Assessment of base color influence on the chromatic appearance of hair colorants

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ABSTRACT

Hair colorants of the so-called 'series of naturals', a scale of ten colors ranging from deep black to light blonde, are universally recognized as a reference basis for hair coloring procedures. However, it is frequently observed that application results are heavily dependent both in tone and in nuance on the underlying hair pigmentation. We hereby assess the chromatic appearance of a selection of globally marketed series of naturals, both on animal fur and on human dyed hair. Notably, the latter are chosen so to span a consistent range of melanin base, with a varying degree of interlaced depigmented strands. The analysis is carried out by means of a perceptual test based on the Munsell Book of Color, aimed at assessing the perceived tone and nuance with a special focus on the linearity of the scaling.

KEYWORDS hair coloring, cosmetic, color appearance, Munsell Book of Color

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1. Introduction

Judging the appearance of hair color is an essential task for proper salon service. Hair professionals routinely assess hair color at different stages of the coloring process including, but not limited to, once at the beginning, when hair current situation must be evaluated both in terms of tone and nuance; every time hair is rinsed from excess product; after a potential bleaching, by means of which hair basic tone is heavily lightened; after tonalization, a slight nuance correction usually employed to balance out residual and undesired undertones. These assessments leave little room for error, and in fact, customer satisfaction is reportedly low for a variety of technical reasons (Negretti, 2021).

Setting aside high-level human perceptual processing, color appearance is strictly dependent on a multitude of external factors. The artificial lightning of hair salons, for instance, is often designed around scenic impact, while its functional side leaves much to be desired. Not only are common LEDs spectral distributions unsuited to appropriate color evaluation, but their spatial placement is critical with respect to human vision. As an example, light bulbs framed behind mirrors may create glare, and directional lamps usually cast unwanted shadows over customers' heads and faces. Moreover, color blindness should be accounted for, ideally both in customers and in hair professionals (Fusari, 2021), and so should their ability to discriminate subtle color differences. Contrary to direct colors, which can be very easily told apart because of their brightness and saturation, more traditional (and vastly more requested) oxidizing products cannot. To name but an example, nuance 7.34 is golden copper blond, while 7.43 is copper golden blond: very similar to one another, yet slightly different in their predominant nuance. Finally, no actual standard exists in hair salon practice for proper color identification. A simple yet smart color naming scheme does in fact exist (Toninelli *et al.*, 2021), but its practical adoption is highly arbitrary among different color brands, so that hair color charts may very well associate different colors to the same nuance, both in terms of lightness and of predominant hue (Rizzi *et al.*, 2021).

In this paper, a method is described for assessing hair color that tries to compensate for all of these factors in a controlled environment. This method has already been detailed in (Toninelli *et al.*, 2021) for nylon swatches out of hair color charts, but this time, special emphasis is being put on the relevance of the effect of base color on the final appearance of hair colorants on actual hair samples.

2. Materials and methods

Three series comprised of ten hair swatches each were used for testing. Series number one (S_1) is composed of yak hair strands collected from Mongolian and Chinese animals, with next to no residual melanin, about 17 cm long (of which 14 cm available for coloring) and 1.4 g heavy, clipped at one end by means of a plastic zip-tie (Fig. 1-left). Series number two (S_2) is a mixture of grey hair (80%) and white hair (20%), mimicking a situation frequently occurring on the heads of beauty salon customers (Fig. 1-middle). Finally, series number three (S_3) was originally comprised of ten chestnut brown swatches (tonal height 4.0, see below), on which a preliminary depigmentation was carried out by means of a 10-tones bleaching powder (21VENTUNO by Universal Beauty Products) (Fig. 1-right). In order to attain greater consistency, all swatches in S_3 were bleached at the same time by means of a mixture of the abovementioned powder and a 40-volume oxidizing agent (21VENTUNO by Universal Beauty Products) in a 1:2 ratio. Swatches were then wrapped in tinfoil and left in a stove at 30° C for 50 minutes. Excess product was washed away in lukewarm tap water, rinsed in ~1 g of pH 5.5 shampoo (Post Color Back Bar Luxury), washed a second time and then coated in ~1 g of a pH 4.5 hair conditioner (Post color Back Bar Luxury) in order to seal cuticles. Swatches were rinsed one last time, and finally blow-dried at about 160° C temperature.

