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Colour maps for fisheries acoustic echograms

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Echograms are used to visualize fisheries acoustic data, but choice of colour map has a significant effect on appearance. Quantitative echograms should use colour maps, which are colourful (have a perceived variety and intensity of colours), sequential (have monotonic lightness), and perceptually uniform (have consistency of perceived colour contrast over their range). We measure whether colour maps are colourful ($\hat{M}^{(3)} > 0$), sequential ($r_s = \pm 1$), and perceptually uniform ($\rho = 1$) using an approximately perceptually uniform colour space (CIELAB). Whilst all the fisheries acoustic colour maps tested are colourful, none is sequential or perceptually uniform. The widely used *EK500* colour map is extremely colourful ($\hat{M}^{(3)} = 186$), not sequential ($r_s = 0.06$), and has highly uneven perceptual contrast over its range ($\rho = 0.26$). Of the fisheries acoustic colour maps tested, the Large Scale Survey System default colour map is least colourful ($\hat{M}^{(3)} = 79$), but comes closest to being sequential ($r_s = -0.94$), and perceptually uniform ($\rho = 0.95$). Modern colour maps have been specifically designed for colour contrast consistency, accessibility for viewers with red-green colour-blindness, and legibility when printed in monochrome, and may be better suited to the presentation and interpretation of quantitative fisheries acoustic echograms.

Keywords: acoustic, colour, echogram, visualization

Introduction

Echosounders are routinely used in marine science to survey the underwater environment. Sound pulses ("pings") are transmitted into the water and reflections from targets (e.g. seabed, plankton, zooplankton, fish) are measured, integrated, and recorded. Signals are typically recorded as power, in Watts, and converted to target strength (TS), or volume backscattering strength (S_v), in decibels, to study the distribution, abundance, and behaviour of animals (Simmonds and MacLennan, 2005).

Acoustic data are recorded as a matrix of signals $X(i, j)$, where i is the range index and j is the along-track distance index. $X(i, j)$ can be mapped to pixels $\mathbf{c}(i, j)$, where $\mathbf{c}(i, j)$ is usually a three-dimensional colour vector, to form a digital image (an echogram) using colours drawn from a colour map. A colour map, $C = \{\mathbf{c}_1, \mathbf{c}_2, \ldots, \mathbf{c}_k\}$, is an ordered set of k colours used to assign numbers to colours such that $\mathbf{c}(i, j) \in C$. The range of X to be visualized (determined by the scale bar) is divided into k equal bins, and pixels are mapped accordingly. The available radiometric resolution of an echogram reduces as k reduces, and an echogram often has lower dynamic resolution than the original acoustic data. Changing the colours in an echogram affects the visual appearance of its content in the same way that changing the colours in a photograph would change the appearance of its subject.

The first fisheries acoustic echograms were published in the 1930s, e.g. Sund (1935). Early systems used "wet" paper processes to record measurements and these produced monochromatic images (Mitson, 1983). By the 1980s, computers could store echograms in memory and display them on monochrome cathode ray tubes (CRT) or print them using dry photographic processes. By the 1990s, echograms could be rendered in colour using colour CRT monitors, and the Bergen Echo Integrator (BEI) included purposely designed colour maps (Foote *et al.*, 1991). The Simrad EK500 was one of the first scientific

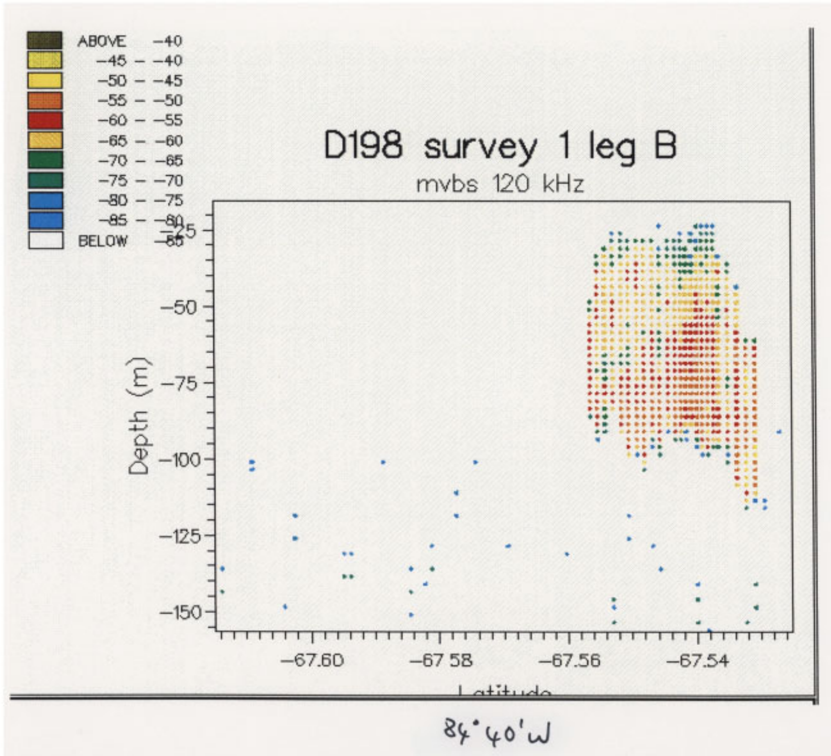

Figure 1. Echogram dating from 1992, rendered using a colour plotter. Note the limited colour and spatial resolution. Data recorded using a Simrad EK400 (120 kHz) connected to a Biosonics Echo Signal Processor, during cruise D198, RRS Discovery, Bellingshausen Sea, 1992 (Archives ref: 2001/5).

echosounders to have an attached colour display, but the hardware only had four bit planes, of which one was used for fixed lines, limiting the number of available colours to 12. Colour dot matrix printers and pen plotters were available, but also had a limited range of colours (e.g. Figure 1). As the number of available display colours increased, *k* increased, giving rise to the Simrad EK80 colour map based on EK500. As of 2019, we now have high definition monitors that use light emitting diodes and colour laser printers; both can render echograms in millions of colours. This gives rise to a wide variety of colour map options (Figure 2).

