True colours or red herrings?: colour maps for finite-element analysis in palaeontological studies to enhance interpretation and accessibility

Stephan Lautenschlager

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Review History

RSOS-211357.R0 (Original submission)

Review form: Reviewer 1

Is the manuscript scientifically sound in its present form?
Yes

Are the interpretations and conclusions justified by the results?
Yes

Is the language acceptable?
Yes

Do you have any ethical concerns with this paper?
No

Have you any concerns about statistical analyses in this paper?
No
Recommendation?
Accept with minor revision (please list in comments)

Comments to the Author(s)
This is an excellent study and very relevant now. The range of example models and colours is
great to give an idea of what can work for future publications. The quantitative results are
particularly helpful, because it gives some guidance on the best colour plot for the type of data,
rather than a subjective preference based on appearance.
At the start, I expected to change my mind about the rainbow colour plot and want to use
something different, but since you conclude that there is no single colour plot that solves “all”
issues, I feel like the rainbow plot is still the one that will be chosen in future. Especially because
it’s also the default plot from software and is easy to produce.
I particularly like the recommendation though to add a second set of contour plots (or more) with
a different colour map in the supplementary material. This could really help those with CVD. I
think adding multiple colour plots in the main article may be confusing, and most people are
used to the rainbow colour plot.
One thing I’d like clearer is how to apply the colour plots; I found this confusing or unclear and if
I was to do this myself, I wouldn’t know how. So, if this can be made clearer in the Methods or
supplemental material, that would be great. I found the supplementary figures in the included
files, but I could not find the supplementary material that was referred to on pages 4 and 6 in the
Methods. If a step-by-step guide is included in the supplementary information, that would be
good. The thing I found most confusing is you say the outputs were generated in ABAQUS and
then converted using convertColor function in R? Were the outputs saved as images and
converted from the default rainbow, or were the models exported and the colour was resampled
in R? I would love to know how to do it.
Otherwise, very happy to recommend this for publication.

Review form: Reviewer 2

Is the manuscript scientifically sound in its present form?
Yes

Are the interpretations and conclusions justified by the results?
Yes

Is the language acceptable?
Yes

Do you have any ethical concerns with this paper?
No

Have you any concerns about statistical analyses in this paper?
No

Recommendation?
Accept with minor revision (please list in comments)

Comments to the Author(s)
The manuscript has intriguing results for legible visualization that I hope to put into practice
soon (see Appendix A). Among minor improvements to the language, I suggest that the authors
spell out acronyms more often, and be more specific for lines 217-218.
More substantive but still minor improvements will be:
1. To explain more clearly the commercial propriety or openness of various color schemes, and how generally they’re available amongst relevant simulation and visualization programs.
2. To explain how well the mathematical discrimination between colors matches perceptual discrimination.

Decision letter (RSOS-211357.R0)

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on behalf of Dr Jennifer Botha (Associate Editor) and Peter Haynes (Subject Editor)
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Associate Editor Comments to Author (Dr Jennifer Botha):
Comments to the Author:
This paper has been reviewed by two researchers who are both enthusiastic about the results of the study. They both suggest only minor revision. I do not think it will take much time to incorporate the extra explanations that have been asked for, thus I recommend accept with minor revision.

Reviewer comments to Author:
Reviewer: 1
Comments to the Author(s)
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**Author's Response to Decision Letter for (RSOS-211357.R0)**

See Appendix B.

**Decision letter (RSOS-211357.R1)**

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on behalf of Dr Jennifer Botha (Associate Editor) and Peter Haynes (Subject Editor)
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### True colours or red herrings? - colour maps for finite element analysis in palaeontological studies to enhance interpretation and accessibility

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| Subject Category                     | Earth and Environmental Science |
**Author-supplied statements**

Relevant information will appear here if provided.

**Ethics**

*Does your article include research that required ethical approval or permits?:*
This article does not present research with ethical considerations

*Statement (if applicable):*
CUSI_IF_YES_ETHICS :No data available.

