Effect of Color Saturation and Hue on Image Quality

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Abstract

In this paper, it will be shown that the effect of color saturation and hue on image quality can be described in a very simple way.

From measurements given in this paper it appears that there is a remarkable agreement between color saturation and gamma with respect to their effect on image quality. From an earlier investigation it was found that image quality increases with the square root of gamma up to an optimum value of gamma and decreases with the inverse of the square root of gamma at higher values. It now appears that the eye reacts in a similar way on an increase of colorfulness, so that both effects can be described by the same type of equations.

From measurements on the effect of hue on image quality it appears that the image quality decreases linearly with the angular rotation of the color coordinates in CIELUV or CIELAB space, if the image quality is expressed in jnds. This decrease varies symmetric with the direction of the rotation.

Introduction

As described in a previous paper,[1] the eye reacts in a nonlinear way on luminance variations in an image around the average luminance. This effect can be explained by the voltage response of the cones at a variation of luminance. An example of this response is given in Figure 1. This figure shows the voltage response of the cones of a turtle measured by Burkhardt[2] for a single adaptation luminance. At a different adaptation luminance, the curve shifts to that level. As the cones of a turtle behave similarly as that of humans, these data can be used for a general description of the visual response of the eye at a variation of luminance. The measured voltage variation can be described by the following equation:

$$V = \frac{L}{L + c\,L_{\mathrm{ad}}} \tag{1}$$

where V is the voltage expressed in relative units varying from 0 to 1, L is the luminance, L_{ad} is the adaptation luminance, and c is a constant close to 1. The exponential slope γ of this relation can be calculated as follows:

$$\gamma = \frac{d(\ln V)}{d(\ln L)} = \frac{L}{V}\frac{dV}{dL} = \frac{1}{1 + \dfrac{L}{c\,L_{\mathrm{ad}}}} \tag{2}$$

For $L = cL_{\mathrm{ad}}$, $V = 0.5$ and $\gamma = 0.5$. This means that the voltage varies with the square root of the luminance around the average luminance of an observed image. This nonlinear behavior of the visual system was taken into account in the SQRI, or square-root integral, for the description of image quality.[3,4] At the time of development of this method, the here given data were not yet available, but perceptual data indicated already this behavior. The SQRI is given by the following equation:

$$J = \frac{1}{\ln 2}\int_{u_{\min}}^{u_{\max}} \sqrt{\frac{M(u)}{m_{\mathrm{t}}(u)}}\, \mathrm{d}(\ln u) \tag{3}$$

where u is the spatial frequency in angular units for the eye, $u_{\min}$ and $u_{\max}$ are the lowest and highest spatial frequency, respectively, of the image, $M(u)$ is the MTF of the imaging system, and $m_{\mathrm{t}}(u)$ is the modulation threshold of the eye. The SQRI expresses the image quality in units of just-noticeable differences, or jnds. The SQRI value increases with the square root of the modulation, as expressed by the square root of the MTF occurring in the formula.

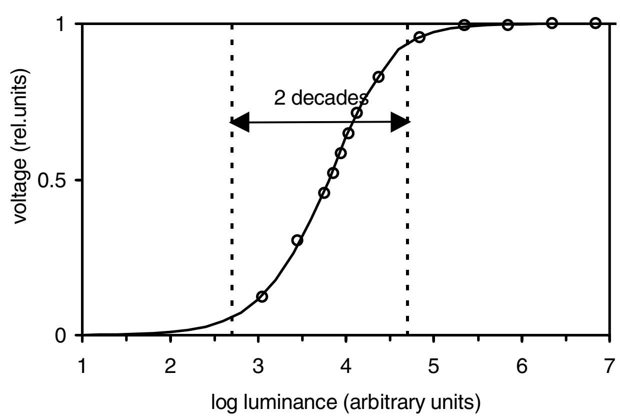

Figure 1. Voltage response of the cones of a turtle at a variation of luminance, measured by Burkhardt[2].

