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PERSPECTIVE

COLOR RESEARCH AND APPLICATION WILEY

Munsell and Ostwald colour spaces: A comparison in the field of hair colouring

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Abstract
Colour science has had a very long history, dotted over the millennia with many contributions from the most diverse fields of human knowledge. At the beginning of the 20th century, Albert Henry Munsell, an artist formally trained in academia, and Friedrich Wilhelm Ostwald, Nobel prize for chemistry in 1909 and amateur painter, each envisioned and developed a colour system with a related colour atlas. Both authors recognized the importance of the visual relationship between colours, which they conceived as sensations stemming from, but not merely confined to, pigments and light. We hereby describe the salient features of these colour spaces, their strengths and weaknesses, the authors' analogy of intents and divergence in execution. The contribution of this paper is a discussion on how these are employed both in Italian educational facilities, and salon practice, as well as a suggestion about their use within the industry of human hair cosmetics.

KEYWORDS
colour atlas, hair colouring, Munsell, Ostwald

1 | COLOUR-ORDER SYSTEMS

Decades of colour science have seen the rise and fall of a variety of colour attributes under the most different theoretical and practical applications. Since its first inception, colorimetry has been providing us with plenty of colour coordinates, yet not always do these describe colour the same way we would in our everyday life. To name but the most famous, tristimulus values are as far removed from the layman's colour terms as can possibly be imagined. In fact, X, Y, and Z are said to be imaginary primaries, whose existence is an abstraction explicitly intended to overcome practical issues stemming from Wright and Guild's matching experience with red, green, and blue light sources. Additive mixing from three such sources is nowadays the key into colour display functioning, and yet, its comprehension is only manageable up to a certain degree. A more intuitive approach would try to quantify colour features such as "light" and "dark," "strong" and "weak": these being attributes that all of us were implicitly taught about from the very early stages of our lives. Of course, not everyone may be strictly accustomed to the concepts of value and saturation, even less so to their formal definitions. Yet, a glimpse of understanding is to be found provided a very basic approach to art has been established.

On one hand, colorimetry mainly aims at defining absolute colour attributes. On the other hand, artists are usually concerned with colour relationships: colour appearance and colour constancy are arguably more important to them than an unequivocal colour determination. Conversely, an exact, quantifiable colour match is often desirable in industrial applications. The divide on colour between science and art can be traced at least as far back as the Goethe versus Newton debate, and fruitful attempts to reconcile these two apparently opposing approaches are quite scarce. In this paper, a comparison of two such attempts is carried out regarding Munsell and Ostwald colour spaces, with particular regard to hair colouring.

Both are examples of a so-called colour-order system, which may be defined as a "systematic and rational method of arranging all possible colours or subsets by means of material samples" (Graham, 1985 through[1]), or alternatively "a set of principles for the ordering and denotations of colours, usually according to defined scales" (ISO/TC187 through[1]). Both definitions highlight the need for a set of rationally devised ordering principles, ultimately meant to serve practical purposes. In this way science, or more properly a "scientific" approach of sorts, meets the figurative and applied art's needs. The act of trying to order colour is of course at least as old as the concept of colour itself, but not so is the contribution of science to the cause. Since we find the historical context to be instrumental to the topic, we begin with a short journey into the lives F. W. Ostwald and A. H. Munsell.

2 | MUNSELL AND OSTWALD: TWO BIOGRAPHIES IN A SKETCH

Born in Riga in 1853, Friedrich Wilhelm Ostwald was a Baltic German Nobel laureate, perhaps best known to chemists for his many contributions to the field. He spent the second half of his life dealing with politics, philosophy, and especially art, himself being a passionate yet formally untrained artist.[2] A modern Renaissance man, Ostwald stated that art and science both aim at "coping with the infinite diversity of appearances through the formation of appropriate concepts."[3] To him, science deals with ideas, whereas art with the practical and visual manifestation thereof. Colour seemed to be a bridge between these two apparently irreconcilable worlds. For instance, when dissolving chemical compounds in water, Ostwald observed hue shifts in ionized salts, stating that colours themselves were a clue into the ins and outs of the process.

In 1914, the German Association of Craftsmen tasked him with the creation of a rational colour atlas meant for the flourishing German colouring industry, especially for the systematic creation and management of synthetic colourants.[2] This broader view on colour was certainly influenced by the Bauhaus School, whose training courses heavily favored the bridging of fine arts with traditional crafts.[4] Industrial processes required a rational approach to colour, for which any hint of science was to be warmly encouraged. Into this undertaking did Ostwald pour heart and soul, producing both an exhaustive atlas and a large body of related literature of which he felt incredibly proud. In fact, he devised a full set of rules for colour harmony, that is, the choice and combination of colours in a visually pleasing arrangement (at least according to Ostwald himself).

Despite his relentless efforts and enthusiasm, neither scientists nor artists for the most part ended up appreciating his body of work. The former were skeptical of a few issues that he seemed to have disregarded in favor of the beauty of his model, which he fervently considered a proof of formal correctness. The latter's reception was lukewarm at best. For instance, by the time Ostwald's theory of colour harmony had fully developed, the main responsible for colour teaching at the Bauhaus was none other than Wassily Kandinsky, whose ill-concealed ambivalence on the matter carried well over into his lectures. Surely though, one of the fiercest opponents was Paul Klee, also a teacher at the Bauhaus, whose open aversion to Ostwald's theory of colours can be best synthesized in his own words: "to hold that the possibility of creating harmony using a tone of equal value should become a general rule means renouncing the wealth of the soul."[2] During a lecture held in Stuttgart in 1919 to his associates, Ostwald exhibited the colour-order system with the visual aid of his own pieces of art, only to be ridiculed for the chromatic unpleasantness of those old-fashioned "paintings of little flowers" of his. He was forced out of the Association, and so was his work from the art world, amidst judgments the likes of "militarism in art."[2] A small number of artists, such as Mondrian with his grid-styled paintings, actually seem to have drawn inspiration from Ostwald's colour harmony rules. But even then, the Colour Manual has been out of print since 1972.[5] It is however true that Ostwald system serves as a foundation for the modern Natural Colour System®© (NCS).[6] Since current educational and practical materials explicitly (albeit wrongly) revolve around Ostwald, at least in Italy, and because we actively propose Munsell as an alternative, an analysis of the NCS colour-order system goes beyond the scope of this paper.