**Data**

*It is a condition of publication that data, code and materials supporting your paper are made publicly available. Does your paper present new data?:*
Yes

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Raw measurements and code are included in the supplementary information. FEA results files are available here (and may be transferred to a Dryad repository upon acceptance if necessary):
https://figshare.com/articles/dataset/FEA_models_from_True_colours_or_red_herrings_-_Colour_maps_for_finite_element_analysis_in_palaeontological_studies_and_how_they_can_enhance_interpretation_and_accessibility_/14905104

**Conflict of interest**

I/We declare we have no competing interests

*Statement (if applicable):*
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**Authors’ contributions**

I am the only author on this paper

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True colours or red herrings? - colour maps for finite element analysis in palaeontological studies to enhance interpretation and accessibility

Stephan Lautenschlager
School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK

Keywords: biomechanical analysis, digital visualisation, fossils, 3D models

1. Summary

Accessibility is a key aspect for the presentation of research data. In palaeontological sciences, new data on the palaeobiology of extinct organisms is routinely obtained with computational techniques, such as finite element analysis (FEA). FEA is used to calculate stress and deformation in objects such as the skulls or limb bones when subjected to external load forces. Results are displayed using false-colour contour plots in which colour information is used to convey the underlying biomechanical data. The Rainbow colour map is nearly exclusively used to present these contour plots in palaeontological studies using FEA. However, numerous studies in other disciplines have shown the Rainbow colour map to be problematic due to uneven colour representation and its inaccessibility for those with colour-vision deficiencies.

Here, ten different colour maps were tested for their accuracy in representing the underlying stress values of FEA models. Differences in stress magnitudes (ΔS) and colour values (ΔE) of subsequent points taken from the FEA models were compared and their correlation was used as a measure of the accuracy. The results demonstrate that the Rainbow colour map is not well suited to represent the underlying stress distribution of FEA models. Most of the other colour maps tested here showed a higher discriminative power. However, the performance of the different colour maps varied with the different tested scenarios and stress types. It is therefore recommended to use different colour maps for specific stress types.

2. Introduction

The last two decades have witnessed a surge in the use of computational techniques to study the anatomy and functional morphology of fossil organisms with the aim to reconstruct their palaeobiology [1-3]. Tools for the biomechanical analysis of fossils, such as finite element analysis (FEA) [4,5], computational fluid dynamics analysis (CFD) [6,7], and multibody dynamics analysis (MDA) [8], are now routinely applied to investigate the form-function relationships of fossils. Of these, FEA has become a powerful and seemingly ubiquitous method to test hypotheses about the functional capabilities of extinct organisms, in particular for species for which no living analogues may exist.
Originally developed as an engineering technique, FEA predicts the deformation in objects with complex geometries and different materials subject to external load forces. Key to the technique is the subdivision (discretisation) of the analysed object into numerous, small, and geometrically simple elements connected by shared nodes, for which the deformation calculations are subsequently performed. This simplification allows a quick but generally accurate approximation to solve the problem for any given object and the calculation of biologically relevant performance measures, such as stress and strain [5]. Based on the discretisation, discrete stress or strain values can be associated with each element and node in an FEA model. For the presentation of the results, these values can be reported quantitatively, for example as model averages or mean values [9,10], values of individually selected elements or sections [11,12], as stress intervals [13], or using a landmark-based approach on the deformed models [14]. However, reporting a large amount of numerical values may not intuitively convey the observed results to the reader. Therefore, it is common practice to present FEA results more qualitatively in the form of contour plots. For these pseudo-colour (or false-colour) plots, the numerical value of each element in an FEA model is represented by different colours. Such colour coding can be a powerful tool to differentiate and convey information provided a suitable colour scheme is used. Although the use of different colour maps does not change the underlying results (e.g. stress and strain magnitudes), they have a substantial impact on the accessibility of the same. Consequently, the choice of a colour scheme can substantially impact the readability, interpretation, and also accessibility of the data. This is particularly true for the use of FEA in a comparative context, which aims to identify (subtle) differences between models (e.g. species) [5].

Traditionally, and with very few exceptions [15-17], the colour scheme of choice for FEAs of palaeontological and biological specimens has been (and still is) the classic Rainbow colour map. It is based on the colours in the visible light spectrum from blue (usually lower values) via green, yellow, and orange to red (usually higher values). It is one of the most common colour schemes for data visualisation and the default option in many software toolkits. Despite its ubiquitous use and popularity, a number of studies in the last two decades have identified considerable problems with the Rainbow colour map [18-25]: (i) The perceived transitions between the individual colours of the Rainbow map are not uniform [25,26], with some colours (i.e. red, green) seemingly taking up a larger part of the colour map (Fig. 1a). This effect can simulate sharp transitions in sequential data, making small variations in the underlying data appear more important [27,28]. Similarly, yellow is the brightest colour in the Rainbow colour map. Although it is not at the extreme end of the colour map it tends to attract the eye more than other colours in the spectrum [25,29,30]. (ii) While ordered from shorter (blue) to longer (red) wavelengths, the Rainbow map does not follow any naturally perceived order. This means, that in contrast to greyscale or gradient colour maps (which can be arranged from dark to light or vice versa), there is no implicit order to the Rainbow colour map [23,26,31], making the comparison between two relative values difficult (Fig. 1b). (iii) Lastly, but importantly, the Rainbow colour map creates considerable accessibility problems for those with
colour vision deficiencies (CVD). Approximately 5-10% of the population may suffer from some form of CVD, such as red-green blindness (Deuteranopia), which renders data represented by the Rainbow colour map largely unreadable [32-34]. Furthermore, similar issues arise when results using the Rainbow colour map are converted to a greyscale format, such as for example for printing.