Effect of Gamma

The gamma of an image is the exponent of the exponential relation between input luminance L and output luminance L' of an imaging system:

$$L' = \text{const}\, L^{\gamma} \tag{4}$$

Although this exponential relation has a different effect on low luminance parts of an image than on high luminance parts, the average effect of gamma can be described[5] by a multiplication of the MTF with a factor γ. So, the effect of gamma on the SQRI value would be a multiplication with the square root of gamma:

$$J' = \sqrt{\gamma}\, J \tag{5}$$

where J is the SQRI value for $\gamma = 1$ and J' is the SQRI value for other values of gamma. However, it appears that this relation only holds for low values of gamma. At high values of gamma the dynamic luminance range of an image is increased, and the limited range of the eye of about two octaves, indicated in Figure 1, makes that image details in the dark and light parts of the image are not visible anymore. In practice, the luminance distribution of a natural scene can roughly be described by a rectangular probability density distribution over the logarithm of the luminance.[6] This is indicated by the continuous line for gamma = 1in Figure 2. The width of this distribution increases proportionally with gamma. However, above a certain gamma value, a part of the luminance area extends outside the visible range. If γ_o is the optimum value of gamma, the visible area is reduced with a factor γ_o/γ. Therefore:

$$J' = \sqrt{\gamma}\,\frac{\gamma_o}{\gamma}\, J = \frac{\gamma_o}{\sqrt{\gamma}}\, J \quad \text{for} \quad \gamma > \gamma_o \tag{6}$$

whereas Eq. (5) is valid for $\gamma \leq \gamma_o$. According to this model, the image quality increases with the square root of gamma up to an optimum gamma value, and decreases inversely with the square root of gamma at higher gamma values. An example of this behavior is given in Figure 3 with measurements by Mitsubayashi et al.[7] The measurements were made with five ITEJ standard images displayed on a CRT monitor with an average luminance of 14 cd/m^2. The measured data are the average of the judgments by fifteen observers on a 5-point rating scale. The optimum gamma appears to be 1.17 and the correlation between measurements and calculations is 99.3%, which is very high.

Similar measurements were made by Janssen et al.[8] with four images of natural scenes taken from a Kodak Photo CD and displayed on a CRT monitor with an average luminance of 9 cd/m^2. The results are shown in Figure 4. The measured data are the average of the judgments by seven observers on a 10-point rating scale. The optimum gamma is 1.25 in this case and the correlation between measurements and calculations is 98.0%. The measurements were made over a considerably larger range of gamma's than the measurements shown in Figure 3 and show, therefore, the typical behavior predicted by Eqs. (5) and (6) in a more pronounced way.

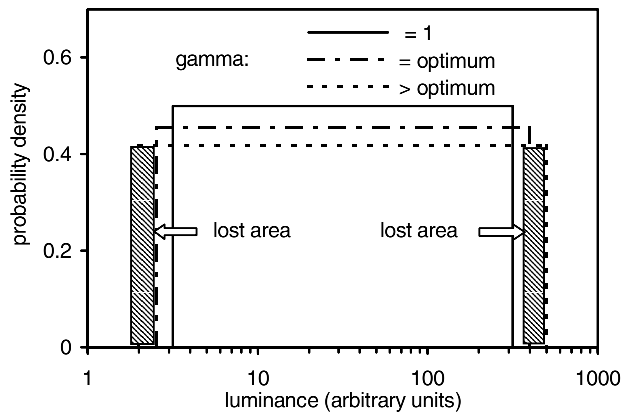

Figure 2. Schematic representation of the luminance distribution of a natural scene and the change of this distribution at an increase of gamma.

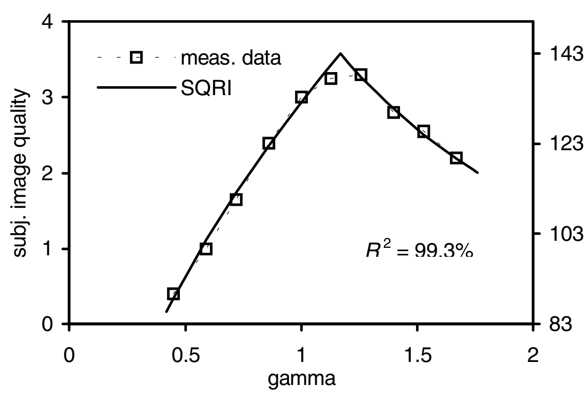

Figure 3. Effect of gamma on image quality measured by Mitsubayashi et al.[7]