Fig. 1. Samples of the different swatches: yak hair (S_1 left); 80/20 mixture (S_2 middle); bleached 4.0 (S_3 right - original 4.0 can be seen at the top).

The series of naturals was chosen for application on these samples. Such series broadly classifies and arranges ten colors commonly occurring in human hair: '*Black*' (1.0), '*Deep Dark Chestnut Brown*' (2.0), '*Dark Chestnut Brown*' (3.0), '*Chestnut Brown*' (4.0), '*Light Chestnut Brown*' (5.0), '*Dark Blond*' (6.0), '*Blond*' (7.0), '*Light Blond*' (8.0), '*Very Light Blond*' (9.0), and '*Platinum Blond*' (10.0). In order to minimize inconsistencies, every color in the series was applied simultaneously to a single swatch out of S_1, S_2, and S_3. Thus, because no differences existed either in the mixture or in the application thereof, variations in color appearance could safely be ascribed to the base color alone.

The dyeing process was carried out in a controlled laboratory environment at 25° C, by mixing a 20-volume (21VENTUNO by Universal Beauty Products) developer in a 1:1.5 ratio. Colorants (Color Space Primary by Universal Beauty Products) were applied lengthwise on both surfaces and in both directions in order to achieve maximum penetration within the shafts—then wrapped in tinfoil and put inside a stove at 30° C. After 25 min, swatches were removed from their encasing, washed in lukewarm tap water to remove excess product, rinsed in ~1 g of pH 5.5 shampoo (see above), rinsed a second time and then coated in ~1 g of a pH 4.5 hair conditioner (see above). Swatches were rinsed one last time, dried with a dabbing cloth and a hairdryer (160° C maximum temperature), all the while straightening and disentangling them with a round hairbrush and a fine-toothed comb. Finally, they were arranged in a horseshoe-like flat shape by tying loose ends together with a thin cord after a 180° folding about the midpoint (see again Fig. 1 for reference).

In order to evaluate the predisposition to differentiate between minute hue variations, all test participants were administered the Farnsworth-Munsell 100 Hue test before the actual perceptual experiment. In it, eighty-five colored caps [1] that span the entire range of Munsell Hues at both Munsell Value and Chroma 5 needs to be arranged along four black plastic rows. Test participants were instructed to rebuild the Hue series connecting the two anchored caps at both ends of each row, one cap at a time. The rebuilt order can easily be checked by turning caps upside down, for they are unequivocally numbered. The result (called Total Error Score, TSE in short) is an integer figure that accounts for positioning mistakes: the further apart two consecutive caps are placed, the greater the score.

Perceptual experiments were carried out inside a custom-made lightbox on whose inner ceiling two LED lamps were mounted and directed towards the core of the observation chamber. These sunlike LEDs by Toshiba are meant to cast a nominal 5000 K light closely mimicking the ideal behavior a black body emitter, i.e.: the Sun. In order to better diffuse this light within the box, a frosted glass panel was securely fitted under the lamps, and inner walls were painted in uniform white. Illuminance measurements were acquired with a CL70F illuminance meter by Konica Minolta: luminance was 6900 lx; correlated color temperature was 4880 K; the visible spectrum is plotted in (Fig. 2).

At the core of the perceptual experiment lies The Munsell Book of Color, matte edition. Rather than providing the participants with entire Hue pages, a pre-emptive selection of colored chips was arranged for perceptual matching. Since each Hue page contains about thirty chips on average, providing two to three pages in order to guarantee a sufficient degree of variability with respect to Hue could have rapidly led to visual fatigue.

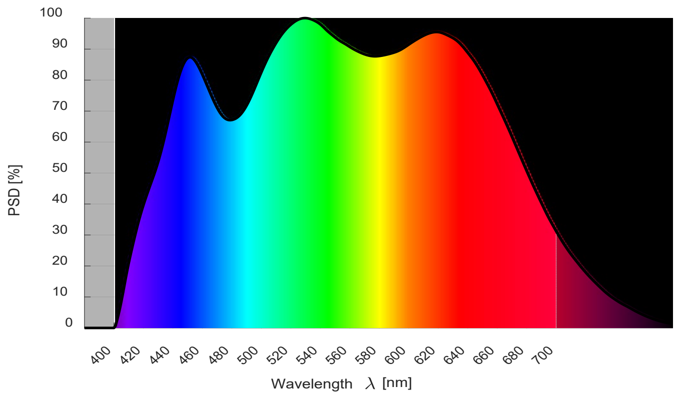

Fig. 2. Illuminance spectrum of the Toshiba LEDs used in the custom-made lightbox (normalized by its peak value around 530 nm).