Given these inherent problems with the Rainbow colour scheme, several disciplines, including oceanography [35], meteorology [36,37], and geosciences [25,38], have started to address this issue and proposed the use of alternative colour schemes. Here, different colour maps are tested and their effectiveness for the visualisation of FEA results of palaeontological models is evaluated.

3. Materials and Methods

In order to evaluate their visual effect and accessibility, different colour maps were tested for a variety of FEA models of fossil specimens and different FEA stress measures. In addition to the traditional Rainbow map (see also [39]), nine further colour maps were selected (versions numbers are provided where present): (a) The five sequential colour maps Batlow (7.0), Inferno, Parula, Viridis, and YlGnBu [25,40-43]. Sequential colour maps vary between two colours ranging from dark to light (or vice versa) and are suitable for ordered data ranging gradually from low to high values (i.e. ratio data with an absolute zero value) [27]. (b) The three diverging colour maps Cork (7.0), Polar, and Roma (7.0) [25,43]. Diverging colour maps range between two contrasting colours at either end separated by a neutral colour in the middle and are suitable for interval data that can have positive and negative values [27]. (c) As a further option, a variant of the classic Rainbow colour map known as Turbo was included in the analysis. Although Turbo similarly consists of a sequence of colours in the visible light spectrum, it has been suggested to represent a perceptually improved rainbow map with a uniform luminance [44,45].

Other colour maps, such as qualitative, categorical or cyclic colour maps were not tested as these are not appropriate for FEA data. The colour maps tested here were selected following their use and popularity in different applications. However, not all of the colour maps are perceptually uniform (e.g. the difference between two colours as perceived by the human eye is proportional to the numerical distance within the given colour space). Batlow, Cork, Inferno, Roma, Viridis, and YlGnBu are all perceptually uniform, whereas Parula, Polar, Rainbow, and Turbo are not (see also [43]).

All colour maps used for this study consist of 24 individual colour values (definitions (order and HEX colour codes) are available in the supplementary information) and all outputs presented here were generated in Abaqus. Several FEA models of fossil specimens and different skeletal elements were used here to evaluate the perceptual effects of the tested colour maps with different three-dimensional morphologies: (a) A simplified, planar model of the mandible of the sabre-toothed cat Dinofelis cristata as used in [46] (fig. 2). This model was chosen to represent a geometrically simple
morbidity as used for FEA models not derived from computed tomography (CT) or surface-based
digitisation methods [47,48]. For this model, contour plots displaying the distribution of von Mises
stress were chosen as an example for ratio data. (b) A three-dimensional model of the mandible of
Thrpanodon liorhunus representing a geometrically more complex morphology compared to the
model of Dinofelis and derived from CT scanning [49]. For the contour plots, tensile (positive) and
compressive (negative) absolute stresses were displayed as an example for interval data. (c) A model
of the skull of the therizinosaurian dinosaur Erlikosaurus andrewsi as used in [50]. In addition to the
different contour plots displaying von Mises stress, the models were also displayed as perceived with
a deuteranopia-type CVD. For this purpose, the images were converted accordingly using Adobe
Photoshop CC 2020. (d) A model of the skull of the capitosaurian temnospondyl Parotosuchus
helgolandicus [51] representing a dorsoventrally flattened skull morphology. In addition to the
different contour plots displaying von Mises stress, the models were also displayed as perceived with
a protanopia-type CVD. For this purpose, the images were converted accordingly using Adobe
Photoshop CC 2020. (e) A model of a dorsal vertebra of the ornithischian dinosaur Stegosaurus
stenops [47] representing a post-cranial skeletal element. In addition to the different contour plots
displaying von Mises stress, the images of the contour plot models were also converted into greyscale
using Adobe Photoshop CC 2020 (Image -> Adjustments -> Black & White and using the default
setting for greyscale mode). (f) A model of the manual claw of the therizinosaurian dinosaur
Nothronychus graffami [52] to illustrate the effect of colour maps against a different background
colour. The boundary conditions for these models have no direct effect on the colour map
interpretation. Therefore, please refer to the original publications for further details on the boundary
conditions of the respective models.