Acoustic data analysis still entails echogram interpretation by skilled fisheries acousticians. Echograms are post-processed to remove unwanted signal, e.g. seabed reflections (Blackwell *et al.*, 2019) and noise (Ryan *et al.*, 2015), before identifying acoustic targets and quantifying distribution, abundance and behaviour. Thresholding is a common way of discriminating targets from surrounding backscatter, with thresholds set based on visual interpretation of echograms and the scattering characteristics of target species, validated by target fishing (Korneliussen, 2018). Whilst automated, unsupervised algorithms exist for some aspects of fisheries acoustic data processing, much work is still undertaken manually using graphical, interactive software such as Echoview (Echoview Software Pty Ltd), Large Scale Survey System (LSSS; Korneliussen *et al.*, 2016), MOVIES (Trenkel *et al.*, 2009), or ESP3 (https://sourceforge.net/projects/esp3, accessed November 2019). It is, therefore, important that echogram data are displayed faithfully, clearly, and consistently, and that colour maps are chosen to optimize human–computer interaction.

The visual representation of data has a powerful effect on the perception and interpretation of the structure of those data (Rogowitz *et al.*, 1996). Our ability to perceive the details of a visual scene is determined by the relative size and contrast of the detail present (Campbell and Robson, 1968). Studies in medical imaging have shown that poorly designed colour maps can lead to imprecise readings and inaccurate interpretation (Borkin *et al.*, 2011). Colour map choice affects the visual appearance of an echogram (Figure 2), but the colour map used by a particular fisheries acoustician may be based on a number of factors: the colour map may have been chosen to optimize a particular detection, comparison, or estimation task; the display software may only provide a default colour map or a limited choice; the user may have been trained using a particular colour map and now have experience, familiarity and learned expertise specific to that map; or the user may simply have a subjective preference.

Pseudo coloured images are used to show *Metric* (or value) information as well as *form* (shape and structure; Ware, 1988). In psychophysical tests, greyscale colour maps better revealed form, whilst colourful maps better revealed metric. To create a colour map that reveals both metric and form, the colour sequence should increase monotonically in luminance and use a range of hues. The hues provide accurate readings from a key, while the luminance conveys form. Greyscale is, therefore, best for detecting shape in echo traces and colour for presenting backscattering strength (Foote *et al.*, 1991). Based on Ware (1988), Foote *et al.* (1991) combined greyscale and red–blue as a colour map option for BEI and this is the origin of the default echogram colour map in LSSS.

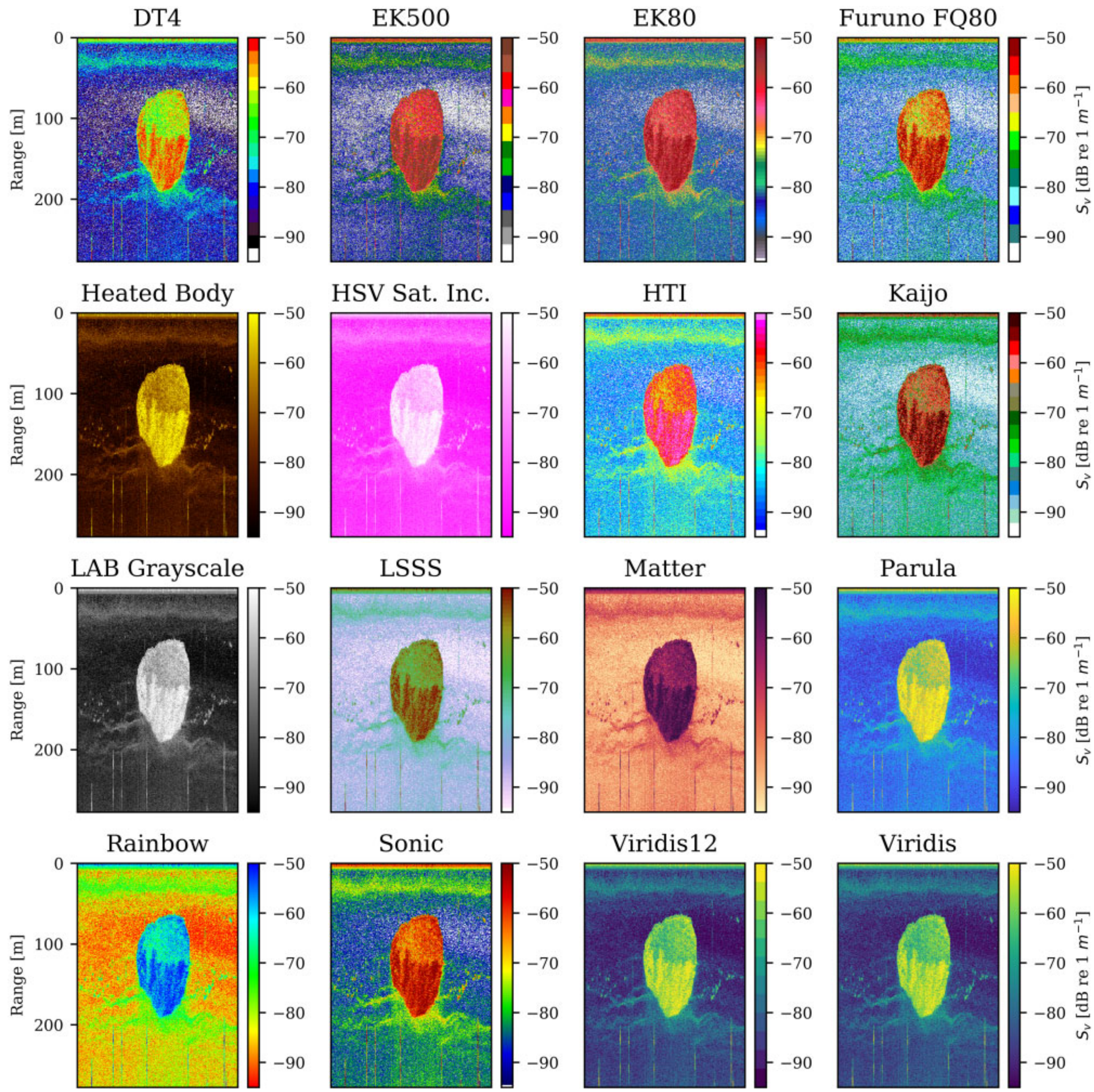

Figure 2. Echograms depicting an Antarctic krill swarm plotted using a selection of colour maps. The swarm is ∼150 m in height and 1 km in plan. Data collected using a Simrad EK60 scientific echosounder (120 kHz, ping interval $I_T = 2s$, nominal speed = 10 kts) on board RRS James Clark Ross, Cruise JR230, Southern Ocean, December 2009.

