Perception of visual information: the role of colour in seismic interpretation

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Abstract

Interpretation of geological features in seismic data is a subjective process, relying on one's visual perception and experience built up over several years. Based on these human factors, financial decisions are made that may have serious consequences to a petroleum company. The aim of this study is to review the role of one key visual cue in this interpretative process: colour. Colour is a powerful cue that can have a significant impact on the interpretation of seismic data. However, compensation mechanisms within the human perceptual system can sometimes lead to unexpected visual effects, such as luminance sensitivity and simultaneous contrast, which have the potential to bias the interpretation of geoscientific information and therefore increase interpretation uncertainty and risk. Here we examine these visual effects, and present the findings of an experiment aiming to illustrate bias dependent on the use of colour. Both inter- and intra-operator differences were found in the manual delineation of a sedimentary geobody from seismic data. The results clearly suggest that measurements from seismic data based on manual delineation of imaged object boundaries can be associated with uncertainties that are usually unquantified.

Introduction

Seismic data contain vast amounts of information and interpreters often face the need to analyse a number of attributes simultaneously and collate the different type of information into a single, comprehensive interpretation (Henderson et al., 2008). The increasing trend to interpret multiple attributes simultaneously has been supported by improvements in colour data visualization technologies over the past five years. Despite colour representation limitations that still exist in current commercial software (Dao and Marfurt, 2011), effective use of colour as a visual cue has made composite attributes such as RGB blended volumes a mainstay of seismic exploration workflows, especially when information from multiple volumes needs to be compared and contrasted.

Using colour to represent data has proven to be a powerful tool, but one whose subtleties can lead the unaware into potential pitfalls. These stem from the non-linear behaviour of our own visual systems, and subtle visual effects that can affect how objects appear to us and potentially bias an interpretive decision.

In this paper we discuss a number of visual effects related to colour perception, namely luminance and hue sensitivity, false colour contours, chromostereopsis, induced atmospheric perspective, and simultaneous contrast. We then present a pilot experiment that highlights the potential impact that colour perception and visual effects have on the interpretation of geological features in a real case study.

Human visual and colour perception

Colour is the visual percept that derives from the way our visual system responds to and elaborates light. In the natural world, more than a trillion levels of light can be registered (Pokorny and Smith, 2004), ranging from a dark night scene in the forest to the bright scene of snow in full sunshine. A typical human eye is tuned to respond to light wavelengths approximately in the range 400–700 nm (Palmer, 1999), which defines the visible spectrum.

Although the human visual system allows individuals to interpret visual information, it is uncertain what exactly an individual perceives. This is because perception is a neurological process; humans gather information from the world around them using sensory receptors and interpret this information largely based on memory. One may assume visual perception is an exception to this rule and is unbiased; however, what people see is not just a simple case of translating the retinal stimuli. Vision is the result of unconscious inference, making assumptions based on visual clues and previous experience stored in memory (von Helmholtz, 1866). During the process of visual perception humans quickly scan a scene and unconsciously decide on the salient features on display, as demonstrated by eye tracking (Kim et al., 2010). As memory influences the interpretation of this visual information, knowledge, experience, cultural background, and social background all affect an individual's perception. In addition, it should be noted that knowledge transmitted by colleagues can also be influential in altering one's interpretation (Davies et al., 2005).

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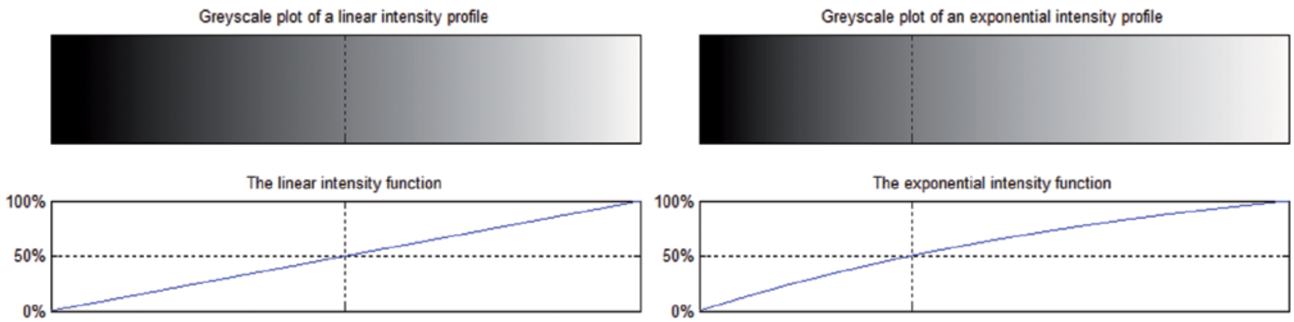