Albert Henry Munsell was born in Boston, Massachusetts, in 1858. There he trained at the Massachusetts Normal Art School, where he graduated in 1881 and was soon after hired as an instructor. Eager for more education and perspective, he traveled to Europe from 1885 to 1888, spending time at the École des Beaux Arts in Paris. His French stay was arguably a determining factor in the development of his later work.[7] The academic tradition was beginning to crumble under the weight of the

Impressionist *avantgarde*, but come the closing of the century, Impressionism itself was already being superseded by Neo-Impressionism. Also, science had long since set its firm grip on colour.

Much of Munsell's endeavors are finely detailed in his personal journal, which he regularly filled in from the late 1880s up to his demise in 1918.[8] Through it, we learn he was well aware of the scientific debate then raging among physicists, physiologists, and psychologists about the nature of colour. This was somewhat mirrored by the world of art: Impressionists maintained that a thorough comprehension and use of colours was innate, so it could not be taught at all. Neo-Impressionists, eager to delve into the latest scientifical discoveries, identified colour with spectral wavelengths entirely. On his part, Munsell chose not to busy himself with definitions, though it must be noted that he did not renounce the ambition to use his own system as a foundation for teaching colour harmony. Indeed, teaching was his greatest passion, to the point that he devised a complete, 9°-colour course especially tailored to children and young students. What perhaps sets him apart from Ostwald is the lack of adamant confidence in the absolute truth of his theories. Ostwald was so convinced on having reached the peak of formal colour harmony that he reportedly proclaimed Titian had once used a blue "two tones too high." Instead, Munsell set up a system whose aim was, and still is, the rational description of colour, and whose modern survival is perhaps testimony to the wisdom of such choice.

Before venturing into a description of Ostwald's and Munsell's works, a fundamental distinction must be made. A colour-order system is, as already hinted at, a set of rules and principles by which every possible colour can be described and ordered. A colour manual, atlas, or book is a physical collection of colour samples realized and arranged according to said rules and principles. For entirely practical reasons, these collections show but a limited subset of all perceivable colours, which are in the millions for a human observer with no colour deficiencies.

3 | OSTWALD'S COLOUR HARMONY MANUAL

A three-dimensional object in our surrounding space can be roughly defined by its length, width, and height. Likewise, each and every colour system must be based on three independent colour attributes. Having set about to describe surface colours, Ostwald chose, quite unsurprisingly for a chemist turned painter, white content (W), black content (B), and full colour (C) as his system-defining dimensions.[9] These surface colours he called "related," because they are seen under a given illuminant with respect to a surrounding context, as opposed to "unrelated" colours which appear in aperture mode and only contain pure colour and white. For the quantities W, B, and C, Ostwald provided a description in spectral terms. The reflectance spectrum of any maximally saturated, ideal surface pigment comes in the form of a step function reminiscent of a band pass filter: any wavelength comprised within an interval is fully reflected; any wavelength without, fully absorbed. Ostwald described full colours as "semichromes," that is, spectral halves comprised within a wavelength and its complementary. Supposing the latter could not be identified, as is the case for the portion of the spectrum spanning the sea-greens to the leaf-greens, a second type of semichrome was defined out of a single wavelength splitting the visible spectrum into an absorption half and a reflection half. By also taking each semichrome complement to 1, a further pair of subtypes was identified: the complementary hues relative to a given semichrome (Figure 1).

Within the scope of this theoretical framework, white content can be represented by a perfectly flat line across the whole of the visible spectrum, whose relative reflectance depends on the prevalence of the pigment. In other words, white contribution to the reflectance curve of an ideal surface pigment is an even baseline increase: the greater the amount of white in the mixture, the higher its spectrum with respect to the zero line. Conversely, black pigment lowers the full reflection region(s), again by an amount proportional to its content in the mixture. The composite (and opposite) action of white and black contents shrinks the full colour spectrum to the point where the step function of the ideal pigment simply becomes a straight line. This is the spectrum of a fully desaturated colour, that is: a gray.

Because W, B, and C all span the normalized reflectance codomain [0;1], they always sum to 1, such that $W + B + C = 1$ (Figure 2). Thus, for any given pigment, C, W, and B represent the proportions of pure colour, white, and black that mix up as percentages of its overall amount. For pure white, $C = B = 0$, $W = 1$. For pure colours, $C = 1$, $W = B = 0$. And finally for pure black, $C = W = 0$, $B = 1$. Because of the equation, it is clear that B, W, and C are not independent attributes, as any and each of them is automatically established once the other two are, by means of a simple subtraction. For instance, supposing W and C are given, $B = 1 - W - C$. Because three independent attributes are needed to uniquely identify colour, the missing attribute is the wavelength at which the transition from absorption to reflectance occurs. The second transition, if present, is intrinsically defined owing to the complementarity pairing.