Colour maps may be either qualitative (sometimes called categorical; where colour represents a category but does not imply magnitude), sequential (where colour implies ordering and magnitude), diverging (where colour implies ordering and magnitude in two directions from a central value), or cyclical (where colour implies ordering in "wrap around" data; Brewer, 2015). Echograms of S_v or *TS*, which are intended to represent the magnitude of acoustic backscatter should, therefore, use a sequential colour map.

The human vision system is complex and there is a huge literature on colour perception (for a primer, see Baylor, 1995). Colour is not intrinsic to objects, and we perceive colour using reflected light, which varies depending on lighting conditions. Light energy entering the eye has two fundamental dimensions: intensity, which determines brightness and frequency, which determines colour. The eye consists of rods and cones, which are sensitive to intensity and frequency, respectively. We can perceive millions of colours (Judd and Wyszecki, 1975), but different people perceive colour in different ways as demonstrated by the 2015 internet sensation known as #thedress where some audiences reported dress colours as blue and black, and others as gold and white (Gegenfurtner *et al.*, 2015).

The "Which Blair Project" provides a quick visual test for evaluating colour maps (Rogowitz and Kalvin, 2001). In psychophysical testing, the perceptual quality of colour maps was assessed by using them to render a photograph of a human face. A strong correlation was found among the perceived naturalness of images, the luminance monotonicity, and the suitability of colour maps for rendering continuous scalar data.

Colour spaces organize colours within a vector space. For example, the RGB colour space organizes colours according to their red, green, and blue components. Standard RGB (sRGB) is commonly used for computer displays, which mix red, green, and blue light additively on a black screen to produce images. CMY colour spaces are used for print media, mixing cyan, magenta, and yellow ink on a white page to produce colours subtractively. These colour spaces are device-dependent, with different screens, cameras, scanners, and printers producing different colours. A colour space is said to be perceptually uniform if a small perturbation to a component value is equally perceptible across the range of that value (Poynton, 1996); however, neither RGB nor CMY colour spaces have this property. The CIELAB colour space was designed by the International Commission on Illumination (CIE) to have approximate perceptual uniformity by describing any colour in a device independent manner using three dimensions, L^* for lightness (black–white), a^* for green–red, and b^* for blue–yellow (Robertson, 1977, 1990). Euclidean distances in CIELAB colour space can be used to approximate the magnitude of perceived colour differences making it useful for the measurement and comparison of colours (Brainard, 2003) and the perceptual uniformity of colour maps.

Colour maps such as *Rainbow* have been widely criticized for a lack of perceptual uniformity (Borland and Ii, 2007). MathWorks™ changed its default MATLAB™ colour map from *Rainbow* to *Parula* in 2014 (revised in 2017) and Matplotlib (Hunter, 2007) to *Viridis* in 2016. Both *Parula* and *Viridis* have been carefully designed for colour contrast consistency, accessibility for viewers with red–green colour-blindness, and legibility when printed in monochrome. Some scientific disciplines employ specialized colour maps tailored to the subject matter. Many oceanographic publications use *cmocean* (Thyng *et al.*, 2016) and the *Brewer colour maps* are commonly used in geography (Brewer, 2015). These colour maps have also been designed explicitly with colour contrast consistency in mind.

Based on the evidence from Ware (1988), Brewer (2015), and Borland and Ii (2007), we conclude that echogram colour maps for displaying quantitative acoustic backscatter should be colourful, sequential, and perceptually uniform. In this article, we measure whether fisheries acoustic colour maps are colourful, sequential, and perceptually uniform using CIELAB. We compare our results with colour maps used by the wider scientific community and make recommendations concerning colour map selection for the presentation and interpretation of fisheries acoustic echograms.

Materials and methods

A selection of fisheries acoustic echogram colour maps was obtained from echosounder data collection and processing systems. These include *BioSonics DT4*, *Simrad EK500*, *Simrad EK80*, *Furuno FQ80*, *HTI*, *Kaijo*, and *Sonic* from Echoview, and *LSSS*, the default colour map from the LSSS. It is common for echogram colour maps to have dark and light variants by using black or white as a background colour. These background colours were excluded from our analyses.

Data science tools include modern colour maps, which were designed for colour contrast consistency, and so for comparison, we also selected *Matter* from cmocean, *Parula* from MATLAB, and *Viridis* from matplotlib. A subsampled version of *Viridis* having 12 colours, $\{\mathbf{c}_1, \mathbf{c}_{24}, \mathbf{c}_{47}, \ldots, \mathbf{c}_{254}\}$ called *Viridis12* was created to test the effect of reducing the number of colours (k). All colours were converted into CIELAB colour space using the Colors.jl software library (https://github.com/JuliaGraphics/Colors.jl, version v0.9.5).

The colour maps from Rogowitz and Kalvin (2001) were recreated and included in our analyses (the colour maps used in The Which Blair Project are no longer available and were reconstructed following advice from the original author). For *LAB Greyscale*, *Heated Body*, *Rainbow*, *HSV Greyscale*, *HSV Saturation* (*increasing*), and *HSV Saturation* (*decreasing*), we recreated the colour maps programmatically in accordance with their descriptions in the paper. For *Isoluminant Rainbow* and *LAB Isoluminant Saturation*, we scanned the colour maps from the paper, adjusted L^* to ensure isoluminance, and interpolated to find 100 colours for each map.

One hundred journal papers matching the search term "fisheries echogram", published after 2009 in the *ICES Journal of Marine Science*, were examined (retrieved November 2019, list available at https://github.com/RobBlackwell/hundred-fisheries-acoustic-papers). Echogram colour maps were identified by visual inspection. A paper was attributed to a colour map if that colour map occurred at least once in the paper. If a paper contained more than one colour map, it was attributed to all colour maps present.

