Photo-Identification of Narwhals

by

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The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled “Photo-identification of narwhals” by Marie Auger-Méthé in partial fulfillment of the requirements for the degree of Master of Science.

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To Devin

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Abstract

We urgently require better knowledge of the narwhal if we are to ensure their sound management. Thus, I developed a photo-identification method for this species. Photo-identification is a vital tool in cetacean studies that uses natural marks to identify individuals. I described marks observed in photographs of narwhals and found that notches in the dorsal ridge, which are found on 91% of individuals and likely permanent, are the most promising marks for photo-identification. I wrote a computer program that uses the location of notch features to compare photographs, and ranks the potential matches of a photograph in decreasing order of similarity. The program accelerates the matching process by 1.4-4.5 times, and its efficiency increases with catalogue size. Given that the main drawback of photo-identification, the time required to process the photographs, is alleviated, the method will facilitate efforts to increase our knowledge of the narwhal.

List of Abbreviations and Symbols Used

COSEWIC	Committee On the Status of Endangered Wildlife in Canada
NWMB	Nunavut Wildlife Management Board
MP	Mark point
Q	Quality value
r_s	Spearman rank correlation coefficient
sd	Standard deviation

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Chapter 1

General Introduction

Conservation bodies, such as the Committee On the Status of Endangered Wildlife in Canada (COSEWIC), recently acknowledged that there is a need to increase our understanding of the narwhal (*Monodon monoceros*) (COSEWIC 2004). While little is known about the species, its populations are potentially threatened by levels of aboriginal hunting. In addition, climate changes recorded in the Arctic appear to increase the vulnerability of narwhals to ice entrapment (Laidre and Heide-Jørgensen 2005b). Essential information such as the number and size of the separate populations is still unclear and many other aspects of the narwhal's ecology need increased attention. Although research methods previously used to study narwhals allow us to increase our understanding of this species, they are expensive, often invasive, and most effective at addressing a restricted set of questions. Thus, there is a need for an inexpensive, non-invasive, and easy-to-use method that would allow not only field biologists, but also members of Northern communities, to address a wider range of questions about narwhal biology. To address this need, I developed a photo-identification method for the use with narwhal. Photo-identification is widely used in cetacean studies, employing photographs of natural markings, such as scars and pigmentation patterns, to identify individuals. The method can be used to address both subjects of conservation interest and of broader scientific interest.

1.1 The Narwhal

1.1.1 Distribution and Migration

The narwhal (*Monodon monoceros*) is a medium-sized odontocete inhabiting Arctic waters (COSEWIC 2004). It is common to the waters of Nunavut, West Greenland, and the European Arctic, with the greatest concentration of narwhals found in Baffin Bay, but is rare in other regions of the Arctic. Narwhals have annual migration patterns. The narwhals wintering in Baffin Bay migrate to different coastal summering grounds in the Canadian high Arctic and northwestern Greenland (Dietz and Heide-Jorgensen 1995; Heide-Jørgensen et al. 2002a; Heide-Jørgensen et al. 2003). I studied narwhals in one of these summering grounds, Koluktoo Bay, northern Baffin Island, Canada.

1.1.2 Vulnerability to Climate Change

Of the three cetacean species which inhabit Arctic waters year-round, the narwhal is the most vulnerable to the changes in ice conditions associated with global warming (Laidre and Heide-Jørgensen 2005b; Laidre et al. 2008). This high sensitivity to climate change can be partly explained by the narwhals' high site fidelity, preference for dense pack ice, and their vulnerability to ice entrapment (Laidre and Heide-Jørgensen 2005b; Laidre et al. 2008). In addition, climate change is opening the Northwest Passage, and facilitating the development of non-renewable resources in the Arctic. Both of these factors will significantly increase shipping traffic, to which narwhals have been shown to be sensitive (Finley et al. 1990).

1.1.3 The Hunt and its Importance for Northern Communities

The narwhal is culturally and economically important for communities in Greenland and the Canadian Arctic and a subsistence hunt is conducted in both of these countries. The muqtuk (skin of narwhals and some adhering blubber) is a highly valued food that is an important source of energy for northerners, and rich in essential nutrients such as vitamin A and C (Fediuk et al. 2002; Kuhnlein et al. 1996). In addition, the sale of narwhal tusks is an important source of income for members of northern communities (Armitage 2005; Reeves 1992). Regulations regarding the hunt have changed in recent years in both Canada and Greenland. In Canada, the quota system was removed in 1999 and replaced in 2002 by a co-management system involving the Nunavut Wildlife Management Board (NWMB), the Canadian Department of Fisheries and Oceans, and the local Hunters and Trappers Organizations. The average catch of narwhals by Canadian communities for the two years after the removal of quotas (1999-2001) was 443 landed animals per year (NWMB 2004). The average catch for the first two years of the co-management system

(2002-2003) was 332 landed animals per year for five of the most important hunting communities in Canada (Ditz 2004). In Greenland, the first quotas were established in 2004. Their quotas were 300 narwhals for the year of 2004-2005 (NAMMCO 2004), and were increased to 385 for the year of 2006-2007 (NAMMCO 2006). Although most communities report the number of animals landed, they do not count the number of animals that are killed but lost. Thus the landed catch cannot be used as a true value for the numbers of animals removed from the population by the hunt. In 2001, the loss rate was roughly estimated to between 19-46% of the landed catches (COSEWIC 2004).

1.1.4 Survival and Reproduction

Narwhal mortality can be caused by many natural factors, including ice entrapment (Heide-Jørgensen et al. 2002b; Siegstad and Heide-Jørgensen 1994), and predation by polar bears (*Ursus maritimus*) (Smith and Sjare 1990) and killer whales (*Orcinus orca*) (Jefferson et al. 1991). The only information available on such events is from a few reported observations. This is partly because these events occur in isolated areas and are difficult to predict. However, they are thought to be important limiting factors for population size. For example, narwhal is one of the most recorded prey species of the killer whale (Jefferson et al. 1991) and ice entrapments can kill hundreds of narwhals at a time (e.g.: Heide-Jørgensen et al. 2002b; Sergeant and Williams 1983; Siegstad and Heide-Jørgensen 1994).

In addition to the lack of information on the mortality rates of narwhal, the longevity and life history of the narwhal are still debated. Depending on the technique used, narwhals have been estimated to live up to 52 or 115 yrs (Bada et al. 1983; Garde et al. 2007). Males are thought to sexually mature between 9-16 years and females between 4-9 years (COSEWIC 2004; Garde et al. 2007). Most mature females produce one calf every three years and calves are thought to be weaned after one or two years (Hay and Mansfield 1989). Although details of the longevity and life history are still imprecise and possibly inexact, it is evident that the narwhal is a long-lived and slowly reproducing species.

1.1.5 Population Size and Trends

Although narwhals have been divided into different populations for hunt management purposes, it is unclear whether these populations are truly isolated, or whether each should be further divided into distinct subpopulations. Two of these narwhal populations, in Baffin Bay and Hudson Bay, reside in Canadian waters during the summer. For the Baffin Bay population, the most exhaustive population estimate was done in 1996 and the population was estimated to be 45 358 (95% CI = 23 397-87 932) (Innes et al. 2002). This survey covered areas that were previously surveyed (e.g.: Richard et al. 1994) and provided similar estimates. However, uncertainty in the population estimates, couple with low statistical power, would not allow the detection of a trend in population size if there had been one (COSEWIC 2004), a problem that is not uncommon in marine mammal studies (Taylor et al. 2007). Although there have been other surveys (e.g.: Kingsley et al. 1994; Koski and Davis 1994) and surveys are currently conducted in order to update population estimates (NAMMCO 2006), none provided data that have made it possible to either detect population trends or give an recent estimate of the total population of Baffin Bay (COSEWIC 2004). There is one exception, an estimated 10% decline from 1985-1986 to 2001-2002 in part of the narwhal population of Northwest Greenland, narwhals that winter in Baffin Bay (Heide-Jørgensen 2004). The state of knowledge of the much smaller Hudson Bay population is similar. Systematic surveys were conducted in 1982 to 1984 and 2000 (COSEWIC 2004; Richard 1991). The population estimate is roughly 3 500, and no trends have been detected (COSEWIC 2004).

1.1.6 Gaps in Knowledge and Status of the Species

In addition to the need for more recent and complete population estimates, and an adequate estimate of population trends, many aspects of the narwhal's ecology are in need of increased attention. As mentioned above, there is very little information available on mortality rates. Although the migration patterns of the narwhal are quite well understood (Dietz et al. 2001; Heide-Jørgensen et al. 2002a; Heide-Jørgensen et al. 2003) and the diving behaviour has been studied in some detail (Dietz et al. 2007; Heide-Jørgensen and Dietz 1995; Heide-Jørgensen et al. 2001; Laidre et al. 2002; Laidre et al. 2003; Lydersen et al. 2007), few other aspects of the narwhal behaviour have been studied. Some research has been conducted on the narwhals' feeding behaviour, (Finley and Gibb 1982; Laidre et al. 2003; Laidre and Heide-Jørgensen 2005a), habitat selection (Laidre et al. 2004), vocalizations (Ford and Fisher 1978; Miller et al. 1995; Shapiro 2006; Watkins et al. 1971), use of tusks (Best 1981; Gerson and Hickie 1985), and grouping behaviour (Cosens and Dueck 1991; Silverman 1979). However, the information that resulted from these studies is not similar to the extent of knowledge available on these subjects for many other cetacean species. In addition, most other aspects of the behaviour are unknown and very little is known of the about the physiological requirements of narwhals (COSEWIC 2004).

COSEWIC assigned the status of 'Special Concern' to the narwhal, in part because there is not enough information on the population size and trends, or on the survival rates of narwhals. The Joint Commission on the Conservation and Management of Narwhal and Beluga and North Atlantic Marine Mammal Commission similarly concluded, after a joint meeting, that it is impossible to assess the status of narwhals in the Baffin Bay area without improving our knowledge of the recent catch history and without recent and accurate population estimates (NAMMCO 2001). Similarly, in the 2000 International Union for Conservation of Nature Red list of Threatened Species, the narwhal is listed under 'Data Deficient'. Finally, other authors such as (Laidre et al. 2008) have indicated that there is a need for more knowledge of this species if we hope to understand the impact that climate change might have on this potentially extremely vulnerable species.

Although there is general recognition that increased study of the narwhal is required, it is not surprising that there are large gaps in our knowledge. The remoteness of the species and the harsh environment it inhabits complicate field work. For instance, narwhals spend the winter in an area with very little daylight, and working in the Arctic is extremely expensive. Most of the previous methods used, such as satellite tags and aerial surveys, have been extremely useful in elucidating migration patterns, diving behaviour, and estimating the abundance of narwhals (e.g.: Dietz et al. 2007; Heide-Jørgensen et al. 2003; Innes et al. 2002). However, such studies are expensive and can only address targeted questions. Thus there is a need for a relatively inexpensive method which can be used to address a wide range of questions and that would, preferably, allow members of the northern communities to become involved in the work.

1.2 Why Photo-Identification

Photo-identification is a vital tool in cetacean studies. An effort to develop the method for cetacean species was initiated by the International Whaling Committee, which devoted a special issue of its publication to the subject (Hammond et al. 1990). Since then, the method has been developed for many cetacean species for which it was previously unavailable (e.g.: Gonzalez 1994; Gowans and Whitehead 2001; Hartman et al. 2008). The development of photo-identification, in conjunction with the development of models and programs which can be applied to the data the method produces (e.g.: Lusseau et al. 2008; White and Burnham 1999; Whitehead 2001a), has allowed scientists to study a wide array of subjects such as survival rate, population trends, social structure, mating system, population size, movement patterns, and habitat use (Bejder et al. 2006; Bradford et al. 2006; Coakes and Whitehead 2004; Gero et al. 2007; Gowans et al. 2000; Karczmarski et al. 2005; Mizroch et al. 2004; Wilson et al. 1997).

Photo-identification is relatively inexpensive and non-invasive. Once the method is developed, anyone with a good camera can gather data. By developing a simple-to-use method, I hope to enable members of northern communities to become involved in studying the narwhals, a species which is so important to them. This would allow easy access to data, and hopefully provide job opportunities for members of northern communities. Most importantly, it would provide an opportunity to involve members of the northern communities in research, which would complement the co-management of the hunt.

One of the reasons why photo-identification has not yet been applied to narwhals is that the features commonly used for the individual identification of other cetaceans cannot be used with this species. Narwhals lack dorsal fins and show marked change in body pigmentation and tail morphology with age (Hay and Mansfield 1989). Therefore, one of the first goals of my project was to find a feature of narwhals that could be used to identify the individuals. The natural marks found on narwhal are described and some of their aspects, such as their distribution in the population, are explored in the second chapter of this thesis. The main drawback of photo-identification is the time required to process the photographs. For example, comparing one photograph to a catalogue of a few hundred individuals can easily require an hour of effort. In addition, since the advent of digital photography, the number of photographs taken in photo-identification studies and requiring processing is becoming extremely large. Therefore, an important aspect of the development of the photo-identification method is to develop a computer program that can accelerate the matching process. This was the second goal of my thesis, described in the third chapter.

Chapter 2

Nicks and Notches of the Dorsal Ridge: Promising Mark Types for the Photo-Identification of Narwhals

2.1 Introduction

Most recent research on narwhals (*Monodon monoceros*) has used aerial surveys (e.g. : (Heide-Jørgensen 2004), satellite tags (e.g.: Heide-Jørgensen et al. 2003; Laidre et al. 2004), or samples from the aboriginal hunt (e.g.: Dietz et al. 2004; Garde et al. 2007). Although these methods allow us to increase our understanding of narwhal biology and ecology, they are expensive, often invasive, and most effective at addressing a restricted set of questions. The costs and limits of these methods, as well as the remoteness of the narwhals' Arctic habitat, contribute to our incomplete knowledge of the species. This largely explains why narwhal populations have been assigned the status of 'Data Deficient' by the International Union for Conservation of Nature and of 'Special Concern' by the Committee on the Status of Endangered Wildlife in Canada. Thus, there is a need for an inexpensive, non-invasive, and easy to use method that would allow not only field biologists, but also members of Northern communities, to address a wider range of questions about narwhal biology. Photo-identification, which fulfills all of these criteria, is a method using photographs of natural markings, such as scars and pigmentation patterns, to identify individuals. This method is extensively used in cetacean studies (Hammond et al. 1990) and can address a diverse set of subjects. For example, population parameters were estimated and movement patterns were modelled using photo-identification (e.g.: Gowans et al. 2000; Wilson et al. 1997).

