**Enhanced Image-Colour-Transfer**

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*An Enhanced Implementation of the Colour Transfer Method Proposed by E Reinhard et al*.

***This document is applicable to l$\alpha\beta$ processing. For L*a*b processing see separate document.***

## The Reinhard Colour Transfer Method

Reinhard et al [Ref 1] presented a method for matching the colour distribution of a target image to that of a source image by use of a linear transform in the lαβ perceptual colour space so as to match the mean values and standard deviations of the target image to those of the source image along each of the colour space axes. By resetting the parameters of the target image to match those of the source image, the colour information in the target image is modified to better resemble that of the source image.

The processing steps are as follows.

1. Convert the both the source and target images from RGB colour space to lαβ colour space
2. Compute the mean and standard deviation of each of the three l, α and β components for both images.
3. Standardise the three components of the target image by subtracting the respective mean values and dividing by the respective standard deviation values.
4. Reformulate new target values by applying the respective source standard deviations as scaling factors to the standardised components and adding in the source mean values.
5. Convert the resultant from lαβ colour space to obtain the output image in RGB colour space.

The third and fourth steps can be represented as follows.

$z_c = (x_c - \hat{\mu}t_{tc})/\hat{\sigma}_{tc}$ $X_c = z_c * \hat{\sigma}_{sc} + \hat{\mu}_{sc}$ for outputs $X_l,\ X_\alpha,\ X_\beta$, and inputs $x_l,\ x_\alpha,\ x_\beta$.

Effectively here, the $x_{l,}\, x_{\alpha,}$ and $x_\beta$ values are reworked for every pixel in the target image so that collectively their mean values and their standard deviations are reset to match the values observed in the colour source.

Processing is performed in the lαβ colour space because the three components in this space have been observed to show low inter-dependency for certain classes of natural imagery and it can be more acceptable to process components independently in this colour space.

## The Enhanced Colour Transfer Method

The basis of the enhanced colour transfer method is as follows.

Let $s_1$ and $s_2$ be two independent (zero correlation) variables with mean values equal to zero and standard deviations equal to one. It possible to construct variables $a_1$ and $a_2$ with mean values equal to zero and standard deviations equal to one but with mutual cross correlation 'R' by means of the following operations.

$$a_1 = \sqrt{\frac{1+R}{2}} \times s_1 + \sqrt{\frac{1-R}{2}} \times s_2 \quad \text{and} \quad a_2 = \sqrt{\frac{1+R}{2}} \times s_1 - \sqrt{\frac{1-R}{2}} \times s_2$$

Conversely, the inverse relations can be applied to derive independent variables s1 and s2 from correlated variables a1 and a2.

$$s_1 = \frac{a_1+a_2}{\sqrt{0.5\times(1+R)}} \quad \text{and} \quad s_2 = \frac{a_1-a_2}{\sqrt{0.5\times(1-R)}}$$

The enhanced colour transform method incorporates additional steps compared to the original method by which the correlation between the colour components 'α' and 'β' is modified so that it corresponds to the value observed in the colour source image rather than that in the target image.

This can be achieved by inserting additional steps into the previously described method as follows.

- 3.0 Standardise the three components of the target image by subtracting the respective mean values and dividing by the respective standard deviation values.
  - 3.1 Cross-multiply the corresponding values of the 'α' and 'β' components and hence determine the average cross product value for both the target and source images.
  - 3.2 Denote the two average cross products as the correlation values $R_t$ and $R_s$ respectively.
  - 3.3 Using the value $R_t$, which represents the correlation between the 'α' and 'β' channels in the target image, form new independent variables from the values $z_\alpha$ and $z_\beta$.
  - 3.4 Using the value $R_s$, which represents the correlation between the 'α' and 'β' channels in the sample image, form new standardised variables $z'_\alpha$ and $z'_\beta$ with correlation value $R_s$.
- 4.0 Reformulate new target values by applying the respective source standard deviations as scaling factors to the (modified) standardised components and adding in the source mean values.

The new intermediate steps can be represented as follows.