***Figure 1** Left: linear intensity profile image and corresponding value plot. Right: exponential ($1 - e^{(1-\alpha x)/\beta}$) intensity profile that better aligns the apparent middle grey level in the centre of the scale.*

Geological interpretation is very much based on inference as interpreters make visual assumptions based on incomplete data using visual clues, and generally compare the visual information on seismic data with a frame of reference based on geological analogues retained in their memory. This process becomes easier over time as the level of experience increases.

Within the context of the visual interpretation of geological features, colour perception is of key importance as colour is a very powerful means we can use to represent data (Froner et al., 2012). The perception of colour is dependent on the activation of the three different types of cone cells located in the retina of the eye. Each cone type is responsive to a different frequency in the light spectrum, that is to a different wavelength, resulting in the remarkable ability to distinguish 10 million colours, as compared to a mere 500 shades of grey (Judd and Kelly, 1939; Vision Health Optometry, 2013). This is why multi-dimensional seismic attributes can be displayed so effectively in colour blends (Henderson et al., 2007, 2008).

From a qualitative point of view, wavelength discrimination is best in the spectral regions around 480 nm (blue-green) and 580 nm (green-yellow) (Pokorny and Smith, 2004). However, colour acuity and chromatic discrimination are very subjective, due to the individual differences in the physiology of the photoreceptors in the eye, the viewing conditions, and the unconscious inference influenced by previous experience. Colour is therefore perceived in a subjective non-linear fashion as our visual system adopts a number of compensating mechanisms in order to adapt to different stimuli, visual scenes and experience, resulting in a number of somewhat unexpected visual effects.

What are we interpreting? Data or our colour bars?

As we continue to use colour in more sophisticated ways within seismic analysis, we need to become more aware of its impact on our interpretive decisions, as visual effects do have a significant impact in the simplest of situations.

The first effect that we discuss is luminance sensitivity, sometimes also called intensity sensitivity. Figure 1 (left) shows a typical greyscale colour bar found in any interpretation software package. Luminosity increases linearly from left to right. When examining the colour bar and attempting to interpret the position of a middle (50%) grey level, the apparent middle point is often placed well to the right of the centre line; a second obvious effect is that the transition from dark grey to black is more abrupt than is reflected in the profile. The result is that when such a greyscale colour bar is used to display reflectivity data, seismic sections may appear darker than they actually are, giving the impression of lower amplitudes or a dominance toward troughs. The transitions from peaks to troughs are exaggerated, and manual interpretation of zero-crossing events or other low amplitude features is likely to be error-prone.

On the right of Figure 1, the profile has been modified to better align the middle grey value in the centre of the scale. In this example, we have made a highly subjective adjustment to compensate for the effect. More rigorous studies on the subject have been performed by Welland et al. (2006) and Donnelly et al. (2006).

Similar non-linear effects occur when perceiving different hues on a linear chromatic colour bar; here the impact of the effects can be more striking and misleading. This is due to the non-linear sensitivity of our visual system to different parts of the spectrum and to our visual ability to infer apparent structure from variation in colour (Dejoie and Truelove, 2000).

On the left of Figure 2, the two images have been generated using the same dataset, i.e., a radial pattern decreasing linearly with distance from the centre. When displayed in greyscale the smooth radial variation is clear; in the colour image a number of steps appear. The image has been created using a colour table where hue varies uniformly, similar in nature to the rainbow or spectrum colour bars found in seismic interpretation software packages.