Moreover, pages in the Book are consistently organized in an orderly fashion, with Values steadily increasing from bottom to top, Chromas from left to right. Such framing was feared to enable undesired patterns in the choice of chips. All this considered, fifty chips total were provided in order to encompass a sufficient variety of Hues, Values and Chromas. The final shortlist was agreed upon within the lightbox and arranged across two concentric circumferences on a white disc where slits were cut to accommodate the chips, and then numbered randomly from 1 to 50. An unbleached paper was chosen whose colour would closely match the one found on pages of the Book, which is inherently designed to be neutral [2]. On the 45°-sloped upper surface of a hollow wooden hemi prism a similar paper was affixed, and a metal peg was clasped in its center. The disc with Munsell chips was hooked on the peg, and then hair swatches on top of it, one at a time, so that the disc could be spun by participants to better match chips to swatches.

Visual matchings took place strictly inside the lightbox. The order of presentation of the swatches never followed the rightful sequence of the natural series. Instead, they were shown in steps of 3, i.e.: 1-4-7-10-2-5-8-3-6-9. This way, biases by virtue of reasoning were avoided, and actual perception was relied upon. Participants were instructed not to touch nor to remove neither swatches nor chips, and were only allowed to spin the disc. When a match was found, the test administrator recorded the corresponding number, and matched it to its Munsell nomenclature for further processing. Finally, test participants were asked a qualitative evaluation of test difficulty on a scale ranging from 1 to 5, namely: 1 - easy; 2 - somewhat easy; 3 - neither easy nor hard; 4 - somewhat hard; 5 - hard. An answer was requested after every match, but only for S_3, which was administered last. By that point participants were confident with the overall task, so judgements could be passed on the swatch matching alone.

3. Results

A total of 15 test participants was recruited, of whom six males and nine females, aged 21 y to 40 y. No subject suffered from any kind of medically certified or self-reported color anomaly or color blindness. The mean total error score (TES) of their Farnsworth-Munsell 100 Hue tests was ~17 ('*Average Discrimination*', yet very close to the range 0 to 16: '*Superior Discrimination*'). Errors made had likely little to no influence on the perceptual performance. The Munsell Colour Solid accounts for a total of 100 Hues, but in fact only 40 of them are physically available in the most complete versions of the Book. Thus, all chips there contained—which were also those displayed in the matching test—are set two and a half Hue steps apart (100 divided by 40). The original Farnsworth-Munsell's test consisted of 100 caps, which were consequently set more or less 1 Hue step apart. Because the modern version of the test is comprised of 85 caps, these are set ~1.18 Hue steps apart (100 divided by 85) [3]. Therefore, a two-steps cap misplacement is required to approach the 2.5 Hue gap typical of painted chips. Since the greatest portion of misplacements in the test was made up of one-step swaps, test-participants were expected to tell Book chips apart confidently, at least as far as Hue was concerned. Furthermore, Hues involved in the actual perceptual test (mostly desaturated oranges and yellows) were all comprised within the less misjudged row.

Dealing with results of the perceptual test requires working on Munsell alphanumerical specifications, e.g.: 5GY 4/10. Values and Chromas are always numbers (respectively 4 and 10 as per the example), whereas Hues are composite of an arabic digits (5) followed by a short character tag (GY). The latter specifies Hue itself among a set of 10 total, of which 5 primaries (Red-Yellow-Green-Blue-Purple) and 5 secondaries (YR-GY-BG-PB-RP). The former provides instead a degree of membership to such label, with 5 being the center-most eponymous step, and the remaining 2.5, 7.5 and 10 stretching both sides towards adjoining Hues on the circle. Another nomenclature also exists coined by A.H. Munsell himself (the so-called *inner loop*), that orders Hues on a purely numerical basis starting from 1 at 1R and ending at 100 at 10RP. This decimal scale is precisely the naming convention that was used for Hue calculations.