One reason why this method has not yet been applied to narwhals is that the features commonly used for the individual identification of other cetaceans cannot be used with this species. Narwhals lack dorsal fins and show marked change in body pigmentation and tail morphology with age (Hay and Mansfield 1989). However, a preliminary analysis of the narwhal photographs supplied by photographer Mamoru Yasuda revealed that nicks and notches found on the dorsal ridge could be used to identify individuals. This ridge was previously described as a low (4-5cm high) irregular ridge found on the posterior half the back (Hay and Mansfield 1989). The goal of this study was to verify whether the nicks and notches of the dorsal ridge are adequate marks for photo-identification and whether other mark types, such as bullet scars (Finley and Miller 1982), could also be useful in the identification of individuals. Aspects of natural marks, such as their variability in size, shape, and colour, were used to investigate whether these marks could allow one to distinguish between the individuals bearing them. The prevalence of a mark type in the population was used to estimate the proportion of the individuals that would be considered identifiable using the mark type in question. Finally, the relationship between the age of an individual and the number of marks found on its body was used to address the possible permanency of different mark types.

2.2 Methods

2.2.1 Field Methods

Narwhals summering in Koluktoo Bay, Nunavut, were studied during the months of August and September of 2006 and 2007. A total of 53 days were spent on a peninsula called Bruce Head (72^{o} 02'N, 80^{o} 40'W) where I took a total of 3261 digital photographs of the sides of narwhals. These photographs were either 3008 by 2000 pixels images taken with a Nikon D70s equipped with 500mm autofocus lens or 3504 by 2336 pixels images taken with a Canon EOS 20D equipped with a 400mm autofocus lens. Photographs were taken from land when weather and light conditions permitted. I attempted to photograph individuals without bias related to probability of identification (e.g.: presence of distinctive marks) or the number of pictures previously taken of an individual. The photographic effort was divided into encounters, a spatio-temporal unit used to delineate narwhal herds. An encounter began when a narwhal was seen within about 500 m of the peninsula and ended when no narwhals were observed for 30 min.

2.2.2 Photographic Analysis

I assigned a quality value to each photographed narwhal. As some photographs contained more than one narwhal a total of 3718 quality values were given. Quality values ranged from 1-5 (referred hereafter as Q1-Q5), Q5 being the highest quality. These values were assigned using five criteria, similar to the ones described for sperm whales (*Physeter macrocephalus*) by Arnbom (1987). These criteria were: the size of the ridge, represented by the length of the ridge in proportion to the size of the photograph; the orientation of the ridge, represented by the angle the ridge formed with the frame of the photograph; the exposure, a measure of the relative darkness of the photograph; the focus; and the proportion of the ridge that is visible. To receive a Q5 a narwhal needed to be almost perfect in all of the criteria: length of the ridge being at least a quarter of the size of the frame, the ridge forming a maximum 10 degree angle with the horizon, the contrast allowing one to clearly differentiate the narwhal from the surrounding water and the absence of glare, the edge of the ridge being in focus, and the ridge being completely visible (for more information, see Appendix). Photographs in which the ridge was not visible were excluded.

All photographs of Q4 to Q5 were selected and matched to the other photographs of the same encounter. As photographs of the same encounter were taken within hours of one another, all marks, including nicks, notches, scars, and pigmentation patterns, could be used to match the individuals as they are unlikely to change over such short periods of time. Calves were excluded because they had neither nicks, notches, nor other marks that could be used to identify them. For each encounter, I chose the best photograph available for each side of an individual. If an individual had at least one nick or notch it was compared to the individuals of the catalogue, using a prototype of the matching program described in chapter 3. A new identification number was given to every narwhal that could not be matched to any of the catalogue's narwhals. If I had any doubts regarding a match, the opinion of a minimum of three other people was required before a decision was made. Restricting the sample to individuals with at least one nick or notch would have positively biased some of the values I was interested in calculating, such as the average number of nicks per individual. Therefore, I also matched the individuals that had neither nicks nor notches on their ridge. Since these individuals could not be matched with the computer program, I used the pigmentation patterns and other marks to discriminate between different individuals. This was possible since all of the photographs for these individuals were of the same side of their body. In addition, since all of the photographs of individuals without nicks and notches were taken within a two-week period and their marks were likely stable for such a period of time, it is unlikely that these individuals were sampled more than once.

2.2.3 Mark Description

Mark Description and Distribution

I described the marks found in narwhal photographs using a method similar to Auger-Méthé and Whitehead (2007). I randomly selected one photograph of the highest quality value for each individual. For each individual, the number of nicks and notches were counted and the widest, deepest, narrowest, and shallowest nicks and notches were measured as a proportion to the size of the ridge. All other marks were counted and their longest axis was measured. The colour, shape, and location of all marks were also noted.

Using the characteristics described above, these marks were assigned to one of the following mark types previously described in the literature (Auger-Méthé and Whitehead 2007; Finley and Miller 1982; Gowans and Whitehead 2001; Keith et al. 2001): bullet scar, noncircular light patch, nick, notch, parallel linear scrape, single linear scrape, and tooth rake. Note that I define notches as indentations that cut the dorsal ridge through its entire depth and nicks as all other shallower indentations. Marks from the sample that could not be assigned to one of the previously described types were compared to one another and new types were created as appropriate. The average number of marks and the average number of mark types per individual were calculated. In addition, the average number of marks of each type per individual, and the prevalence of each mark type, defined as the proportion of individuals that possess a given mark type, was calculated.

Body Location and Association with Age

In order to investigate whether the marks are seen more often on certain sections of the body, sets of χ^2-tests were performed. The observed frequencies were obtained by counting the number of marks on each of the four body sections: the dorsal ridge, the flank, the front, and the back (fig. 2.1). If a mark spanned more than one section a fraction of its value was assigned to all the sections it spanned. The expected frequencies were calculated using the following method. I estimated the relative size of each body section that was visible in a photograph. These were coarse estimates based on how many standard rectangles were needed to contain a given section. Standard rectangles were defined as an area the length of the ridge by one eighth of its length. If part of the ridge was masked, the estimated length of the ridge was used. Fractions of the standard rectangle were only used as a unit when estimating size of the dorsal ridge, which never exceeded half a standard rectangle. The values for the expected frequencies were calculated as exemplified for the ridge:

$$\textit{expected frequency for the ridge} = \frac{m\sum ridge_i}{\sum\left(ridge_i + flank_i + front_i + back_i\right)},$$

where m is the total number of observed marks of a given type for all individuals, and $ridge_i$, $flank_i$, $front_i$, and $back_i$ are the relative size of the ridge, flank, front, and back for one of the individuals in the sample.

Only the parallel linear scrape, the single linear scrape, and the small white dot (see fig. 2.2 and table 2.1) had appropriate sample according to (Zar 1999) recommendations for χ^2-tests for more than two categories. Note that the nicks and notches were eliminated from this analysis since they are, by definition, on the dorsal ridge. The first set of χ^2-tests examined whether a given mark type was distributed differently across body sections. If the distribution differed significantly ($p<0.05$), another set of χ^2-tests was performed to investigate which of the body sections differ from the others. Each of these post-hoc tests compared the frequencies of the given mark type for a pair of body sections. As all of the expected frequencies were greater than five, the recommended minimum for χ^2-tests with two categories (Zar 1999), all possible pairs of body sections could be tested.

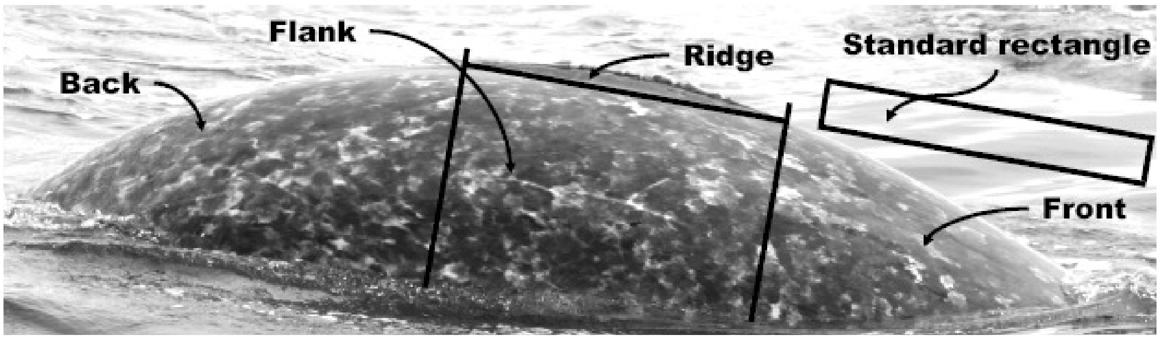


Figure 2.1 Example of the four body sections and of the standard rectangle used to estimate their relative size. In this case the front section would equal to three rectangles; the ridge, half a rectangle; the flank, five rectangles; and the back, five rectangles.

As narwhals whiten with age (Hay 1984; Hay and Mansfield 1989; Silverman 1979), it is possible to use the amount of white found on the skin as an indicator of age when investigating the association between the mark frequencies and the age of animals. In order to estimate the proportion of skin that is white I used a random point estimating method similar to those used by ecologists to estimate percent cover (Meese and Tomich 1992). I estimated the proportion of white in a standard area located on the flank just under the ridge. This rectangular area was the same size as the standard rectangle described above. Fifty random points falling within the standard rectangle were selected and the colour of the pigmentation for each of those points was visually inspected and noted. The amount of white of the skin was represented as the proportion of the 50 points that were white.

To test whether the frequencies of marks are correlated with the proportion of skin that is white, I used the same sample as previously selected for the mark description and χ^2-tests. However, I only included the photographs for which the standard area used to estimate the proportion of white was completely visible. In addition, only prevalent mark types (prevalence > 0.15, see table 2.2) were considered. This limited the analysis to the nick, the notch, the single linear scrape, and the small dot. Since these mark types were found to be associated to different body sections (see table 2.3 and fig. 2.3) and I did not have a sample for which all the body sections were sufficiently visible, I used different samples for each of the mark types. For example, I only used photographs in which the ridge was completely visible to count the frequencies of nicks and notches. For the single linear scrape, I only used photographs in which the flank was sufficiently visible and I only counted the single linear scrapes found on the flank. A Spearman's rank correlation was used to investigate the association between the mark frequencies and the proportion of white. I corrected for tied ranks by assigning them their average rank value (Zar 1999). For the single linear scrape and the small white dot, a Spearman's rank correlation was also performed to verify that there was no significant association between the mark frequencies and the size of the visible body section.

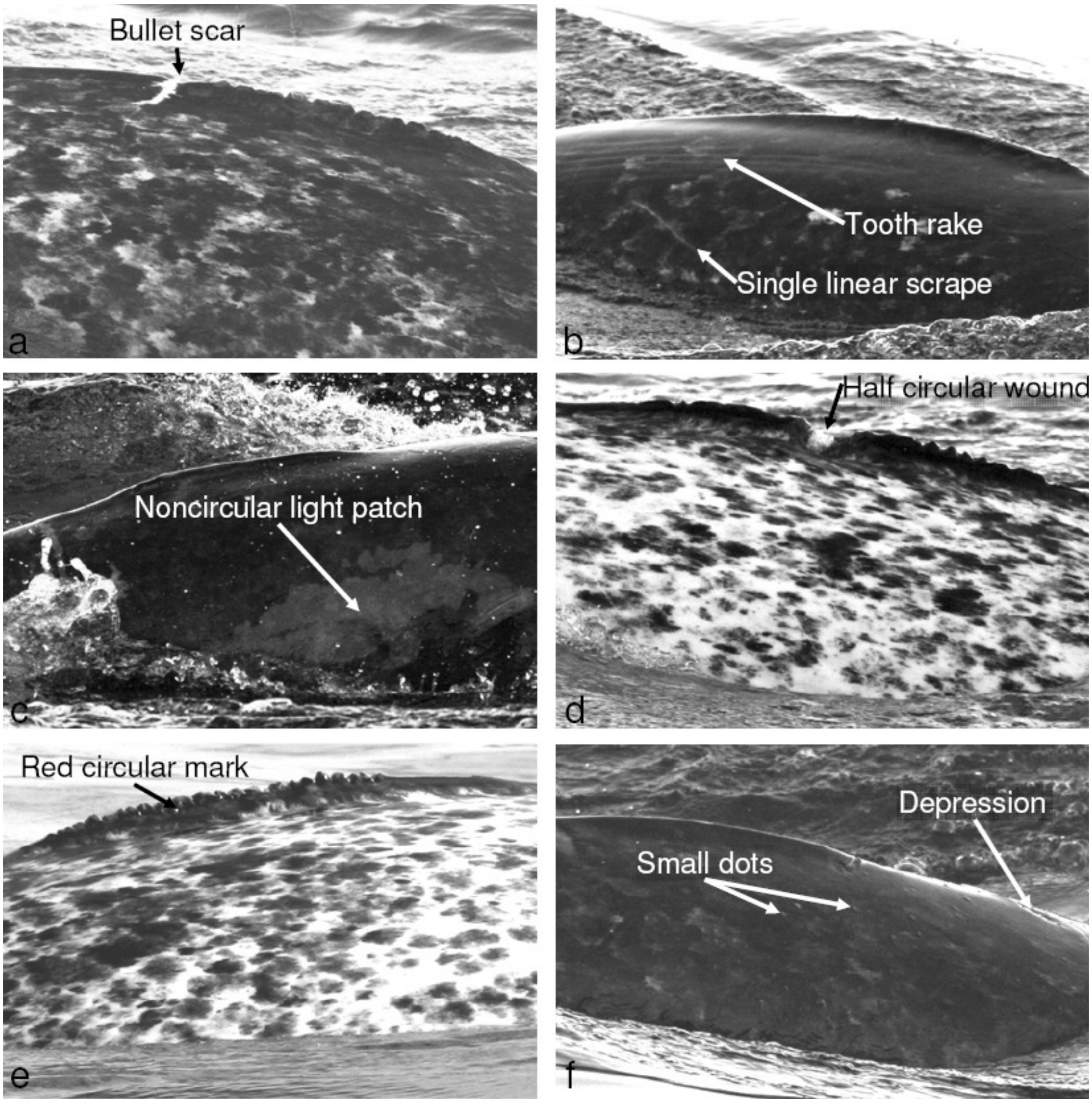


Figure 2.2 Photographs displaying the mark types described: (a) bullet scar; (b) tooth rake and single linear scrape; (c) noncircular light patch; (d) half circular wound; (e) red circular mark; (f) small dots and depression; (g) the wrinkles of the body in this photograph is an example of a mark falling in the miscellaneous category; (h) large scar; and (i) nick, notch, and parallel linear scrape. Note that in colour photographs the red circular mark is grayish red and that most of these photographs have both nicks and notches.