The correlation values are computed as follows.

$$\hat{R}_t = \frac{1}{n}\sum Z_{t\alpha}(i) * Z_{t\beta}(i) \quad \text{and} \quad \hat{R}_s = \frac{1}{m}\sum Z_{s\alpha}(i) * Z_{s\beta}(i)$$

The standardised colour components are modified as follows.

$$s_\alpha = \frac{z_{t\alpha}+z_{t\beta}}{\sqrt{0.5\times(1+\hat{R}_t)}} \quad \text{and} \quad s_\beta = \frac{z_{t\alpha}-z_{t\beta}}{\sqrt{0.5\times(1-\hat{R}_t)}}$$

$$z_\alpha = \sqrt{\frac{1+\hat{R}_s}{2}} \times s_\alpha + \sqrt{\frac{1-\hat{R}_s}{2}} \times s_\beta \quad \text{and} \quad z_\beta = \sqrt{\frac{1+\hat{R}_s}{2}} \times s_1 - \sqrt{\frac{1-\hat{R}_s}{2}} \times s_2$$

In the former relationships the 'n' and 'm' values denote the number of pixels in the respective images. In the latter relationships, the transforms are applied to each pixel within the target image. Note that the computation of correlation values normally requires the subtraction of mean values and division by standard deviation values, but this is not necessary here because the correlation is computed directly from standardised values which have already been pre-processed.

The implementation described in this document uses the lαβ colour space rather than the Cielab L*a*b colour space. Reinhard and Pouli [Ref 2] found that L*a*b mostly outperforms lαβ for colour transform processing. However, their study was based upon processing that was different to that described here. An implementation for L*a*b processing is provided elsewhere in this repository.

## Alternative Formulation

The intermediate steps 3.1 to 3.4, as described previously, can be represented as follows.

$$z_\alpha = W_1 z_{t\alpha} + W_2 z_{t\beta} \quad = \frac{1}{2}\left[\sqrt{\frac{1+\hat{R}_s}{1+\hat{R}_t}} + \sqrt{\frac{1-\hat{R}_s}{1-\hat{R}_t}}\right] z_{t\alpha} + \frac{1}{2}\left[\sqrt{\frac{1+\hat{R}_s}{1+\hat{R}_t}} - \sqrt{\frac{1-\hat{R}_s}{1-\hat{R}_t}}\right] z_{t\beta}$$

$$z_\beta = W_1 z_{t\beta} + W_2 z_{t\alpha} \quad = \frac{1}{2}\left[\sqrt{\frac{1+\hat{R}_s}{1+\hat{R}_t}} + \sqrt{\frac{1-\hat{R}_s}{1-\hat{R}_t}}\right] z_{t\beta} + \frac{1}{2}\left[\sqrt{\frac{1+\hat{R}_s}{1+\hat{R}_t}} - \sqrt{\frac{1-\hat{R}_s}{1-\hat{R}_t}}\right] z_{t\alpha}$$

The output standardised variables are computed as weighted sums of the input standardised variables. Each output channel is derived as a scaled contribution from the corresponding primary input colour channel plus a contribution from the other secondary channel. If the contribution from the secondary channel is zero then the original Reinhard method is implemented with no additional enhancement processing. If the contribution from the secondary channel is similar in size to that from the first channel then the colour transfer can sometimes be too intense and the colouring can appear somewhat artificial. To address this, the enhanced implementation of colour transfer incorporates an option to limit the size of the secondary channel contribution relative to that of the primary channel. Even when limiting is applied some level of additional colour enhancement will be implemented over and above that of the standard processing method.

## Data Rescaling

Data rescaling has been provided as an option in the L*a*b version of enhanced image-colour-transfer processing, however it is not provided here. Data rescaling potentially offers an alternative to data clipping but experimental measurement suggests that processing in the lαβ colour space is less prone to significant clipping. From a practical viewpoint, a transformation from the BGR colour space to the lαβ colour space involves a logarithmic transform which introduces non-linear effects and it has not been possible to identify a robust rescaling method for such data.

## Iteration

It has been seen that the colour transfer operation may be distorted by the need to clip the transformed data to its permitted range. It has been found that repeated processing may offer an improvement for the colour transfer quality. Initially colours from the source image can be applied to the target image to produce a resultant image. Subsequently, the colours from the source image can be reapplied to the resultant image to produce a new resultant image. This latter operation may be repeated for a number of iterations. Iteration processing has been found to deepen the colour of the resultant image in some cases. It is normally sufficient to perform just one further iteration in additional to the initial processing. The impact of iteration is less pronounced for this version of enhanced image-colour-transfer than it is for one based upon the L*a*b colour space.

