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Investigation of Hue Effects in Tooth Whiteness Perception

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Abstract

Objective: To identify the hue angles that provide the optimal perception of tooth whitening.

Methods: Thirty-three male/female adult observers with normal colour vision were recruited to assess teeth images on a colour calibrated display. Images of teeth were generated which simulated colour changes in each of eight hue directions in the CIE a*b* plane, each equi-distant from a baseline tooth colour. Using a paired comparison study design, observers were asked to indicate which of two images had whiter teeth. The data were converted into an interval scale using Thurstone's Law of Comparative Judgment. The relationship between the hue angles and the scores was modelled by curve fitting.

Results: The optimal hues were found in a region between green and blue in the CIE a*b chart. When the tooth colour travels in an optimal hue direction, the same amount of colour change will result in a greater change in whiteness perception than when travelling in other hue directions.

Conclusions: The optimal hues for tooth whitening were identified from the visual perception study. The most effective tooth whitening direction is to change tooth colour towards the greenish-blue hue direction.

Clinical Significance:

This study gives clinicians and researchers a better understanding of tooth colour hue effects in tooth whiteness perception.

Keywords:

Tooth whitening, hue, perception, visual assessment, psychophysics, appearance

1. Introduction

Tooth whitening has become increasingly popular in dental procedures and in home use products.[1] This trend has driven the development of many types of tooth whitening methods and materials. Tooth whitening products usually help to improve the overall whiteness of teeth, either by removing extrinsic stains or by changing the intrinsic colour.[2-5] Products that use the former approach typically contain an optimised abrasive cleaning system to remove and control extrinsic stains and may contain other materials to enhance this process.[6] Products that use the latter approach typically use hydrogen peroxide or carbamide peroxide to bleach the coloured materials within teeth to make them whiter.[5] An alternative approach to improving the intrinsic colour of teeth is via blue optical technologies, such as blue covarine, which when deposited onto the tooth surface can reduce the yellowness of teeth and make them appear whiter.[7]

Increased demand for tooth-whitening products means that the need to be able to quantify changes in tooth colour and whiteness changes is growing.[8] Conventionally, dentists and dental professionals assess tooth colour using a shade guide which provides a reference standard for visual comparison.[9,10] However, the consistency of human assessors is hard to guarantee because of variations in lighting condition, experience, age, fatigue of the human eye and colour blindness.[11] Alternatively, instrumental assessments are widely applied for tooth colour measurements, including colorimeters, spectrophotometers, spectroradiometers and digital cameras.[5]

Tooth colours measured by instruments are usually represented by CIELAB values. The variable L* represents lightness; the variables a* and b* represent chromatic values on red-green and yellow-blue axes respectively. Since colour systems are three dimensional, a colour can also be specified by lightness (L*), chroma (C*) and hue angle (h) in CIELAB colour space or L*C* h colour space as well. Chroma is the quality of a colour's purity, intensity or saturation. Hue angle is the degree to which a stimulus can be described as similar to, or different from, stimuli that are described as red, orange, yellow, green, blue, purple, and is represented in a range of 0^{o} to 360^{o} in the CIELAB system.[12] For example, the hue angle of the negative b* axis is 270^{o}, which represents blue colours.

In addition to these three-dimensional colour specification systems, tooth whiteness is generally considered as a one-dimensional perception scale and can therefore be quantified by a tooth whiteness index (WIO) [13]. The WIO index is based on the CIE whiteness index (WIC) and the CIE Yxy colour space.[12, 22] The tooth whiteness index WIO has been used in tooth whitening studies as a measure of efficacy for tooth whitening technologies, e.g. tooth bleaching products with hydrogen peroxide,[14,15] and toothpastes containing Blue Covarine.[16-20]

In colorimetry, whiteness is defined as an attribute of colours of high luminous reflectance and low purity situated in a relatively narrow region of the colour space.[21] It has been found that variations in whiteness can be caused by changes in colorimetric saturation in a range of dominant wavelengths (λ_d) approximately between 465nm and 475nm in the light spectrum. Thus, λ_d = 470 nm is selected as the reference dominant wavelength for neutral whites.[21,22]

For the WIO equation, the dominant wavelength of the hue preference for whitening is about 490nm[23], which is a cyan colour and this may suggest that green-bluish whites would appear whiter than reddish whites for teeth of equal saturation. However, this prediction is only a theoretical model, and the data is in the CIE chromaticity diagram (Yxy colour space), the true optimal colour change direction for tooth whitening, especially for the colour change in the more widely-used CIELAB colour space is unknown and needs to be investigated through psychophysical studies based on visual perception.