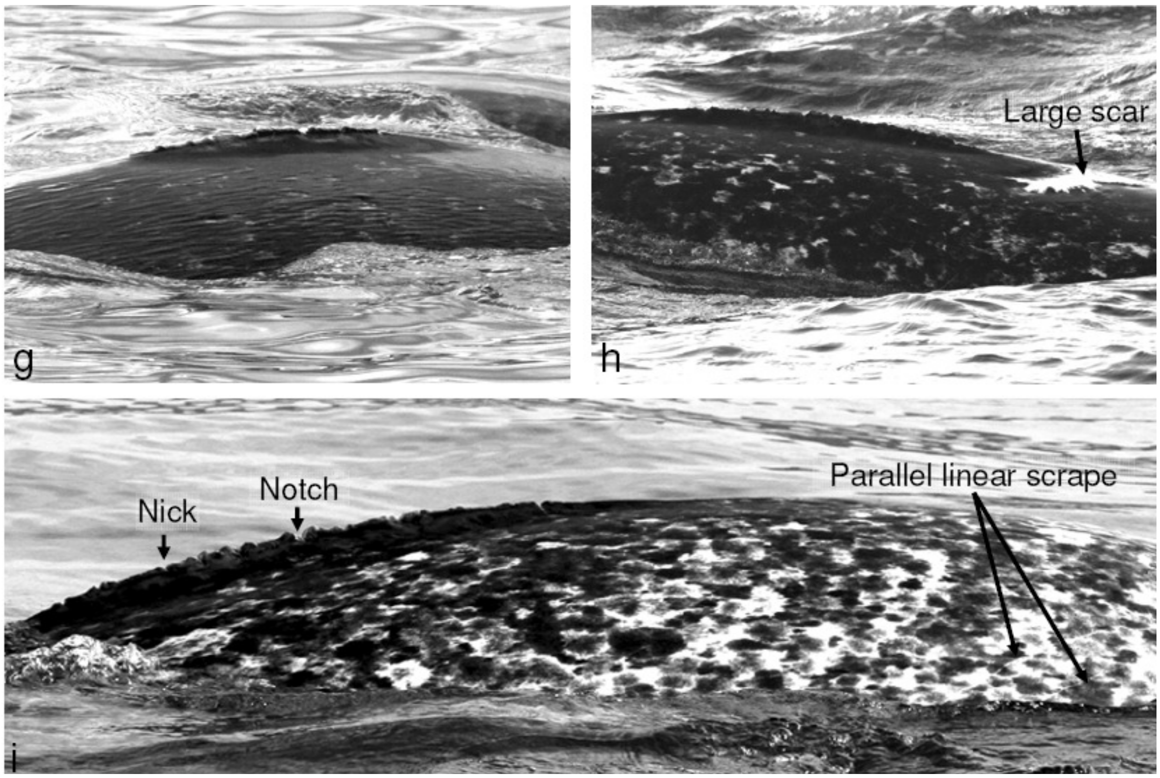


Figure 2.2 (Continued) See previous page for figure caption.

Table 2.1 General description of the marks found on the 110 individuals sampled. The size of only completely visible marks found on narwhal with an entirely visible ridge was included, and it was presented as a proportion of the length of the ridge. Note that the colour 'skin' was ascribed to marks for which the pigmentation of the mark did not differ from the surrounding skin and was visible as depressions in, or protrusions from, the skin.

Mark type	Description	Body Location	Color		Size[a] Min	Max
Bullet scar	irregular shaped	ridge (associated with a large notch)	white		0.10[b]	-
Depression	irregular shaped depression in the skin	back, flank or front	skin		0.10	0.17
Half circular wound	large half circular notch on the ridge	ridge (associated with a large notch)	white sometime with red		0.07	0.09
Large wound	irregular shaped white mark	back, flank, or ridge	white sometime with either red or brown		0.17	0.24
Nick	shallow indent in the dorsal ridge			width depth	<0.01 <0.01[c]	0.24 0.01
Noncircular light patch	irregular shaped mark	back or flank	gray		0.15	0.42
Notch	deep indent in the dorsal ridge, cutting through the entire depth	ridge		width depth	<0.01 <0.01[c]	0.17 0.06
Parallel linear scrape	2 parallel lines	all body sections	skin or white		0.08	0.66
Red circular mark	circular protruding mark	ridge	red		0.01	0.01
Single linear scrape	1 line	all body sections	mostly white, few are skin or black		0.02	1.11
Small dot	small circular protruding mark	all body sections	skin		<0.01	0.01
Tooth rake	more than 2 parallel lines	back or flank	skin or white		0.40[b]	-
Miscellaneous	all other marks	all body sections	-		0.02	0.06

[a] Size of mark expressed as a proportion of the length of the ridge. The length of the ridges of 4 hunted whales (1 female, 3 males) was measured in the field. The average size of the ridge was 50.3 cm (sd: 20.5).
[b] Only one mark was completely visible and on a narwhal with an entirely visible ridge.
[c] The difference in the ridge length and height from one individual to another, and the difference in height between the ends and center of a ridge explain the overlap in the depth measures of the nicks and notches.

2.3 Results

Thirteen mark types were described (fig 2.2, table 2.1), which included the nicks, the notches, three types of linear marks and several types of wounds. Five of the 13 types had not been previously described and an additional eight marks that could not be assigned to any type were placed under a 14^{th} category, "miscellaneous". The marks ranged in size from less than 1% to 111 % of the ridge length and varied in colour. Most were white, gray, and "skin" colour, with a few red or black marks. Note that "skin" colour was ascribed to marks for which the pigmentation of the mark did not differ from the surrounding skin and was visible as depressions in, or protrusions from, the skin. All of the 110 individuals had at least one mark. On average, individuals had 31.65 marks (sd: 17.76) of 3.55 (sd: 1.06) types.

The two mark types only found on the dorsal ridge were the most prevalent (table 2.2). The nick was found on 98% of the individuals, which had on average 16.36 of them, and the notch was found on 91% of the individuals, which had on average 6.16 of them. Most individuals in the sample that did not have nicks nor notches appeared to be juveniles, too big to be considered as calves but lacking the white pigmentation typical of adults (Hay and Mansfield 1989) (see fig 2.2c). Only three other mark types were found in more than 10% of the photographs: the parallel linear scrape, the single linear scrape, and the small dot. Of these three types, only the distribution of the single linear scrape and the small dot were associated with body sections. Unlike the parallel linear scrape ($\chi^2 = 4.70$, n = 13, df = 3, p-value = 0.195), their observed frequencies were significantly different than the expected frequencies (single linear scrape: $\chi^2 = 44.07$, n = 300, df = 3, p-value < 0.001; small dot: $\chi^2 = 440.01$, n = 655, df = 3, p-value < 0.001). The single linear scrapes and small dots were seen more often on the flank and front, respectively (table 2.3 and fig. 2.3).

Narwhals appear to gain nicks and notches with age, as indicated by the correlation between their numbers and the proportion of white of the skin (table 2.4 and fig. 2.4). However, the notch had the strongest association with the proportion of white. Neither the single linear scrape nor the small dot appear to have an association with the proportion of

Table 2.2 Distribution of the mark types represented as the mean number of marks of a given type per individual and by the prevalence in the sample of each of these mark type. The prevalence is defined as the proportion of the 110 individuals which bear the given mark type. Note that the nick and notch have both the highest average number of marks per individuals and the highest prevalence.

Mark type	Mean n^{o} marks per individual	Prevalence
Bullet scar	0.02	0.02
Depression	0.04	0.03
Half circular wound	0.05	0.05
Large wound	0.06	0.05
Nick	16.36	0.98
Noncircular light patch	0.03	0.02
Notch	6.16	0.91
Parallel linear scrape	0.12	0.11
Red circular mark	0.04	0.04
Single linear scrape	2.73	0.80
Small dot	5.95	0.46
Tooth rake	0.02	0.02
Miscellaneous	0.07	0.06

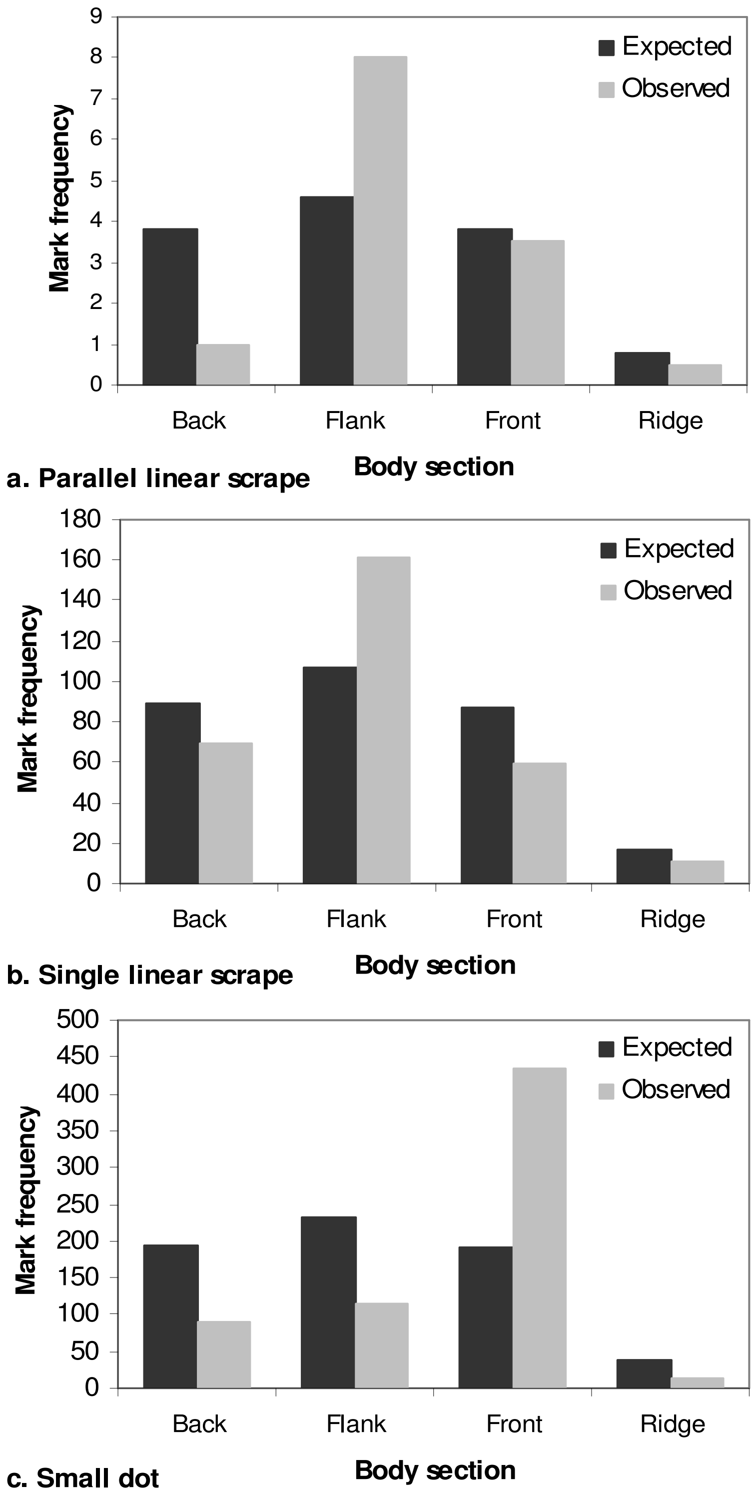


Figure 2.3 Observed and expected frequencies of marks found on the body sections visible in photographs for: a) parallel linear scrape, b) single linear scrape, and c) small dot. Of the χ^2-tests which examined whether a given mark type was distributed differently across body sections, only the tests for the single linear scrape and small dot were significant (see text). There are more small dots on the front and more single linear scrape on the flank than expected (see table 2.3).

Table 2.3 Post-hoc χ2-tests comparing the mark frequencies for pairs of body sections. Note that for a mark that spanned more than one body section a fraction of its value was attributed to all the body sections that it spanned, which explains the decimals values for the n. The only significant comparisons are the ones including the flank for the single linear scrape and the ones including the front for the small dot.

Mark type	Body sections included	n	df	χ^2	p-value
Single linear scrape					
	flank, back	230	1	22.24	<0.001
	flank, front	220.5	1	29.32	<0.001
	flank, ridge	171.5	1	8.83	0.003
	back, front	128.5	1	0.57	0.449
	back, ridge	79.5	1	0.56	0.453
	front, ridge	70	1	0.12	0.733
Small dot					
	front, flank	550	1	256.17	<0.001
	front, back	525	1	231.68	<0.001
	front, ridge	450	1	56.72	<0.001
	flank, back	205	1	0.21	0.649
	back, ridge	105	1	0.32	0.573
	flank, ridge	130	1	0.65	0.419

Table 2.4 Spearman rank correlation results for the association between the number of a given mark found on individuals and the proportion of white of their skin, which is an indicator of age. The p-values presented are taken from (Zar 1999) table of critical values of the Spearman rank correlation coefficient.

Mark type	r_s	n	p-value
Notch	0.517	70	< 0.001
Nick	0.454	70	< 0.001
Single linear scrape	0.219	34	> 0.200
Small dot	0.017	23	> 0.500

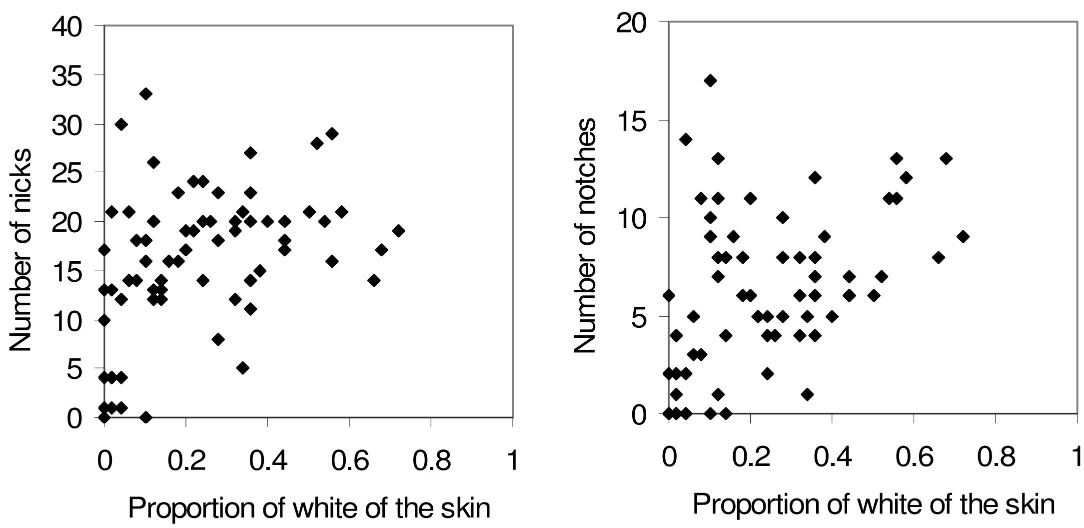


Figure 2.4 The number of nicks and notches appear to increase as narwhals whiten, a proxy for increasing age. The rank correlation is significant (table 2.4), although the correlation of the nicks is weaker than the one for the notches.

white (table 2.4) and this did not appear to be due to a confounding association between the number of marks and the size of the body section visible (single linear scrape: r_s = -0.067, n = 34, p-value > 0.500; small dot: r_s = 0.032, n = 23, p-value > 0.500).

