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ORIGINAL ARTICLE

Shape variation in the eye patch and dorsal fin of southern hemisphere killer whales (*Orcinus orca*)

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Abstract

Morphological variation within and among species plays a critical role in evolutionary processes, influencing adaptation, survival, and reproductive success. Killer whale (*Orcinus orca*) morphology is known to vary on both an individual and population level with several ecotypes or forms documented worldwide. However, the extent of morphological variation among killer whales in Australian waters remains unclear, both among individuals within the region and in comparison to those in other parts of the southern hemisphere. This study assessed eye patch and dorsal fin shape variation in Australian and Antarctic killer whales to explore the evolutionary relationships among these groups. A large dataset of imagery was compiled and processed to achieve this, which provided representative sample sizes for five separate study groups: northwest Australia (NW), southwest Australia (SW), southeast Australia (SE), Antarctic type A (AA) and Antarctic type B1 (AB). Elliptical Fourier analysis was used to extract the feature outlines and enable multivariate data analyses. Principal component analysis and pairwise comparisons revealed significant morphological differences both within and between Australian and Antarctic killer whales. Eye patch shape variation was driven by the degree of taper and overall width whereas dorsal fin shape variation was driven by falcateness and broadness at its base. Hierarchical cluster analysis revealed considerable variation amongst these features, while linear discriminate analysis indicated that individuals could not be reliably classified into their respective study groups based on eye patch and dorsal fin shape alone. Nonetheless, these findings suggest the presence of both a tropical and temperate form of killer whale in Australia, with the latter resembling both the Antarctic Type A and B2s morphologically. To better understand their connectivity and divergence, dedicated research is needed to assess the evolutionary history of these populations. Such knowledge will be vital in defining global conservation management units for killer whales which are still considered a single, data deficient species by the International Union for Conservation of Nature (IUCN).

Keywords Orca · Australia · Antarctica · Ecotype · Form · Morphology · Pigmentation · Elliptical fourier analysis

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Introduction

Phenotypic traits provide one of the most useful tools for identifying and classifying species. These are defined as sets of observable and measurable attributes related to an organism's morphology, physiology and behaviour (Relethford 2009). Phenotypic traits may be either inherited through the genome or determined environmentally, but typically occur as an interaction of the two (Monroe et al. 2022). Natural selection and evolution can thus influence both the phenotype and genotype of organisms over several generations (Yuan-Chuan 2020). This can produce differences at both the individual and population level, the latter of which has complicated the taxonomic classification of many species (Mayr 1970).

The killer whale (*Orcinus orca*) is one of the most easily identifiable cetaceans with its striking black and white colouration (Jefferson et al. 2015). Distinct ecotypes or forms of this species have evolved, independent of physical barriers to gene flow, through matrilineal social units filling novel environmental niches and promoting genome-culture coevolution (Morin et al. 2015; Foote et al. 2016). Many phenotypic and genotypic differences thus exist over fine spatial and temporal scales (De Bruyn et al. 2013). Some of these ecotypes are thought to be reproductively isolated and separate species, but further research is needed to confirm these assumptions (Foote 2022). For example, most studies on killer whale morphology have relied on descriptive approaches such as tracing outlines from field imagery and using broad terms to categorise variants (Evans and Yablokov 1978; Baird and Stacey 1988; Visser and Mäkeläinen 2000). The subjective nature of which make it difficult to compare and replicate results.

Dedicated research on killer whales in Australian waters has come a long way in recent years, but it still lags behind the more established studies of well-known populations in the Northern Hemisphere. While this species has been recorded year-round across all coastal states and territories, there are only a few places where they can be studied with any reliability of presence: the northwest (NW) Ningaloo Reef (Totterdell and Wellard 2022), southwest (SW) Bremer Sub-basin (Wellard and Erbe 2020) and Australia's southeast (SE) (Donnelly et al. 2019) (Fig. 1). Effort has been made to study the social structure (Wellard 2018), feeding ecology (Pitman et al. 2015; Wellard et al. 2016; Cieslak et al. 2021; Totterdell et al. 2022), bioacoustic repertoire (Wellard et al. 2015), population genetics (Reeves et al. 2022, 2023) and distribution (Jones et al. 2019; Kämpf 2021; Salgado Kent et al. 2021; Hutchings et al. 2025) of these killer whales. Photo identification (photo-ID) of individual animals underpins most of this research, however there are no matches currently known between these three regions (Donnelly et al. 2021). Based upon this fact, it is believed that there are at least three geographically separate groups of killer whales occurring in Australian waters. More generally, there appears to be both a tropical and temperate form displaying both phenotypic and genotypic differences (Reeves et al. 2022). The latter of which most closely resembles those from Antarctic waters, particularly the type A ecotype (Donnelly et al. 2021).