Here the effect of using hue variation to visualize attribute data is clear, as a number of false contours are now apparent on the radial profile, most prominently around the yellow and cyan hues. If the structure of the data is not known in advance, this effect becomes more dangerous as we risk interpreting the false contours' strong visual features as strong data features, when in reality they may not be the most important. Besides, the sharp colour transition highlighted by the false contours may not correspond to an equally sharp variation in the underlying data. In this regard, it should be noted that the human brain is remarkably good at detecting patterns, and has the

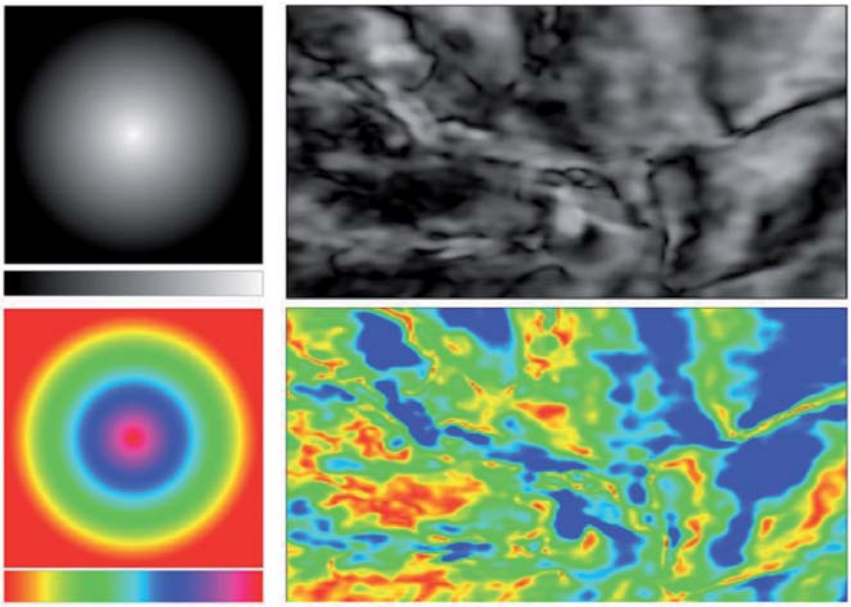

Figure 2 *Top left: radial greyscale pattern uniformly decreasing in amplitude away from the centre. Bottom left: the same image data displayed with a varying hue colour bar. Right: envelope volume time slice displayed in greyscale (top) and with a spectrum colour bar (bottom).*

ability to extract and group low level image features into more meaningful, higher level structures without prior knowledge of the image context, a process known as perceptual grouping (Iqbal and Aggarwal, 2002; Grossberg et al., 1997).

A further visual effect is also apparent in the hue colour bar of Figure 2, where different hues appear more prominent than others, most notably the green hue, although the colour bar has been constructed uniformly. This effect is better highlighted in Figure 3, where an RGB image has been created using three of the radial profiles from Figure 2 mapped to the red, green, and blue channels of the image. In the resulting image the radial profiles all tend to appear as different sizes, the green being the largest, followed by red, and finally blue.

So far, the effects we have highlighted have been related to how colour affects our perception of the underlying image intensity values. However, colour can have a significant impact on depth perception, and therefore on how we perceive the position of different objects within 3D scenes (Froner, 2011). Two notable effects are chromostereopsis (Allen and Rubin, 1981) and induced atmospheric perspective (Guibal and Dresp, 2004). Figure 4 illustrates these effects. In the top left image, the red circle appears to be at a different depth to the blue ring as an effect of the difference in wavelength of the red and blue colours and the chromatic aberrations occurring in the eye; most people perceive the red circle as nearer, but the opposite can also occur. Red-green stimuli may also cause this effect. The same effect can be perceived by looking at the two delineated geobodies at the bottom of Figure 4: the two geobodies appear to be at different depths. On the top right of Figure 4 the brightness of the object affects our perception of its depth, with the dimmer circle appearing further away, as an effect of luminance contrast simulating the principles of atmospheric perspective.

The last phenomenon that we will show is called the simultaneous contrast effect, i.e., the tendency of the appearance of an object to be influenced by the visual characteristics of adjacent or intersecting objects. In Figure 5, the two pink central squares are exactly the same colour but appear to be different due to the surrounding colours. Similarly, the grey inner squares in the lower part of the figure are of the same grey shade despite the fact that they appear to be different: the darker the surround the lighter the square.