2.4 Discussion

2.4.1 Suitability of Mark Types for Photo-Identification

Characteristics Required for Photo-Identification

In order to identify a large part of the population, mark types used for photo-identification are preferably prevalent. As mark change, loss, or gain can result in an increase in the number of identification errors (Carlson et al. 1990; Dufault and Whitehead 1995), it is important to choose marks that are relatively stable over time. It is also important to limit the chance of erroneously identifying two individuals as one (often referred as a false positive error) as these types of errors can produce bias when estimating population parameters (Gunnlaugsson and Sigurjónsson 1990; Hammond et al. 1990). The probability of making a false positive error depends on the size of the population and on the similarity of the markings compared (Agler 1992; Pennycuick and Rudnai 1970), and complex patterns that have more information content are less likely to be similar (Pennycuick and Rudnai 1970; Stevick et al. 2001). Information content increases with variation in shape and size, and the number of marks available per individual. Therefore, a perfect mark type would be prevalent, permanent, and complex.

Nicks and Notches

The nick and the notch were the most prevalent mark types and generally found in large numbers on individuals (table 2.2): 98% of individuals had on average 16.36 nicks and 91% had on average 6.16 notches. Although no indication of the source of the narwhals nicks and notches could be found in the literature, the association of some notches with the bullet scar and the half circular wound (table 2.1) could indicate that a few of these notches could be the result of injuries of the sort. However, the nicks and most notches likely have a different source, as they are much smaller than the notches associated with these marks. Both nicks and notches varied in size (table 2.1) and in shape, sometimes forming large half circles, narrow triangular indentations, or wide but shallow depressions in the ridge. It is apparent that narwhals are not born with nicks and notches, as they were not present on calves and many juveniles. In addition, the significant correlation between the proportion of white and their numbers (table 2.4, fig. 2.4) might indicate that narwhal accumulate these marks with age, and thus possibly indicate permanency. However, this association would also be found for non-permanent marks that are acquired at a faster rate than they are lost, or that are gained more frequently with increasing age. To help resolve this issue, I investigated the nicks and notches found on the only two individuals matched between years. Neither notches nor nicks were lost or gained, which supports the permanency hypothesis. However a few of the nicks appeared to have changed in shape. These apparent changes could be an artifact of quality differences between the photographs. However, they might also indicate that nicks are less stable over time, which would explain their weaker correlation with the proportion of white, the proxy for age used in the present study.

As the notches and the nicks are the most prevalent mark types, likely permanent, fairly complex, and found in large quantity on individuals, they appear to be suitable for photo-identification. In addition, using the nicks and notches to identify narwhals has the advantage of allowing one to match both sides of an individual to one another, something which would not be possible with any mark found on the skin of the animals. Although I could identify individuals with only one nick or notch, one such reference point is likely insufficient information to match individuals in large a catalogue, especially if nicks change in shape with time. Therefore, I would recommend using only individuals with at least three simple notches or a smaller number of complex notches, similar to the three mark point restriction used for pilot whales (*Globicephala melas*) (Auger-Méthé and Whitehead 2007; Ottensmeyer and Whitehead 2003). This would allow the identification of 84% of the individuals, which is higher than the 33-66% of the pilot whales and bottlenose whales (*Hyperoodon ampullatus*) (Auger-Méthé and Whitehead 2007; Gowans and Whitehead 2001) and close to the 91% of sperm whales (Arnbom 1987).

Other Mark Types

The nicks and the notches appear to be promising mark types for photo-identification and allowed the matching of individuals within and across years. However, a few of the 11 other mark types described met some of the criteria required for photo-identification. For example, the small dots are prevalent, found on photographs of 48% of the individuals. However, they are small inconspicuous marks that are probably not permanent. No relationship was found with the proportion of white of the skin (table 2.4), which indicates that these marks do not accumulate with age, and may be constantly lost and gained. While this lack of accumulation could also result from a rapid gain at a young age with no subsequent loss, these marks are similar to the small white dots found on pilot whales, which are not permanent (Auger-Méthé and Whitehead 2007). In contrast, the bullet scar and the large wound are large, conspicuous marks that are likely permanent. They are at least partly composed of white scar tissue (fig. 2.2 a,h) which is permanent in other species (Auger-Méthé and Whitehead 2007; Lockyer and Morris 1990). However, they are found only in 2% of the sample (table 2.2), and therefore could not be the sole mark types used for photo-identification. The prevalence of the bullet scar would be increased if one were to photograph the area 30 to 80 cm behind the blowhole, where most of the bullet scars are found on hunted narwhals (Finley and Miller 1982). This could increase their prevalence to match the one reported for landed catch, 0.23-0.42, (Finley et al. 1980; Finley and Miller 1982), which is still much lower than the prevalence of nicks and notches. Therefore small dots are likely unsuitable for photo-identification and, although the bullet scars and large wounds can help with confirming matches across multiple years, they are not sufficiently prevalent to be the sole mark types used for photo-identification.

Of the remaining mark types, the single linear scrape was the most prevalent, found on 80% of the individuals. These are similar to the scars found on the heads of narwhals (Silverman 1979). These head scars are thought to be caused by aggressive behaviour between tusked males and are found in greater numbers on males, similar to linear scars of other odontocetes species, (Bloch 1992; Gerson and Hickie 1985; Heyning 1984; MacLeod 1998; Scott et al. 2005; Silverman and Dunbar 1980). In some species, such as

Risso's dolphin (*Grampus griseus*), linear marks remain stable over a period of multiple years and are used, along with the shape of the dorsal fin, to identify individuals (Hartman et al. 2008). However, in other odontocete species linear marks have been shown to heal, and disappear within a year (Auger-Méthé and Whitehead 2007; Gowans and Whitehead 2001; Lockyer and Morris 1990). Unlike the scars found on narwhals' heads (Gerson and Hickie 1985; Silverman and Dunbar 1980), no relationship was found between the number of scars and age (table 2.4). However, two of three single linear scrapes found on the narwhals matched across years remained unchanged, which suggests that some single linear scrapes persist for at least one year. As single linear scrapes are prevalent and can be stable for a year they can be useful in confirming matches across years. However, as they are likely not permanent, and may introduce a sex bias into the catalogue, they are not the most promising mark types for photo-identification.

The remaining marks types were found on less than 15% of the individuals and thus not suitable for primary use in photo-identification. However, most of them could be used to help confirm matches of photographs taken within a short period of time. It is difficult to assess whether they could be used over a longer period. These other marks were too few to investigate whether their frequencies were correlated with my proxy for age and most of them were not previously described in the literature, thus I could not find indication of their permanence. The pigmentation pattern was not formerly analyzed in this study because it is known change with time (Hay 1984; Hay and Mansfield 1989; Silverman 1979). However, the pigmentation pattern of one of the two individuals matched across years remained similar enough to be useful in confirming the match. In addition, the pigmentation pattern is more complex than any of the other marks described in this study and is therefore useful in comparing photographs taken over a short period of time.

2.4.2 Future Directions

Although the use of the dorsal ridge nicks and notches appear to be promising for the photo-identification of narwhals, their permanence should be formally investigated by estimating their rates of change and loss. Since the narwhals are possibly accumulating notches over time (table 2.4 and fig. 2.4) and this could make an individual unidentifiable over a period time, it is also important to formally estimate the rate of gain of the notches. The marks used for photo-identification of other species are often gained at rate lower than 0.1 mark per year per individual (Auger-Méthé and Whitehead 2007; Childerhouse et al. 1996; Dufault and Whitehead 1995; Gowans and Whitehead 2001). As long as gaining a mark does not completely change the appearance of the individual, and this gain is gradual, conducting photo-identification studies frequently will allow one to track the changes, and thus minimize identification errors (Dufault and Whitehead 1995). These errors can also be minimized if more than one reference point is available for matching. This further supports restricting the catalogue to individuals having a minimum of three notches.

As the presence and change of natural marks can be sex- and age-dependant (Blackmer et al. 2000; Scott et al. 2005), and thus produce heterogeneity in capture probabilities, it may be important to look at differences in number of nicks and notches on narwhals of different sex and age classes. Natural markings have been used as indicators of disease, and interaction with predators, hunters, and conspecifics (Finley and Miller 1982; George et al. 1994; Naessig and Lanyon 2004; Scott et al. 2005; Wilson et al. 2000). It would, thus, be interesting to investigate these marks and their distribution in the population. Since matching photographs is time consuming, developing a computer program to expedite the process would be extremely valuable. Finally, I recommend the calculation of rates of error in identification (e.g.: Agler 1992; Stevick et al. 2001) before using the photo-identification method to estimate population parameters.

Chapter 3

Computer-Assisted Photo-Identification of Narwhals

3.1 Introduction

The study of the social structure, survival rates, and other aspects of a species' ecology often requires the ability to identify individuals, and any study of a population is much richer if its individuals are known (Lebreton et al. 1992; Whitehead and Dufault 1999). This explains why methods such as photo-identification and tagging are widely used by field biologists (e.g.: Bubb et al. 2006; Karczmarski et al. 2005; Kelly 2001b; Lavers et al. 2007; Meekan et al. 2006). Photo-identification, which uses photographs of scars or pigmentation patterns to identify individuals, has the advantages of being inexpensive and non-invasive. Its development for the use with narwhals (*Monodon monoceros*) will help increase our understanding of a species for which increasing knowledge in several areas is urgently required for sound management and conservation (COSEWIC 2004). However, processing photographs is a time-consuming task. For example, comparing one photograph to a catalogue of a few hundreds individuals can easily require an hour of effort. A number of computer programs have been developed to accelerate the identification process (e.g.: Arzoumanian et al. 2005; Gamble et al. 2008; Hiby and Lovell 1990; Hillman et al. 2003). However, none appear to be directly applicable for the identification of narwhals.

All of the computer programs that aid photo-identification are similar in process (e.g.: Hillman et al. 2003; van Tienhoven et al. 2007; Whitehead 1990). The user is presented with a photograph and, although some programs automatically retrieve information from the image, the user is generally prompted to enter some of the information describing the animal found therein. Once the information from the photograph has been extracted, it is compared to the information of the individuals previously entered into the catalogue. A similarity coefficient is calculated for each of the comparisons. Finally, the program lists the individuals in the catalogue in decreasing order of similarity and the user visually confirms whether the photograph to be matched corresponds to one of the listed individuals. Programs vary in the algorithm they use to calculate the similarity coefficients and in the amount of the information entered by the user. The choice of this algorithm is highly dependent on the type of information used for the photo-identification of the species of interest.

Nicks and notches of the dorsal ridge appear to be the most suitable marks to identify individual narwhals (see previous chapter). There are multiple programs that use the presence or shape of such marks, which are found in other species on the dorsal fin or fluke. These programs either use the location of these marks along the appropriate body part (Whitehead 1990) or they use the contour of the body part where these marks are found (Hillman et al. 2003; Huele and Ciano 1999). When used on sperm whale fluke photographs, these methods were found to be similar in performance (Beekmans et al. 2005) and I chose to base my program on the simple, yet efficient, program used to identify sperm whales developed by Whitehead (1990). This computer program, for which an updated version is still currently used (Marcoux et al. 2007; Whitehead et al. 2008), has facilitated the processing of the large amount of the photo-identification data used to investigate the social structure, mating system, population size, and movement patterns of sperm whales (Christal et al. 1998; Coakes and Whitehead 2004; Gero et al. 2007).

In this chapter, I will describe the matching program that I developed, in particular: (1) the input of the descriptive information into the computer, (2) the comparison of the narwhal photograph entered to the narwhal photographs of the catalogue, and (3) the visual confirmation of matches. In addition, I will address the choice of parameters, the accuracy, and the speed of the program.

3.2 Methods

3.2.1 Program Language and Database Information

I based my program on an updated version of the sperm whale identification program developed by Whitehead (1990). I wrote this program using MATLAB 6.5 and its imaging and database toolboxes. The matching program interacts with two Microsoft Access databases, the 'Catalogue' and the 'Match database'. The Catalogue contains the information on previously-entered individuals which is used to compare them with new photographs and is filled automatically by the computer program. The Match database contains the information associated with the narwhal photographs selected for matching. Each of its rows represents one narwhal photograph and contains information such as the name of the photographic file, the encounter number, and whether this is the best photograph of the encounter for this side of the individual. The Match database can also contain peripheral data, such as the sex or age class of the animal, and information on photographs of narwhals that will not be used for matching.

3.2.2 Matching Process

Photograph Selection

Based on the set of criteria explained in the previous chapter, narwhal photographs were assigned a quality value (Q) and selected to be matched with the computer program. Quality values vary between one (Q1) and five (Q5) (see Appendix for more details) and, for this chapter, photographs of Q3 and above are considered of high enough quality to be matched. As discussed in the previous chapter, one reference point, such as one nick or notch, is likely insufficient information to match individuals in a large catalogue. Therefore, the sample of matchable individuals is further limited to individuals which have a minimum of three adequate reference points, similar to the method used for pilot whales (Auger-Méthé and Whitehead 2007; Ottensmeyer and Whitehead 2003). Since notches are deeper and likely more stable marks than nicks (see previous chapter), a minimum of three of the main features describing them, the *deep* mark points, are used as a restriction (see section 3.2.3 Optimization of the program for description of mark points). Only the best photograph of each side of an individual in an encounter is selected for matching by the program. Although not necessary, it is advisable to crop photographs around the ridge and try to increase the contrast between the ridge and the water. This can be done with almost any commercial imaging software.