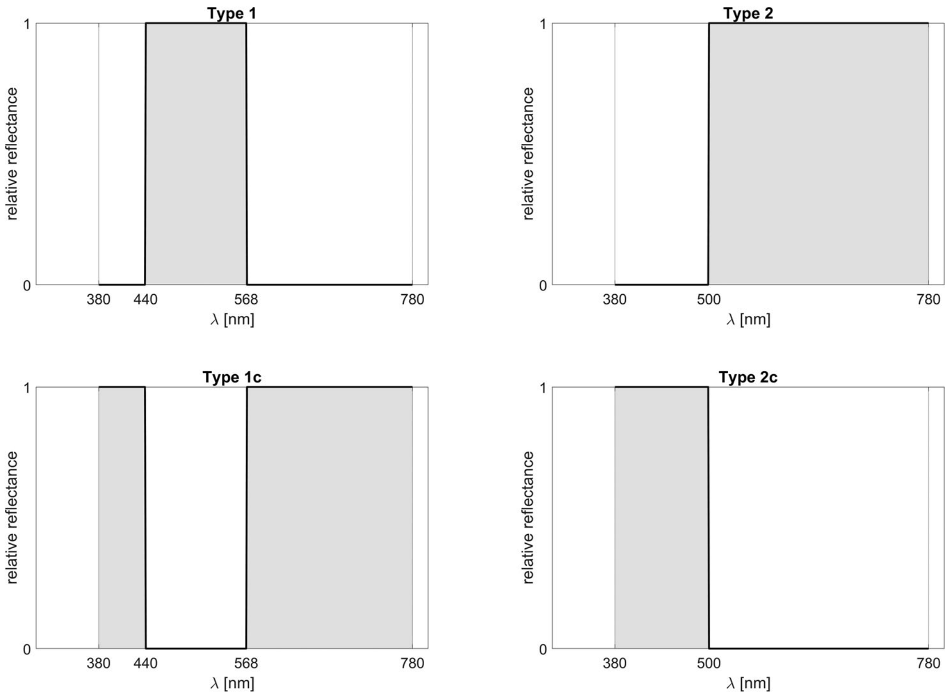

FIGURE 1 Ostwald's semichromes: spectral portions comprised between a wavelength and its complement (left column, top row); or, greater than a wavelength without physical complement (right column, top row). Complement colours for both types are shown in the bottom row

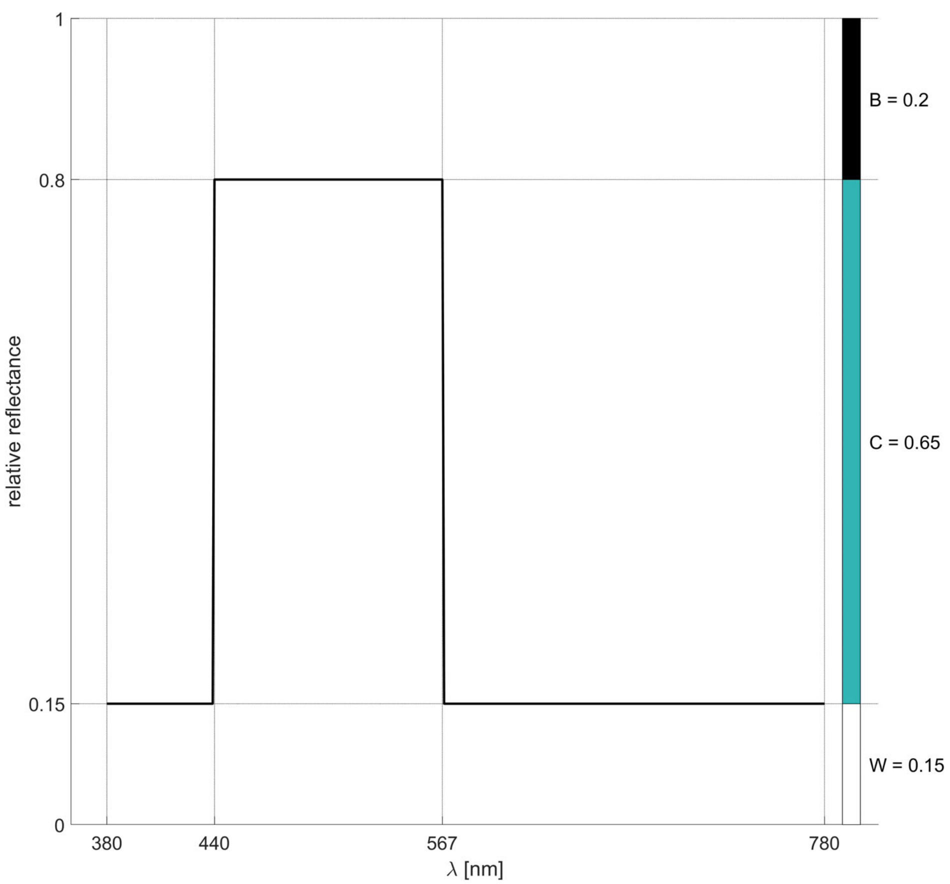

FIGURE 2 Spectral interpretation of Ostwald's basic rule (W + B + C = 1) in term of relative reflectance of a pigment

For ideal pigments, this allows for an easy computation of tristimulus values. Let us proceed for a type 1 pigment defined by a transition wavelength λ_T, its complementary λ_C, and the pair (W, C). An ideal white illuminant with constant normalized luminance $(L(\lambda) = 1)$ is considered for simplicity. The reflectance spectrum is:

$$R(\lambda)=\begin{cases}\boldsymbol{W}, 380\,\text{nm}\le\lambda<\lambda_\text{T}\cup\lambda_\text{C}<\lambda\le 780\,\text{nm}\\ \boldsymbol{W}+\boldsymbol{C}, \qquad \lambda_\text{C}\le\lambda\le\lambda_\text{T}\end{cases}$$