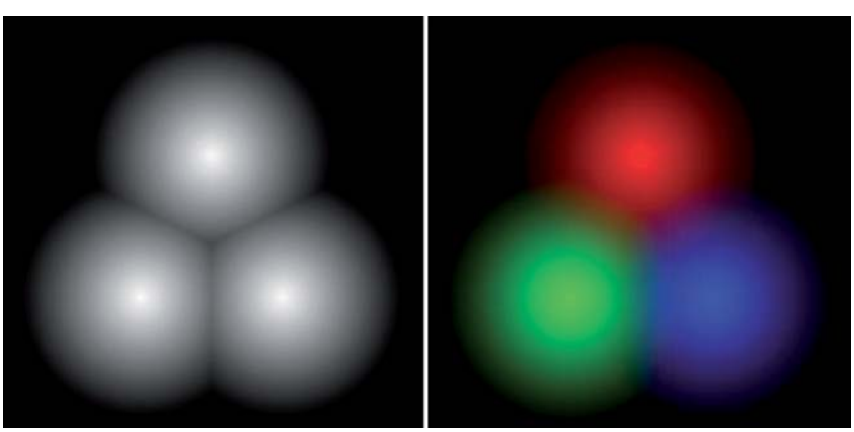

Figure 3 *Left: composite image of three radial profiles viewed with a greyscale colour bar: the three profiles are symmetrical and of the same size. Right: an RGB image of the same data.*

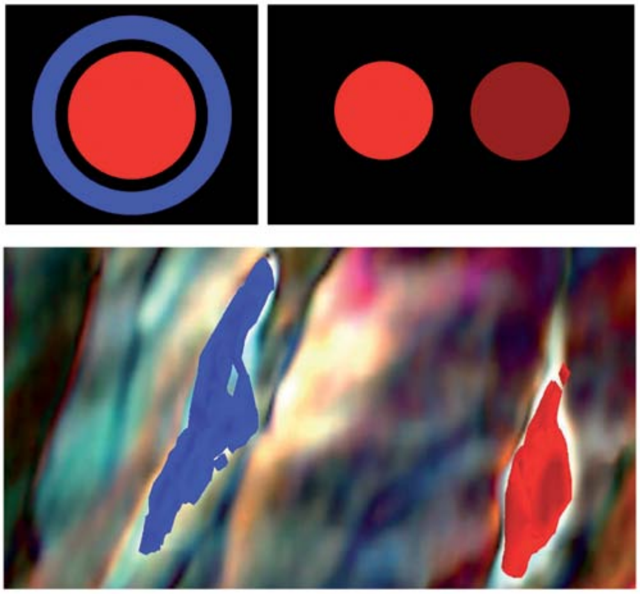

Figure 4 *Top: Chromostereopsis (left) and induced atmospheric perspective effect (right). Bottom: the two delineated geobodies appear at different distances from the observer as an effect of their colour.*

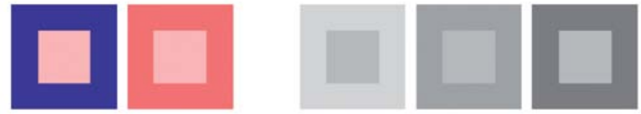

Figure 5 *Simultaneous contrast effect in chromatic stimuli (left) and black and white stimuli (right). In both cases the inner square appears of different colour depending on the colour of the surrounding square.*

Simultaneous contrast effects can cause significant problems when attempting to visually compare seismic attribute responses in different parts of a large seismic section or extracted map; those responses may in fact be the same, even though they appear to be different because of the colour of the surrounding data.

Effect of colour on manual geobody delineation: a pilot study

The way we perceive colour and variations in colour can have a significant impact on the accuracy and precision of measurements made from seismic and seismic attribute data that rely on manual definition of boundary or edge points.

The potential magnitude of the inter- and intra-operator variability associated with such manually directed measurements was illustrated in a simple experiment. Six interpreters manually delineated a geobody on a single time slice through an envelope/instantaneous amplitude attribute. The geobody was interpreted as a spit system, which is shallow marine sandstone bar (Nielsen and Johannessen, 2009). Interpreters were provided with four images of the system, each visualized with one of the following four colour bars: spectrum, white–black greyscale, reversed black–white greyscale, and heat (black–red–white). Each interpreter was asked to digitize the outline of the spit eight times on each of the four images, giving a total of 192 measurements. Figure 6 shows the time-slice image used during the experiment displayed with the four colour bars. A 3D view of the geobody of interest is given in Figure 7.