Medians and interquartile ranges (IQR: 2^{nd} to 3^{rd} quantiles, or 25^{th} to 75^{th} percentiles) were chosen over mean and standard deviation. Data are discrete, because chips are as well, but not strictly ordinal: interval scales are known, and in fact Munsell color-order system is explicitly built on the premise of having adjacent Hues, Values, and Chromas scale uniformly with respect to human perception. There is no reason to believe the distribution to be normal, and in fact data contain a few outliers. As for symmetry, IQRs often show a distinct skewness, which is useful for inferring a qualitative tendency of the data. For instance, Munsell Values for 80/20 swatches 5.0 and 6.0 are both 3, but the IQR of 5.0 is fully compressed onto the median, whereas 6.0 only has a non-zero third quartile. Therefore, 5.0 and 6.0 have about the same tonal height, but 6.0 could in fact appear slightly lighter. Results are shown for the three types of swatches on a per Hue (Fig. 3a), Value (Fig. 3b), and Chroma basis (Fig. 3c). Median values are also shown for the difficulty evaluation task: the top row in Table 1 shows results relative to swatches, the bottom row relative to test participants. Finally (Fig. 3d), the three types of swatches are grouped for a three-way comparison (again based on Hue, Value, and Chroma).

1.0	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**7.0**	**8.0**	**9.0**	**10.0**					
2	2	3	2	3	3	3	2	2	3					
#01	**#02**	**#03**	**#04**	**#05**	**#06**	**#07**	**#08**	**#09**	**#10**	**#11**	**#12**	**#13**	**#14**	**#15**
4	1.5	2.5	2.5	3.5	2.5	2	2	2	3	3	2.5	3	2	2.5

Table 1. Qualitative evaluation of test difficulty (only median values are reported on a scale ranging from 1 to 5, namely: 1 - easy, 2 - moderately easy; 3 - neither easy nor hard; 4 - moderately hard; 5 - hard), grouped per hair swatch (first row), and test subjects (second row).

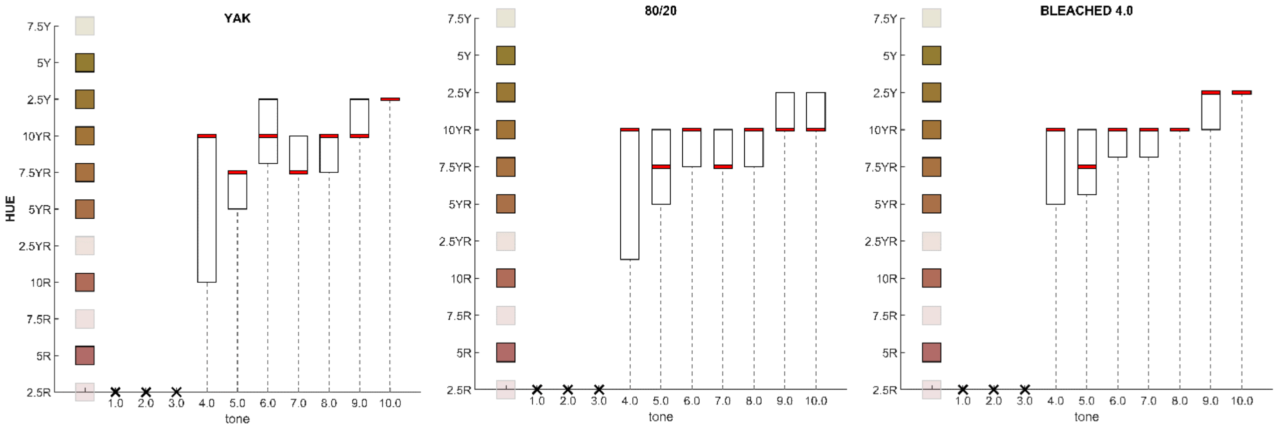

Fig. 3a. Left to right: Hue results of the perceptual experiment for Yak, 80/20, and Bleached 4.0 hair swatches. Medians are marked in red; the second and third quartiles with white vertical bars. Small black crosses indicate an absence of Hue, i.e., an achromatic swatch (here: black). Colored squares next to the y axis are approximations of Munsell chips (Value 5, Chroma 5). Colors are solid for attributes available in the chip selection, transparent otherwise.