Step 1: Input of the Marks Points

After some startup procedures, such as entering the location of the databases and digital photographs on the computer, the program retrieves the information from the Match database and presents the user with the first narwhal photograph to match. By typing a letter code and using the mouse to place the point, the user enters the location of the ends of the ridge and of a set of mark points (subsequently referred as MPs). These MPs represents different aspects of the nicks and notches found on the ridge and will be described in section 3.2.3. The points are entered from the front to the back of the animal, starting by entering the location of the front end of the ridge, then locating all MPs in between, and ending with the location of the back end of the ridge. Multiple cues, such as the presence of the blowhole and the abrupt rise from the body of the front section of the ridge, indicate where the front of the animal is found.

For each entered MP, the program records the letter code representing its type and its position (in pixels) in relation to the x-axis of the photograph (fig. 3.1). Once all of the MPs are entered, their proportional distance from the front end of the dorsal ridge is calculated as follows:

$$distMP_i = \frac{MP_i - front\ end}{back\ end - front\ end}, (1)$$

where MP_i is the location of the *i*th MP found on the ridge, *front end* is the location of the front end of the ridge, and *back end* is the location of back end of the ridge. In cases where one of the ends of the ridge is masked by water or by another individual, the user places the end where the true end of the ridge is estimated to be found and marks an additional point, referred to as the '*visible limit*', where the ridge becomes visible. Although the proportional distance of MPs is still calculated using the location of the true end of the ridge, this additional point allows the program to calculate the size of the

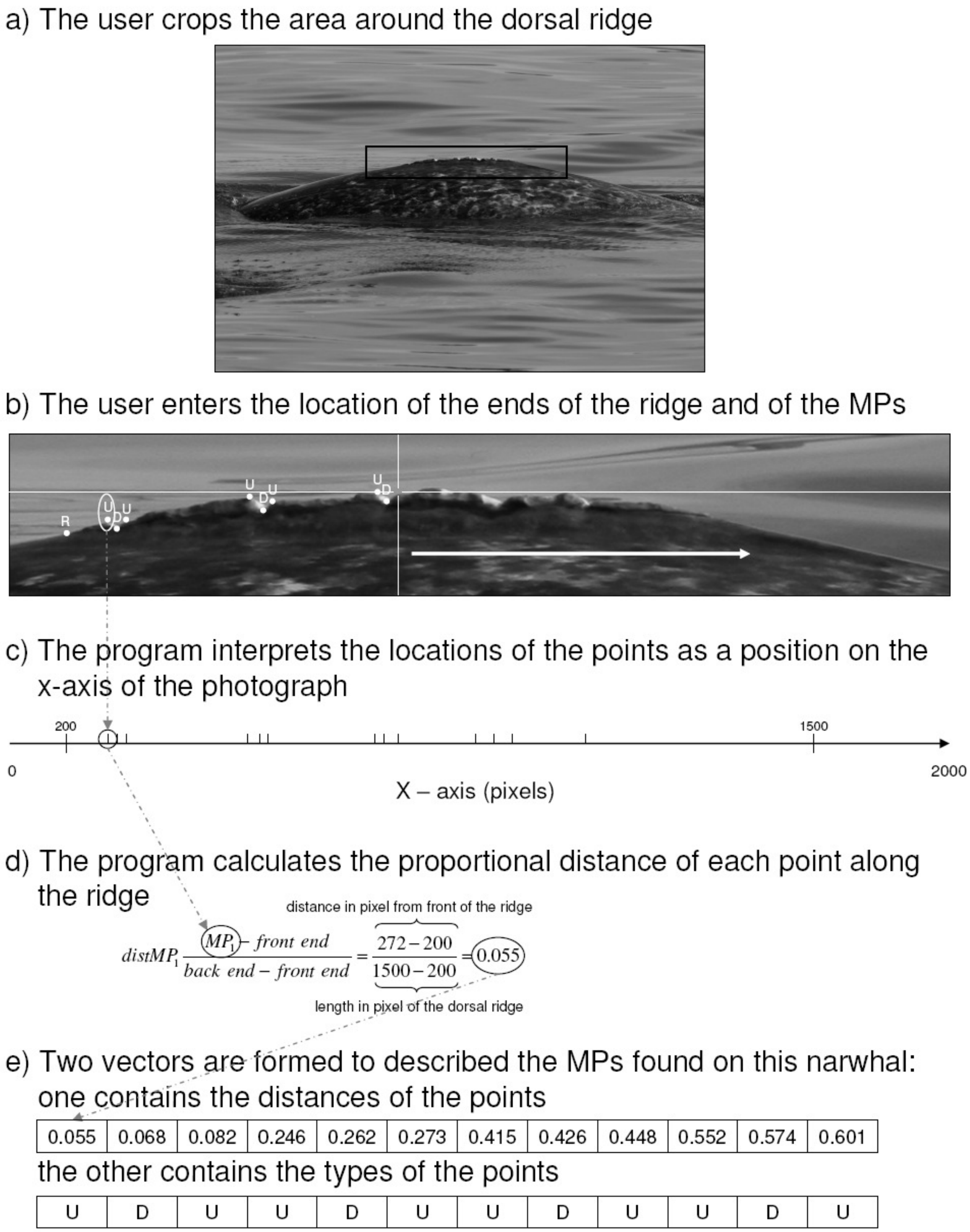


Figure 3.1 Description of the first step of the matching program when using the ends of the ridge to calculate the proportional distance of MPs. The process is similar for the no ends version except that the first and last MPs, rather than the ends, are used to calculate the proportional distance of the MPs. Note that U represents up MPs and D represents deep MPs.

section that is masked. When the first step of the matching process is finished the photograph of the narwhal is represented by two vectors, one containing the information regarding the type of the MPs, and the presence of the visible limit when appropriate, and the other containing their distance from the front end of the ridge.

Step 2: Comparing the Photograph Entered to the Individuals in the Catalogue

Using the vectors describing its MPs, the photograph to be matched is compared to every individual in the catalogue (fig 3.2). For each of these comparisons, a similarity coefficient value is calculated based on the proportion of the MPs that are common to both photographs and on how similar the locations of these MPs are. The number of common MPs is limited to the number of MPs found on the photograph with the fewest MPs. Therefore, each of the MPs on the photograph with the fewest is compared to all of the MPs of the other photograph, from which the MP which matches best is selected. The similarity between two MPs is based on whether two MPs of the same type are found at a similar proportional distance along the ridge, and is calculated with the following equation.

$$MPcomp_{ij} = e^{-\frac{1}{2}\left(\left(distMP_i - distMP_j\right)/\left(sd\right)\right)^2}, (2)$$

where $distMP_i$ and $distMP_i$ are the proportional distances from the front of the ridge for the *i*th MP of the photograph to be matched and of the *j*th MP of one of the photographs from the catalogue. This equation is based on the density function of a normal distribution and thus depends also on the amount of error allowed in the assessment of distance, which is represented by the standard deviation, *sd*. The resulting value for the comparison between MPs varies between zero and one, with one indicating that the two MPs are exactly at the same distance along the ridge, and zero indicating that the two MPs are too far from each other to be considered likely to be the same.

In order to calculate the overall similarity coefficient value between two photographs, the highest values selected for each of the common MPs is summed and the total is divided by the average number of MPs for the two photographs. This equation penalizes

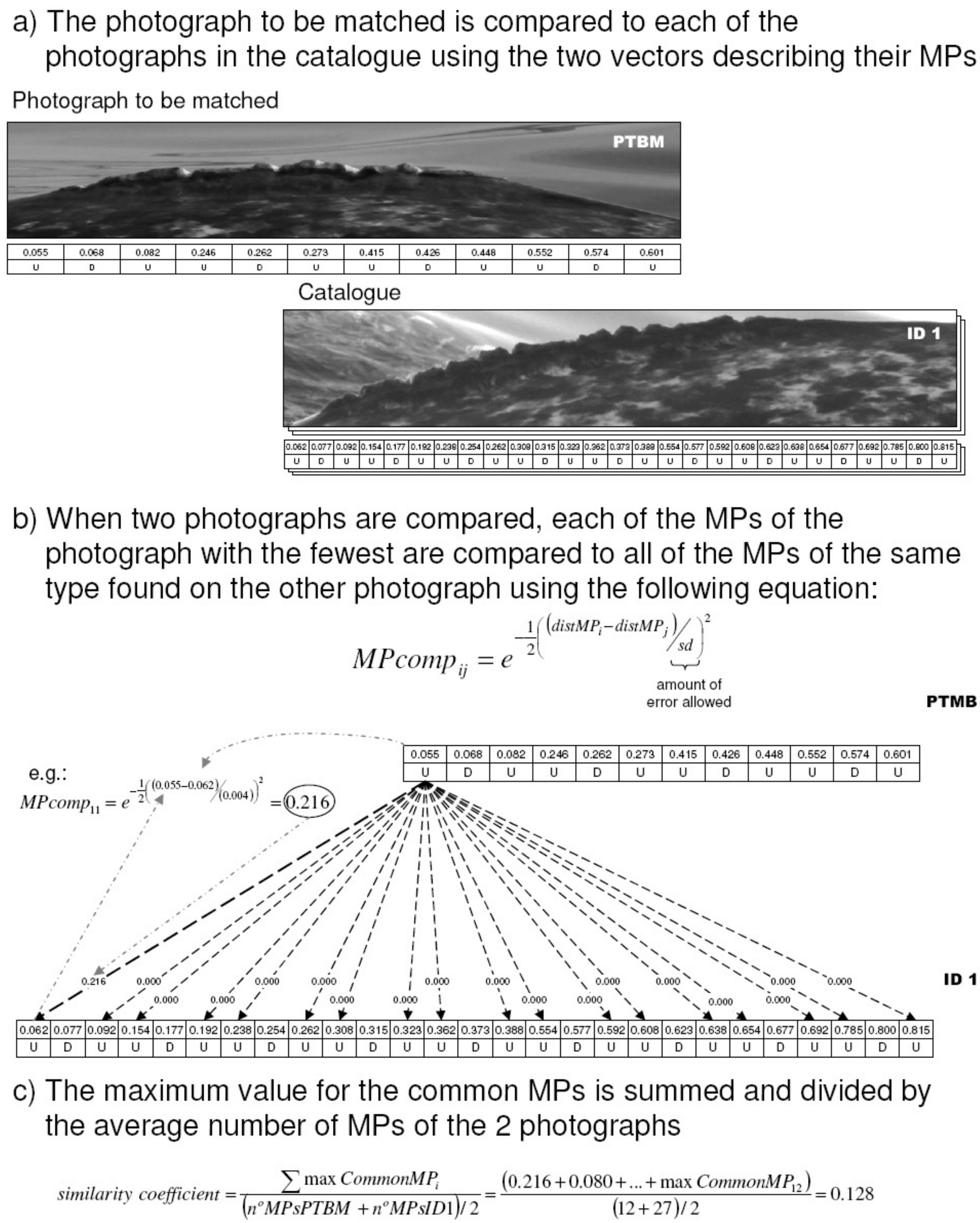


Figure 3.2 Description of the second step of the matching program. Note that U represents *up* MPs and D represents *deep* MPs. Step b and c are repeated 81 times for each comparison. Each time the ends of one of the ridges is shifted either towards or away from the other end (see text and fig. 3.4).

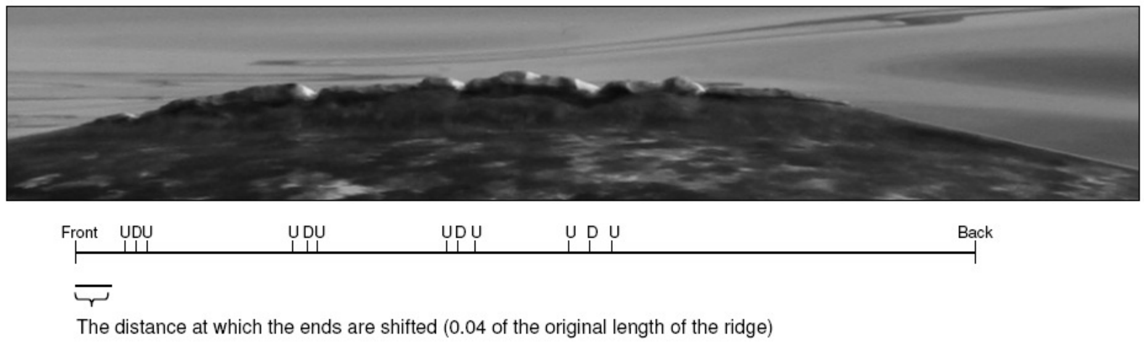
comparisons between narwhals which differ in their number of MPs. For example, even if all of the MPs of the narwhal with the fewest match perfectly with one of the MPs of the narwhal with the most MPs, the similarity coefficient will be lower than one. Only MPs found on a section of the ridge that is visible for both narwhals are compared. Thus all MPs found on a section corresponding to a section from the other narwhal which is masked are eliminated from the matching.

It is difficult to assess exactly where the ends of the dorsal ridge are located, especially if they are masked. Since the proportional distance of MPs depends on the position of these ends and photographs are compared using the proportional distance of their MPs, errors in the location of the ends may produce matching errors. To decrease the chance of such errors, the proportional distance of the MPs are altered by shifting the ends of the ridge either towards or away from each other and by recalculating the proportional distance of the MPs with these new positions of the ends (fig. 3.3). The distance at which the ends are shifted is one of the parameters that were optimized (see section 3.2.3 and table 3.2). The optimized value was 0.04 of the original length. Both ends can be placed in three positions: the original position, away from the other end (lengthening the ridge), and toward the other (shortening the ridge), which creates a set of nine proportional distance vectors for each photograph (fig. 3.3). This is done for each of the photographs compared, and all of their vectors are compared to one another. Therefore, the program calculates 81 similarity coefficient values, from which the highest is selected to represent the comparison between these two photographs.