To quantify the discriminative power of the individual colour maps (i.e. relating individual
colour values to their respective FEA stress magnitudes) the correlation between the colour maps and
stress results of the FEA models was calculated. For consistency across the models, twenty points
(i.e. elements) along a line across the FEA model were selected that covered the morphology evenly.
Stress magnitudes (von Mises and compressive/tensile stresses) were recorded for all sampled points.
This approach follows the practice to sample a subset of elements of an FEA model [11,12,50] to
quantify its biomechanical properties.

In the next step, the colour values for the sampled points for each tested colour map were
recorded as RGB values. Although defining colour as RGB values is a common practice for many
(web-based and digital) applications, they were specifically designed for the use on monitors and
does not reflect human colour perception as the RGB colour space is not uniform [53]. A solution to
this problem is using the CIELAB (also known as CIE L*a*b*) colour space [54] which has been
designed to be perceptually uniform. Here, the distance between two points defining individual
colours is proportional to the perceptual difference between them [55,56]. Therefore, the collected
RGB values were converted into CIELAB colour values. The collection of the RGB colours from
images of the FEA models and subsequent conversion to CIELAB colour space was done via the convertColor function in R [57].

For a colour map to represent the underlying data correctly it must reflect changes in magnitude between two sampled points accordingly. To test this correlation, the absolute difference $\Delta S$ in stress magnitude was calculated for subsequent points sampled for each model (eq. 1).

$$\Delta S = \text{stress magnitude of point 1} - \text{stress magnitude of point 2} \quad (1)$$

Similarly, the difference in colour value $\Delta E$ was determined for each colour map [53] by calculating the Euclidean distances between two subsequent points (eq. 2).

$$\Delta E = (\sqrt{(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2})^{0.5} \quad (2)$$

In a final step, $\Delta E$ and $\Delta S$ were subjected to an ordinary least square regression and the $R^2$ value was obtained as a measure for the discriminative power of the individual colour maps (see supplementary material).

It should be noted that Abaqus applies a shading algorithm when displaying FEA contour plots in that it simulates an artificial light source positioned to the top left of the 3D space. To avoid the effects of artificial shadows on the colour representation, all measurements were performed with the model exposed to the maximum light intensity (usually with models in left lateral or dorsal view).

### 4. Results

Overall, ten different colour maps were tested for their accuracy to represent the underlying stress magnitudes of finite element models in the form of contour plots. In addition to the default Rainbow map, nine further colour maps were tested and the $R^2$ value was used as a measure for the correlation between stress magnitudes and colour maps.

Across the different colour maps, models, stress types, and visual appearances, the $R^2$ values range from nearly no ($R^2 = 0.008$) to strong correlations ($R^2 = 0.967$) (table 1). No single colour map was found to show consistently the strongest correlation for the different test settings, with rather more nuanced variations in representative performance for the different colour maps. It is noteworthy, that the Rainbow colour map performed worse than most of the other colour maps.

For results in the form of ratio data, such as von Mises stress (Figs. 2, S1), the sequential colour map Inferno produced the highest correlation ($R^2 = 0.802$). In contrast, the commonly used Rainbow map showed only a weak correlation ($R^2 = 0.571$), and only the colour maps Roma ($R^2 =$
0.563) and YiGnBu ($R^2 = 0.547$) had a weaker performance. The rainbow variant Turbo performed only moderately better than the classic Rainbow ($R^2 = 0.664$).

For interval data, such as compressive (i.e. negative) and tensile (i.e. positive) stresses plotted together (Figs. 3, S2), the sequential colour maps YiGnBu ($R^2 = 0.967$) and Parula ($R^2 = 0.959$), as well as the diverging colour map Polar ($R^2 = 0.934$) showed the highest correlation between stress magnitudes and colour representation. The Rainbow colour map produced a strong, although not the highest, correlation ($R^2 = 0.887$), whereas Turbo performed worst in this scenario but with still a strong correlation ($R^2 = 0.852$).