Killer whales show both intraspecific and geographic variation in their morphology, allowing not only individuals, but also populations, to be told apart (Evans et al. 1982;

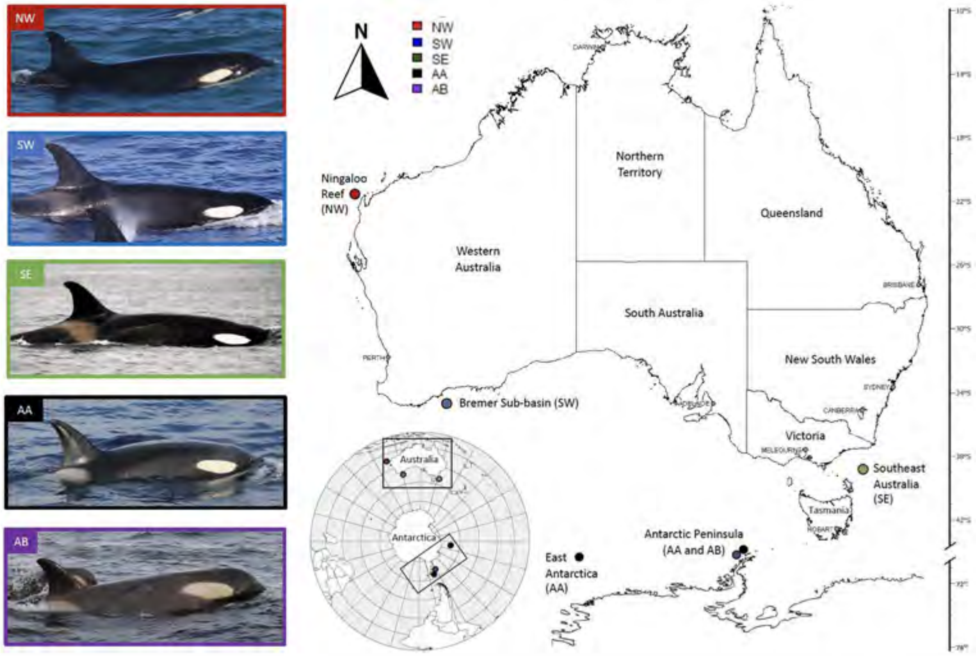


Fig. 1 This study assessed shape variation in the eye patch and dorsal fin of southern hemisphere killer whales (*Orcinus orca*) belonging to five study groups in Australian and Antarctic waters: the northwest (NW) Ningaloo Reef, southwest (SW) Bremer Sub-basin, Australia's southeast (SE), Antarctic type A (AA) and Antarctic type B2 (AB). Please note – map is not to scale. Image credit – John Totterdell (NW), Rebecca Wellard (SW), Trevor Long (SE), Dave Donnelly (AA) and Rebecca Wellard (AB)

Bigg et al. 1987). However, this variability remains difficult to quantify and is poorly understood for killer whales in less studied regions such as Australia. It is unclear how the morphology of killer whales in Australian waters compares to each other and to others in the southern hemisphere. This study assessed shape variation in the eye patch and dorsal fin of Australian and Antarctic killer whale populations to shed light on the relationships among these groups. It is hypothesised that statistically significant differences will arise to reflect both a tropical and temperate form of killer whale in Australia, the latter of which will show resemblance to the Antarctic type A.

Methods

Data collection

This study used a 25-year dataset of killer whale imagery provided by RW, DMD and JAT, with most images collected during dedicated research surveys in Australian and Antarctic waters. Additional imagery was also donated by citizen scientists, tourism operators and other marine users to the co-authors above who then made them available to be included in this study. Most of the photographs were taken from land or a vessel, but some underwater footage was available and used to supplement analyses. Accompanying this imagery was adjacent sighting information including the time, location, group size, behaviour and, if assessed for photo-ID, the catalogue numbers of individuals present. In addition to genetic biopsy, sex and age class information was available for some of these killer whales through long-term observations of their development and reproduction. For example, females with calves and males with erect dorsal fins are known to be sexually mature.