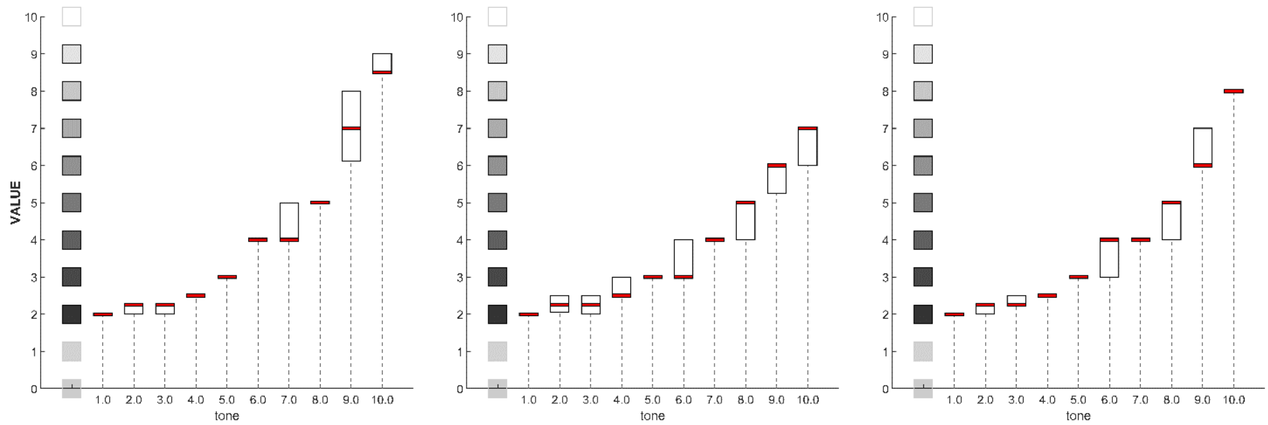

Fig. 3b. Left to right: Value results of the perceptual experiment for Yak, 80/20, and Bleached 4.0 hair swatches Medians are marked in red; the second and third quartiles with white vertical bars. Colored squares next to the y axis are approximations of Munsell chips. Colors are solid for attributes available in the chip selection, transparent otherwise (please note that Neutrals 0 and 10 represent perfect black and perfect white. As such, they are physically unavailable).

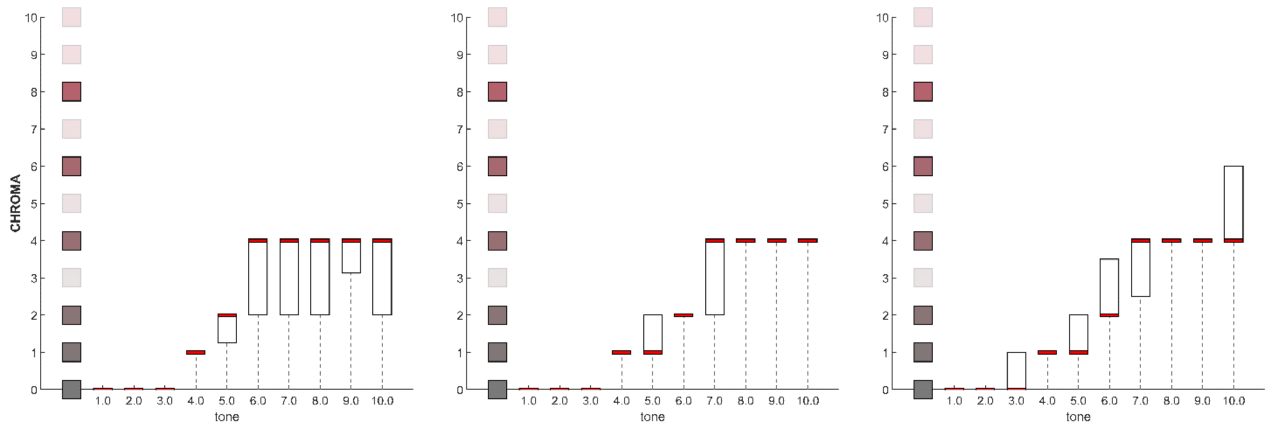

Fig. 3c. Left to right: Chroma results of the perceptual experiment for Yak, 80/20, and Bleached 4.0 hair swatches. Medians are marked in red; the second and third quartiles with white vertical bars. Colored squares next to the y axis are approximations of Munsell chips. Colors are solid for attributes available in the chip selection, transparent otherwise. The discrete nature of the chips is especially apparent here. In fact, Chroma steps are arguably too wide for this application.