To test for the discriminative performance of the different colour maps when perceived with a colour vision deficiency, contour plots were converted to deuteranopia- and protanopia-type appearances (Figs. 4, 5, S3, S4). For the deuteranopia type, the sequential colour map Batlow ($R^2 = 0.89$) and the diverging colour map Cork ($R^2 = 0.696$) were found to represent the stress data the most accurately. Again, the Rainbow colour map ($R^2 = 0.504$) was not able to represent the underlying stress results fully, while Turbo showed only a very weak correlation ($R^2 = 0.117$). For the protanopia type contour plots, Viridis ($R^2 = 0.876$) and Inferno ($R^2 = 0.738$) showed high correlation scores, whereas Polar ($R^2 = 0.458$) recorded only a weak correlation.

In a final analysis, FEA contour plots were converted to greyscale and the discriminative performance of the colour maps was tested (Figs. 6, S5). In this scenario, all colour maps produced only a moderate to no correlation ($0.578 < R^2 < 0.008$). The best performance was found for Inferno ($R^2 = 0.578$); Rainbow, Roma, and Turbo showed the least correlation ($R^2 < 0.098$).

5. Discussion

The Rainbow colour map has been a ubiquitous tool in data visualisation for decades [25,37]. Engineering techniques, such as FEA, which has increasingly been used in palaeontological studies over the last 20 years, are no exception. Results from FEAs are routinely visualised in the form of contour plots using the Rainbow colour map. Contour plots typically display von Mises stress, a common measure to evaluate the stability of a model under loading conditions. However, as shown by the results from this study, the Rainbow colour map correlates only poorly with the underlying von Mises stress data (Table 1, Fig. 2) and its discriminative power is equally poor when perceived with different types of CVD (Figs. 4, 5). This should not come as a surprise as the Rainbow colour map has been considered problematic and misleading in other disciplines [18,19,22,23-25].

Other colour maps tested here performed considerably better. However, no one colour map was found to be optimally suited for all types of stress and visual perception. For interval-type stresses, such as compressive and tensile stresses plotted on the same model, the Rainbow colour map showed a high correlation (Table 1, Fig. 3) similar or even better than the diverging colour maps in this study. Interestingly, diverging colour maps did not necessarily perform better for interval data,
whereas sequential colour maps were not always found to show the best correlation for ratio data (i.e. von Mises stress). *Inferno, Batlow,* and *Parula* generally showed the highest discriminative power, but not consistently so (Table 1). It is noteworthy, that differences in the performance were recorded when colour maps were tested in CVD settings. The same colour maps (*Inferno, Batlow,* and *Parula,* and to a lesser degree *Polar* and *Viridis*) represented the underlying stress values reasonably well despite the reduced colour information. However, this means that a single colour map cannot be used as a silver bullet to perform equally well under all conditions. Consequently, their use may have to be decided on a case to case basis using custom-made or existing colour maps (see, for example, [38] for available colour maps). For interval-type data, other considerations than the discriminative power (expressed as the $R^2$ value here) may need to be considered. For such data, the central zero value can be an important identifier of stress-free regions in the model, which can be recognised more easily when diverging colour maps are used.

In this context, it should be noted that the correlation analysis used here to discriminate stress/colour changes is not perfect. As the correlation analysis only considers absolute changes along a trajectory, the analysis may not record the exact correlation when non-monotonic changes on the stress scale are associated with changes in different directions in the CIELAB space. However, this is less likely to be a problem for the perceptually-based colour maps.

The choice of an appropriate colour map may further depend on the nature of the results of an FEA. Models spanning a wide range of stress magnitudes, but with an uneven distribution of values will be biased towards certain regions of the colour map. This situation could result in a lower resolution of stress (and thereby colour) values towards to lower end of the colour map to encompass the full range of stress magnitudes present. Sequential colour maps will be a better option in such cases as their colour gradient is expressed along the whole range of the colour map in comparison to divergent colour maps.

It is important to note that CVD is only one form of visual impairment and of course further improvements for accessibility should be aimed for when considering the presentation of results from FEA (and other analyses more broadly). Due to the nature of FEA contour plots and the respective colour maps, CVD is an obvious but not the only factor that needs to be considered. The Web Content Accessibility Guidelines (WCAG) [58] provide further recommendations to improve accessibility, including appropriate contrast ratios between colours to allow their distinction. For example, *Cork, Polar,* and *Roma* have high contrast ratios, whereas *Inferno* and *Viridis* have poorer contrast ratios. These ratios are, of course, lower if subsequent colours along the gradient were to be tested, not just extreme and mid-point values. However, this goes to show that not only the uniform sequence of colours but also the contrast between them plays a role in making contour plots accessible.
This situation is further complicated in that FEA contour plots cannot be regarded in isolation but need to be considered in the context of background and environmental settings. In the simplest of cases, this could mean that the choice of background colour can influence the readability of the contour plots [25,59,60] (Fig. 7). Especially colour maps with a large amount of dark components can become invisible against a black background. Colour maps with strong contrast and luminosity (e.g. Parula, Polar) can work well in such a case. For the presentation on a white background, colour maps with a decreasing chroma (= colour intensity), such as Batlow, Inferno and, in particular, YlGnBu are more appropriate to convey the results [25,60,61].