Thus, if $\overline{x}(\lambda),\overline{y}(\lambda),\overline{z}(\lambda)$ are the colour matching functions:

$$\begin{aligned}X&=\sum_{380}^{780}R(\lambda)L(\lambda)\overline{x}(\lambda)\\&=\sum_{380}^{\lambda_\text{T}}R(\lambda)L(\lambda)\overline{x}(\lambda)+\sum_{\lambda_\text{T}}^{\lambda_\text{C}}R(\lambda)L(\lambda)\overline{x}(\lambda)\\&\quad+\sum_{\lambda_\text{C}}^{780}R(\lambda)L(\lambda)\overline{x}(\lambda)=\end{aligned}$$

$$=\sum_{380}^{\lambda_\text{T}}\boldsymbol{W}\cdot 1\cdot\overline{x}(\lambda)+\sum_{\lambda_\text{T}}^{\lambda_\text{C}}(\boldsymbol{W}+\boldsymbol{C})\cdot 1\cdot\overline{x}(\lambda)+\sum_{\lambda_\text{C}}^{780}\boldsymbol{W}\cdot 1\cdot\overline{x}(\lambda)=$$

$$=\boldsymbol{W}\sum_{380}^{\lambda_\text{T}}\overline{x}(\lambda)+\boldsymbol{W}\sum_{\lambda_\text{T}}^{\lambda_\text{C}}\overline{x}(\lambda)+\boldsymbol{C}\sum_{\lambda_\text{T}}^{\lambda_\text{C}}\overline{x}(\lambda)+\boldsymbol{W}\sum_{\lambda_\text{C}}^{780}\overline{x}(\lambda)=$$

$$=\boldsymbol{W}\left(\sum_{380}^{\lambda_\text{T}}\overline{x}(\lambda)+\sum_{\lambda_\text{T}}^{\lambda_\text{C}}\overline{x}(\lambda)+\sum_{\lambda_\text{C}}^{780}\overline{x}(\lambda)\right)+\boldsymbol{C}\sum_{\lambda_\text{T}}^{\lambda_\text{C}}\overline{x}(\lambda)=$$

$$=\boldsymbol{W}\sum_{380}^{780}\overline{x}(\lambda)+\boldsymbol{C}\sum_{\lambda_\text{T}}^{\lambda_\text{C}}\overline{x}(\lambda)$$

Finally:

$$(X;Y;Z)=\begin{pmatrix}\boldsymbol{W}\sum_{380}^{780}\overline{x}(\lambda)+\boldsymbol{C}\sum_{\lambda_\text{T}}^{\lambda_\text{C}}\overline{x}(\lambda);\boldsymbol{W}\sum_{380}^{780}\overline{y}(\lambda)\\+\boldsymbol{C}\sum_{\lambda_\text{T}}^{\lambda_\text{C}}\overline{y}(\lambda);\boldsymbol{W}\sum_{380}^{780}\overline{z}(\lambda)+\boldsymbol{C}\sum_{\lambda_\text{T}}^{\lambda_\text{C}}\overline{z}(\lambda)\end{pmatrix}$$

And its complementary colour:

$$(X;Y;Z)=\begin{pmatrix}(\boldsymbol{W}+\boldsymbol{C})\sum_{380}^{780}\overline{x}(\lambda)-\boldsymbol{C}\sum_{\lambda_\text{T}}^{\lambda_\text{C}}\overline{x}(\lambda);\\(\boldsymbol{W}+\boldsymbol{C})\sum_{380}^{780}\overline{y}(\lambda)-\boldsymbol{C}\sum_{\lambda_\text{T}}^{\lambda_\text{C}}\overline{y}(\lambda);\\(\boldsymbol{W}+\boldsymbol{C})\sum_{380}^{780}\overline{z}(\lambda)-\boldsymbol{C}\sum_{\lambda_\text{T}}^{\lambda_\text{C}}\overline{z}(\lambda)\end{pmatrix}$$

For type 2 pigments, where only λ_T is defined, formulas change accordingly:

$$(X;Y;Z)=\begin{pmatrix}\boldsymbol{W}\sum_{380}^{780}\overline{x}(\lambda)+\boldsymbol{C}\sum_{\lambda_\text{T}}^{780}\overline{x}(\lambda);\boldsymbol{W}\sum_{380}^{780}\overline{y}(\lambda)\\+\boldsymbol{C}\sum_{\lambda_\text{T}}^{780}\overline{y}(\lambda);\boldsymbol{W}\sum_{380}^{780}\overline{z}(\lambda)+\boldsymbol{C}\sum_{\lambda_\text{T}}^{780}\overline{z}(\lambda)\end{pmatrix}$$

And its complementary colour:

$$(X;Y;Z)=\begin{pmatrix}\boldsymbol{W}\sum_{380}^{780}\overline{x}(\lambda)+\boldsymbol{C}\sum_{380}^{\lambda_\text{T}}\overline{x}(\lambda);\boldsymbol{W}\sum_{380}^{780}\overline{y}(\lambda)\\+\boldsymbol{C}\sum_{380}^{\lambda_\text{T}}\overline{y}(\lambda);\boldsymbol{W}\sum_{380}^{780}\overline{z}(\lambda)+\boldsymbol{C}\sum_{380}^{\lambda_\text{T}}\overline{z}(\lambda)\end{pmatrix}$$

The effect of a generic illuminant on these results is twofold: firstly, its values need to be taken care of within the summation signs when multiplying by the colour matching functions; second, since pairs of complementary wavelengths can (at least nowadays) be determined on the chromaticity diagram by elongating the line from a point on the spectral locus through the white point and again toward the spectral locus, by changing the illuminant the white point also changes, and so does the complementary wavelength.