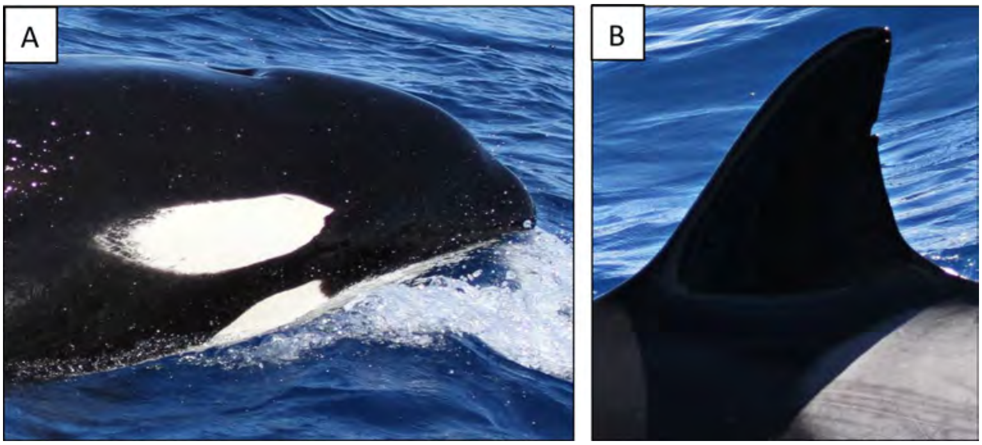
Imagery selection

Facilitated by prior and ongoing photo-ID, subsets of imagery were compiled for as many catalogued individuals from Australian and Antarctic waters as possible. Whilst some of these images had already been assessed for identification purposes, they were regraded to ensure their suitability for photo morphometric analysis. Grading criteria (Table S1) was thus developed to consider the visibility of the feature, orientation of the individuals, angle of the individual, size of the feature and quality of the image. An image scoring 12 or more points was deemed suitable and renamed according to catalogue number, encounter date, side of the body and feature shown. The required score was only achieved if the feature was entirely visible with no artifacts and if the image was sharp, well contrasted and in focus. In addition, the feature needed to be perpendicular to the camera, parallel to the photographic plane and fill more than 25% of the frame. If multiple images of the same feature were available, they were numbered as replicates. However, only the best image of each individual's eye patch (EP) and dorsal fin (DF) were considered for further analysis (Fig. 2).

Study groups

Killer whales from Australian waters were divided into three study areas: the northwest (NW), southwest (SW) and southeast (SE). In contrast, those from Antarctica were placed into their respective ecotypes, by RW and DMD, regardless of sighting location: type A (AA) and type B2 (AB) (Fig. 1). Within these five study groups, all individuals were pooled when assessing the EP as this feature is known to be independent of sex and age (Baird and Stacey 1988). However, only sexed adults were assessed for the DF so that its shape was not obscured by ontogeny. Males and females were also separated to account for sexual dimorphism whereby the male DF grows much taller and straighter than that of the female (Clark and Odell 1999). Only the higher

Fig. 2 Example of high-quality images of the left-hand side eye patch (**A**) and right-hand side dorsal fin (**B**) used in the analysis of individual SW075. Image credit – Rebecca Wellard



sample size of the left or right-hand side EP was assessed due to asymmetry and incomplete photographic coverage of some individuals. Although mostly symmetrical, the DF was only assessed for the higher sample size of the left or right-hand side to maintain consistency between the two analyses and minimise the possibility of introducing false negatives. The saddle patch was not assessed given its inability to distinguish between populations as suggested for Northeast Pacific killer whale ecotypes in a foundational study (Emmons et al. 2019). There was also not enough imagery to include the Antarctic type B1, C or D ecotypes. Similarly, imagery of killer whales was sought from other tropical locations, but sample size was not sufficient for analysis.

Feature extraction

ImageJ (v1.54i 03) (Rasband 2018) was used to crop, centre and adjust the contrast and brightness of the EP and DF in the imagery. The entire EP was used, but the base of the DF required defining from the rest of the body. As further detailed in Emmons et al. (2019), this was done by placing anchor points at the anterior and posterior insertion points and then drawing a straight line to connect these. The final product of each feature was a black outline on a white background which was saved as an 8-bit greyscale JPEG.

Elliptical fourier analysis

The feature outlines were then batch imported into RStudio (v2023.12.1 + 402) (R Core Team 2023) for elliptical Fourier Analysis (EFA) using the package Momocs (Bonhomme et al. 2014). EFA is a non-invasive shape reconstruction method that can be used for morphometric analysis of pre-collected datasets (Claude 2008). It decomposes complex forms in a stepwise manner using a harmonic series of ellipses generated along the outline of images. Information is extracted as sets of x and y coordinates to estimate four coefficients for each ellipse that describe its size, shape and orientation (Lestrel 1989). The analysis was performed separately for each feature and all outlines were visually inspected for any inconsistencies. Normalisation was carried out by scaling and centring their shapes to the first fitted ellipse. The outlines were also smoothed by a factor of 25 to minimise the effects of digitisation (Emmons et al. 2019). Pseudo landmarks (PLs) were then placed along the outlines at homologous points to further align the features with Procrustes alignment. Four PLs were used for the EP, one pair at both ends of its length and one pair at either side of its width. Three PLs were used for the DF, one at the tip and another two on each side of the base. When reconstructing the outlines, the number of harmonics required to retain 99.9% of the Fourier power was chosen (Claude 2008). This was nine for the EP and 10 for the DF.