Within a digital, three-dimensional environment pseudo-colouring creates a further difficulty as the choice of colours interact with the shading and perception of spatial cues [24]. Properties such as the number, direction, and intensity of light sources, specularity (i.e. reflectiveness of a surface) and other settings can have an impact on the appearance of colour maps as well. Most FEA software allows turning off shading effects. However, this could possibly result in a reduced perception of the model morphology, especially for flattened surfaces with low topography (e.g. Fig. 5). Although not tested here, it should further be taken into consideration that different FEA software packages may use slightly different variations/colour definitions of the Rainbow colour map, further exacerbating comparisons between outputs from different software.

The eye-catching quality of the Rainbow colourmap with its high luminance and contrast is likely the reason for its continued prevalence despite its problems with data distortion. Different reasons have been discussed in the past [24,25] for why the Rainbow colour map is still the visualisation tool of choice for many studies and applications. For finite element models, this has likely historic reasons and it is the default colour map in most software. Furthermore, the colour distribution of the Rainbow map has a very strong signalling function and communicative power: cold colours (i.e. blue) are associated with no or low stresses, whereas warm colours (i.e. yellow, red) indicate high stress magnitudes. For von Mises stress, high magnitudes indicate possible material failure and an association with a colour such as red which is commonly used to convey danger is intuitive [62]. However, this concept can also be conveyed with other colour maps such as Inferno.

A recent study has used a variety of colour maps to display the results from FEAs [63]. Similarly, for palaeontological studies using other engineering tools, different colour maps have started to appear in publications. Computational fluid dynamics (CFD), an engineering technique to simulate fluid flow within or around objects, uses a similar approach to FEA to represent data with pseudo-colour plots [7]. Although the Rainbow colour map is routinely used to visualise CFD results, different colour maps have been used recently in some studies [64].

6. Conclusion
Results from this study demonstrate that the Rainbow colour map is not well suited to represent the underlying stress distribution of FEA models. Although most of the other colour maps tested here showed a higher discriminative power, no single colour map was found to perform consistently well throughout all scenarios and for all stress types. It is therefore recommended that different colour maps without data distortion are used to present results. This could mean using different colour maps for ratio (e.g. von Mises stress) and interval data (e.g. compressive and tensile stresses).

Alternatively, a second set of contour plots with a different colour map could be provided in the supplementary material to increase accessibility.

The perception of colour is highly dependent on multiple factors, including display devices, colour standards for display and printing, and differences in the human visual apparatus. A variety of different colour maps displayed on different models of palaeontological specimens have been presented here. It is hoped that the reader will use these examples alongside the quantitative evaluation as guidance for their applications and studies. However, the tested colour maps in this study are far from exhaustive and a variety of tools exist to access pre-designed colourmaps (see [25], Box 2).

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Ethical Statement
No ethical issues arose in the course of this study.

Funding Statement
No funding source to report.

Data Accessibility
Raw measurements and code are included in the supplementary information. FEA results files are available here (and may be transferred to a Dryad repository upon acceptance if necessary):
https://figshare.com/articles/dataset/FEA_models_from_True_colours_or_red_herrings_
Colour_maps_for_finite_element_analysis_in_palaeontological_studies_and_how_they_can_enhance_interpretation_and_accessibility_/14905104