The enhanced implementation of colour transfer allows a number of iterations to be performed with the default number set to two iterations.

## Shading

Although the Reinhard method is called a colour transfer method, shading (lightness and darkness) is also transferred from the source to the target image. This is appropriate for an application such as image stitching because it is desirable that the constituent images be comparable in both colour and shading to ensure an invisible join. It is also appropriate in a situation, say, where colour transfer is applied to modify a daytime image to a night time scene. Strictly, however, the phrase ‘colour transfer’ implies the transfer of colour only and there are situations where this is desirable.

In the context of the Reinhard colour transfer method, the transfer of colour but not shading is a simple matter. In the standard approach, the lightness component of the target image is modified to match the lightness component of the source image using similar processing to that applied to the two colour components. In ‘pure colour’ processing the colour components are processed but the lightness component is left unmodified.

The enhanced implementation of colour transfer allows an option for retaining the shading of the target image, independent of the source image shading.

## Observations

The enhanced colour transfer method achieves a potential advantage over the standard method by taking account of the correlation between the colour components in the lαβ colour space. In some image pairs it could be that the correlation is similar in both the target and the source image (perhaps even near to zero in both). Under such circumstances, enhanced processing will provide no benefit over standard processing although it should not give rise to any noticeable disadvantage.

For the processing described here it can be expected that improved colour fidelity will be achieved with increasing iteration. In cases where the source image colours are particularly vivid it may be that the muted colours of a single iteration are more ascetically pleasing. Generally though, it would better to select a source image whose colour content is appropriate and to iterate sufficiently to achieve full colour transfer. An example overleaf shows an image subject to a single iteration and the same image subject to two iterations.

A novel application for colour transfer is that of indirect colour shading. Here the colour source image is a modified version of the target image. As an example, consider a situation where it is required to adjust the sky colour in an image. Commercial software applications offer various tools to address this requirement, but an alternative and sometimes simpler approach would be to use indirect colour shading. Here, a duplicate of the original image would be taken and a block within the sky would be set to a different colour perhaps directly or perhaps by pasting from another image. The colour of the original target image would then be modified by the colour transfer from the customised source image. In the examples overleaf the ‘ocean scene’ is an example of indirect colour shading.

The enhanced method of colour transfer only addresses the cross correlation between the colour components. It does not address any cross correlation between either of the colour channels and the lightness/darkness channel. It is not clear whether it would be useful to modify the target image to incorporate any relationship between colour and brightness as observed in the source image, let alone any dependency of brightness on colour. A brief and approximate investigation has been undertaken and this suggests that, in some circumstances, the transfer of colour brightness dependencies could create anomalous effects in the final image.

Published reviews of colour transfer methods often distinguish between photorealism and painterly effects. The latter addresses the process of generating images that mimic the colour palette and style of a particular artist such as Van Gogh or Seurat. The style of some artists is more susceptible to this process than others. Magritte and Dali, for example, are two artists whose style would be difficult to replicate by colour transfer methods since surrealist art depends more on image content than image rendition. Colour transfer does however, offer the interesting possibility of photo-surrealism, where colour transfer can be used to generate ascetically pleasing images that look realistic but whose colours are clearly unreal. Such images typically look realistic in monochrome but not in colour.

Commercial photo processing applications offer options such as ‘Solarize’, ‘Gradient Map’ and ‘Posterize’ which can be used to transform images to achieve multi-colour or psychedelic outcomes. Colour transfer can also offer the possibility of colourful imagery but with the possibility of greater subtlety and control. The ‘brick wall’ imagery overleaf illustrates this.