Table 1 Dataset statistics highlighting the number of RAW images of killer whales (*Orcinus orca*) assessed versus the number of images deemed suitable for photo-morphometrics by the grading criteria

Study group	No. RAW images	No. images suitable for photo-morphometrics	% Useful *mean
NW	43,347	2270	5.24
SW	190,642	1829	0.96
SE	6874	46	0.67
AA	2049	79	3.86
AB	1410	179	12.70
Total	244,322	4403	4.69*

Multivariate analyses

Principal component analysis (PCA) of Euclidean distances between the outline coordinates was undertaken to visualise variation in feature shape, with both 2D and 3D plots drawn. Pairwise multivariate analysis of variance (MANOVA) with Wilks Lambda was then applied to test for any statistically significant differences between the study groups. Mean shapes were also drawn to further visualise these results. To explore where individuals from the study groups would be placed based on the morphological variation, hierarchical clustering analysis (HCA) of the outlines with k-means, agglomerative and complete linkage was also performed (Huang 1998). The elbow method was used to determine optimal cluster number, which was four in all cases. The dendrograms themselves were evaluated with divisive coefficients and cophenetic correlation (Saraçli et al. 2013). Lastly, linear discriminant analysis (LDA) was employed to test how effectively the shape of the EP and DF can be used to classify the study groups, with leave-one-out cross-validation to evaluate fit of modelled estimates to the data. Preliminary data analysis was performed with even sample sizes to ensure the results were not biased towards study groups with more individuals.

Results

From the almost 250,000 images assessed, approximately 4.69% were considered suitable for photo morphometric analysis by the grading criteria (Table 1). The right-hand side (RHS) of the eye patch (EP) and left-hand side (LHS) of the dorsal fin (DF) provided the highest sample size of individuals within each of the Australian study areas and Antarctic ecotypes (Fig. 2). The total number of RHS EPs considered was $n = 187$ (30 NW, 125 SW, 20 SE, 7 AA, 5AB). The total number of LHS DFs considered was $n = 53$ (8 NW, 24 SW, 6 SE, 7 AA, 8 AB) for adult males and $n = 48$ (4 NW, 19 SW, 10 SE, 9 AA, 6AB) for adult females. For the EP and DF respectively, this sample size represented approximately 64% and 26% of the currently catalogued killer whales in Australian waters. It is unknown what proportion of individuals were considered here for the Antarctic ecotypes as these were opportunistic samples provided by the authors who do not hold full photo-ID catalogues of these populations.

A high proportion of variation in shape was explained by the first two axes in the 2D principal component analysis (PCA) plots, accounting for 76.4% for the EP and 78.9% and 82.4% for adult male and female DFs respectively (Fig. 3A, B and C). The third axes also proved somewhat informative in the 3D PCA plots of each feature, but there was still a considerable amount of spread between points (Fig. S3A, B and C). For the EP, principal component one (PC1) was largely driven by the degree of taper and principal component two (PC2) by the overall width. For the DF, PC1 was largely driven by falcateness and PC2 by broadness at its base. Overall, there was a statistically significant difference in EP and DF shape found between the study groups. However, certain combinations of study groups contributed to this result more than others (Table 2). For example, only AA against AB and NW against SW remained statistically significant at the pairwise level for the EP. In contrast, there were four study group pairings of statistical significance common to both adult males and females DFs. These were AA against AB, AB against SE, AB against NW and NW against SW. In addition, a statistically significant difference in adult male DF shape was found between AA and SW as well as SE against SW. For adult female DFs, statistical significance was instead obtained AA against NW and SE against NW. Mean shapes showed that AB individuals featured a unique rise towards the posterior end of their EPs and that those of the NW were noticeably thinner (Fig. 4A). Similarly, AB and SW adult males had very broad DF bases compared to the other study areas. The DF also appeared more falcate for both sexes in the NW (Fig. 4B and C).