In order to define a grayscale, values for W and B were initially identified by postulating that linearly scaling ratios would connect pure black to pure white through a set number of intermediate steps. On Ostwald's part, choosing the grayscale as a steppingstone into any further development of his system seems to be fairly consistent with general art practice, where a firm foundation in lightness values comprehension and application is usually taught before colour is even tackled (think of the *chiaroscuro* technique). To Ostwald's dismay, moving from black to white in regular variations of pigments did not yield the expected result, that is, a perceptually uniform grayscale, where adjacent steps appear as equally distant, irrespective of the level in the scale, and according to an average human observer. Remembering the Weber–Fechner's law of perception, according to which a geometric progression of the stimulus equals an arithmetic progression of the perception, Ostwald chose a logarithmic scale instead.

When no amount of black and white is used in a pigment mixture, a pure colour is obtained. In Ostwald's system, pure colours are orderly organized along an equator of hues reminiscent of the spectral sequence, with magentas and purples connecting reds to violets. Colours are spaced according to Herring's red versus green and yellow versus blue opponencies: yellow is set half a circle distance from ultramarine blue, and so is red with respect to sea green.[10] Earlier versions of the system included a copious number of hues, while later versions were comprised of 24 hues total. This way, secondary and tertiary colours could be more easily highlighted, and harmony schemes clearly defined by means of inscribing regular polygons with vertexes pointing to harmonious couples, triples, quadruples, and sextuples.

Lying at the center of the pure colours circle, and perpendicular to it, is the neutral axis, that is, the series of grays moving from a theoretically absolute black at the bottom to the purest white at the top, such that the colour equator is flush with the medium gray. This way, pure colours are as far removed from the grayscale as can be contrived. For each pure colour, an isosceles triangle can be drawn that connects it both to white and black, which are in turn connected along the grayscale. The resulting overall shape is that of a double cone (Figure 3), whose sections are comprised of the shared gray axis, of two complementary pure colours at the opposite ends of the triangles, and of all intermediate colours.

The central axis was divided in 10 steps: the bottommost pure black, the topmost pure white. The upper rows connecting white to pure colours, the so-called light clear series, are an exclusive mixture of white and pure colour. The lower rows connecting black to pure colours, called dark clear series, of black and pure colour. All the samples contained within these three outer boundaries are mixtures of pure colour, white and black (Figure 4), at all times bound by the rule $W + B + C = 1$, where W and B are given by the grayscale amounts. Because of this, the model possesses three viewpoints: rows parallel to a light clear series contain the same level of black and are therefore called isotones; rows parallel to a dark clear series contain the same level of white and are therefore called isotints. Rows parallel to the gray axis are called shadow series (Figure 5A,B).

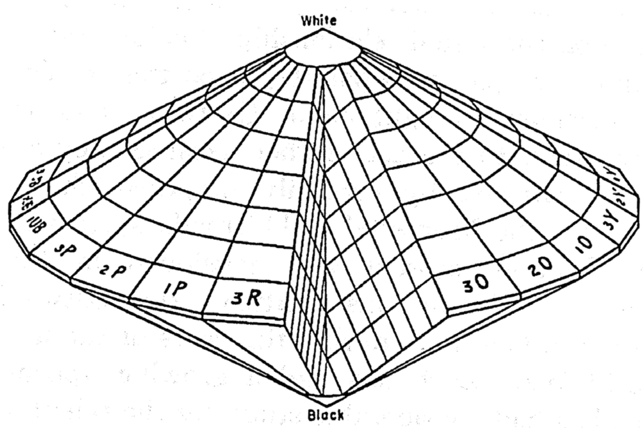

FIGURE 3 Three-dimensional structure of the Ostwald colour-order system[11]

The last step when defining a colour-order system is providing it with a proper notation, a naming convention for users to identify and communicate colours rapidly and unequivocally within that system. In the 24-steps version, each hue is denoted with a number from 1 to 3 and one or two capital letters. For instance, yellows are labeled 1Y, 2Y, 3Y, sea greens 1SG, 2SG, 3SG, and so on and so forth. Each of the physically available eight steps in the gray axis is identified with a lowercase letter: "a" for white, then "c," "e," "g," "i," "l," "n," and finally "p" for black. These same letters are also used for white and black contents in the mixture: for instance, 3LGge is leaf-green number three, having a "g" amount of white, to be read on the neutral axis and prolonged on the isotint, and intersected with an "e" amount of black, to be read likewise on the neutral axis and prolonged on the isotone.

4 | THE MUNSELL BOOK OF COLOUR

As an artist, Munsell too thought of a system meant for describing and ordering surface colours. He decided that every colour had to be specified according to physical measurements, but only as a means into actual human