Colourfulness is the subjective human perception of the variety and intensity of colours in an image, with greyscale images being not colourful and rainbow images being highly colourful. We determined the colourfulness of each colour map by using it to plot a sample echogram (Figure 2) and measuring the colourfulness of the resulting image according to Hasler and Süsstrunk (2003). They used non-expert viewers to rate the colourfulness of a set of natural images and fitted a statistical model yielding a metric $\hat{M}^{(3)}$, where $\hat{M}^{(3)} = 0$ means not colourful, $\hat{M}^{(3)} = 15$ slightly colourful, $\hat{M}^{(3)} = 33$ moderately colourful, $\hat{M}^{(3)} = 45$ averagely colourful, $\hat{M}^{(3)} = 59$ quite colourful, $\hat{M}^{(3)} = 82$ highly colourful, and $\hat{M}^{(3)} = 109$ extremely colourful.

A colour map is sequential if it is monotonically increasing in luminance (Rogowitz and Kalvin, 2001; Brewer, 2015). The Spearman rank correlation coefficient can be used to measure the monotonicity of an ordered set of numbers. We used the Spearman rank correlation coefficient of lightness, $(r_s(\{\mathbf{c}_{L^*}|\mathbf{c} \in C\}, \{1\ldots k\})$ if $\mu_{\Delta L^*} > 0)$ to measure monotonicity and thus determine whether a colour map is sequential. A colour map is sequential and monotonically increasing in lightness if $r_s = 1$ and sequential and monotonically decreasing in lightness if $r_s = -1$.

The CIEDE2000 colour distance metric (ΔE^*_{00}) is a refinement to the CIELAB Euclidean distance metric (Witt, 2007). We defined a colour map as perceptually uniform if CIEDE2000 colour distances were uniform across the colour map range. The Pearson's correlation coefficient of CIEDE2000 colour distances, from the first colour to each of the other colours in turn $\rho(\{\Delta E^*_{00}(\mathbf{c}_1, \mathbf{c})|\mathbf{c} \in \{\mathbf{c}_2, \ldots, \mathbf{c}_k\}\}, \{1\ldots k-1\}))$, was used to determine linearity of colour distance. A colour map was defined as perceptually uniform if $\rho = 1$.

Results

Of the 100 journal papers analysed, 78 contained data from a Simrad instrument. Echoview was used for analysis in 48 papers,

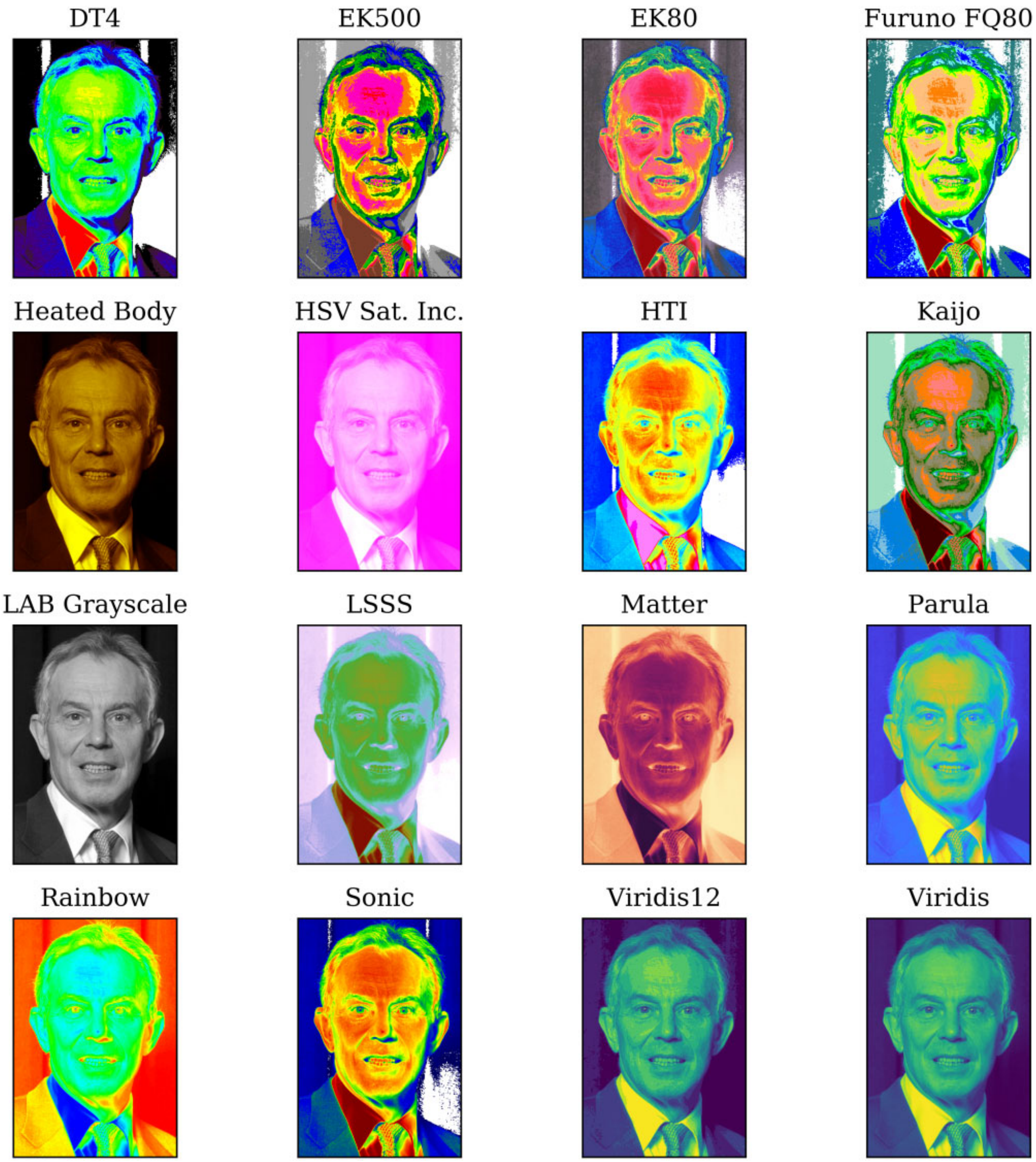

Figure 3. A human face rendered using a selection of colour maps. According to Rogowitz and Kalvin (2001), those images that appear most natural use colour maps better suited to visualizing continuous scalar data.