The measurements were taken in eight batches by each interpreter over two days. In each batch, one measurement was made on an image with each of the four colour maps. The order of the colour map used to show the image within a batch was randomized, and there was a gap of at least one hour between the batches of measurements. This helped to minimize colour map bias and the impact of fatigue and loss of concentration. To further reduce unsystematic variation, colour bar settings and compression levels were fixed across trials and all measurements were carried out using the same workstation. Display settings, such as monitor brightness and contrast, were fixed. The group had different levels of experience in seismic interpretation and was composed as follows: two junior interpreters, two intermediate interpreters, and two advanced interpreters.

The results of this simple experiment (Figure 8) show both intra-operator variation and systematic differences between operators (i.e., interpreters). Interestingly, the amount of intra-operator variation is very operator-dependent, with the results of four of the interpreters showing a standard deviation of less than 10% of the mean and two of the interpreters showing a standard deviation of greater than 10% of the mean. In general terms, the interpreters that produced the lower standard deviation in the results also defined the feature as occupying the smallest area.

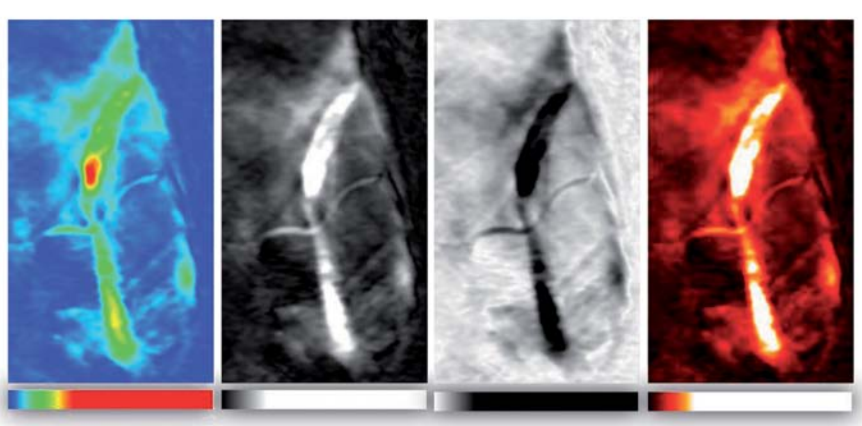

Figure 6 *Time-slice image used in the experiment displayed with four different colour maps, from left to right: spectrum, greyscale black–white, greyscale white–black, and heat.*

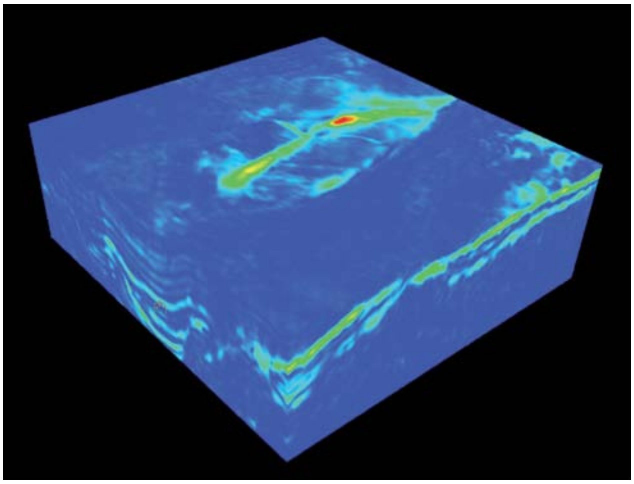

Figure 7 *3D view of the geobody delineated during the pilot experiment.*

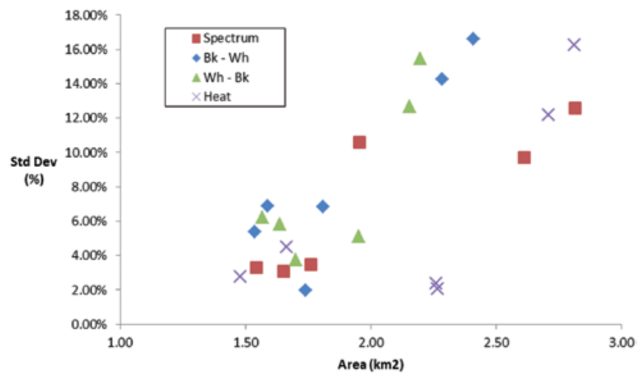

Figure 8 *Relationship between the mean area of the feature, identified by the amplitude anomaly shown in Figure 6, and the standard deviation of the measurements from each operator as defined by manual digitization of the feature boundary.*