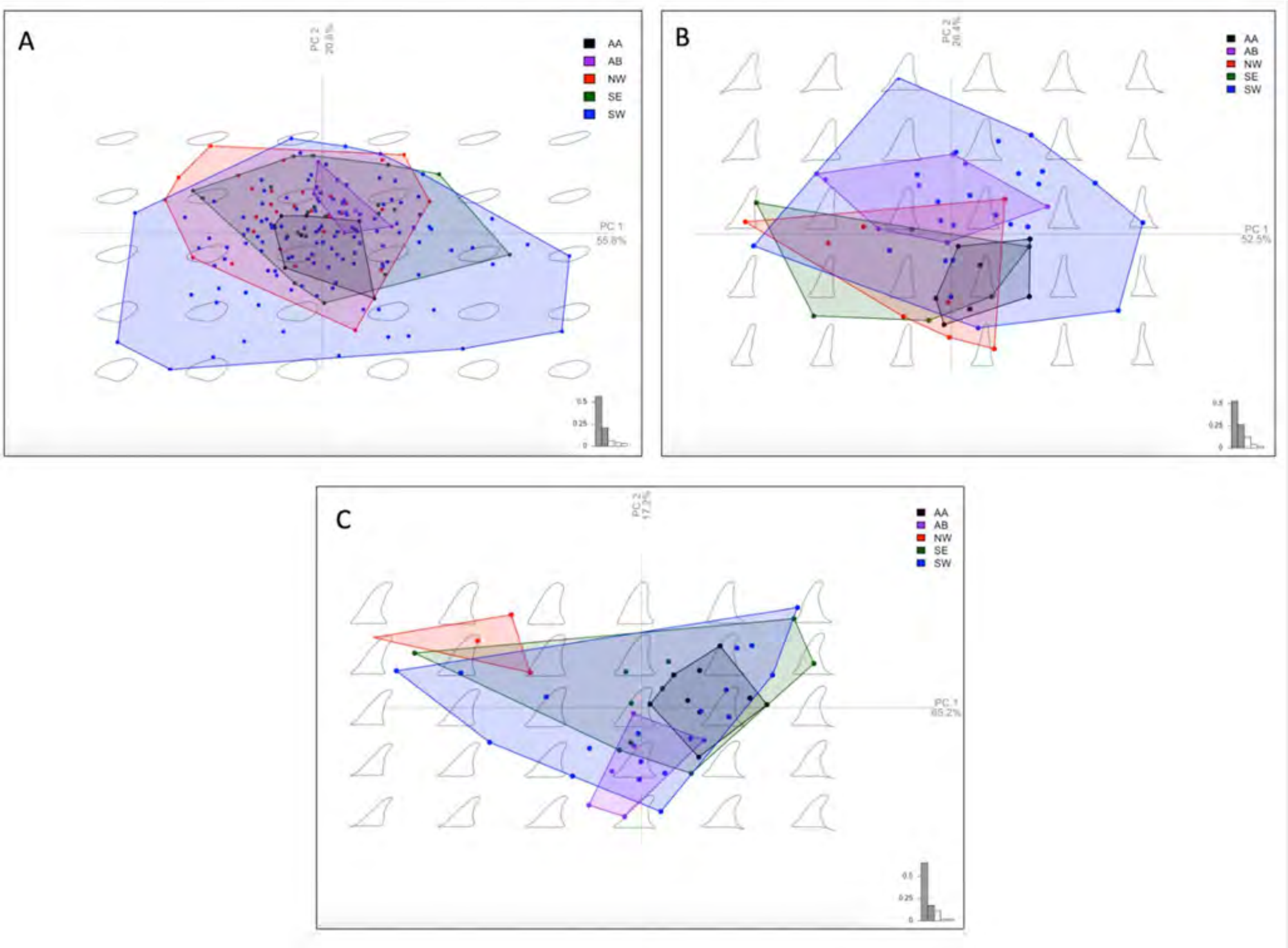


Fig. 3 2D principal component analysis plots for the eye patch (A), adult male (B) and female dorsal fin (C) show morphological differences both within and between Australian and Antarctic killer whale (*Orcinus orca*) populations. The percentage of variation explained for the first two principal components is noted alongside each axis with a cumulative proportion graph for the first five principal components also displayed in the bottom right hand side corner.

Table 2 MANOVA results indicating pairwise statistical significance for morphological differences between certain study groups of killer whales (*Orcinus orca*) in Australian and Antarctic waters

Feature	Degrees of freedom (numerator, denominator)	Approximate F statistic	*P*-value	Study groups with pairwise statistical significance
Eye patch	8, 362	2.669	0.007	AA-AB* NW-SW***
Adult male dorsal fin	8, 94	4.180	< 0.001	AA-AB*** AA-SW* AB-NW** AB-SE* NW-SW** SE-SW*
Adult female dorsal fin	8, 84	4.916	< 0.001	AA-AB** AA-NW*** AB-NW*** AB-SE* NW-SE* NW-SW**

Divisive coefficients (DC) and cophenetic correlations (CC) for each of the dendrograms indicated strong clustering and a moderate to good representation of the distance matrix built from the PCAs. Individuals from each of the study groups were scattered throughout most of the clusters. However, there were some instances when those from a certain study group where all found in a single cluster. For example, all of the individuals from AB were found in the first cluster for EP (Fig. S1A). Similarly, all except one of the adult males from AA were found in the first cluster for DF (Fig. S1B). And lastly, all of the adult females from NW were found in the fourth cluster for DF (Fig. S1C).

LDA achieved 71.1%, 50.9% and 37.5% correct classification of individuals to their respective study group for EP, adult male and female DF shape (Fig. S2A, B and C). Those from the SW were the most accurately assigned for all three features. However, a small number of these individuals were still incorrectly placed within the other study groups. For the EP, AA were the least accurately assigned and often