LSSS in 11, and MOVIES in 4. The *EK500* (34%) and "Rainbow" (16%) colour maps were the most frequently used for echograms, followed by *LSSS* (8%), "Greyscale" (7%), and "Other" (14%).

Each colour map under test was used to render a photograph of a human face as in the Which Blair Project (Rogowitz and Kalvin, 2001) (Figure 3). There is a large variation in the naturalness of the images and the results appear to be consistent with Rogowitz and Kalvins' observation that *LAB Greyscale* and *Heated Body* produce more natural images than either *HSV Saturation Increasing* or *Rainbow*.

All of the fisheries acoustics colour maps bar *LSSS* are extremely colourful ($\hat{M}^{(3)} > 109$). LSSS is quite colourful ($\hat{M}^{(3)} = 79$). *Parula* is the most colourful of the modern colour maps, being extremely colourful ($\hat{M}^{(3)} = 158$), but most are quite colourful

Table 1. Colour maps ordered by lightness monotonicity (r_s) and perceptual uniformity (ρ).

Name	k	$\hat{M}^{(3)}$	r_s	ρ
LAB Iso. Sat.[1]	100	35		0.96
Iso. Rainbow[1]	100	62		0.67
EK80[2]	64	151	0.02	0.28
Furuno FQ80[2]	11	186	0.03	0.78
EK500[2]	12	186	0.06	0.26
HTI[2]	31	235	0.06	0.24
Rainbow[1]	100	236	−0.21	0.46
Sonic[2]	96	193	0.25	0.34
Kaijo[2]	15	165	−0.53	0.83
DT4[2]	16	198	0.65	0.70
LSSS[2]	52	79	−0.94	0.95
HSV Sat. Dec.[1]	100	93	−1.00	0.94
Heated Body[1]	100	82	1.00	0.97
HSV Sat. Inc.[1]	100	125	1.00	0.98
Parula[3]	64	158	1.00	0.98
LAB Greyscale[1]	100	0	1.00	0.99
Viridis[3]	256	95	1.00	0.99
Viridis12[3]	12	91	1.00	0.99
HSV Greyscale[1]	100	0	1.00	0.99
Matter[3]	256	83	−1.00	1.00

The first column is the colour map name with a superscript indicating its origin [(1) from Rogowitz and Kalvin (2001), (2) a fisheries acoustic colour map, or (3) a modern colour map designed for colour contrast consistency]. k is the number of colours; $\hat{M}^{(3)}$ is colourfulness; r_s is the Spearman rank correlation coefficient of lightness (L^*; −1.0 or 1.0 indicates a sequential colour map) and ρ is the Pearson's correlation coefficient of CIEDE2000 colour distance (1.0 indicates perfect perceptual uniformity).

($\hat{M}^{(3)} > 59$) or highly colourful ($\hat{M}^{(3)} > 82$). The *Rainbow* colour map is the most colourful ($\hat{M}^{(3)} = 236$) and the isoluminant colour maps the least colourful (*LAB Isoluminant Saturation*, $\hat{M}^{(3)} = 35$ and *Isoluminant Rainbow*, $\hat{M}^{(3)} = 62$) not including the grey scales. In general, fisheries acoustic colour maps are more colourful than modern colour maps.

Using r_s, we determine those colour maps, which are sequential (Table 1 and Figure 4). None of the fisheries acoustic colour maps is sequential, but *LSSS* comes closest ($r_s = -0.94$). Of the sequential colour maps, *Heated Body*, *HSV Saturation* (*Increasing*), *Parula*, *LAB Greyscale*, *Viridis*, *Viridis12*, and *HSV Greyscale* are monotonically increasing ($r_s = 1.00$). Whereas *Matter* and *HSV Saturation* (*Decreasing*) are monotonically decreasing ($r_s = -1.00$).

None of the fisheries acoustic colour maps is perceptually uniform ($\rho = 1$), but *LSSS* comes closest ($\rho = 0.95$). *Matter* is perfectly perceptually uniform ($\rho = 1.00$), but *LAB Greyscale*, *Viridis*, *Viridis12*, and *HSV Greyscale* are approximately perceptually uniform ($\rho \approx 1.00$).

The colour maps contain between 11 and 256 individual colours (k), with *Furuno FQ80* having 11 colours and *Viridis* having 256 colours. Notably, reducing the number of colours in the *Viridis* colour map to 12 (*Viridis12*), did not change whether it was sequential, did not reduce its perceptual uniformity, and had only a small effect on its colourfulness. The colourfulness ($\hat{M}^{(3)}$) of a colour map is not proportional to its length (k).

Discussion

The purpose of an echogram image is to effectively convey acoustic information to a human viewer. Echosounder receivers are sensitive and have a very high dynamic range. It is typical to use a logarithmic scale (decibels) to make power measurements easier to work with, and to allow sufficient colour contrast between values in an echogram display. The logarithmic scale is monotonically increasing and it is reasonable to require equal perceptual contrast increments per decibel across the colour map range.

The choice of colour map has a significant effect on the appearance of an image and the detail revealed (Campbell and Robson, 1968). The Which Blair Project used a subjective test (image naturalness) to assess colour maps (Rogowitz and Kalvin, 2001); in this article, colour maps are ordered by objective measures of lightness monotonicity (r_s) and uniformity of colour distance (ρ) with consistent results. We use these measurements to compare colour maps from fisheries acoustics with modern colour maps designed for colour contrast consistency.

Although sequential colour maps are widely recommended for visualizing continuous scalar data such as S_v and *TS* (Rogowitz and Kalvin, 2001), none of the fisheries acoustic colour maps tested is sequential. When a colour map is not sequential, greater-than and less-than relationships are not immediately evident (Borland and Ii, 2007). Non-sequential colour maps can introduce false gradients that can covertly exaggerate features in some regions, whilst minimizing features elsewhere (Thyng *et al.*, 2016).