References

Ref1 https://www.cs.tau.ac.il/~turkel/imagepapers/ColorTransfer.pdf

Ref2 https://link.springer.com/content/pdf/10.1007%2F978-3-642-20404-3_1.pdf

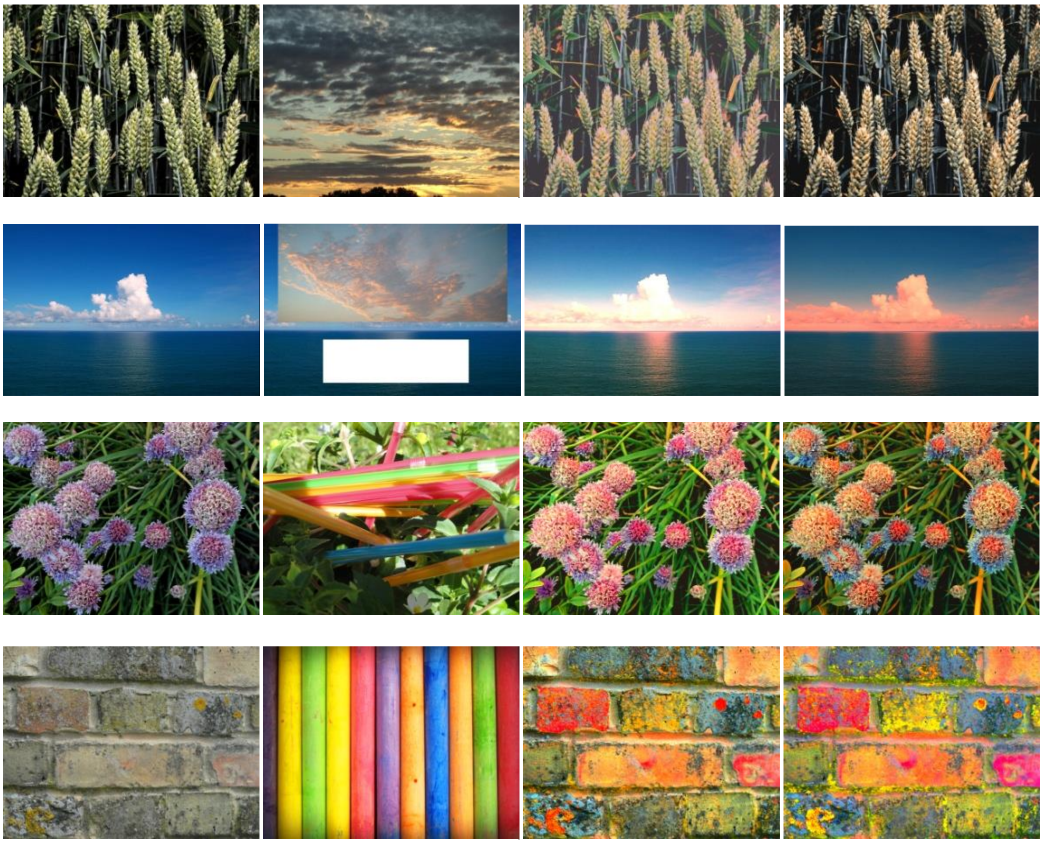
See overleaf for processing examples.

1. **Processing Examples**:

Various images are displayed below. There is a discussion of image quality thereafter.

In the examples below, ‘Basic Processing’ corresponds to a single iteration with data clipping, no cross correlation processing and source-image-derived shading, whereas ‘Enhanced Processing’ corresponds to two iterations, with data scaling, cross correlation processing and target-image-derived shading.

Target Image Source Image Basic Processing Enhanced Processing



## 2. Processing Comparisons:

Enhanced Processing Gradient Processing Posterize Processing Solarize Processing

Continued over

### 3. Iteration Comparison:

Target Image | Source Image | Enhanced Processing One Iteration | Enhanced Processing Two Iterations

Here the second iteration intensifies the colour but in this case the more muted colour of the single iteration is probably preferable.