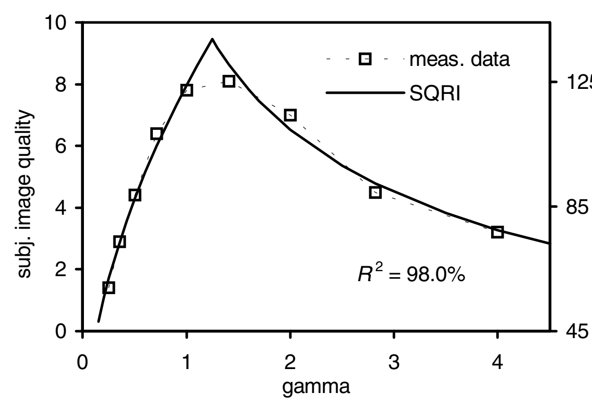

Figure 4. Effect of gamma on image quality measured by Janssen et al.[8]

Effect of Color Saturation

Janssen et al. also measured in the same investigation the effect of color saturation on image quality. They changed the chroma at a constant hue by a multiplication of the *u**, *v** coordinates of the images in seven steps, ranging from 0,5 to 2.0. The results are given in Figure 5. The dependence of the image quality on chroma shows a remarkable resemblance with the dependence on gamma. Therefore, the continuous curve through the data has been calculated with the same equations as used for Figures 3 and 4, apart from the fact that gamma was replaced by chroma and that the optimum value of gamma was replaced by the optimum value of chroma. The optimum value of chroma appeared to be 1.03. The correlation between measurements and calculations is 98.3%.

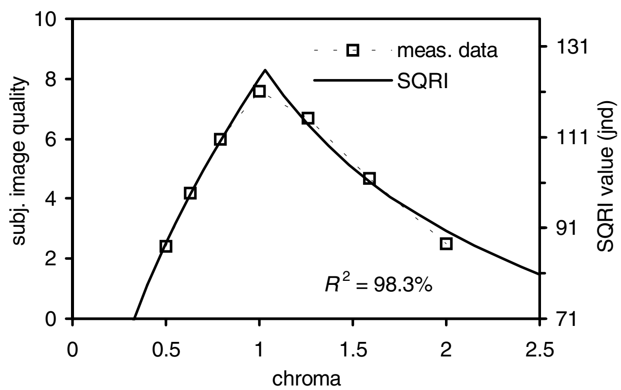

Figure 5. Effect of chroma on image quality measured by Janssen et al.[8]

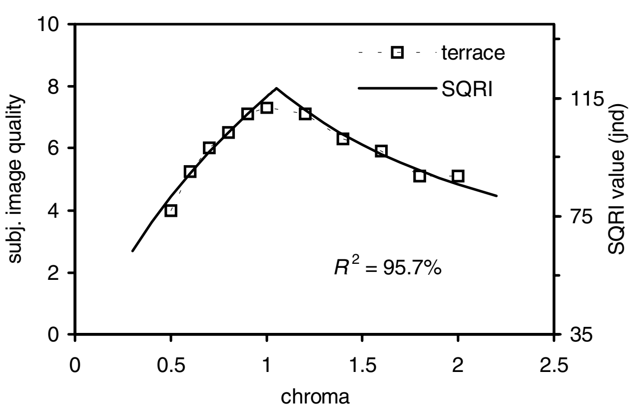

Figure 6. Effect of chroma on image quality measured by de Ridder et al.[9] *for "terrace" image.*

Similar measurements were made by de Ridder et al.[9] with four natural images displayed on a CRT monitor with an average luminance of 9 cd/m^2.The results for one image, "terrace", are shown in Figure 6. The measured data are the average of the judgments by ten observers on a 10-point rating scale. The optimum chroma value is 1.05 and the correlation between measurements and calculations is 95.7%. Compared with Figure 5, the observers used a much smaller range of the rating scale. This is caused by the fact that the same scale was also used for other experiments where the image quality varied over a larger range.