Competing Interests
I have no competing interests

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Figure 1. Problems of the Rainbow colour scheme: (a) Non-uniform distances between individual colours (adapted from [27]). (b) Lack of intuitive perceptual order (c) Rainbow colour map as seen without and with colour vision deficiency (i.e. deuteranopia and protanopia type) and in greyscale.
**Figure 2.** Contour plots for different colour maps for Von Mises stress values shown for the simplified planar mandible model of the sabre-tooth cat *Dinofelis cristata*. In addition to the standard *Rainbow* colour map (A), nine further colour maps were tested: *Batlow* (B), *Cork* (C), *Inferno* (D), *Parula* (E), *Polar* (F), *Roma* (G), *Turbo* (H), *Viridis* (I), and *YlGnBu* (J). Grey regions in the contour plots represent stress magnitudes beyond the applied scale limit. $R^2$-values are given for each colour map (see supplementary information for full correlation plots).
Figure 3. Contour plots for different colour maps for compressive and tensile stress values shown for the mandible model of the cynodont *Thrionaxodon liorhinus*. In addition to the standard Rainbow colour map (A), nine further colour maps were tested: Batlow (B), Cork (C), Inferno (D), Parula (E), Polar (F), Roma (G), Turbo (H), Viridis (I), and YlGnBu (J). Grey regions in the contour plots represent stress magnitudes beyond the applied scale limit. $R^2$-values are given for each colour map (see supplementary information for full correlation plots).
Figure 4. Contour plots as seen without and with deuteranopia-type colour vision deficiency for different colour maps. Von Mises stress values shown for the cranium model of the dinosaur *Erlikosaurus andrewsi*. In addition to the standard *Rainbow* colour map (A), nine further colour maps were tested: *Batlow* (B), *Cork* (C), *Inferno* (D), *Parula* (E), *Polar* (F), *Roma* (G), *Turbo* (H), *Viridis* (I), and *YlGnBu* (J). Grey regions in the contour plots represent stress magnitudes beyond the applied scale limit. $R^2$-values are given for each colour map (see supplementary information for full correlation plots).
Figure 5. Contour plots as seen without and with protanopia-type colour vision deficiency for different colour maps. Von Mises stress values shown for the cranium model of the capitosaurian temnospondyl Parotosuchus helgolandicus. In addition to the standard Rainbow colour map (A), nine further colour maps were tested: Batlow (B), Cork (C), Inferno (D), Parula (E), Polar (F), Roma (G), Turbo (H), Viridis (I), and YlGnBu (J). Grey regions in the contour plots represent stress magnitudes beyond the applied scale limit. R²-values are given for each colour map (see supplementary information for full correlation plots).
Figure 6 Contour plots as seen in full colour and grey scale for different colour maps. Von Mises stress values shown for a vertebra of the ornithischian dinosaur Stegosaurus stenops. In addition to the standard Rainbow colour map (A), nine further colour maps were tested: Batlow (B), Cork (C), Inferno (D), Parula (E), Polar (F), Roma (G), Turbo (H), Viridis (I), and YlGnBu (J). Grey regions in the contour plots represent stress magnitudes beyond the applied scale limit. $R^2$-values are given for each colour map (see supplementary information for full correlation plots).
Figure 7. Contour plots depicted in the context of different background colours for the same model and colour maps. Von Mises stress values shown for a manual claw of the therizinosaurian dinosaur *Nothronychus graffami*. Grey regions in the contour plots represent stress magnitudes beyond the applied scale limit.
Table 1. $R^2$ values for all tested colour maps, stress and visual appearances. Score with the highest value highlighted for each test setting.

|         | Batlow | Cork | Inferno | Parula | Polar | Rainbow | Roma | Turbo | Viridis | YIGnBu |
|---------|--------|------|---------|--------|-------|---------|------|-------|---------|--------|
| Von Mises | 0.644  | 0.635| 0.802   | 0.653  | 0.578 | 0.571   | 0.563| 0.664 | 0.787   | 0.547  |
| Tensile/compressive | 0.910  | 0.871| 0.905   | 0.959  | 0.934 | 0.887   | 0.872| 0.852 | 0.933   | 0.967  |
| Deuteranopia | 0.890  | 0.696| 0.693   | 0.460  | 0.604 | 0.504   | 0.476| 0.117 | 0.475   | 0.511  |
| Protanopia  | 0.547  | 0.555| 0.738   | 0.642  | 0.458 | 0.564   | 0.485| 0.717 | 0.876   | 0.670  |
| Grey scale  | 0.476  | 0.440| 0.578   | 0.360  | 0.348 | 0.086   | 0.098| 0.008 | 0.306   | 0.500  |
Response to reviewers and list of requested changes to the manuscript

This paper has been reviewed by two researchers who are both enthusiastic about the results of the study. They both suggest only minor revision. I do not think it will take much time to incorporate the extra explanations that have been asked for, thus I recommend accept with minor revision.