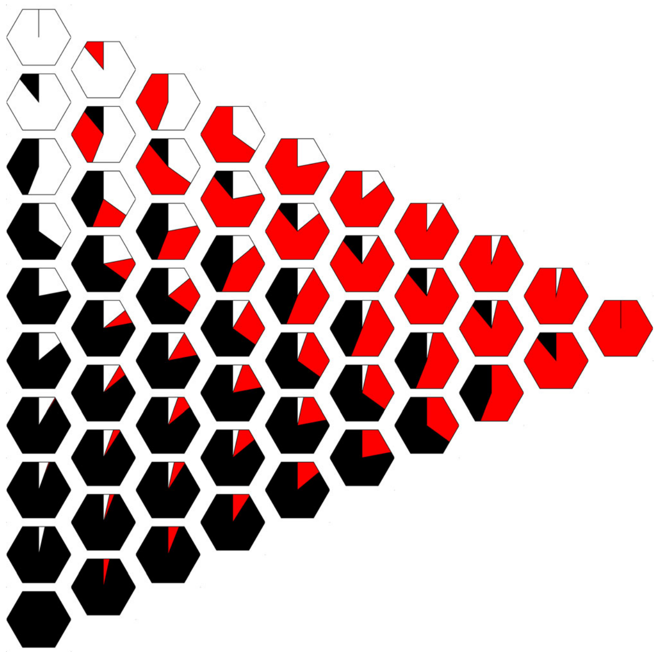

FIGURE 4 Representation of one of Ostwald's triangles highlighting black, white, and pure colour contents for every coloured chip. The gray axis on the left is comprised of white and black only (in visibly non-linear amounts); the chip on the right is the pure colour. The topmost series, connecting pure white to pure colour, is called light clear series; the bottommost, connecting pure black to pure colour, dark clear series

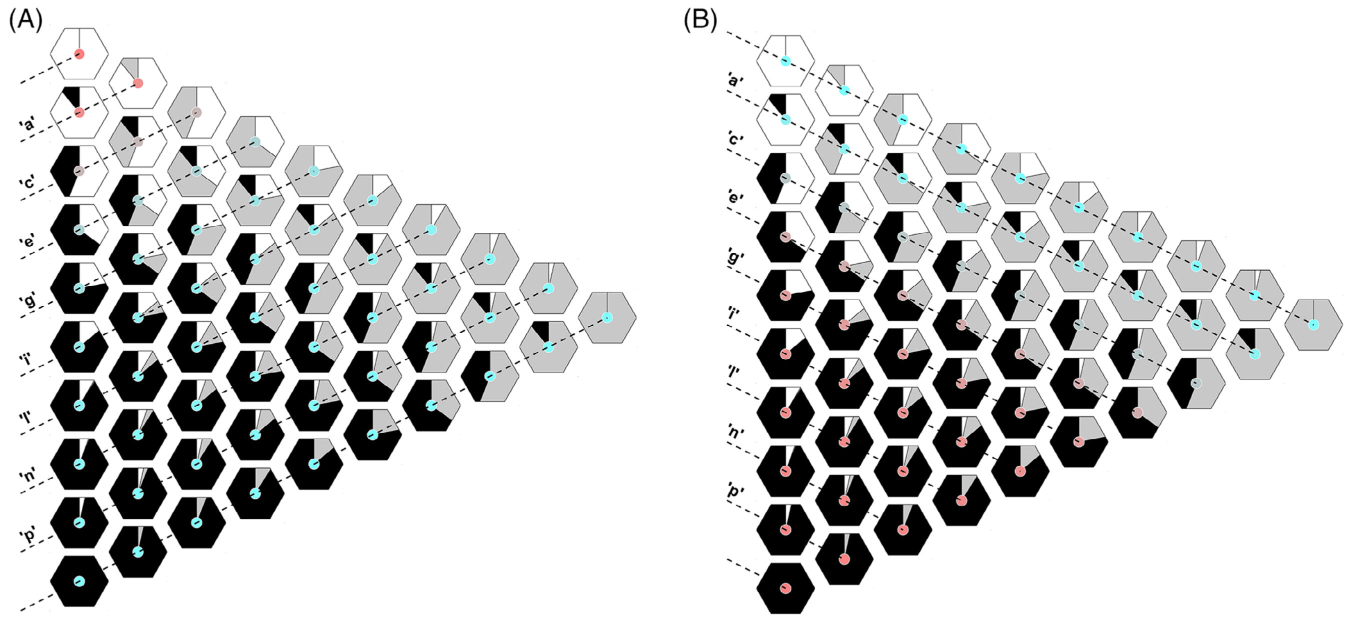

FIGURE 5 (A) Ostwald isotints, that is: series having an equal amount of white content. The latter is shown through a heatmap going from cyan to red, whose scaling makes it apparent that proportions are non-linear. Isotints are labeled with a letter, except for the dark clear series and the light clear series. (B) Ostwald isotones, that is: series having an equal amount of black content

perception.[12] For instance, at one point in his years-long research path he used a photometer to establish his own version of the gray scale. Imagine a closed off box, partitioned depthwise along the middle, having a reference white sample on one side, and a painted sample on the other. By shining gradually lower light on the white sample, this could be made to appear as dark as the painted sample on the other side. Furthermore, by providing the shutter with a numbered dial, the amount of impinging light could be quantified and duly noted. Every fundamental step, starting from the middle gray, was chosen by Munsell with the help of artists, dyers, and art students. So, even if the photometer could in practice provide physical measurements, the final scaling was dictated entirely by the eye. Munsell called the gray series Value scale, subsuming in one colour attribute Ostwald's white and black contents. Of course, Munsell's gray chips were painted in white and black pigments as well, but the system remains uninterested as to their proportions, as long as they contribute to a perceptually uniform scale.

Much like Ostwald's system, Munsell placed his gray axis, comprised of 11 values ranging from pure black (0) to pure white (10), at the center of, and perpendicular to, a colour equator. In order to determine the main hues, Munsell used Maxwell's disk: a spinning circular base on which coloured samples can be mounted and arranged by varying their visible areas. By reaching a sufficient speed, monochromatic samples fuse into a single colour by additive mixing. This solution practically allows for the blend of pigments without actually mixing them, their visible areas corresponding to the relative proportions in the mix. By choosing couples of monochromatic pigment samples that spun to gray when shown in equal proportions, Munsell singled out five sets of primary-complementary hues, which he placed opposite one another along the colour equator. Hue is therefore the second colour attribute in his system.