On-screen visual assessments have been used to investigate perception of tooth colour and dental appearance. For typical studies, digital images of teeth with varied dental appearances were assessed on a screen, for example, social impacts of tooth whitening were investigated in studies using such an approach.[24,25] The perceptive threshold of the tooth whiteness index WIO was investigated from a paired comparison psychophysical study with simulated teeth images. The colour of the simulated tooth was varied and observers were asked to respond whether there was a difference in whiteness between the original tooth and a simulated tooth.[26] In a recent study, a new CIELAB-based whiteness index (WI_D) has been proposed based on correlations with visual perception of shade guide tabs and dental materials.[27] The perceptibility and acceptability thresholds of the WI_D index were also investigated from a paired comparison psychophysical study with images of simulated upper central incisors.[28] The objective of this study is to identify the optimal hue angles in the CIELAB colour space that provide the greatest visual tooth whitening effect using an on-screen paired comparison visual assessment method.

2. Materials and methods

2.1 Tooth stimuli preparation

Two baseline tooth colours were used in this study. Baseline1 was defined by the mean L*, a* and b* values of baseline natural tooth colours from a previously published tooth whitening clinical study, where 160 upper central incisors of 80 subjects were measured.[19] The L*, a* and b* values for Baseline1 were 78.14, 7.51 and 30.44, respectively. Baseline2 was randomly selected from the same clinical study with L*, a* and b* values of 81.63, 5.37 and 27.27, respectively. Baseline2, with higher L* values and lower a* and b* values, indicate whiter teeth appearance than Baseline1.

The baseline teeth images were captured by a mobile digital imaging system[29] that was used in the previously published clinical study mentioned above.[19] The digital imaging system was calibrated and validated for tooth colour measurements *in vitro* and *in vivo*.[29] Camera RGB values of the teeth were obtained from the image and converted into CIE L*a*b* values through a camera characterisation model. Then the tooth colours in the image were modified in the CIELAB colour space to ensure the average L*a*b* values of the central upper incisors matched the specification of Baseline1 and Baseline2.

Tooth colours were then simulated with changes in each of eight hue directions in CIELAB colour space, all had which has an equal colour difference compared to the baseline tooth colour. The distance between the simulated tooth colour and the baseline tooth colour was set according to the average tooth colour change for a blue optical technology measured in a clinical whitening study, where the ratios between ΔL^*, Δa^* and Δb^* are 0.35:1.01:1.39.[19] After simulating the tooth colour with the ratios, the L* value was kept constant, while the a* and b* values were changed towards to eight hue angles with 10 degree intervals from 194^{o} to 264^{o} for the tooth colour simulations.

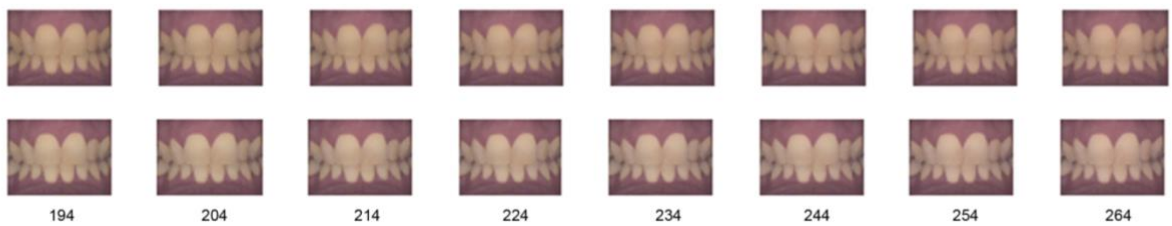

Figure 1: The simulated images for the eight angles, where the upper and lower rows are for Baseline1 and Baseline2, respectively.

Figure 1 shows the simulated teeth images for Baseline1 (upper row) and Baseline2 (lower row). A display unit (HP LP2480zx Firmware) was calibrated and characterised to ensure the accuracy of colour reproduction for image display.[30,31] A monitor characterisation model was conducted based on 27 colour samples with 9 neutral samples, 3 pure colours (red, green and blue) and 15 other coloured samples. The channel independence was estimated and its CIELAB colour difference ΔE^*_{ab} was 1.3 units with black correction.

2.2 Psychophysical study

Following independent ethical review and informed consent, a psychophysical study with 33 male/female adult observers with normal colour vision was conducted to investigate the hue effects in tooth whiteness perception. Using a paired comparison study design, pairs of images were shown in a random order on the colour calibrated display. For each trial a pair of images (17.6 cm × 13.2 cm each) were presented on the center of the display (see Figure 2 for the user interface) and viewed from a distance of approximately 80 cm. Observers were presented with a button underneath each image that they were instructed to click in order to make a choice about 'which image has whiter teeth'. Observers were asked to focus on the two central upper incisors when making their judgements. Each observer compared 28 pairs of images for each baseline (Baseline1 or 2) and in total 1848 observations (33 observers x 28 pairs x 2 repeats) were conducted in the psychophysical study.