Another approach for decreasing the chance of errors resulting from misplacement of the ends was investigated. A second version of the program was created in which the ends of the dorsal ridge were not used. In this program, the first and last MPs are the basis of the proportional distance of the MPs, and thus equation 1 is changed to:

$$distMP_i = \frac{MP_i - MP_{front}}{MP_{back} - MP_{front}}, \quad (3)$$

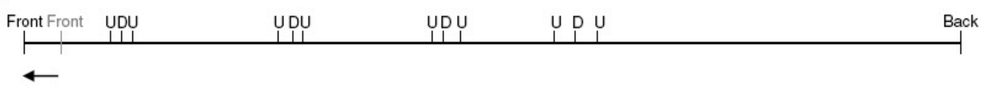
a) The original location of the MPs



b) The original proportional distance of the MPs

0.055	0.068	0.082	0.246	0.262	0.273	0.415	0.426	0.448	0.552	0.574	0.601
U	D	U	U	D	U	U	D	U	U	D	U

c) One of the ends is shifted



d) The proportional distance of the MPs is recalculated

0.091	0.104	0.117	0.275	0.290	0.301	0.438	0.448	0.469	0.569	0.590	0.616
U	D	U	U	D	U	U	D	U	U	D	U

e) This is repeated for each ends

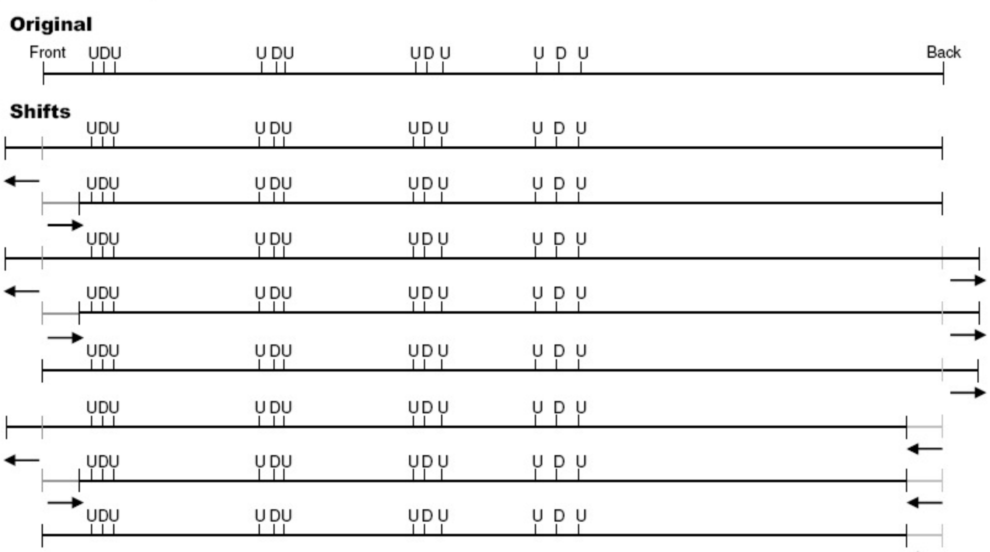


Figure 3.3 Illustration of the process of shifting ends and recalculating the proportional distance of MPs. This is done for both of the photographs being compared. Note that U represents *up* MPs and D represents *deep* MPs.

where MP_{front} is the first MP at the front of the narwhal and MP_{back} is the last MP at the back. The rest of the program uses the same equations and processes, including the calculation of multiple sets of proportional distances for each narwhal. The only other difference occurs when photographs with masked ends are compared. Although the exact process depends on whether the ridge in one or both photographs have masked ends and on whether they greatly differ in their numbers of MPs, the program generally only compares a number of MPs equivalent to the number to the MPs observed on the photograph with the masked end. All extra MPs from the other photograph are removed from the section where the narwhal has the masked end.

Step 3: Visual Confirmation of the Match and Creation of a New Individual

Once the photograph to be matched is compared to all of the individuals in the catalogue and a similarity coefficient value is assigned to each of the comparisons, a list is formed ranking the all catalogued narwhals in decreasing order of similarity with the input photograph. The user is presented with this list which contains additional information, such as the similarity coefficient value and which side of the narwhal was photographed. The user can open the images to visually verify whether the photograph matches one of these individuals. It is up to the user to confirm whether the photograph to be matched corresponds to one of the individuals in the Catalogue or whether it is a new individual. The user can chose to only consider as potential matches the individuals with a similarity coefficient higher or equal to the threshold value (0.286) described in sections 3.2.4 and 3.3.2. Using this threshold allows the user to ignore all the other individuals listed before deciding that the photograph inputted has no match in the Catalogue and is, thus, of a new individual (see sections 3.4.2, 3.4.3, and 3.4.4 for discussion of the advantages and disadvantages associated with the usage of this threshold value). If the user decides that the photograph is of a new individual, its information, including the two vectors describing its MPs, is automatically entered in the Catalogue. If the photograph matches one of the individuals in the catalogue, the user can choose to keep the original information in the catalogue or replace it with the new information associated with the photograph just entered. Both sides of a narwhal can be matched to one another (as the marks used are visible from either side of the animal) and given the same identification number. However, the information for each side of the narwhal is kept separately in the catalogue.

3.2.3 Optimization of the Program

Photographic Sample

I investigated different aspects of the matching process in order to decide which options would result in the most accurate routine. To do so, true matches were selected from a catalogue of photographs taken in Koluktoo Bay, Nunavut (72^{o} 02'N, 80^{o} 40'W) in 2006 and 2007. Although the matching of these photographs was aided by a prototype of the matching program described here, all matches were confirmed visually and new individuals needed to be compared to every individual of the catalogue before receiving a new identification number. If I had any doubt on a match, the opinion of a minimum of three other people was required before making a decision. The catalogue contained 212 individuals, all of which had the required 3 *deep* MPs and were represented by photographs of Q3 and above (see chapter 2 for more details regarding the field, dataset, and quality assessment). Only 57 of the individuals in the catalogue were present in more than one photograph.

In order to optimize the program, I selected a sample of 80 photographs, representing 40 individuals. I selected only individuals that had multiple photographs of the same side taken within a year and used just two photographs of each individual. The possible effect of quality on the matching process was one of the factors that I investigated and thus the sample was selected to represent the different possible pairs of quality comparison. As few Q5 photographs were available, I selected all possible pairs of comparisons between a Q5 photograph and a Q3, Q4, or Q5 photograph of the same individual. I selected a random sample from all other possible comparisons: Q4 to Q4, Q4 to Q3, and Q3 to Q3. Two sets of photographs were made, each of them containing one of the photographs from the 40 individuals. The first set of photographs was considered as those to be matched and the second set was considered as the catalogue. The photographs used for this analysis were cropped images of the dorsal ridge that varied in size from about 300 by 100 pixels to 1800 by 600 pixels.

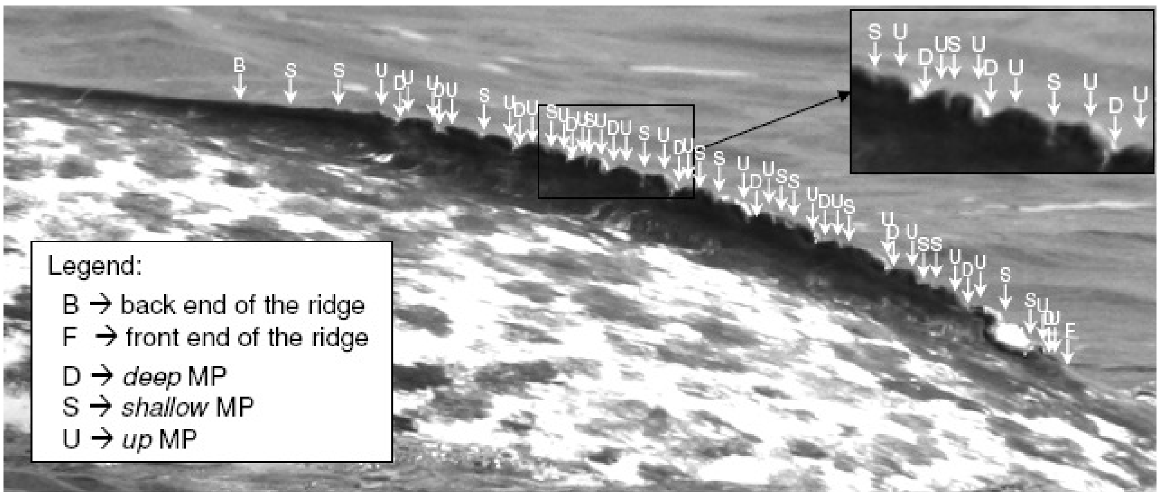


Figure 3.4 Example of the MPs located on an individual narwhal. Although the final version of the computer program only uses *deep* and *up* MPs, the figure contains all original MP types. The *deep* and *up* MPs represent features of the notches. The *shallow* MPs represent features of the nicks, and its use is eliminated from the final version of the program. The front and back ends of the ridge are also represented.

MP Types and Error Rates

The choice of MPs was the first aspect of the matching program to be addressed. Three types of MPs were originally created to describe the nicks and notches of the dorsal ridge (figure 3.4). The MP type '*deep*' represented the deepest points of notches and the MP type '*up*' represented their upper limits, notches being indentations that cut the ridge through its entire depth (see first chapter for more details). The MP type '*shallow*' represented the deepest points of nicks, which are indentations that only partly indent the ridge. For each photograph, I assigned all MPs to a type by placing a coloured dot under them. The colour of the dot represented the type of the MP. To minimize the possibility of remembering where I had placed the MPs in photographs of the same individual, the photographs were processed in random order. Once the sample was processed accordingly, the photographs of the same individual were compared to one another and the number of MPs the two photographs had in common, the number only visible in one of the photographs, and the number of MPs which differ in type but not in location was noted. I excluded the MPs that were in an area that was not visible in one photograph of the pair (e.g. MPs on a section of the ridge that is underwater in one of the photographs) when I calculated the proportion of missing and misclassified MPs.

For each pair of photographs, the proportion of missing and misclassified MPs of a given type was calculated as exemplified for missing MPs:

$$proportion\ of\ MP\ missing = \frac{N^o MPV1}{N^o MPC + N^o MPV1 + N^o MPM}, \quad (4)$$

where $N^o MPV1$ is the number of MPs of the given type only visible in one photograph, $N^o MPC$ is the number of MPs common to both photographs, and $N^o MPM$ is the number of MPs of the given type misclassified for another type in the other photograph. When calculating the proportion of MP misclassified the numerator of equation 4, $N^o MPV1$, is replaced by the $N^o MPM$. As *up* MPs were never misclassified, misclassification errors were only calculated for *deep* and *shallow*. Note that since only *deep* and *shallow* MPs were confused for one another, the term $N^o MPM$ used in equation 4 will be equal for both the proportion of *deep* misclassified and the proportion of *shallow* misclassified and only the denominator will differ.

I calculated the error rates for missing or misclassified MPs by averaging the proportion of missing or misclassified MPs across the sample pairs. In addition, I used a Kruskal-Wallis test to compare the error rates for missing or misclassified MPs across the pairs of different quality. This was done in order to investigate whether the photographic quality affects the visibility and classification of MPs. As only two individuals were available, the Q3-Q5 comparisons were excluded for this test.

Comparison Between Program Versions

I compared the accuracy of three different versions of the program. The first calculated the similarity coefficient value of two photographs using the proportional distance of MPs from the ends of the ridge (referred as the 'with ends' program). The second calculated the similarity coefficient using the proportional distance of MPs from the first and last MPs of the ridge and, thus, without using the end of the ridge (referred as the 'no ends' program). The third, a hybrid between the other two, calculated a similarity coefficient value using both methods and the highest value was selected as the similarity coefficient for the comparison.

In order to investigate which of these versions had the greatest matching capacity, each of their parameters, the values for *sd* in equation 2 and the distance at which the ends are shifted, was optimized and the optimized versions of the programs were compared to one another. To do so, each photograph from the match set was compared to the 40 photographs of the catalogue set. As the program lists the photographs in decreasing order of similarity coefficient value, the rank of the true match was noted. The probability of having the true match rank in the first ten narwhals of the list was calculated and was used to compare the different versions. Although the optimization of the parameters and the comparison between narwhals was done separately for each version, the MPs were only entered once. This ensured that differences between the versions were not the results in differences in the entry of MPs, but true differences in the versions of the matching program.

3.2.4 Speed and Accuracy of the Final Program

The version found to be the best in the previous section was tested for its speed and accuracy using a different sample. I selected three sets of photographs: a new match set, a new catalogue set, and a no-match set. Each of the match and catalogue sets contained one of the two photographs representing 40 individuals. The no-match set contained photographs of 30 individuals not found in the catalogue set. I selected this sample of individuals at random from the catalogue of 212 narwhals described above. Since only 57 of its individuals are found in multiple photographs, I used in this section many of the individuals used in the previous section. About half of the photographs used in the match and catalogue sets were previously used to optimize the program. I did not limit this sample to photographs of the same side, and I included matches of narwhal photographed a year apart. I reentered the MPs of all the photographs.

I compared the individuals from the match and no-match sets to all of the individuals in the catalogue set. For the match set, I noted the rank and the similarity coefficient of true matches. Similarly to Gamble *et al.* (2008), I calculated the probability of ranking the true match in the first ten narwhals. In addition, I set a threshold value for potential matches using the lowest similarity coefficient value I noted for a true match. For each individual of the no-match set, I counted the number of comparisons against the individuals in the catalogue that resulted in a similarity coefficient value higher than or equal to the threshold.

Finally, as the goal of using this program is to reduce the time spent matching, I compared the speed of the matching process, with and without the program. I measured the time spent to enter the MPs of ten of the individuals and the time the program took to compared these to a catalogue of 40 individuals on a 1.18GHz computer with 240 MB of RAM. I did not include the time spent cropping the photographs or changing their contrast as these cropped photographs were used to help the matching process, both with, and without the computer program. When the computer program was not used, the individuals from the catalogue set were viewed in order of their filename.

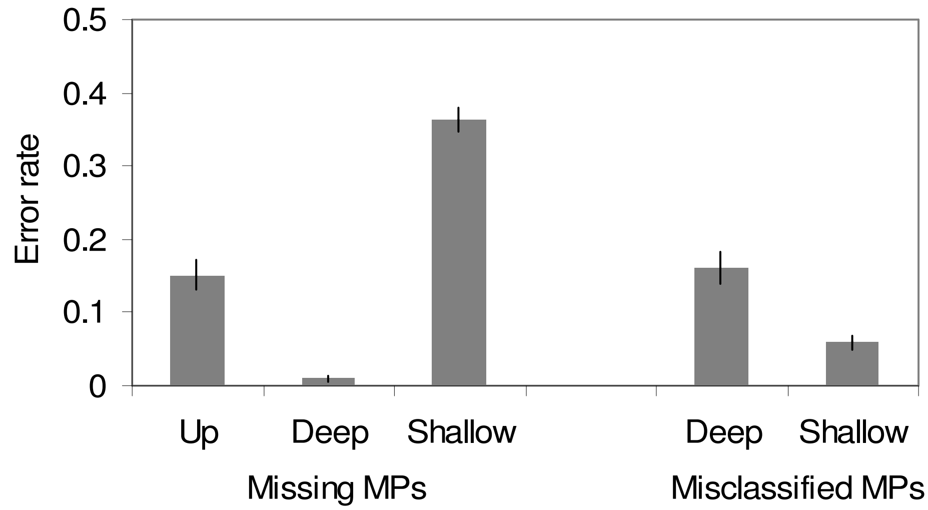


Figure 3.5 The error rates of the different MPs types, represented by the mean proportion of MPs of a given type which are missing or misclassified, and their standard error. Note that the missing *shallow* MPs have the highest error rate and that the missing *up* and the misclassified *deep* MPs have similar error rates. As only *shallow* and *deep* can be misclassified for one another, the smaller error rate of *shallow* misclassifications compared to *deep* misclassifications is driven by a greater number of *shallow* MPs observed on the individuals, not by a difference in the actual number of errors.