Effect of Hue

De Ridder et al. also measured in the same investigation the effect of hue on image quality. They changed the hue by an angular rotation of the coordinates of the images in the CIELUV system. As equal distances in *u*', *v*' color space should correspond with equal perceptual differences, equal angular rotations should correspond with equal differences in jnd. Therefore, it may be expected that the image quality expressed in jnds varies linearly with the angle of rotation. This has to occur in a symmetric way around the optimum hue angle. Figure 7 shows that this is indeed the case. This figure gives the measurement results for one image, called "Wanda", with the portrait of a female. The optimum rotation is -1° and the correlation between measurements and calculations is 95.9%. Figure 8 shows the results for a different image, called "building". The optimum rotation is -5° and the correlation between measurements and calculations is 94.8%. The slope of the curves in this figure is much smaller than in Figure 8 due to the smaller variation of the colors in this image.

It must further be remarked that the measured curves of Figures 3 through 8 show a rounding off in the top instead of a sharp peak. This is due to the spread of the measurement data caused by individual differences for the optimum value.

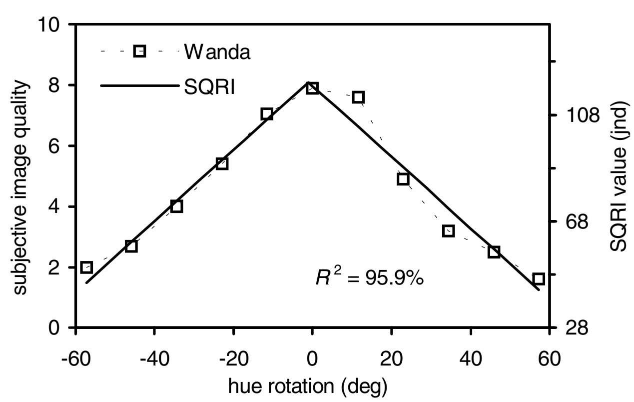

Figure 7. Effect of hue on image quality measurement by de Ridder et al.[9] *for "Wanda" image.*

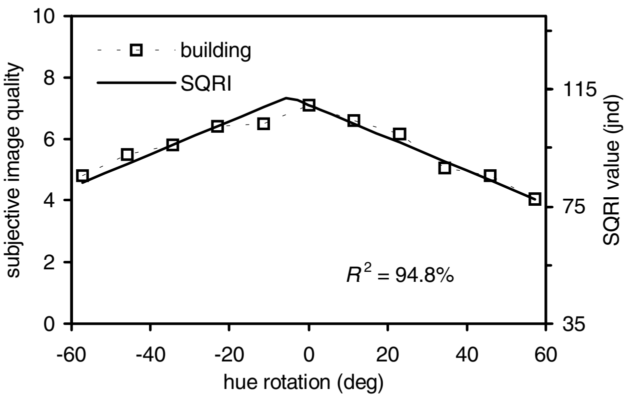

Figure 8. Effect of hue on image quality measured by de Ridder et al.[9] for "building" image.

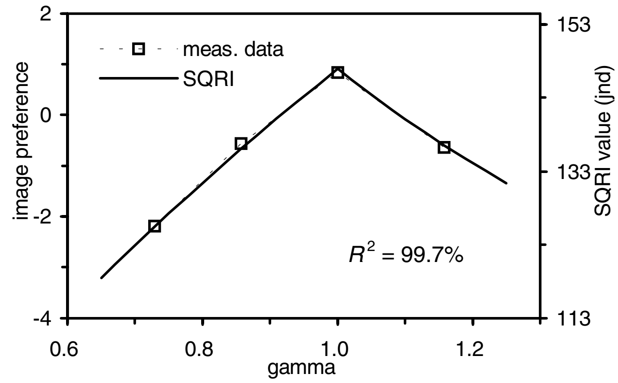

Figure 9. Effect of gamma on image quality measured by Calabria et al.[10]

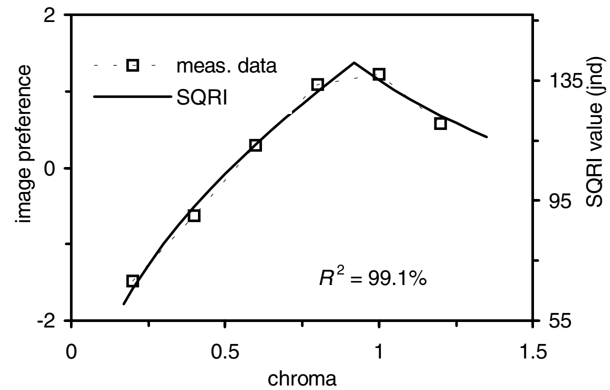

Figure 10. Effect of chroma on image quality measured by Calabria et al.[10]

Other Measurement Data

The trend that we noticed in the measurements by Janssen et al. and de Ridder et al., which were all made at the IPO (Institute for Perception Research) of the Technical University in Eindhoven, is also confirmed by measurements that were recently made at Munsell Color Science Lab in Rochester by Calabria et al.[10] and by Fernandez et al.[11] In these investigations various image parameters were varied and observers were asked for their preference. We will use here only the results for the variations of gamma, chroma and hue and will consider the image preference scale as scale of subjective image quality.