Figure 2: The graphic user interface of the paired comparison experiment for choosing which image has whiter teeth.

2.3 Data analyses

For both baselines, frequency matrices were obtained for showing the results of the choices made by observers on every possible pair of images with different hue angles. Then the frequency matrices were converted into the percentage preference matrices by dividing the data with observer number, they were converted into standard normal deviate (z-scores) matrices by Thurstone's Law of Comparative Judgment.[32] Each image stimulus corresponds to a value in the scale of perceived tooth whiteness. The relationships between the hue angles and the visual scores were modelled by curve fitting in MATLAB (MathWorks. US). The findings of the model were also compared with the real hue changes of teeth from a published clinical tooth whitening study.[19]

3. Results

Table 1 shows the z-scores values of all teeth images obtained from the paired-comparison experiment for both tooth colour baselines. The z-scores measures the deviation of an observation from the mean value of the group, which represents the average perception scale of the stimuli for whiteness in this study.

Table 1: The z-scores of stimuli with different hue angles obtained from the paired comparison experiment for both baselines.

Hue angle	194°	204°	214°	224°	234°	244°	254°	264°
Baseline1	-0.6440	-0.2685	0.1726	0.1469	0.3696	0.2375	0.0886	-0.1028
Baseline2	-0.8304	-0.3565	-0.0636	0.2248	0.3388	0.4707	0.2033	0.0129

Second-order polynomial models were fitted between the z-scores and their corresponding hue angles for both baselines. Figure 3 and Figure 4 show the plots and curves fitted to the z-score values. The peak hue angles of the curves were found to be 235.5° and 239.5° for Baseline1 and Baseline2 respectively, which are considered the optimal hues for tooth whitening in visual perception. An 80% range to the peak values was identified for the two prediction curves, the hue angles of the borders of the 80% range are listed in Table 2.

Table 2: The peak hue angles and 80% border angles for the two baselines.

Tooth Image	Peak Hue Angle	Lower 80% border	Higher 80% border
Baseline1	235.5°	216.5°	254.0°
Baseline2	239.5°	220.0°	258.5°

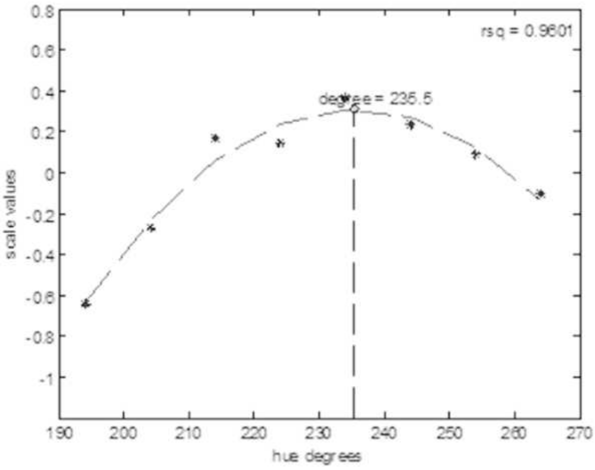

Figure 3: The plots of scale values against hue angles for Baseline1.

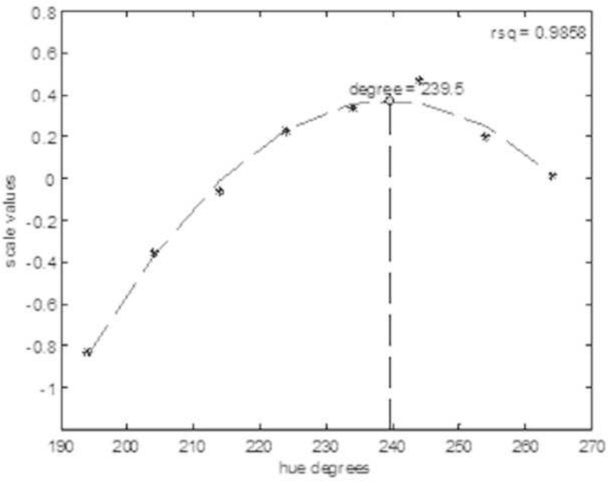

Figure 4: The plots of scale values against hue angles for Baseline2.

The optimal hue angle identified from the current study was plotted in the CIE a*b* chart in Figure 5, as well as the hue angles of a real tooth colour change from a published clinical study. [19] From the published clinical study, following use of a toothpaste containing blue covarine, a* decreased 1.01 units and b* decreased 1.39 units for the average tooth colour change, The clinically measured tooth colour change direction of this blue covarine technology was found to be 234° in the CIELAB colour space, comparable with the optimal hue angles identified from the current study.