S. Lautenschlager: I would like to thank the editor and the two reviewers for the constructive comments which have substantially improved the manuscript

Reviewer comments to Author:

Reviewer: 1

Comments to the Author(s)
This is an excellent study and very relevant now. The range of example models and colours is great to give an idea of what can work for future publications. The quantitative results are particularly helpful, because it gives some guidance on the best colour plot for the type of data, rather than a subjective preference based on appearance.

At the start, I expected to change my mind about the rainbow colour plot and want to use something different, but since you conclude that there is no single colour plot that solves “all” issues, I feel like the rainbow plot is still the one that will be chosen in future. Especially because it’s also the default plot from software and is easy to produce.

I particularly like the recommendation though to add a second set of contour plots (or more) with a different colour map in the supplementary material. This could really help those with CVD. I think adding multiple colour plots in the main article may be confusing, and most people are used to the rainbow colour plot.

S. Lautenschlager: Many thanks for the positive feedback.

One thing I’d like clearer is how to apply the colour plots; I found this confusing or unclear and if I was to do this myself, I wouldn’t know how. So, if this can be made clearer in the Methods or supplemental material, that would be great. I found the supplementary figures in the included files, but I could not find the supplementary material that was referred to on pages 4 and 6 in the Methods. If a step-by-step guide is included in the supplementary information, that would be good.

S. Lautenschlager: More information has been added to the methods (lines 82-88) and the used colour map codes (including instructions) have been added to the supplementary figures so that all supplementary information in one place.

Depending on the software, custom colour maps can be created. In this example, all colour maps were created in Abaqus via a command line script detailing the colour components via

Appendix B
HEX codes individually (see script in supplementary information). Alternatively, new colour maps (so-called spectra in Abaqus) can be created via a tools menu and selecting successive colours via a colour picker. This process will differ for individual software. However, specific pre-designed colour maps can be generated and accessed via online tools, such as Colourbrewer.org [40].

The thing I found most confusing is you say the outputs were generated in Abaqus and then converted using convertColor function in R? Were the outputs saved as images and converted from the default rainbow, or were the models exported and the colour was resampled in R? I would love to know how to do it.

S. Lautenschlager: Outputs were generated using the specific colour maps directly in Abaqus and the view of the models was saved as image files. Colour information was then sampled from the images and converted using the R function (code is included in the supplementary information). More details have also been added to the methods (lines 80-82, 129-131)

All colour maps used for this study consist of 24 individual colour values (definitions (order and HEX colour codes) are available in the supplementary information) and all outputs presented here were generated in Abaqus and model views were saved as image files.

The collection of the RGB colours from images of the FEA models and subsequent conversion to CIELAB colour space was done via the convertColor function in R [57] (see supplementary information).

Otherwise, very happy to recommend this for publication.

Reviewer: 2

Comments to the Author(s)
The manuscript has intriguing results for legible visualization that I hope to put into practice soon. Among minor improvements to the language, I suggest that the authors spell out acronyms more often, and be more specific for lines 217-218.

S. Lautenschlager: As recommended by reviewer 2 all acronyms have been spelt out when first appearing under a new sub-heading. In addition, typos, grammatical aspects and minor comments highlighted in the PDF copy have been incorporated as suggested.

More substantive but still minor improvements will be:
1. To explain more clearly the commercial propriety or openness of various color schemes, and how generally they're available amongst relevant simulation and visualization programs.

S. Lautenschlager: More explanation has been added (as also requested by reviewer 1) (lines 71-73, 82-88).
All colour maps are non-proprietary, in some cases versioned and available/defined via the respective references above. Not all colour maps are readily and equally available by default in all software but can be added in most cases (see also below).

... Depending on the software, custom colour maps can be created. In this example, all colour maps were created in Abaqus via a command line script detailing the colour components via HEX codes individually (see script in supplementary information). Alternatively, new colour maps (so-called spectra in Abaqus) can be created via a tools menu and selecting successive colours via a colour picker. This process will differ for individual software. However, specific pre-designed colour maps can be generated and accessed via online tools, such as Colourbrewer.org [40].

2. To explain how well the mathematical discrimination between colors matches perceptual discrimination.

S. Lautenschlager: More detail has been added explaining the match between colour space and human perception (lines 218-224):

Human colour perception is not uniform, often subjective and dependent other factors such as age and individual variation and as such does not correspond to Euclidean distances in colour space [57]. The CIELAB colour space is an attempt to replicate human colour differentiation. As the correlation analysis only considers absolute changes along a trajectory, the analysis may not record the exact correlation when non-monotonic changes on the stress scale are associated with changes in different directions in the CIELAB space. However, this is less likely to be a problem for the perceptually-based colour maps.