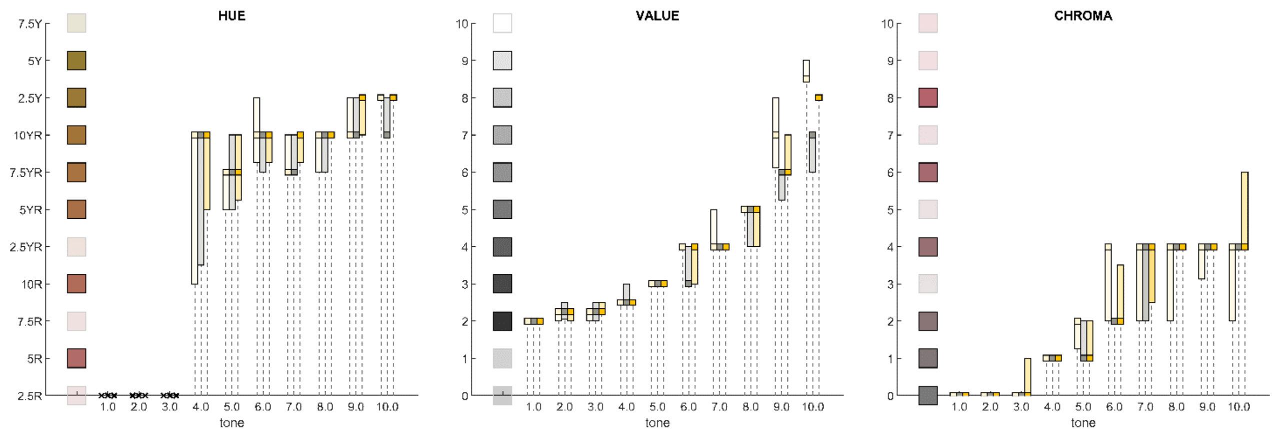

Fig. 3d. Comparison of Yak (white), 80/20 (grey), and Bleached 4.0 (yellow) hair swatches, grouped by Hue (left), Value (center), and Chroma (right). Medians are solid squares; quartiles are discolored bars.

4. Discussion

A method for the evaluation of dyed human hair color appearance has been described. Three different kinds of hair swatches were colored with the same series of naturals: yak hair; a mixture of 80% grey hair and 20% white hair; and finally, bleached brown hair. Observations were made under sunlike Toshiba LEDs by 15 participants previously tested for their ability to distinguish among colors. Results were reported in terms of the Munsell color-order system, which is widely employed worldwide for color appearance test, yet not for hair. We think, on the contrary, that its attributes Hue, Value and Chroma can be used for evaluating specific hair features such as, respectively, nuance, tone, and intensity (Liberini and Rizzi, 2022). The test has been generally well received: 10 out of 15 participants judged it overall easy, and the matching was considered moderately easy for half of the available swatches, neither easy nor hard otherwise, usually in this case due to a greater variety of undertones.

Contrary to common salon practice and color wheels depicted on hair color charts, where usually all tones of a given nuance are arbitrarily assigned a single hue (Rizzi *et al.*, 2021), Munsell Hue suggests differences along the series. As the Munsell Book of Color clearly outlines, the generic color ‘brown’ can refer to dark and desaturated versions of either red, orange, or yellow. Considering both median values and quartiles (Fig. 3a), hair browns (2.0 to 5.0) start in the orange region and slowly drift towards the yellow region, where blonds (6.0 to 10.0) are also identified. The transition is not smooth, partly due to swatch 6.0 appearing a little too yellow both on yak and on 80/20 in this particular color line. When compared on the basis of Hue (Fig. 3d, left), the three different hair types show small differences especially in the lighter swatches: assuming yak as a reference, the same 10.0 appears slightly less yellow once applied to the 80/20 mix, and conversely more yellow on bleached hair. This is likely due to swatch 10.0 shortcomings both in removing pre-existing melanin, and in covering up its residuals. In fact, it is easier and more reliable to cover fair hair in dark colors than the opposite, where bleaching is also required. For dark hair, on the other hand, judging Hue appears more prone to error, as the generally wider IQR bars clearly show. In this case, another misjudgment appears: very dark brown 2.0, and dark brown 3.0 were, on average, perceived as blacks. This shows through the combined reading of Hue and Chroma: the latter being 0 implies the absence of the former. The fact that this holds true for all tested hair types suggests on one hand a very good coverage of the underlying hair, yet on the other hand, that 2.0 and 3.0 should perhaps be better formulated in order to appear more chromatic. That being said, failure in perceiving a weakly chromatic Hue might in this case be ascribed to the reduced ability of the human visual system to discriminate colors of dark stimuli with reference to the white of the paper sheet and lightbox walls, due to crispening. Swatch 1.0, i.e.: black, was correctly perceived as achromatic.