The measurements by Calabria et al.[10] were made with five natural images displayed on a 22" Apple Cinema Display LCD in a darkened room. The measured data are the average of the judgments by 32 observers. Figure 9 shows the results for a variation of gamma. As gamma was varied by a variation of the exponent of L^*, the corresponding value of gamma was calculated by multiplying this exponent by 3, as L^* is proportional to $L^{1/3}$. The optimum value of gamma was 1 and the correlation between measurements and calculations is 99.7%. In comparison with the measurements of Figure 3 and 4, gamma was varied in a much smaller range. Figure 10 shows the measurements by Calabria for a variation of chroma. This variation was made by a multiplication of the C^* values of the images in CIELAB space with six factors varying from 0.2 to 1.2. The optimum chroma value appears to be 0.92 and the correlation between measurements and calculations is 99.1%.

The measurements by Fernandez et al.[11] were made with eleven natural images printed with six variations on a Fujix Pictrography 3000 with a resolution of 300 dots per inch. They were observed at four different places in the world in office rooms with an illuminance of 2000 lux. 73 subjects of different cultures took part in the investigations. Main object of the investigation was to find out, if there were differences between the different cultures in their preferences. As the difference between the different cultures was not very significant (apart from a few exceptions), we will use here only the results averaged over all subjects. Figure 11 shows the results for a variation of gamma that was varied in a similar way as in the experiment of Calabria. The optimum value of gamma was 0.77 and the correlation between measurements and calculations is 97.1%. The data represent very well the characteristic behavior at a variation of gamma, but the low value of the optimum gamma value means that the original prints were made with a too high value of gamma. Especially the Japanese group preferred a lower value of gamma. Figure 12 shows the measurement results for a variation of chroma. This variation was also made by a multiplication of C* in CIELAB space. The optimum chroma value was 1.15. Especially the Japanese and Chinese observers preferred a more colorful picture. The correlation between measurements and calculations is 97.9%. Figure 13 shows the results for a variation of hue expressed in degrees in CIELAB color space. The optimum rotation was 0.9º. The measured data show a remarkable asymmetry for the rotation compared with the symmetric data of Figures 7 and 8. This does not need to be significant, because of the small range of rotations used. However, because of this asymmetry, the correlation between measurements and calculations is only 89.3%.

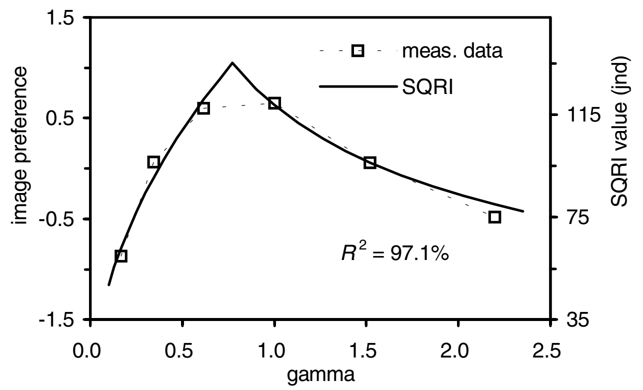

Figure 11. Effect of gamma on image quality measured by Fernandez et al.[11]

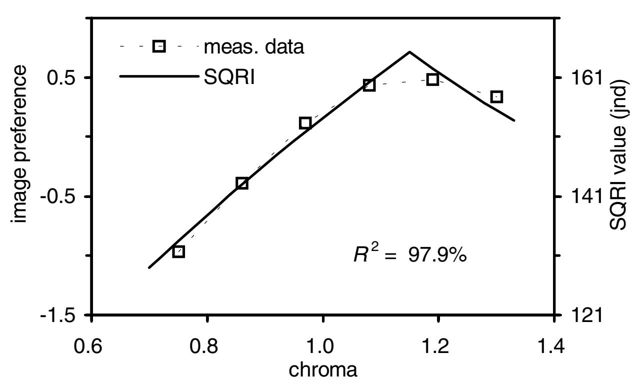

Figure 12. Effect of chroma on image quality measured by Fernandez et al.[11].