Rainbow echogram colour maps are still used in the fisheries acoustic literature (16%), despite being widely criticized for their lack of perceptual uniformity (Borland and Ii, 2007). In our tests, some fisheries acoustic colour maps (*Simrad EK80*, *Simrad EK500*, *HTI*, and *Sonic*) were shown to have even lower perceptual uniformity than the *Rainbow* colour map used by Rogowitz and Kalvin (2001). Like *Rainbow*, these fisheries acoustics colour maps lack perceptual ordering, have uncontrolled luminance variation and non-data dependent gradients. Non-perceptually uniform colour maps can hinder the effective visualization and interpretation of data by confusing, obscuring, and misleading (Borland and Ii, 2007).

The Simrad EK500 scientific echosounder was introduced in 1989 and is now obsolete, but the *EK500* colour map is still widely used (34%), and was even applied to Simrad EK80 data in one of our examined papers. The *EK500* colour map appears to be closely related to *Rainbow* and may have been intended to make colour bars easy to read. Despite its popularity and familiarity, we have shown that the *EK500* colour map is not sequential ($r_s = 0.06$) and has highly uneven perceptual contrast over its range ($\rho = 0.26$). Echoview was used in 48% of the papers, but *EK500* is not the Echoview default, suggesting that users are making a conscious choice of colour map. Simrad instruments were used in 78% of the papers examined, and this may help to explain the continued popularity of *EK500*.

Of the fisheries acoustics colour maps tested, *LSSS* is closest to being sequential ($r_s = -0.94$) and perceptually uniform ($\rho = 0.95$). *LSSS* originates from the combined greyscale and red–blue colour map designed by Foote *et al.* (1991). Like *LSSS*, modern colour maps such as *Parula* and *Viridis* are designed to combine monotonic luminance with a range of hues (Ware, 1988), but are more colourful, truly sequential, and have better perceptual uniformity.

Sequential colour maps with high perceptual uniformity tend to have lower colourfulness than perceptually uneven colour maps, e.g. *Viridis* ($\hat{M}^{(3)} = 95$) vs. *Rainbow* ($\hat{M}^{(3)} = 236$). It is

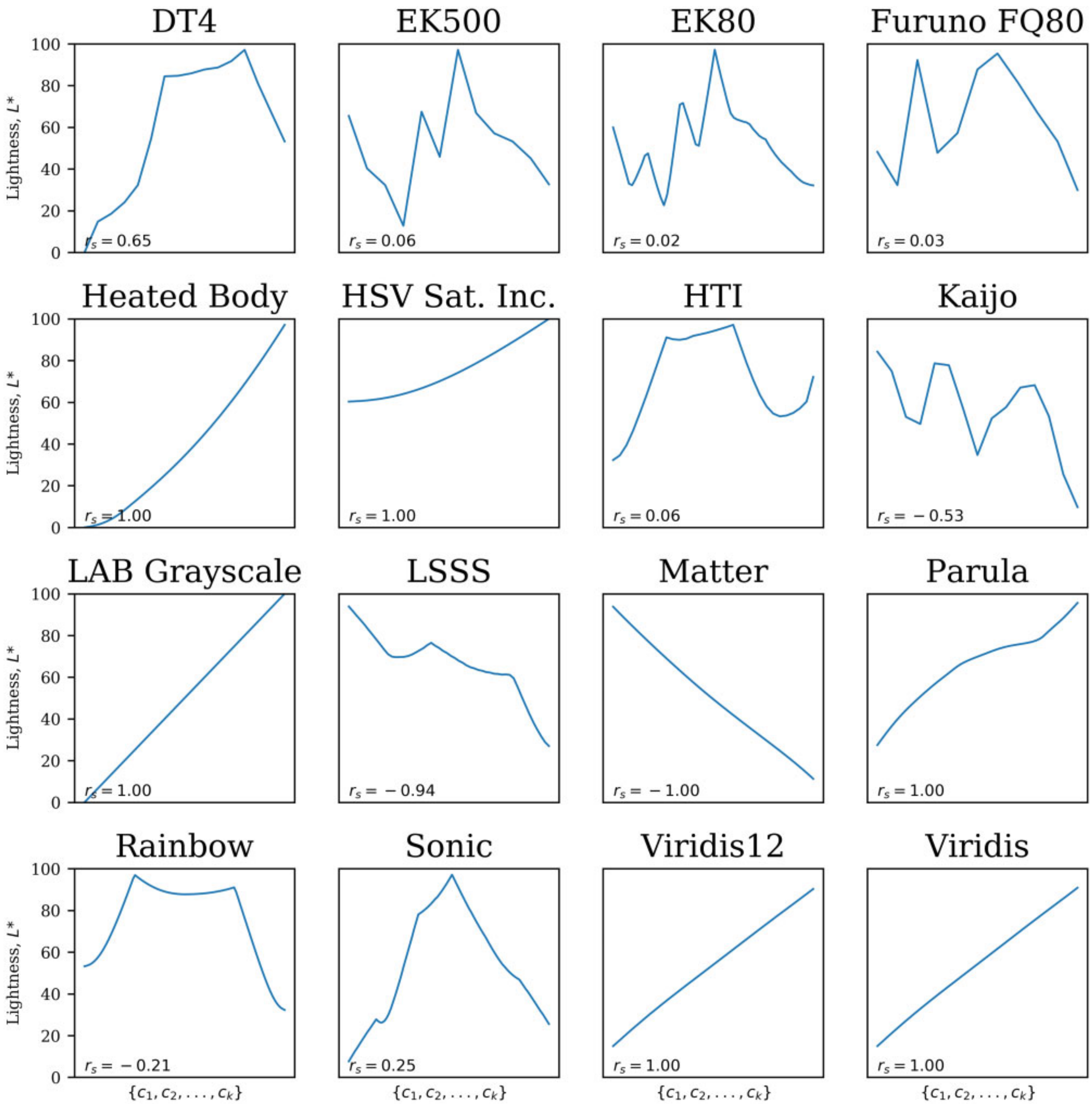

Figure 4. Lightness by colour sequence for each colour map. r_s is the Spearman rank correlation coefficient (1.0 or -1.0 for a sequential colour map).

natural to want colourful echograms, but the lack of perceptual ordering of the rainbow colours red, orange, yellow, green, blue, indigo, and violet, gives rise to a trade-off between colourfulness and perceptual uniformity. It would be difficult or impossible to simply adjust existing echogram colour schemes to improve their perceptual uniformity. All of the fisheries acoustics colour maps, except *LSSS*, are highly colourful and this may help to explain their continued popularity.