The most striking feature regarding Value is its perceptual non-linearity (Fig. 3b). Ideally, should the series of naturals be perfectly scaled at equal intervals, at least as far as human perception is involved, their Values would all fall along a straight line, reflecting Munsell Value linearity. Results suggest a quadratic distribution, where browns are much closer to one another than blonds are. Value is also the attribute which highlights base color effects the most. The endpoint for yak, the most neutral base, is 8.5; it is slightly lower at 8 for bleached brown; and conspicuously lower at 7 for the 80/20 mix. Again, this is due to the fact that lighter blonds have far less impact on the underlying hair color. Because of this, and contrary to Hue, a generally greater variation in Value assessment is attained in the blond half of the series, where residual natural pigment is removed more erratically than intended.

Any comment on Chroma is somewhat slightly marred by the intrinsic limitations of the Book, where this attribute is shown on colored chips in increments of 2. Also, chromatic swatches, i.e.: those from 2.0 upwards, very rarely rise above Chroma 4. All things considered, the useful Chroma range appears rather undersampled. Unfortunately, the Nearly Neutral Munsell collection we possess, on which Chroma increases in 0.5 steps, is in turn undersampled with respect to Hue, and available for Values 6 to 9 which are only really useful for swatches 9.0 and 10.0. Having said that, after a relative peak around swatch 7.0, Chroma decreases slightly for yak; it remains constant for 80/20; and it slopes up for bleached brown, possibly due to the visible residual chromaticity of the base. In any case, lighter swatches are always more chromatic (Fig. 3c).

5. Conclusions

Hair coloring is a delicate matter (Voss and Wong, 2021). Marketwise, no two color lines exists whose colors are actually the same, despite having equal names. Moreover, each head of hair bears differences, either subtle or apparent. This paper has shown how different base colors influence the overall color appearance of the series of naturals, highlighting changes both in tonal values and perceived nuance, especially for lighter tones. Because of this, the great variety of base colors must be considered by hair professionals before any coloring treatment is applied. This entails, for instance: tonalization, or a slightly different nuance choice for compensating the underlying base nuance and/or bleaching residuals; a thorough assessment of the desired bleaching level, if necessary, in combination with the required power of oxidizing agents.

6. Conflict of interest declaration

The authors declare no conflict of interest.

7. Funding source declaration

The authors declare no financial funding.

8. Short biography of the authors

Simone Liberini – MD in biomedical engineering. Consultant at Universal Beauty Products, where he is involved in the production of scientific papers and in the writing of educational and training material on color. He also collaborates with the company's research laboratory in the implementation of perceptual experiments using color atlases in a controlled observation environment.

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Giannantonio Negretti – Entrepreneur and founder of "Beauticon Valley Holding - Benefit Company", the entity that leads the network formed by more than 50 companies that, thanks to a unique and integrated supply chain, produces the most innovative and high-quality cosmetic products sold in more than 130 countries around the world. With him was born the idea of a new Renaissance of Beauty described in his book "Humanistic Cosmetic" in which he denounces the distance between the promise of happiness typical of cosmetics and the result that almost always disappoints expectations, proposing new attitudes and concrete solutions.

Notes

[1] Fifteen caps were removed by test creators, hence the discrepancy.

[2] Common printing sheets are often treated with chemical bleachers. Collaterally, this treatment greatly boosts reflectance within the blue spectral bandwidth, altering visual perception of superimposed colors.

[3] Adjacent Hues are actually not equally spaced.

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