Table 3.1 Kruskal-Wallis tests, which investigate whether the error rates of missing and misclassified MPs of a given type differ across quality comparisons. Probability value is calculated assuming chi-square distribution. The sample had 10 individuals with photographs pairs Q3-Q3, 8 for Q3-Q4, 9 for Q4-Q4, 6 for Q4-Q5, and 5 for Q5-Q5. The difference between the misclassified *deep* and misclassified *shallow* is only due to a difference in the denominator (see method section).

Mark point type		Kruskal-Wallis test statistic	df	p-value
Proportion missing				
	up	6.079	4	0.193
	deep	4.040	4	0.401
	shallow	2.302	4	0.680
Proportion misclassified				
	deep	6.489	4	0.165
	shallow	6.998	4	0.136

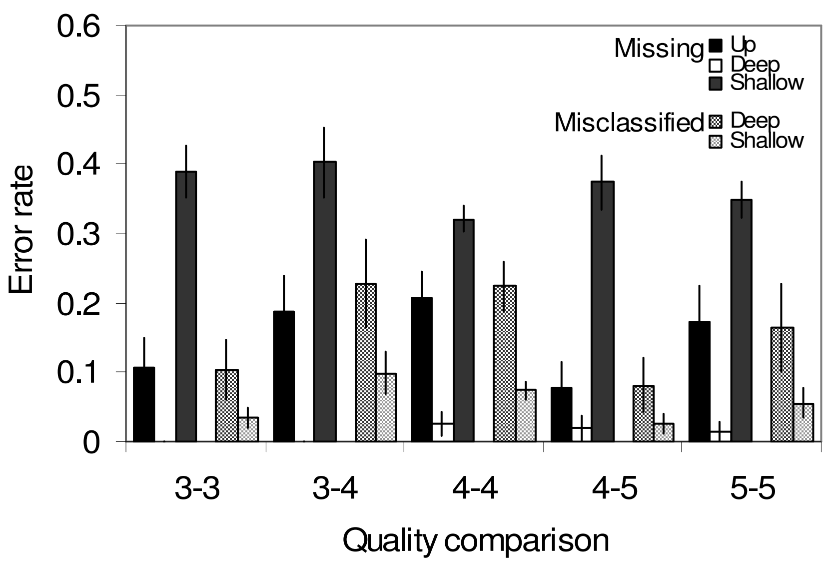


Figure 3.6 The mean and standard error of proportion of missing and misclassified MPs is presented for the different quality comparisons. None of the error rates from the missing or misclassified MPs differ significantly across quality comparison (see table 3.1).

3.3 Results

3.3.1 MP Types and Error Rates

The individuals sampled to investigate the error rates of different MP types had on average 6 *deep*, 12 *up*, and 14 *shallow* common MPs. The error rate for missing *shallow* MPs (mean: 0.36, SE: 0.016) was much greater than that for *deep* (mean: 0.01, SE: 0.005) and *up* (mean: 0.15, SE: 0.020) (fig. 3.5), and, thus, s*hallow* MPs were not used in any of the versions of the program. The *deep* MP was by far the most consistently visible type. However it was often misclassified (mean: 0.16, SE: 0.023) (fig. 3.5). As only *shallow* and *deep* can be misclassified as one another, the smaller error rate of *shallow* misclassifications (mean: 0.06, SE: 0.009) compared to *deep* misclassifications is driven by a greater number of *shallow* MPs observed on the individuals, not by a difference in the actual number of errors. Quality of the photographs had little effect on the error rates of any of the MP types (table 3.1, fig. 3.6).

Compared to the other program versions, the hybrid had the highest probability of ranking the true match within the first ten potential matches (0.925) (fig 3.7). Although lower for the two other versions, the probability of ranking a true match within the first ten (0.875, 0.9) was higher than expected at random (0.25 for 10 out of the 40 individuals of the catalogue). The versions of the program that were compared used their respective optimized parameters. The optimized parameters for the hybrid version are presented in table 3.2. As the hybrid version consistently surpassed the others in selecting the true match within the catalogue, it was chosen as the final version of the program.

3.3.2 Speed and Accuracy of the Final Program

Accuracy

As the performance of a program cannot be truly tested using the sample used to optimize it, I tested the accuracy of the final version of the program with a new sample. The probability of being ranked in the first ten potential matches is 0.90 (fig. 3.8), which is lower than what was observed for the optimizing sample (0.925). The average value for the similarity coefficient of true matches was 0.483 and the lowest value was 0.286. If

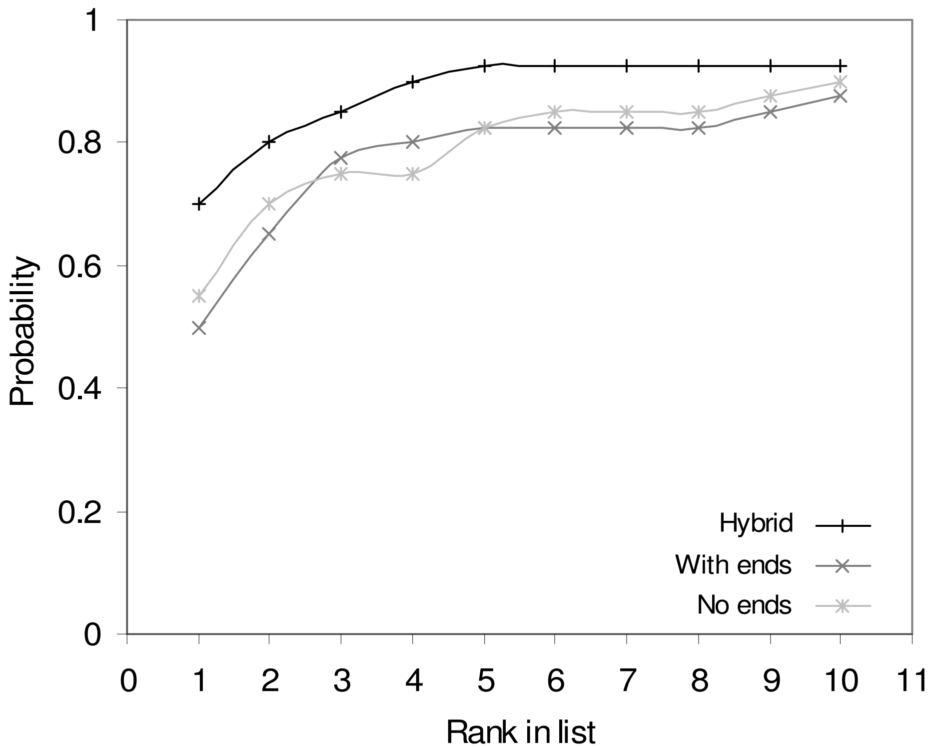


Figure 3.7 Differences between the optimized versions of the program in their capacity of matching individuals. The probability of a true match being ranked in the first 10 individuals corresponds to the proportion of the 40 individuals of the match set which were ranked at a value lower or equal to the one presented on the x-axis. The parameters of each of the version were optimized independently and the best set of parameters for each was used to calculate these results. Note that the hybrid version appears to be more accurate in its assessment of matches.

Table 3.2 Optimized parameters of the best and final version of the program, the hybrid version (fig. 3.7). As the error rate for missing *shallow* MPs is high (fig. 3.5), only *deep* and *up* MPs are used in the final version of the program (see text for more details).

Parameters optimized	Proportion of the ridge length
Distance by which the ends are shifted	0.04
Value of *sd* in equation 2 when comparing	
up MPs	0.003
deep MPs	0.002

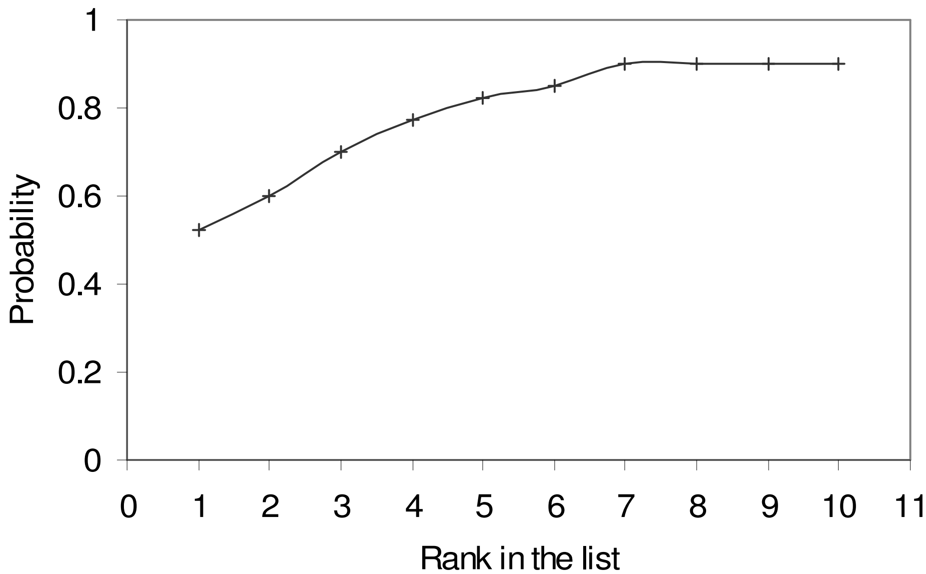


Figure 3.8 Accuracy of the final version of the program. The hybrid version was chosen as the final version of the program and a new sample was used to recalculate the probability of a true match being ranked in the first 10 individuals. The probability corresponds to the proportion of the 40 individuals of the match set which were ranked at a value lower or equal to the one presented on the x-axis.

this lowest value was used as the threshold, an average of 57.5% of the individuals from the catalogue were considered as potential matches for the individuals of the no-match set.

Speed Comparison

When using the best version and only the appropriate MPs, the hybrid version without *shallow* MPs, I spent an average of 1 min 14 sec to match one individual to a catalogue of 40 individuals using the computer program. I needed 41 sec to enter the MPs. The program required 0.09 sec to calculate the similarity coefficient for the comparison of two photographs. The average ranking of true matches is 3.75 and it takes a person about 8 sec to compare two photographs and choose whether the individuals within them are the same or not. Based on these values, the speed of the program at different catalogue size was calculated (table 3.3). Depending on the size of the catalogue and on whether the photograph matches to one of the individuals of the catalogue, using the computer program accelerates the matching process by 1.5-4.5 times.

3.4 Discussion

3.4.1 Optimizing the Program

The final version of the program uses only *up* and *deep* MPs, and calculates the similarity coefficient using both the proportional distance from the ends of the ridge and the proportional distance from the first and last MPs. The *shallow* MPs were eliminated since their rate of error was much higher than that of the other MP types (fig 3.5). *Shallow* MPs differ from the others in that they are used to described nicks rather than notches. Nicks are shallower and less distinctive marks than notches (see previous chapter) which might explain why their visibility was less consistent from one photograph to another. Nicks are also thought to be less stable over time than notches (see previous chapter). Therefore, the discrepancies between *shallow* MPs found in photographs of the same individual will likely increase for photographs taken multiple years apart, and more than for *up* and *deep* MPs. The hybrid version of the program was selected as it consistently surpassed the others in ranking the true match among the first individuals of the list (fig 3.7).

Table 3.3 Comparison between the estimated speed of the matching process, with and without the matching program. The speeds are based on the following values. The visual comparison of two photographs was estimated to take 8 sec, whether using the computer program or not. The time the computer program took to make one comparison is estimated to be 0.09 sec. The proportion of the photographs of the list which need to be checked to find a true match is 0.09. This based on the average rank of 3.75 for true matches in a catalogue of 40. The proportion of the photographs of the list which needs to be checked when there is no true match in the catalogue is based on the average number of photographs which have a similarity value higher than the threshold, 57.5% or 0.58. It is assumed that if photographs are matched without the program the number of photographs to be checked would be, on average, half the size of the catalogue if there is a match in the catalogue, and the complete catalogue if there is no match.

Steps for comparing a photograph to the catalogue	Proportion of potential matches visually checked		Time spent (sec) to match 1 individual to a catalogue of:			
			40 individuals		500 individuals	
	Match	No match	Match	No match	Match	No match
With program						
Entering the MPs	--		41		41	
Comparing to the catalogue	--		4		45	
Visual match verification	0.09	0.58	29	186	360	2320
Total	--		74	231	446	2406
Without program	0.5	1	160	320	2000	4000

3.4.2 Accuracy

The main goal of the program is to reduce the time spent matching, and this is generally achieved by decreasing the number of individuals to be visually verified by the user. A program's accuracy in generating a list of potential matches is usually measured as the proportion of true matches that are ranked first (e.g.: Gamble et al. 2008; van Tienhoven et al. 2007). However, as Defran et al. (1990) noted, identifying a new individual is the most time consuming task, as this individual generally has to be compared to all of the individuals of the catalogue. Therefore, finding a threshold value of the similarity coefficient below which the user does not need to look for potential matches is also an important measure of the accuracy.

It should be noted that the accuracy of this program is more representative of the upper limits of its capacity than its true accuracy. Due to sample limitation, the sample used to test the accuracy had most of its individuals in common with those used for optimization. In addition, the sample used to test the accuracy of the program was originally matched with a prototype of the program, although, as mentioned in the methods section, many precautions were taken to reduce this possible source of bias. Finally, the sample had very few matches across years and thus did not test the possible effect of mark change on the accuracy of the program.