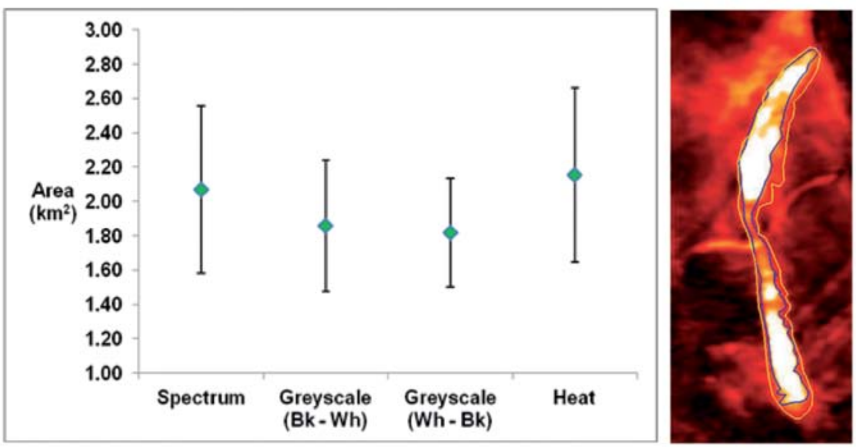

Figure 9 *Left: mean and standard deviation of area as defined by manual digitization of the feature boundary using different colour maps. Error bars represent ±1 standard deviation of the mean of all the measurements for the specific colour map. Right: largest and smallest area delineated by the same operator using two different colour maps.*

However, the largest variations were due to inter-operator differences. Table 1 shows the maximum and minimum areas delineated for each colour map. The smallest area delineated was 1.4 km^2 (white–black greyscale colour map), and the largest was 3.30 km^2 (spectrum colour map), a difference of 235%.

The inter-operator differences in this experiment tend to mask the influence of colour map on boundary selection. Nevertheless, for all interpreters, area measurements made on the greyscale colour maps (black–white and white–black) were smaller than those made on the chromatic colour maps (spectrum and heat). In addition, the greyscale colour maps are associated with a smaller range of measurements (i.e., smaller standard deviation), indicated by the difference between the maximum and minimum area values measured on each colour map. These effects are clearly illustrated by the graph in Figure 9, where mean and standard deviation of all measurements across operators are plotted for each colour map individually. A qualitative indication of how colour can affect the interpretation of geological features is given by the image in Figure 9, which shows the spit system boundary delineated by the same interpreter using two different colour maps (blue and yellow outlines). The difference in size and shape of the delineated boundary suggests that colour can influence the choices of the interpreter.

Generally, the results of this experiment show that there are both inter- and intra-operator differences in the area delineated

	Max (km^2)	Min (km^2)	Ratio Max/Min	Difference Max – Min (km^2)
Spectrum	3.30	1.49	2.15	1.81
Black–white	2.80	1.44	1.94	1.36
White–black	2.51	1.40	1.79	1.11
Heat	3.18	1.51	2.11	1.67

Table 1 *Effect of colour map on measurement of area based on manual boundary delineation.*

and suggest that these differences are due to the effect of colour perception on image interpretation. More rigorous experiments need to be performed to understand whether such effects are significant. However, what the experiment presented in this article clearly suggests is that measurements from seismic data based on manual delineation of imaged object boundaries can be associated with uncertainties that are usually unquantified. In real situations, the differences could be larger because display settings were fixed in this experiment.

Conclusions

Colour plays a principal role in seismic interpretation. Mainstream technologies such as RGB blended volumes effectively use colour to merge different types of information and enable simultaneous multi-attribute analysis. In this paper we presented a number of phenomena related to colour perception and discussed the effects that these may have on seismic interpretation. We also presented a pilot experiment that we performed in order to investigate such effects.

The experiment we conducted suggests that colour perception does have an impact on manual interpretation of geological features in seismic and seismic attribute data. In particular, the results showed both intra- and inter-operator differences in the positioning of the boundary of the delineated feature and suggest that such differences are partially an effect of the colour map used to visualize the geobody. However, more accurate experiments would need to be performed and the experimental design of each would need to be more stringent to allow a detailed statistical analysis to be carried out and clearly understand the significance of such intra- and inter-operator variation and the effect of colour map and display variables on manual delineation of geological features.