Lastly, the colour top allowed for the creation and ordering of the third attribute, Chroma, which can be intuitively understood as the degree of fullness of the colour, defined by Munsell as the degree of distancing from a gray of equal Value. Suppose that two colour samples of complementary Hues and equal Value be placed on Maxwell's disk, for example, red and blue-green, Value 5, in identical measure. Should they spin to a reddish gray, despite being mixed in equal proportion, then that red would be intrinsically more chromatic than the blue-green counterpart, and should accordingly be placed further from the neutral axis. By repeating this experiment tirelessly for a set of Hues at different Values, not only did Munsell fully build his colour-order system, but a first draft of a colour atlas as well. This was later expanded and refined into the modern-day Munsell Book of Colour, which boasts 40 different hues with Values and Chromas whose only limit is set by the stability of currently available pigments on the market, and of course by the limits of human vision. Because of the way our visual system senses and perceives colours, Chroma provides Munsell colour solid, intuitively cylindrical in shape, with an extremely irregular outer surface (Figure 6).

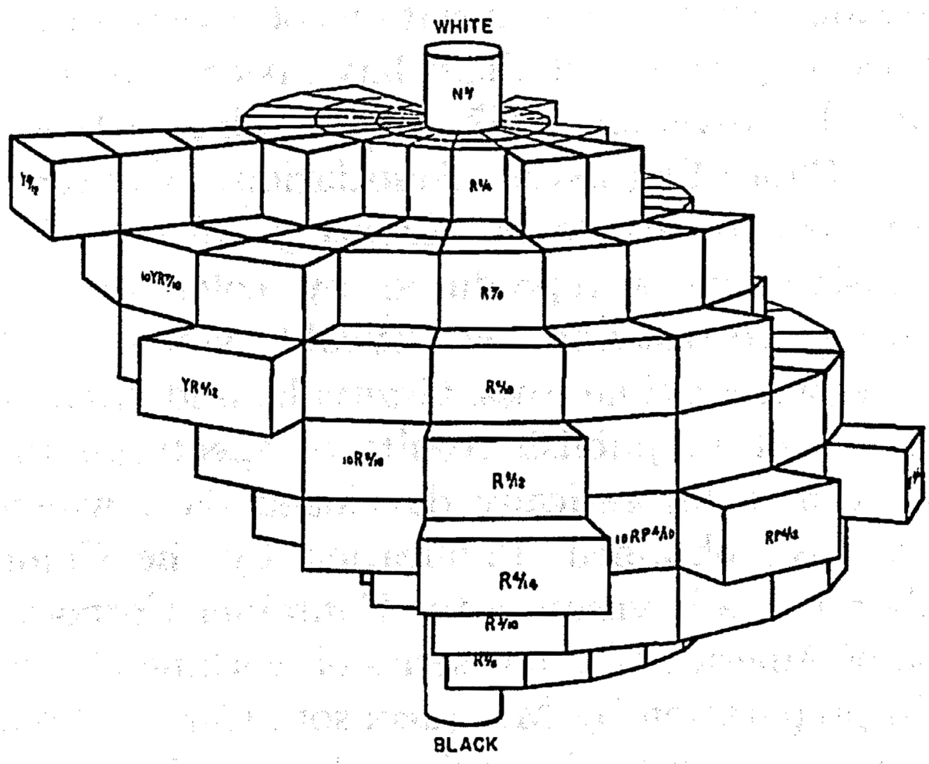

FIGURE 6 Three-dimensional structure of the Ostwald colour-order system[11]

Every coloured chip in the Book follows a standard naming convention in the form Hue Value/Chroma (H V/C). Hues are the combination of a numeral within the set 2.5, 5, 7.5, and 10, followed by capital letters symbolizing each of the 10 main hues: R (red), YR (yellow-red), Y (yellow), GY (green-yellow), G (green), BG (blue-green), B (blue), PB (purple-blue), P (purple), and finally PR (purple-red). Modern Books contain 40 different Hue pages, with a few extra pages where nearly neutral colours—that is: particularly desaturated ones—are arranged. Values range in theory from 0 to 10, but in practice on the Book from 1 to 9.5. This is because no pigments still exist that either completely absorb or reflect all impinging light, such as high lightfastness is also guaranteed. Finally, Chromas range from 2 to typically 12 or 14, depending on the Hue, but higher numbers will be attainable as soon as new lightfast pigments become available. For instance, 5R 4/12 represents a decidedly chromatic, medium-dark characteristic red, while 10 PB 8/4 a somewhat weak, light purplish blue. Neutral colours, having neither Hue nor Chroma, are labeled as NV, V being a Value number. For instance, N1.5 is a very dark gray, N5 the middle gray, and N9 a very light gray. Provided a basic knowledge of the system is acquired, Munsell naming convention appears more intuitive than Ostwald's, and a graphical reference representation in actually not needed for an overall grasp of the kind of colour which is being referenced.

5 | HAIR COLOURING: OSTWALD OR MUNSELL?