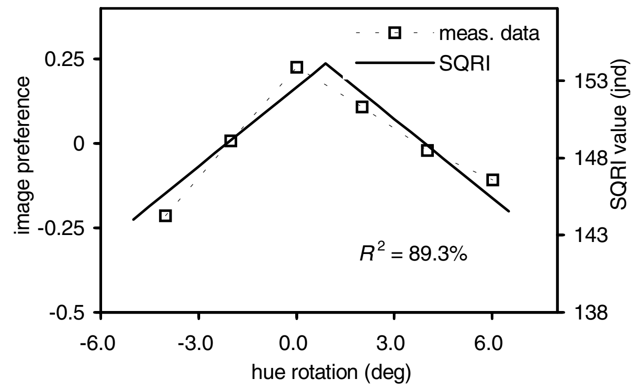

Figure 13. Effect of hue on image quality measured by Fernandez et al.[11].

Conclusion

Two simple laws have been given for the dependence of image quality on chroma and hue, respectively. They were derived from some characteristic qualities of the human visual system and were tested on a large number of measurements. According to these laws, image quality increases with the square root of chroma up to an optimum chroma value and decreases with the inverse of this quantity at higher chroma values. This behavior is similar to the dependence of image quality on gamma, which was earlier published by the author. The dependence on hue can simply be described by a symmetric linear decrease with the rotation angle in CIELUV or CIELAB space, as far as equal distances in these systems correspond with equal perceptual distances.

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References

1. P.G.J. Barten, Nonlinear effect of modulation on image quality. *Proc. PICS 2002*, 109-114 (2002).
2. D.A. Burkhardt, Light adaptation and photopigment bleaching in cone photoreceptors in situ in the retina of the turtle. *J. Neuroscience*, **14**, 1091-1105 (1994)
3. P.G.J. Barten, Evaluation of subjective image quality with the square-root integral method. *JOSA A,* **7**, 2024-2031 (1990).
4. P.G.J. Barten, Contrast sensitivity of the human eye and its effects on image quality. *SPIE Press, Bellingham, WA* (1999).
5. P.G.J. Barten, Effect of gamma on subjective image quality. *SID Digest*, **27**, 421-424 (1996).
6. J.H. van Hateren & A. van der Schaaf, Temporal properties of natural scenes. *Proc. SPIE*, **2657**, 139-143 (1996).

7. T. Misubayashi, Y. Shimodaira, H. Washio, H. Ikeda, T. Muraoka, and S. Mizushina, Gamma range of reproduced pictures having the quality above acceptable limits. *Proc. Eurodisplay '96*, 483-486 (1996).
8. T.J.W.M. Janssen & F.J.J. Blommaert, Image quality semantics. *Journal of IS&T*, **41**, 555-560 (1997).
9. H. de Ridder, F.J.J. Blommaert, and E.A. Federovskaja. Naturalness and image quality: chroma and hue variation in color images of natural scenes. *Proc. SPIE*, **2411**, 51-61 (1995).
10. A.J. Calabria & M.D. Fairchild, Compare and contrast: perceived contrast of color images. *Proc. 10th IS&T/SID Color Imaging Conf.*, 17-22 (2002).
11. S.R. Fernandez & M.D. Fairchild, Observer preferences and cultural differences in color reproduction of scenic images. *Proc. 10th IS&T/SID Color Imaging Conf.*, 66-72 (2002).

Biography

Peter Barten graduated in physics at the Technical University of Delft, the Netherlands, and received his PhD at the Technical University of Eindhoven. He worked many years at Philips in Eindhoven, where he was in charge of the development of color CRTs. After his retirement, he specialized on human vision and image quality. He introduced a formula for the contrast sensitivity of the eye and a new metric for image quality, called SQRI. He recently published a book on "Contrast sensitivity of the human eye and its effects on image quality". He is a member of SPIE and a fellow of the SID.