The number of colours (k) in the colour maps tested did not influence whether colour maps were sequential, their degree of perceptual uniformity nor the colourfulness of resulting echograms. Our methods work irrespective of k. As k decreases so does the radiometric resolution of resulting images (compare *Viridis12* to *Viridis* in Figure 3). As k decreases so does the number of colours on the scale bar, which may make it easier to read (compare *Viridis12* to *Viridis* in Figure 2). However, care must be taken when using colour maps with reduced k that reduced radiometric resolution in echograms does not hide important detail.

More than half of the colour maps tested have increasing lightness ($r_s > 0$) but *Kaijo*, *LSSS* and *Matter* have strongly decreasing lightness ($r_s < -0.5$). This causes them to look much more like colour negative film images in Figure 3. Whilst both monotonically increasing and monotonically decreasing colour maps are considered sequential, it is interesting to compare *Viridis* and

Matter in Figure 2. The former uses lightness to indicate more intense volume backscatter at the bottom of the krill swarm, whilst the latter uses darkness to imply density. For echograms that have been processed for noise removal, monotonically increasing colour maps may be more suited to computer screens (less bright light), and monotonically decreasing colour maps more suited to print media (less ink).

Greyscale colour maps are used in the literature that we analysed (7%), but it is unclear whether the objective was to portray morphological aspects of the data (Ware, 1988) or simply to reduce printing costs. Unlike greyscale, *Viridis* and *Parula*, some fisheries acoustics colour maps are highly non-sequential ($r_s \rightarrow 0$) and do not maintain legibility when reproduced in monochrome.

About 8% of men and 0.4% of women have colour vision deficiency (CVD; Spalding, 1999). When we presented our preliminary results at the Working Group for Fisheries Acoustic Science and Technology (WGFAST) in 2019, a number of fisheries acousticians told us that they had CVD and preferred greyscale colour maps for accessibility. The greyscale colour maps tested here are sequential ($r_s = 1.00$) and approximately perceptually uniform ($\rho \approx 1.00$). Tufte (1983) suggests that colour often generates graphical puzzles and that grey shades may be superior for the presentation of quantitative data; however, there is evidence that we can only distinguish limited shades of grey and potentially millions of colours (Poynton, 1996). Greyscale echograms may be a good choice for accessibility, but *Viridis* and *Parula* have been designed with CVD in mind, and users without CVD may benefit from a wider colour palette. Colour maps can be adjusted for observers with particular CVD variants (Jefferson and Harvey, 2006).

Echograms are sometimes used to show regions segmented according to categories (e.g. fish, zooplankton, seabed, or noise) or multi-frequency characteristics (e.g. Jech and Michaels, 2006). Such qualitative data require qualitative colour maps (Brewer, 2015). Qualitative colour maps are purposely designed to be colourful and use high perceptual contrast between colours to distinguish categories. Where categorization is based on signal intensity (e.g. target strength or acoustic backscattering strength), there is a natural desire for the colour map to be both sequential and qualitative. Our results show that perceptually uniform colour maps tend to be less colourful than non-perceptually uniform, but that colour maps such as *Parula* can provide a compromise.

Split-beam echosounders, described by Foote *et al.* (1986), also record phase angle data diverging from 0°, which can be displayed using a diverging colour map. *DT4* has a single turning point and is thus diverging, but its lightness profile is not symmetric (Figure 4). Despite having three turning points, the *Sonic* colour map has a sharp central peak in its lightness profile and could be used as a diverging colour map (Figure 4). However, *Sonic* is not perceptually uniform and better diverging colour maps are widely available. Good diverging colour maps are symmetrical, having exactly one turning point in their lightness profile, and have colourful, sequential, and perceptually uniform legs (e.g. *cmocean balance*).

As echosounder resolution and precision increases, echogram data contain ever more detail [e.g. the Simrad EK80 has a range resolution of centimetres (Lavery *et al.*, 2017)]. The echogram shown in Figure 1 has low spatial resolution and low radiometric resolution, but a modern computer monitor may display more than 240 dots per inch with millions of colours. Colour maps should be chosen carefully to make best use of the available display capability; however, we have reached a point where the human vision system may not be able to discriminate all the features present in an echogram image. As range and power resolution increases, the use of computational methods for echogram segmentation, classification, and interpretation (Korneliussen, 2018) will likely become more effective than manual methods.

The CIELAB colour space and CIEDE2000 colour distance measurements are approximations of human visual perception. The effectiveness of a colour map is also influenced by factors including simultaneous contrast (Ware, 1988), lighting environment (Baylor, 1995), and the eye's dark adaptation. Still, the methods presented here offer simple, reliable, and objective measures for assessing and comparing colour maps.

None of the colour maps tested is extremely colourful, sequential, and perceptually uniform, so there is no single colour map that meets every requirement. Modern colour maps are available from other scientific disciplines (e.g. Hunter, 2007; Brewer, 2015; Thyng *et al.*, 2016) that are not yet widely implemented in fisheries acoustic software, but may offer additional choice and advantages over traditional fisheries acoustic colour maps. We hope that Table 1 and the methods herein will allow fisheries acousticians to make more informed decisions when selecting echogram colour maps.

Recommendations

When using echograms to detect morphological structure in acoustic data, sequential, perceptually uniform greyscale colour maps are recommended.

When using echograms to present quantitative data (e.g. S_v or *TS*) colour maps should be colourful, sequential, and perceptually uniform. Of the fisheries acoustic colour maps tested, *LSSS* comes closest to being sequential and perceptually uniform. However, modern colour maps have been specifically designed for colour contrast consistency, accessibility for viewers with red–green colour-blindness, and legibility when printed in monochrome (e.g. *Viridis*, *Parula*).

When using echograms to present diverging data (e.g. split-beam angle), diverging colour maps should be used, with symmetrical legs, each being colourful, sequential and perceptually uniform.