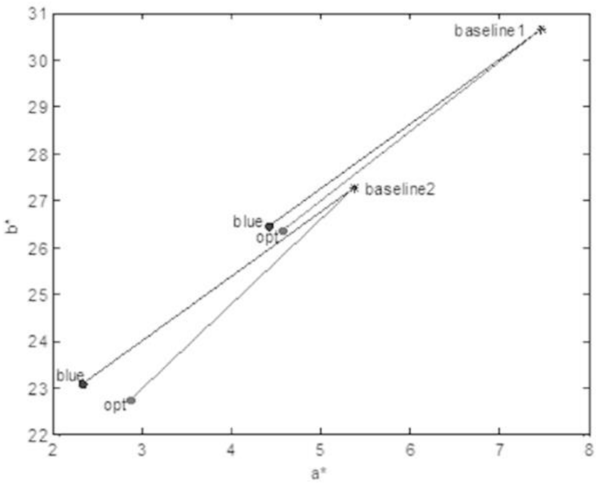

Figure 5: Hue angles of the average tooth colour change following use of a toothpaste containing blue covarine19 (blue) compared with the predicted optimal hue angles for the two baselines (opt).

4. Discussion

Psychophysical methods utilising on-screen visual assessments have previously been described to investigate perception of tooth colour and dental appearance. For typical studies, digital teeth images with constant gum or facial features and varied dental appearances were assessed on a screen, for example, social impacts of tooth whitening were investigated in studies using such an approach.[24,25] In another study, the perceptive threshold of the tooth whiteness index WIO was investigated from a paired comparison psychophysical study with simulated teeth images. [26] The new CIELAB-based whiteness index (WI_D) was proposed based on correlations with visual perception of shade guide tabs and dental materials.[27] The perceptibility and acceptability thresholds of the WI_D index were also investigated from a paired comparison visual assessment study with images of simulated upper central incisors.[28] The current study used a similar method for a typical paired comparison study, with two images placed side by side on the screen and judgements asked from observers. Since the objective of this study was to investigate the optimal hue in the CIELAB colour space for tooth whitening, with the aim to find the most efficient colour change direction in the three-dimensional colour space, the single scale whiteness indices (WIO or WI_D) were not relevant to quantify the colour change directions.

Considering the perceived tooth whiteness scores for the eight stimuli derived from each baseline (Table 1), the z-scores of the hue angles increase then decrease with the hue angle increasing from 194^o to 264^o. Figure 3 and Figure 4 clearly illustrates the bell-shaped curves of the perceived whiteness change versus the hue change. The peaks of the hue angle curves were found around 235.5° for Baseline1 and 239.5° for Baseline2, which is located between the green axis (hue angle equals to 180°) and the blue axis (hue angle equal to 270°) in the CIELAB colour space. This indicates that when tooth colours change with the same amount from the baseline colour, the optimal hue angles for whitening are found in a region between the green and blue colours in the CIELAB colour space. This finding aligns with the previous theoretical prediction from the data modelling of the iso-whiteness lines for WIO, where the dominant wavelength of 490nm, a cyan colour, was found to be the most efficient direction in the CIE xy chromaticity diagram for the tooth whitening.[23]

When the tooth colour travels in an optimal hue direction, the same amount of colour change will result in greater change in whiteness perception than travelling in other hue directions. The data in Table 2 demonstrates that for tooth whitening products, the hue angle of the tooth colour change should ideally be within the 80% borders, which is approximately from 217° to 259° for the hue angle in the CIELAB system to ensure efficient tooth whitening efficacy.

The Baseline2 image had whiter teeth than the Baseline1 image, where L* value was higher, a* and b* values were lower, the results indicated that the baseline tooth colour may have an effect on the optimal hue for tooth whitening. Whitening changes in a bluer direction was more efficient for whiter teeth than darker teeth. In other words, for darker teeth with lower lightness and higher chroma/saturation, a greener hue of colour change is more optimum for tooth whitening.

In Figure 5, the average tooth colour change direction due to use of the toothpaste containing blue covarine was found to be 234° in the CIELAB colour space. It can be seen that the tooth colour change direction as measured in the reported clinical study is very close to the optimal hue angle for tooth whitening as identified in the current psychophysical study, where 235.5° for an average baseline tooth colour and 239.5° for a random baseline tooth colour. For tooth whitening, it is recommended to use the optimal hue angles as guidance for the most efficient whitening direction, by moving along the lines of the optimal hue direction as shown in Figure 5 from a given baseline tooth colour.

The findings from this study, based on human visual perception responding to simulated tooth colour changes, demonstrated that if the tooth colour changes towards to the greenish blue direction in the colour space then the tooth whiteness will be improved more efficiently. The relationship between the colour of oral products (foam or slurry) and tooth colour changes was not in the scope of this study, which remains an open area. Further studies will be needed to identify the most effective material colours for optical tooth whitening.

5. Conclusions

The optimal hues for tooth whitening were identified from the visual perception study. The most effective tooth whitening direction is to change tooth colour towards the greenish-blue hue direction.

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