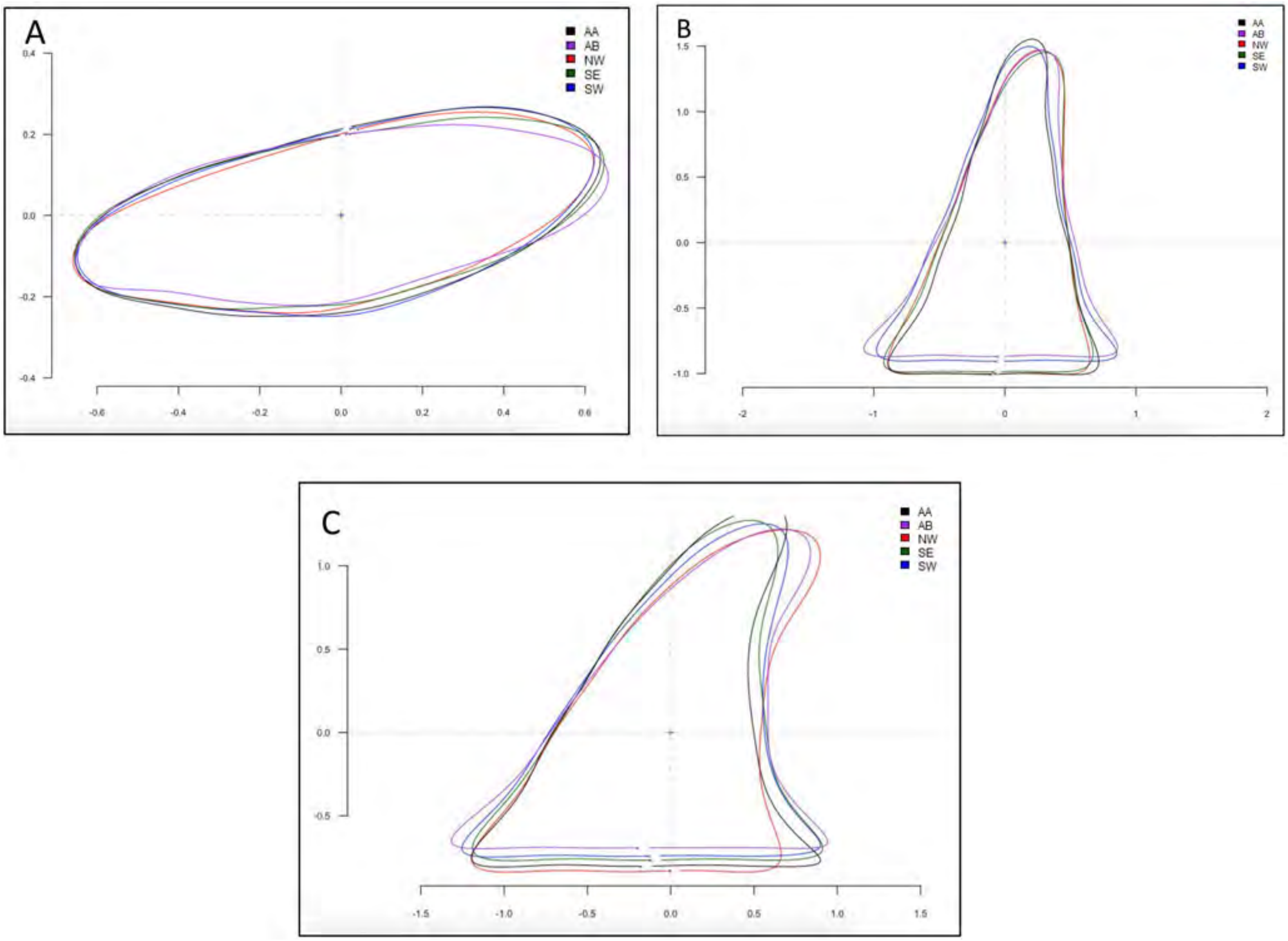


Fig. 4 Mean shapes for the eye patch (**A**), adult male (**B**) and female dorsal fin (**C**) show differences in general form both within and between Australian and Antarctic killer whale (*Orcinus orca*) populations. Please note these are point coordinates drawn on a cartesian plane thus there are no axes labels or units

predicted as being from the SW or SE. For both the adult male and female DF, SE were the least accurately assigned and often predicted as being from the NW, SW, AA or AB.

Discussion

Morphological variation within and among species plays a critical role in evolutionary processes, influencing adaptation, survival, and reproductive success. Killer whales show both intraspecific and geographic variation in their morphology with several ecotypes or forms documented across the globe (De Bruyn et al. 2013). Whilst those in the northern hemisphere and Antarctica are well studied, it remains unclear how killer whales in other parts of the southern hemisphere compare to each other morphologically. This study employed elliptical Fourier analysis (EFA) to assess shape variation in the eye patch (EP) and dorsal fin (DF) of killer whales in Australian and Antarctic waters. Results demonstrate that individuals from northwest (NW) and southwest (SW) Australia are the most dissimilar morphologically, with those of the latter showing much greater scatter across the PCA plots. These findings further support the notion that both a tropical and temperate form of killer whale occur in Australian waters as suggested by a recent distribution study (Hutchings et al. 2025). Interestingly, individuals from southeast Australia (SE) shared diagnostic characteristics with both the NW and SW, indicating that they fall somewhere between these two study groups. Antarctic ecotypes were most different to each other, reaffirming the known variation in EP and DF shape between them (Pitman and Ensor 2003). However, similarities arose between these individuals and those from the SE and SW study groups, suggesting that they do in fact bear morphological resemblance.