When using echograms to present categorical data (e.g. fish schools, seabed), qualitative colour maps should be used.

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Data sharing statement

An open source software implementation of the methods described in this paper, together with colour map data, is available at https://github.com/bas-acoustics/fsz242 (last accessed December 2019). The example echosounder data are published under a Creative Commons license at https://github.com/bas-acoustics/krill-ball (last accessed December 2019).

References

Baylor, D. 1995. Colour mechanisms of the eye. Colour: Art and Science, 7: 103. Cambridge University Press, Cambridge, UK.

Blackwell, R., Harvey, R., Queste, B., and Fielding, S. 2019. Aliased seabed detection in fisheries acoustic data. arXiv preprint arXiv: 1904.10736.

Borkin, M., Gajos, K., Peters, A., Mitsouras, D., Melchionna, S., Rybicki, F., Feldman, C., *et al.* 2011. Evaluation of artery visualizations for heart disease diagnosis. IEEE Transactions on Visualization and Computer Graphics, 17: 2479–2488.

Borland, D., and Ii, R. M. T. 2007. Rainbow color map (still) considered harmful. IEEE Computer Graphics and Applications, 27: 14–17.

Brainard, D. H. 2003. Color appearance and color difference specification. *In* The Science of Color. Ed. by S. K. Shevell. 2: 5. Elsevier, Oxford, UK.

Brewer, C. 2015. Designing Better Maps: A Guide for GIS Users. ESRI Press, Redlands, California, USA.

Campbell, F. W., and Robson, J. 1968. Application of Fourier analysis to the visibility of gratings. The Journal of Physiology, 197: 551–566.

Foote, K. G., Aglen, A., and Nakken, O. 1986. Measurement of fish target strength with a split-beam echo sounder. The Journal of the Acoustical Society of America, 80: 612–621.

Foote, K. G., Knudsen, H. P., Korneliussen, R. J., Nordbø, P. E., and Røang, K. 1991. Postprocessing system for echo sounder data. The Journal of the Acoustical Society of America, 90: 37–47.

Gegenfurtner, K. R., Bloj, M., and Toscani, M. 2015. The many colours of "the dress". Current Biology, 25: R543–R544.

Hasler, D., and Süsstrunk, S. E. 2003. Measuring colorfulness in natural images. *In* Human Vision and Electronic Imaging VIII, pp. 87–96. Ed. by B. E. Rogowitz, and T. N. Pappas. SPIE, Bellingham, WA, USA.

Hunter, J. D. 2007. Matplotlib: a 2D graphics environment. Computing in Science & Engineering, 9: 90–95.

Jech, J. M., and Michaels, W. L. 2006. A multifrequency method to classify and evaluate fisheries acoustics data. Canadian Journal of Fisheries and Aquatic Sciences, 63: 2225–2235.

Jefferson, L., and Harvey, R., 2006. Accommodating color blind computer users. *In* Proceedings of ASSETS'06, pp. 40–47. Portland, Oregon, USA.

Judd, D. B., and Wyszecki, G. 1975. Color in Business, Science, and Industry. Wiley, New York, USA.

Korneliussen, R.J. (Ed.) 2018. Acoustic Target Classification. ICES Cooperative Research Report No. 344. International Council for the Exploration of the Sea, Copenhagen, Denmark.

Korneliussen, R. J., Heggelund, Y., Macaulay, G. J., Patel, D., Johnsen, E., and Eliassen, I. K. 2016. Acoustic identification of marine species using a feature library. Methods in Oceanography, 17: 187–205.

Lavery, A. C., Bassett, C., Lawson, G. L., and Jech, J. M. 2017. Exploiting signal processing approaches for broadband echosounders. ICES Journal of Marine Science, 74: 2262–2275.

Mitson, R. 1983. Fisheries Sonar (Incorporating Underwater Observation Using Sonar by DG Tucker). Fishing News Books Farnham, Surrey, UK.

Poynton, C. A. 1996. A Technical Introduction to Digital Video. Wiley, New York.

Robertson, A. R. 1977. The CIE 1976 color-difference formulae. Color Research & Application, 2: 7–11.

Robertson, A. R. 1990. Historical development of CIE recommended color difference equations. Color Research & Application, 15: 167–170.

Rogowitz, B. E., and Kalvin, A. D. 2001. The Which Blair project: a quick visual method for evaluating perceptual color maps. *In* Proceedings of the conference on visualization'01, pp. 183–190. IEEE Computer Society, Washington DC, USA.

Rogowitz, B. E., Treinish, L. A., and Bryson, S. 1996. How not to lie with visualization. Computers in Physics, 10: 268–273.

Ryan, T. E., Downie, R. A., Kloser, R. J., and Keith, G. 2015. Reducing bias due to noise and attenuation in open-ocean echo integration data. ICES Journal of Marine Science, 72: 2482–2493.

Simmonds, J., and MacLennan, D. N. 2005. Fisheries Acoustics: Theory and Practice, 2nd edn. Wiley-Blackwell, Oxford, UK.

Spalding, J. 1999. Colour vision deficiency in the medical profession. British Journal of General Practice, 49: 469–475.

Sund, O. 1935. Echo sounding in fishery research. Nature, 135: 953.

Thyng, K., Greene, C., Hetland, R., Zimmerle, H., and DiMarco, S. 2016. True colors of oceanography. Oceanography, 29: 9.

Trenkel, V. M., Berger, L., Bourguignon, S., Doray, M., Fablet, R., Massé, J., Mazauric, V., *et al.* 2009. Overview of recent progress in fisheries acoustics made by Ifremer with examples from the Bay of Biscay. Aquatic Living Resources, 22: 433–445.

Tufte, E. R. 1983. The Visual Display of Quantitative Information. Graphics Press, Cheshire, CT.

Ware, C. 1988. Color sequences for univariate maps: theory, experiments and principles. IEEE Computer Graphics and Applications, 8: 41–49.

Witt, K. 2007. CIE color difference metrics. *In* Colorimetry: Understanding the CIE System, pp. 79–100. Ed. by J. Schanda. Wiley-Blackwell, Oxford, UK.

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