Finding a Match in the Catalogue

The program ranked true matches first in the list 52.5% of the time. This is comparable to the accuracy of programs developed for other species which ranked true matches first 32-72% of the time (Gamble et al. 2008; van Tienhoven et al. 2007; Whitehead 1990). However, since an increase in the size of the catalogue negatively affects the ranking of true matches (Gamble et al. 2008) and since most of these programs differ in the size of their catalogue, direct comparisons of this characteristic are of limited use. Rather, the relative accuracy, which can be measured as the proportion of true matches that are ranked within a given percentage of the catalogue and tends to be constant with increasing catalogue size (Gamble et al. 2008), should be used. The true match of 77.5% of the photographs was found ranked within the first four individuals of the list, which represents the first 10% of catalogue. In this respect too, the narwhal program exhibited an accuracy similar to that achieved by other matching programs. For example, 50% of the true matches for sea otter (*Enhydra lutris*) and 80% of true matches for bottlenose dolphins (*Tursiops truncatus*) were found within the top 10% of the individuals from the catalogue (Finerty et al. 2007; Stewman et al. 2006).

Limiting the Number of Potential Matches

Most programs do not employ a threshold value that limits the number of individuals considered to be potential matches. However, using such thresholds can be effective in reducing the time spent matching. For example, Hiby and Lovell (1990) found that true matches for grey seal (*Halichoerus grypus*) had a similarity coefficient greater than 0.5 and that 98% of the comparisons between two different individuals had a similarity coefficient lower than 0.5. Such a clear threshold could not be found for this program. The lowest similarity coefficient for a true match was of 0.286 and on average 57.5% of the comparison between two different individuals had a similarity coefficient greater or equal to 0.286. Although this threshold does not completely distinguish true matches from incorrect matches, its use still decreases the number of individuals to be checked visually by more than 40%.

3.4.3 Speed

Although high accuracy is an important attribute of a matching program, a matching program is only useful if it decreases the time spent matching. The matching process was estimated to be 2.2x faster at finding a match in a catalogue of 40 individuals when the computer program was used, and 4.5x faster for a catalogue of 500 individuals (table 3.3). Although the difference in speed was not as large when assessing new individuals (individuals with no match in the Catalogue), the process was still about 1.4-1.7x faster when the program was used. The computer program accelerates the matching process of a new individual only if the threshold value described above is used. The precise time required for a program to match individuals is dependent on the processing power of the computer on which it is used, but I can confidently say that the program will accelerate the matching process, especially with a large catalogue.

3.4.4 Limiting the Introduction of Identification Errors

MPs Errors and Guidelines

Although removing *shallow* MPs from the final version of the program eliminates the relatively high error rate of missing *shallow* MPs, missing *up*, missing *deep*, and misclassification of *deep* MPs still occur. The error rate associated with missing *deep* MPs is very small (0.01) and inspection of the data revealed that all of these errors were found in situations where wide notches were compared. Unlike the more common narrow notches, which only have one *deep* MP placed at their deepest point, the wider notches have two *deep* MPs placed at each corner of the notch. All of the missing *deep* MPs were found when a notch was assessed as wide, with two MPs, in one photograph and as narrow, with only one MP, in the other. Therefore, I would caution the user to assess a notch as wide only when it falls into the extreme high end of the width range, such as when it is at least as wide as 15% of the ridge (see previous chapter).

The misclassification errors for *deep* and *shallow* MPs indicate that nicks and notches are sometimes confused, which is not surprising given that these two mark types are only differentiated by how deeply they indent the ridge (see previous chapter). As noted by the similarity in their error rates, missing *up* MPs are also associated with misclassification errors. This association results from the fact that *up* MPs were only placed at the upper limits of notches, and not at the upper limits of nicks. Therefore, when a notch was confused as a nick, only one photograph would have the *up* MPs for that mark. Since we are eliminating the use of *shallow* MPs, all misclassified *deep* MPs will be considered as missing *deep*, which will increase the missing *deep* error rate to 0.17. It is, therefore, clear that strict guidelines for MP assessments need to be used and I would recommend limiting the use of *deep* MPs only to notches, which not only indent the ridge through its entire depth, but do so in sections of the ridge where the height of the ridge is greater than 1% of its length. Missing MPs and misclassification errors will likely increase as the number of program users increases and it is thus all the more important that these guidelines be respected.

Increasing the Accuracy

Many additional modifications can be considered in order to increase the accuracy of the program. For example, using more than one reference image for an individual has been found to greatly increase the accuracy of the matching process (van Tienhoven et al. 2007). Thus, it may be useful to keep multiple vectors for each individual in the catalogue. In addition, a decrease in distinctiveness of the features used in matching has been shown to negatively affect the ability of matching programs to rank true matches first (Beekmans et al. 2005; Finerty et al. 2007). One factor which can increase the distinctiveness of an individual is an increase in the number of reference points. It is for this reason that I suggest that only individuals with a minimum of three *deep* MPs be considered for identification. Similarly, a decrease in accuracy of other programs was associated with decrease in photographic quality (Beekmans et al. 2005; Finerty et al. 2007; Whitehead 1990) and a change in angle was found to be the main factor affecting the accuracy of the program (Kelly 2001a; Whitehead 1990). Although the lack of differences in the error rates associated with photographs of different quality (fig. 3.6 and table 3.1) indicates that the marks are equally visible across photograph of different quality, the effect the angle might have on the program was not tested. Differences in angle could affect the proportional distance of MPs and, thus, it is important to limit the sample to photographs in which the narwhal is reasonably parallel to the frame.

Identification Errors

Photo-identification has two inherent types of identification errors: (1) matching two different individuals as one (false positive) and (2) considering one individual as two (false negative). These are generally the consequence of using photographs of poor quality, non-distinct marks, or marks that change with time (Agler 1992; Carlson et al. 1990) and can lead to bias in studies using photo-identification (Gunnlaugsson and Sigurjónsson 1990; Hammond 1986; Stevick et al. 2001). As the user is required to visually confirm matches, the rate of false-positive errors should not be affected by using the program, compared to matching without it. However, the rate of false-negative errors could be increased with the use of a threshold value that limits the number of individuals considered as potential matches. This increase can be easily avoided by ignoring the threshold and considering all photographs of the catalogue as potential matches. However, if the threshold is ignored, using the computer program will not accelerate the matching process when the photograph to be matched is of a new individual. The final version of the program will present the user with all individuals of the catalogue as potential matches and it will be up to the user to decide whether to use the threshold value described here.

3.5 Conclusion

I have developed a computer program which accelerates the photo-identification of narwhals. A free version of the program is available at (http://whitelab.biology.dal.ca/mm/piinup.html). This version requires MATLAB 6.5 with the database and imaging toolboxes. This will facilitate a broadening of research of this species. This computer program could be applied to beluga whales (*Delphinapterus leucas*) as they also have dorsal ridges.

Chapter 4

Discussion

4.1 Summary of Results

4.1.1 Mark Type Used for Photo-Identification

Nicks and notches of the dorsal ridge appeared to be the most promising mark types for photo-identification. Both types were prevalent and numerous on adult narwhals. Ninety eight percent of individuals had at least one nick, and 91% had at least one notch. On average, individuals had 16.36 nicks and 6.16 notches. The significant correlation between the proportion of white on the body (a proxy for age in this study) and numbers of nicks and notches (table 2.4, fig. 2.4) suggests that narwhals accumulate these marks with age, and thus possibly indicates permanency. Using the nicks and notches in the dorsal ridge to identify narwhals has the advantage of allowing one to match both sides of an individual to one another, something which would not be possible with any mark found on the skin of the animals.

The computer program was originally developed to use features of both the nicks and notches to identify narwhals. However, I eliminated the use of the features which described the nicks, the *shallow* MPs. I did so because the error rate in assigning these MPs for two photographs of the same individual was much higher than for the MPs used to describe notches, *up* and *deep* MPs (fig 3.5). In addition, the nicks, which are shallower indents, might be less stable with time than notches. The nicks seen on individuals found across years appeared to change in shape, and the correlation between the numbers of marks and age appeared to be weaker for nicks than for notches (table 2.4 and fig. 2.4).

Although I could identify individuals with only one notch, one such reference point is likely insufficient information to match individuals within a large catalogue. A decrease in distinctiveness of the features used in matching has been shown be associated with increased identification error (Agler 1992) and to negatively affect the ability of matching programs to rank true matches first (Beekmans et al. 2005; Finerty et al. 2007). It is for this reason that I suggest that only individuals with a minimum of three *deep* MPs be considered for identification, which is similar to the three mark point restriction used for pilot whales (Auger-Méthé and Whitehead 2007; Ottensmeyer and Whitehead 2003).

4.1.2 Efficiency of the Method and of the Program

The method, with the three *deep* MPs restriction, allows the identification of 84% of adult narwhals, which is higher than the 33-66% of the pilot whales and bottlenose whales (Auger-Méthé and Whitehead 2007; Gowans and Whitehead 2001) and close to the 91% of sperm whales (Arnbom 1987). The program listed a true match 77.5% of the time within the first 10% of the potential matches in the catalogue. This accelerated the matching process by at least 2.2 times, an efficiency which is estimated to increase to 4.5 times when the catalogue size increases to 500 individuals. Although the computer program is less efficient in limiting the number of individuals to be considered as potential matches, the program still accelerates the matching process by 1.4-1.7 times when no matches are present in the catalogue.

4.2 Limitations of the Study and Future Work

4.2.1 Identification Errors

As mark change, loss, or gain can lead to identification errors (Carlson et al. 1990; Dufault and Whitehead 1995), it is important to adequately investigate the stability of notches. Although the correlation between the white pigmentation of the skin, an indicator of age, and the number of notches (table 2.4, fig. 2.4) could indicate that notches are permanent and accumulate with age, the same result is consistent with non-permanent marks that are acquired at a faster rate than they are lost, or that are gained more frequently with increasing age. Thus, both the rate of gain and the rate of loss should be calculated for notches. However, this will only be possible with a greater photographic sample which spans more than two years and which contains multiple matches between years, as for instance in the work of Auger-Méthé and Whitehead (2007), Dufault and Whitehead (1995), and Gowans and Whitehead (2001).

As previously mentioned, both the distinctiveness of marks and the quality of photographs can affect the number of identification errors (Agler 1992), which is the reason why I recommend restricting photo-identification to individuals which have a minimum of 3 *deep* MPs and to high quality photographs (Q3 and above). However, it will be important to investigate the effect of both of these factors and of the possible gain and loss of marks on the identification error rates and on the accuracy of the program. Investigating the possible increase in error rates by the computer program is simple if true matches are known. As mentioned previously, only false-negative errors can be affected by the program itself, and only if a threshold value is used to limit the number of potential matches. The increase in error rate can be calculated by counting the number of true matches which have a lower similarity coefficient than the threshold value. However, calculating the intrinsic error rates of photo-identification would require double-tagging studies such as those conducted by Dufault and Whitehead (1995) and Stevick et al. (2001) or, less effectively, using discrepancies between users (Agler 1992). Error rates calculated using these methods can be used to correct for possible biases in population estimates (Agler 1992; Stevick et al. 2001) and thus such studies are recommended prior to using photo-identification data in population models.

Many capture-recapture models that are used with photo-identification data, such as the Petersen and Jolly-Seber models, assume that the probabilities of capture are equal across individuals. The violation of this assumption (referred as heterogeneity in capture probabilities) can lead in negative bias in population estimate (Hammond 1990). Heterogeneity in capture probabilities can be caused by differences in behaviour (e.g.: some individuals stay longer at the surface), ecology (e.g.: some individuals prefer to swim next to the coast), and morphology (e.g.: some individuals are not identifiable). On rare occasions, when the number of individuals in the population is known, heterogeneity can be directly estimated (Whitehead 2001b). As the presence and change of natural marks can be sex- and age-dependant (Blackmer et al. 2000; Scott et al. 2005), and thus produce heterogeneity in capture probabilities, it is important to quantify the number of notches on narwhals of different sex and age classes. In addition, the fact that only 84% of the adults are identifiable, and none of the calves are, should be considered when photo-identification data are used in capture-recapture models.

4.2.2 Software Limitation

The computer program is freely available at (http://whitelab.biology.dal.ca/mm/piinup.html). However, this version requires the user to have MATLAB 6.5 with the database and imaging toolboxes. To allow a wider range of people to use the computer program, a compiled version should be developed which could be used without requiring specialized computer programs such as MATLAB.

4.3 Conclusion

The photo-identification method and program developed will help us expand our understanding of narwhal biology. For example, although the sample size is small, the catalogue of photographs collected during the summers 2006 and 2007 in Koluktoo Bay could be used to estimate the number of narwhals in this area. The financial costs of a photo-identification study are much lower than the methods previously used (e.g.: aerial surveys). In addition, the method is simple to use and the computer program is available to anyone. This could allow members of the Northern communities with a camera to become involved in the research of a species which is important to them. All of these advantages of photo-identification could facilitate an increase in the monitoring of population trends, which is important when managing an exploited population.

Appendix

Quality Assessment

Table A.1 The five criteria used for quality assessment based on some of the criteria of Arnbom (1987).

Criteria	Description	Value
Size of ridge	The length of the ridge in proportion to the width of the photograph. For ridges that are partly masked, the estimated size of the whole ridge is used.	1 $< 1/8$ 2 $\geq 1/8$ & $< 1/6$ 3 $\geq 1/6$ & $< 1/5$ 4 $\geq 1/5$ & $< 1/4$ 5 $\geq 1/4$
Focus	Represents how in focus the outline of the ridge is.	1 Outline of the ridge barely visible 2 Only really big notches could be visible 3 Could detect notches but the outline out of focus 4 Notches and nicks could be visible but outline not completely in focus 5 The outline of the ridge is completely in focus.
% of ridge visible	Proportion of the ridge that is visible.	1 1 – 25% 2 25% - 49% 3 50% - 74% 4 75% - 99% 5 100%
Orientation	The angle formed by the ridge and the frame of the photograph. For example, a narwhal swimming towards the camera would form an angle of 90^{o}.	1 $>45^{o}$ 2 35^{o} - 45^{o} 3 21^{o} - 35^{o} 4 11^{o} - 20^{o} 5 0^{o} – 10^{o}
Exposure	A measure of the relative darkness of the photograph and how much the ridge contrasts with the water.	1 Really dark or strong glare on the dorsal ridge 2 Dark or some glare 3 Contrast is acceptable and glare is acceptable 4 Contrast is good and no strong glare 5 Contrast is really good and no glare

Table A.2 Description of the quality values (Q1-Q5). Narwhals for which none of the ridge is visible in the photograph are excluded from the quality assessment and not further considered for matching. The quality values are based on the criteria explained in table A.1. and are assigned by adding the values of the five criteria. Other restrictions are explained.

Q	Total of criteria values	Other restrictions
1	<10	-
2	10-16	Only one of the criteria can have a value of 1
3	17-20	Only one of the criteria can have a value of 2 and no criterion can have a value of 1
4	21-23	No criterion can have a value of 2
5	24-25	-

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