Delphinids display varying phenotypes that can be attributed to several functional, evolutionary and adaptive factors (Mitchell 1970; Perrin 2009). This stems from well-known developmental pathways in their artiodactyl ancestors (Stoner et al. 2003). For example, many group living species, such as the gazelle, display facial markings (Caro and Stankowich 2010). For cetaceans, it has been suggested that light pigment on an otherwise dark body can facilitate interspecific communication (Caro et al. 2011). Whilst their primary form of communication is acoustic, individuals may also recognise each other through their visual appearance. Experiments with captive killer whales have shown that this species does possess the cognitive abilities for self, and likely conspecific, recognition (Delfour and Marten 2001). It has also been suggested that distinctive patches could be useful in coordinating group behaviour during foraging. For instance, the considerably larger EP of the Antarctic type Bs may have evolved to act as a reference point when they are cooperatively swimming in line to wave wash seals off ice floes (Pitman and Ensor 2003). This white pigment would also reflect light to the eye and benefit vision in poorly lit environments. The thinner EPs of NW killer whales may thus be attributed to greater visibility of the clear tropical waters they occur in.

As the only appendage consistently exposed to the ambient air, shape variation in the DF is related to anatomical and physiological adaptions. For example, in the Northeast Pacific, resident killer whales have a rounded DF whereas that of the transients is pointed (Bigg et al. 1987; Ford et al. 2011). Whilst these populations overlap in distribution, the transients range further into the Pacific Ocean and Bearing Sea than the residents which tend to remain within the coastal waters of the Aleutian Islands and Gulf of Alaska (Morin et al. 2024). The difference in their DF shape could thus be due to their preference for nearshore versus offshore habitats which would see them experience different environmental conditions over time. A given shape may also benefit manoeuvrability and stability when foraging for a certain type of prey. Variation in DF shape has also been attributed to thermoregulatory capacity, hydrodynamic performance and foraging behaviour in bottlenose and common dolphins (Félix et al. 2017; Morteo et al. 2017). Killer whales from the NW and SW study groups present a similar case, with the former proving much more falcate for both adult male and female DF shape. Rounded dorsal fins have also been noted for killer whales in other tropical locations, such as off Mexico (Vargas-Bravo et al. 2021) and the Caribbean (Vargas-Bravo et al. 2021). In contrast, the Sub-Antarctic type Ds have a very slender swept back dorsal fin (Pitman et al. 2011), which may be due to the extreme conditions of their preferred habitat. The above are examples of how phenotypic traits have been influenced by the environment, but others may stem from a genetic component.

For most species their morphology differs due to physical barriers to gene flow. However, many killer whale populations are sympatric in range, yet don't often interact. It is known that the Northeast Pacific ecotypes rarely interbreed and that they are socially and reproductively isolated (Morin et al. 2024). To what extent the killer whales in the southern hemisphere interact remains unknown. However, those in Australian and New Zealand waters were shown to have moderate genomic diversity, negligible levels of inbreeding, low migration rates and small effective population sizes (Reeves et al. 2022). The mitochondrial DNA (mtDNA) analysed in Reeves et al. (2022) revealed five closely related haplotypes, some of which were novel for the species, and others which had genetic similarities to both tropical and temperate populations elsewhere around the globe. Another study found that individuals from the NW shared haplotypes with those from the Maldives, Eastern Tropical Pacific (ETP) and Hawaii (Foote et al. 2019). In contrast, individuals from the SE and SW shared haplotypes with those from the Southern Ocean, Crozet Islands and Antarctic Peninsula. It is thus believed there is distinct contemporary population genomic structure between the NW and SW study groups, with ancestral polymorphisms likely arising from admixture (Reeves et al. 2022). Given the nomadic and wide-ranging nature of this species, it is possible that they have mixed, and maybe still mix, with the other ecotypes found in the southern and potentially northern hemispheres. This may be why the morphological variation described here is subtle for some study groups yet more obvious for others.

Elliptical Fourier analysis (EFA) has been previously applied to compare phenotypic traits between killer whales in the Northeast Pacific. Emmons et al. (2019) also used this approach to uncover statistically significant differences in DF and EP shape that were successful in distinguishing between the three ecotypes in the region. EP shape variation was driven by height to width ratio and whether it narrowed in a vertical or horizontal direction. DF shape variation was driven by height to width ratio, falcateness and the angle of the trailing edge. These findings are concurrent with what was observed through the PCA presented here. However, the LDA classification rates of Emmons et al. (2019) were much higher, particularly for the DF. It is thus proposed that EFA successfully extracted feature shapes in both cases, but it's ability to distinguish between the Australian and Antarctic populations studied here was not as effective. Considering the two sympatric Northeast Pacific ecotypes are believed to be a result of secondary contact and are now largely considered separate species (Morin et al. 2024), this result is not surprising. Nonetheless, it must be acknowledged that LDA may not be best suited for classifying this type of data and alternative machine learning algorithms should be considered in the future (Püschel et al. 2018).