Despite advances in the field (Donnelly et al., 2006; Welland and Donnelly, 2006), more investigative work is needed in order to fully understand how to get the best out of our visual system in the context of scientific visualization and ensure that our visualization systems are designed to eliminate visual bias. Current interpretation or visualization software does little to acknowledge or compensate for the visual effects discussed in this paper. Practically, maintaining an awareness of such effects during interpretation is currently the best interpreters can do towards compensating for any bias they introduce.

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References

Allen, R.C. and Rubin, M.L. [1981] Chromostereopsis. *Survey of Ophthalmology*, **26**, 22–27.

Dao, T. and Marfurt, K.J. [2011] The value of visualization with more than 256 colors. *81st SEG Annual Meeting*, Expanded Abstracts, 941–945.

Davies, R.J., Gras, R. and Payre, X. [2005] A vision for 3D seismic technology and visualization. In: Doré, A.G. and Vining, B.A. (Eds) *Petroleum Geology: North-West Europe and Global Perspectives—Proceedings of the 6th Petroleum Geology Conference*. Geological Society, London, 1483–1486.

Dejoie, J. and Truelove, E. [2000] What is meant by "false color"? http://starchild.gsfc.nasa.gov/docs/starchild/questions/question20.html.

Donnelly, N., Cave, K.R., Welland, M. and Menneer, T. [2006] Breast screening, chicken sexing and the search for oil: challenges for visual cognition. In: Allen, M.R., Goffey, G.P., Morgan, R.K. and Walker, I.M. (Eds.) *The deliberate search for the stratigraphic trap*. Geological Society, London, 43–55.

Froner, B. [2011] *Stereoscopic 3D Technologies for Accurate Depth Tasks: a Theoretical and Empirical Study*. PhD Thesis, Durham University, UK.

Froner, B., Lowell, J. and Purves, S.J. [2012] On the perception of RGB multi-attribute displays. *PETEX*. http://www.ffa-geosciences.com/index.php/abstracts/abstracts.

Grossberg, S., Mingolla, E. and Ross, W.D. [1997] Visual brain and visual perception: how does the cortex do perceptual grouping? *Trends in Neuroscience*, **20**, 106–111.

Guibal, C.R.C. and Dresp, B. [2004] Interaction of color and geometric cues in depth perception: when does "red" mean "near"? *Psychological Research*, **69**, 30–40.

Henderson, J., Purves, S., Fisher, G. and Leppard, C. [2008] Delineation of geological elements from RGB color blending of seismic attribute volumes. *The Leading Edge*, **27**, 342–350.

Henderson, J., Purves, S.J. and Leppard, C. [2007] Automated delineation of geological elements from 3D seismic data through analysis of multi-channel, volumetric spectral decomposition data. *First Break*, **25**(3), 87–93.

Iqbal, Q. and Aggarwal, J.K. [2002] Image retrieval via isotropic and anisotropic mappings. *Patterns Recognition*, **35**, 2673–2686.

Judd, D.B. and Kelly, K.L. [1939] Method of designating colors. *Journal of Research of the National Bureau of Standards*, **23**, 355–366.

Kim, Y., Varshney, A. Jacobs, D.W. and Guimbretière, F. [2010] Mesh saliency and human eye fixations. *ACM Transactions on Applied Perception*, **7**(2), 1–13.

Nielsen, L.H. and Johannessen, P.N. [2009] Facies architecture and depositional processes of the Holocene–Recent accretionary forced regressive Skagen spit system, Denmark. *Sedimentology*, **56**, 935–968.

Palmer, S.E. [1999] *Vision Science: Photons to Phenomenology*. MIT Press.

Pokorny, J. and Smith, V.C. [2004] Chromatic discrimination. In: Chalupa, L. and Werner, J. (Eds.) *The Visual Neurosciences*. MIT Press, Cambridge, 908–923.

von Helmholtz, H. [1866] Concerning the perceptions in general. In: *Treatise on Physiological Optics*, vol. III, 3rd edn. (Translated by Southall, J.P.C. [1925] *Optical Society of America*, Section 26. Reprinted by Dover, New York, 1962).

Vision Health Optometry [2013] Facts about the human eye. http://www.vision-health.com/facts-about-the-human-eye.

Welland, M., Donnelly, N. and Menneer, T. [2006] Are we properly using our brains in seismic interpretation? *The Leading Edge*, **25**, 142–144.

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