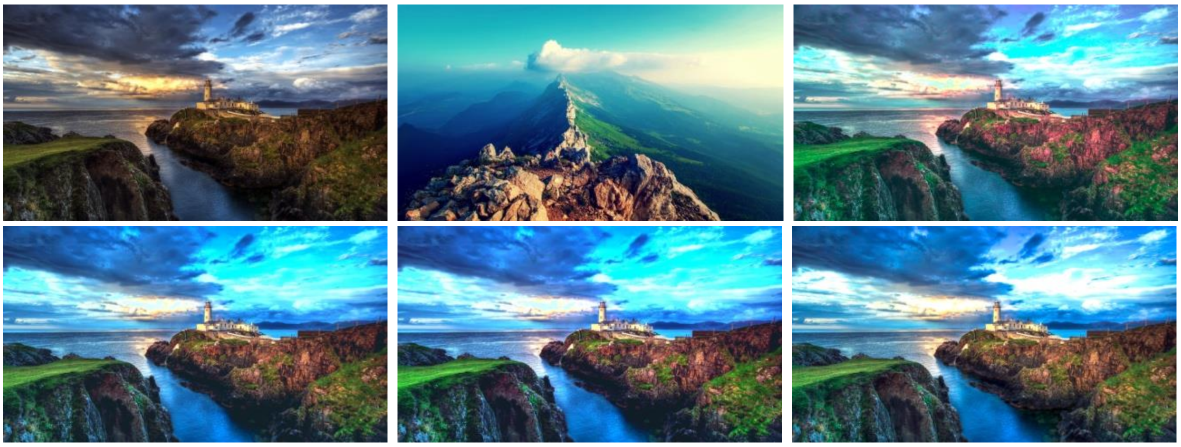
### 4. An Example of Photo-surrealism

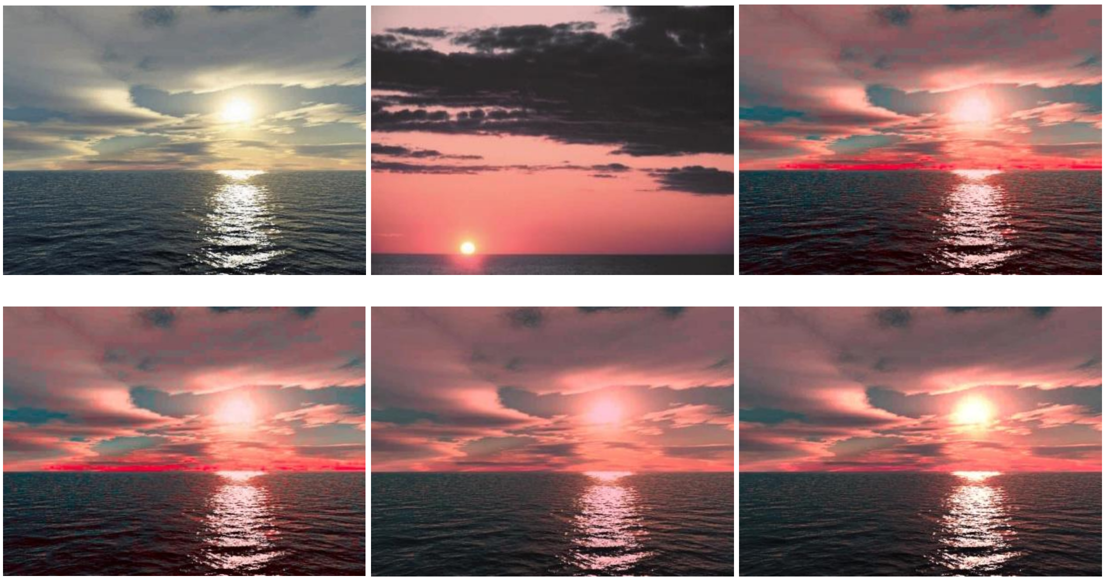
The image below was generated using 'Adaptive Re-colouring' a new processing method which is proprietary to T E Johnson. As with the preceding flower images, this image looks photorealistic in monochrome but the colouration is surreal.

### 5. Further Comparisons

The following show processed images and allow a comparison to the Photoshop images provided by 'ZZPot' ( [https://github.com/ZZPot/Color-transfer](https://github.com/ZZPot/Color-transfer) ). As discussed later, the quality of the processed images is somewhat compromised by the poor quality of the raw images.

The images are as follows: - target image, colour source image, enhanced processed image (L*a*b), standard processed image (lαβ), enhanced processed image (lαβ), Photoshop processed image. The enhanced lαβ processing corresponds to two iterations, cross correlation processing and source-image-derived shading. The enhanced L*a*b processing corresponds to one iteration, cross correlation processing and source-image-derived shading. Source-image derived processing is used to allow direct comparison to the Photoshop image.  Only one iteration is used for L*a*b processing since otherwise the colours are too vivid.





**6. Discussion**

The images which are subject to processing in section 5 originate from the following directory. https://github.com/ZZPot/Color-transfer/tree/master/images

The purpose of processing the above images is to allow some sort of cross check with a previous independent analysis.  That said the ocean images are problematic. There is clear evidence of a blocking effect due to jpeg artefact.  The cross correlation between the α and β channels is measured as 0.92 in the target image and 0.90 in the source image.