Our results suggest that EFA is best suited for assessing broad characteristics rather than fine details. For example, the mean shapes of the EP were largely spherical, but there was a high degree of variation in both the anterior and posterior sections of the outlines when viewed individually. In fact, over 29 shape variants have been described for the EPs of New Zealand killer whales (Visser and Mäkeläinen 2000). Moreover, the size and angle of this feature is known to be population specific (Evans et al. 1982). Those that are very small, like the Antarctic type D's, as well as sharply angled, like the Antarctic type C's, have been attributed to genetic isolation and inbreeding (Pitman et al. 2011; Beck et al. 2013). Whilst EP width was shown to drive variation in the PCA, size and angle was standardised through EFA by adjusting image scale with coefficients. Morphological differences can also be subtle and difficult to detect, particularly under challenging field conditions or by untrained observers. Machine learning has thus been applied to minimise human error in ecotype classification. A recent study demonstrated this by applying two different platforms, Edge Impulse and Google Cloud, which both effectively distinguished between residents and transients with a 93% and 98% success rate (Ismail et al. 2024). Multiple features were able to be assessed within the same image, however it is not yet possible to do this with EFA.

Another caveat of EFA is that image quality plays a major role in the effectiveness of shape reconstruction. A number of individuals were thus unable to be assessed because their limited amount of imagery did not meet the strict parameters of the grading criteria. Furthermore, despite there being more photographs of the DF, sample size was constrained by limited information on sex and age class. Sample sizes were also uneven between the study groups, which could have somewhat influenced the greater variation in EP and DF shape observed for SW individuals in the PCA, as well as favoured this larger study group in HCA and LDA. However, preliminary data analysis performed with even sample sizes returned very similar results, thus the analyses remain informative. Additionally, assessment of both features was restricted to only one side of the body due to potential asymmetry and incomplete photographic coverage of some individuals. Whilst inherent challenges such as this arise when working with imagery, future data collection should aim to capture photographs across both sides of the body. Additional populations and ecotypes should also be considered across both the southern and northern hemisphere to achieve a more complete analysis. Similarly, whilst the phenotypic traits of killer whales are believed to be akin among pod members, due to heritability, this is yet to be properly tested with social and genetic analyses.

This study assessed shape variation in the eye patch and dorsal fin of Australian and Antarctic killer whale populations to shed light on the relationships among these groups. Morphological differences arose to suggest that both a tropical and temperate form of killer whale exists in Australia, the latter of which bears resemblance to the Antarctic type A and B2 ecotypes. These findings provide support towards killer whale populations in the southern hemisphere being treated as distinct units for conservation management purposes. Further studies of morphology are warranted using a range of quantifiable methods alongside genetic and social analyses. Continued research on diet and behaviour is also essential to explore the functional, evolutionary and adaptive factors driving varying phenotypes. Together this work can help differentiate these ambiguous populations against others that are well described around the globe and enhance our understanding of their diversity and divergence.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42991-025-00523-w.

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Author contributions Marissa J. Hutchings: Conceptualization (Equal), Data curation (Supporting), Formal analysis (Lead), Investigation (Equal), Methodology (Lead), Project administration (Equal), Resources (Equal), Validation (Equal), Visualization (Lead), Writing - original draft (Lead), Writing - review & editing (Equal). Rebecca Wellard: Conceptualization (Supporting), Data curation (Lead), Investigation (Equal), Resources (Equal), Validation (Equal), Writing - review & editing (Equal). David M. Donnelly: Conceptualization (Supporting), Data curation (Lead), Investigation (Equal), Resources (Equal), Validation (Equal), Writing - review & editing (Equal). John A. Totterdell: Conceptualization (Supporting), Data curation (Lead), Investigation (Equal), Resources (Equal), Validation (Equal), Writing - review & editing (Equal). Guido J. Parra: Conceptualization (Equal), Formal analysis (Supporting), Investigation (Equal), Methodology (Supporting), Project administration (Equal), Resources (Equal), Supervision (Equal), Validation (Equal), Writing - review & editing (Equal). Luciana Möller: Conceptualization (Equal), Formal analysis (Supporting), Investigation (Equal), Methodology (Supporting), Project administration (Equal), Resources (Equal), Supervision (Equal), Validation (Equal), Writing - review & editing (Equal).

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Data availability The eye patch and dorsal fin outlines and R code used to perform the EFA in this study have been deposited in figshare at https://figshare.com/s/8b514710c8bf7efa0435. The original imagery used to produce the outlines is not publicly available due to sharing restriction imposed by the data owners.

Declarations

Ethical approval This study did not require ethics approval given it used previously collected data.

Conflict of interest The authors have no conflicts of interest to declare.

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