater behaviours related to habitat use or feeding in white sharks, basking sharks and leatherback turtles (Skomal et al. 2015; Dodge et al. 2018; Hawkes et al. 2020). These AUVs allow autonomous tracking of an individual previously tagged with a transponder. However, individuals must be captured and handled to be tagged which can have negative effects.

Importance of underwater observations for sperm whale conservation

Although many cetacean species are highly mobile, and show great dispersal capacities, their intraspecific diversity strongly varies, some species display local cultures and some populations may show high site fidelity (e.g. Gero and Whitehead 2016; Louis et al. 2017; Richard et al. 2018). Conservation priorities cannot then be defined at the species level, but rather at the population level (e.g. Clapham et al. 1999; Baker et al. 2013, Gero and Whitehead 2016, Louis et al. 2017; Richard et al. 2018). Small-scale studies have therefore to be performed, taking into account and focusing on the local characteristics of the groups or populations. Such studies need to be able to estimate the level of differentiation of the studied group in the species, its connectivity with surrounding individuals and/or groups of the same species, the global health of the group, and its trends over years. Anthropic activities are nowadays well known to negatively impact marine mammals in general (e.g. Jung and Madon 2021; Sèbe et al. 2022), and sperm whales in particular (Gero and Whitehead 2016). For instance, collisions with ships (Laist et al. 2001) and ingestion of plastic debris (Jacobsen et al. 2010; de Stephanis et al. 2013; Unger et al. 2016) have demonstrated direct lethal effects on sperm whales. Marine debris accumulation has been recently evidenced in the Indian Ocean (Duhec et al. 2015; Lavers et al. 2019), as well as the direct impact of by-catch on cetaceans (Anderson et al. 2020).

The sperm whale is listed as vulnerable by the IUCN (Taylor et al. 2019). Whitehead (2002) estimated that sperm whale numbers have been reduced to about 32% of their original abundance by commercial whaling. The species was predicted to have recovered since the end of commercial whaling in 1986. But local trends have been shown to vary, to be locally slightly increasing (Moore and Barlow 2014) or not (Carroll et al. 2014), and to be worrying in some places (Reeves and Notarbartolo Di Sciara 2006; Gero and Whitehead 2016). Thanks to a long-term monitoring of well-known social groups, Gero and Whitehead (2016) highlighted the disturbing situation for sperm whales in the West Indies. The authors stress, however, that these negative trends have been difficult to highlight, as immigration from surrounding regions may hide local mortality (Gero and Whitehead 2016).

The expected recovery of sperm whales in the Indian Ocean needs thus to be carefully analysed, and long-term localized monitoring of sperm whale populations, such as the one presented in this study, is therefore strongly needed.

Conclusion

The protocol based on underwater videos has already proven to be highly robust and is widely used for other marine megafauna species (e.g. Glockner-Ferrari and Ferrari 1990; Herzing 1997; Marshall and Holmberg 2018; Pierce et al. 2018). It has been applied here for the identification of sperm whales in Mauritius, based on underwater observations. The relevance of this approach is evidenced by quasi-daily resightings of females and immatures, over the field seasons and from one year to another. These resightings were carried based on marks that can hardly be observed from the sea surface. The markers used proved to be stable and reliable over the nine years of the study. This underwater observation approach using video recordings enables identification of individuals with intact flukes and to sex the entire group, including young and newborns, without using biopsies and molecular sexing. Like any catalogue, it requires annual updates to take into account the possible evolution of morphological markers. It will also soon be extended by around 60 more individuals observed off the coast of Mauritius.

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AUTHORISATIONS

To respect cetaceans and their habitats, the observers strictly followed the ethical rules of the official Charter for responsible approach and observation of marine mammals and the Maritimes zones regulations (Conduct of Marine Scientific Research/ Notice no. 57 of 2017) promulgated by the Mauritius Government. This study was placed under the policies of the Mauritius Department for continental shelf, maritime zone administration and exploration, with appropriate permits to conduct underwater videos, underwater observations on sperm whales and marine scientific research on sperm whales.

Disclosure statement

No potential conflict of interest was reported by the author (s).

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