The purpose of the additional step in the enhanced processing method is to match the cross correlation in the target image to that in the source.  In this case however, the two correlation values are already closely matched so it would not be expected that the enhanced processing method would produce much noticeable improvement over the standard processing method.

Nevertheless, one could argue that the enhanced lαβ image is slightly more photorealistic particularly in regard to any bright red streaking just above the ocean boundary, but this advantage is marginal.

It can be seen that the enhanced lαβ image has less visible jpeg artefact than the enhanced L*a*b image and is therefore a more pleasing image. We cannot conclude however that the former processing is necessarily better. The artefact is a real feature of the image and it might be that the greater visibility of the artefact in the L*a*b image is an indication that the processing method has greater fidelity.

For the lighthouse image both enhanced images look credible. The Photoshop image has whitened cloud to the left of the lighthouse and this feature does not seem to relate too well to the pre-processed target image. The enhanced images are therefore judged to be of better quality. It has to be said that the source colour image is somewhat vivid and colour transfer processing in any case leads to images that appear too vibrant in part.

For the images in section 1, the enhanced images show some differences to the same images processed in the L*a*b colour space. (See sister document.) The same could be said for the images in section 3. It is not always clear which of the two processing methods produce the better images. In some cases where the image for one method is more pleasing, the alternative method may actually be more accurate in capturing the source colours. It has however been noted previously that where good quality images are not provided the enhanced colour transfer processing using the L*a*b space can show image defects with greater fidelity. Further discussion is given below.

Both versions of processing are provided here so that potential users can make their own comparisons and draw their own conclusions. Any feedback on this matter would be gratefully appreciated.

## 7. A Further Observation

There has been some tendency on GitHub to consider 'Lab' and 'lαβ' processing to be roughly equivalent, but in some cases there can be a quite significant divergence. Consider for example, the case where the target image is the so-called 'scotland_house' image and the source the so called 'scotland_plain' image. ([https://github.com/frcs/colour-transfer](https://github.com/frcs/colour-transfer)) The correlations between the target colour channels and the source colour channels for the Lab colour space are +0.88 and -0.90 respectively whereas for the lαβ colour space the correlations are +0.94 and + 0.73. Surprisingly, although the cross channel correlations are similar for the target image, they are grossly different for the source image. Not surprisingly, the images look very different when they are subject to enhanced colour processing as shown below for the case where the default parameters have been specified for processing in each case.

They are also different when subject to 'standard Reinhard processing' as further shown. It can be noted that the latter images are in agreement respectively with those shown in the following locations.

[https://github.com/pengbo-learn/python-color-transfer](https://github.com/pengbo-learn/python-color-transfer) [https://github.com/hangong/reinhard_color_transfer](https://github.com/hangong/reinhard_color_transfer)

These can be taken as independent verification of the difference observed between the cross correlation values for two processing methods.

Target Image

Source Image

Enhanced Processing
Lab Colour Space

Enhanced Processing
lαβ Colour Space

Standard Processing
Lab Colour Space

Standard Processing
lαβ Colour Space

In addition to the preceding images, it is useful also to address again the 'ocean scene' images. The correlations between the target colour channels and the source colour channels for the Lab colour space are +0.91 and -0.97 respectively whereas for the lαβ colour space the correlations are -0.66 and + 0.29. It can be seen that the outcomes of enhanced processing are quite different for the two colour spaces and it is not entirely clear which can be considered better although there might be some preference for the Lab image which looks more realistic. If consideration is given to the images processed by 'standard Reinhard', then the lαβ processed image appears to be a clear winner over the Lab processed image.

Target Image

Source Image

Enhanced Processing
Lab Colour Space

Enhanced Processing
Lαβ Colour Space

Standard Processing
Lab Colour Space

Standard Processing
lαβ Colour Space

It has been found that, in many cases, processing based upon the Lab and lαβ colour spaces produces images that are somewhat different but equally valid. In some instances however it has been found Lab processing can generate images that are clearly of poor quality where those arising from lαβ processing are acceptable. A large study would be needed to determine whether this is a general characteristic, but for the present it is best to err towards use of the lαβ colour space which was the colour space originally favoured by Reinhard et al.