The comparison between Ostwald's and Munsell's approaches is the comparison between chemical mixing on one hand, and perceptual results on the other. We suggest that the second be more suitable both for the education of young professionals, and for cosmetic industry best practices. Whenever hair colouring is involved, it appears Ostwald system largely prevails in educational material devised for young professionals, as well as in colour managing tools such as wheels on sample charts. However, a thorough survey conducted on Italian textbooks suggests that a much-simplified version is actually in use in the form of a six-vertex, bi-dimensional star, as opposed to the tri-dimensional double cone. Red, yellow, and blue are considered by hair colourists primary colours, presumably much like artists do in their colouring practice, and are therefore arranged so as to occupy every other vertex of the star. The three remaining vertexes are taken up by the secondary colours, which are mixtures of all available primary pairs (Figure 7). Each secondary is placed opposite the primary not contributing to its formation: red and green (blue plus yellow), yellow and purple (red plus blue), and finally blue and orange (red plus yellow), all serve as complement pairs whose mixing yields gray. It should be mentioned that primaries in subtractive mixing are actually yellow, magenta, and cyan, with blue, green, and red serving as respective complements.

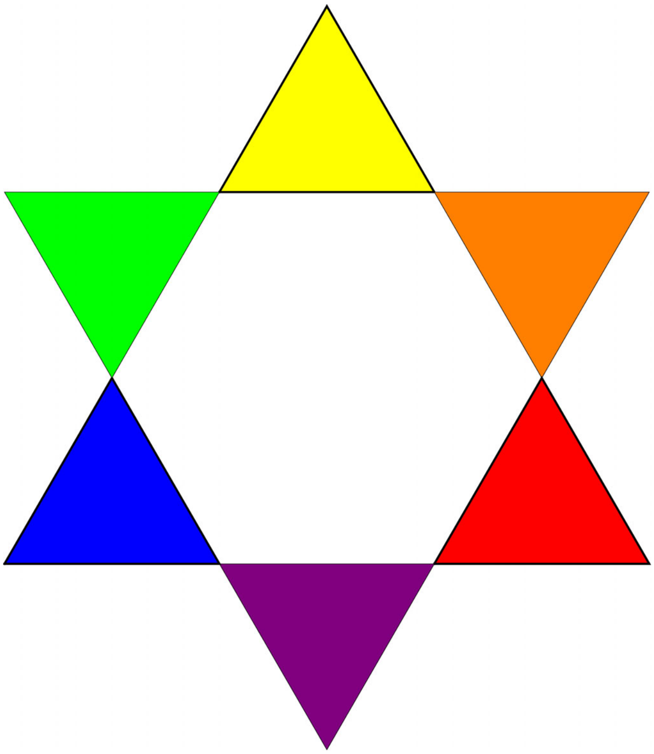

FIGURE 7 Ostwald's Star, appearing on various textbooks for young hair colour students in Italy. Yellow, Red, and Blue are the primary colours, with respective complements Purple, Green, and Orange. This is an overly simplified (and wrong) version of Ostwald system, whose origin we could not trace

Also, red, yellow, and blue are extremely vague terms. For instance, artists know very well that mixing different blues with different oranges yields strikingly varying results. In watercolour, supposing a neutral gray could be obtained by adding ultramarine blue to burnt sienna, the same would not necessarily hold true for, say, cerulean blue or burnt umber (and in any case, both burnt sienna and burnt umber are browns, i.e., a dark orange, not the epitome of orange itself).

The star diagram is usually expanded upon in hair colour charts in the form of fully developed colour wheels, for which no universal coding currently exists (Figure 8). Colours in the product line are encased within the wheel according to their predominant hue and lightness, but the exact placement is for the most part left to arbitrariness. For instance, while the series of naturals is commonly associated with a yellow hue, if slightly greenish, no exact match is to be found among different wheels. Indeed, different hair colour brands are known to favor either colder or warmer versions of the series. As a consequence, in order to maintain an alleged complementarity, other tones are relocated accordingly. Visually, this is easily achieved by encasing complements diametrically opposite on the wheel. Yet, while this complementarity is intuitively intended in terms of subtractive mixing, its rules are often only tentatively applied, and again much subject to personal preference. This overly simplified version of colour opponency is usually referred to in hair colour practice when the need for compensation of undesired residual tones arises. When hair is too red, for instance, a greener nuance is applied to bring it back to a more natural appearance, because red and green are taught to mix to a neutral gray. Then again, natural hair is for the most part brown and blonde, not gray at all. Furthermore, the term "green" is very loosely applied here, since a product from the ash series is likely to be used to balance out red whose appearance only usually actually hints at green. The result is a colour management tool that is often more visually pleasing than it is practically useful.

While of course these oversimplifications (sometimes plain mistakes, even) are not intrinsically attributable to the real version of Ostwald colour-order system, we suggest a different approach. Both Ostwald and Munsell used pigments, and both their systems are aimed at ordering surface colours. Though results might seem similar, a fundamental difference lies at the core. Once made aware of the Weber–Fechner law, Ostwald applied it extensively, satisfied with the purely quantitative nature of his method and adamant on its absolute correctness (even if a few adjustments were made during the course of its lifespan). Amounts of white and black pigment used in building the gray scale were replicated both along isotones and isotints accordingly, so that the amount of pure colour of chromatic samples was entirely determined by summing to one. Munsell, on the other hand, put the law to test against actual human perception. Ostwald's proportions of pigments are set in stone a priori, while Munsell never mentions them explicitly. For Munsell, pigment mixtures are only useful as a means to an end, which lies within the colourist looking at a coloured chip, not in the chip itself.

This has striking practical consequences. The Book consists of chips that are everywhere perceptually equidistant. Furthermore, all chips having the same Value appear equally light or dark, and all chips having the same Chroma equally strong or weak. This is not true for Ostwald's chips, as the same amount of white and black mixed to different pure colours does not create the same variation in appearance, for instance altering hue. This phenomenon was well known to artists. According to Itten:

> A pure colour may be diluted with white. This renders its character somewhat colder. Carmine assumes a bluish cast as it is mixed

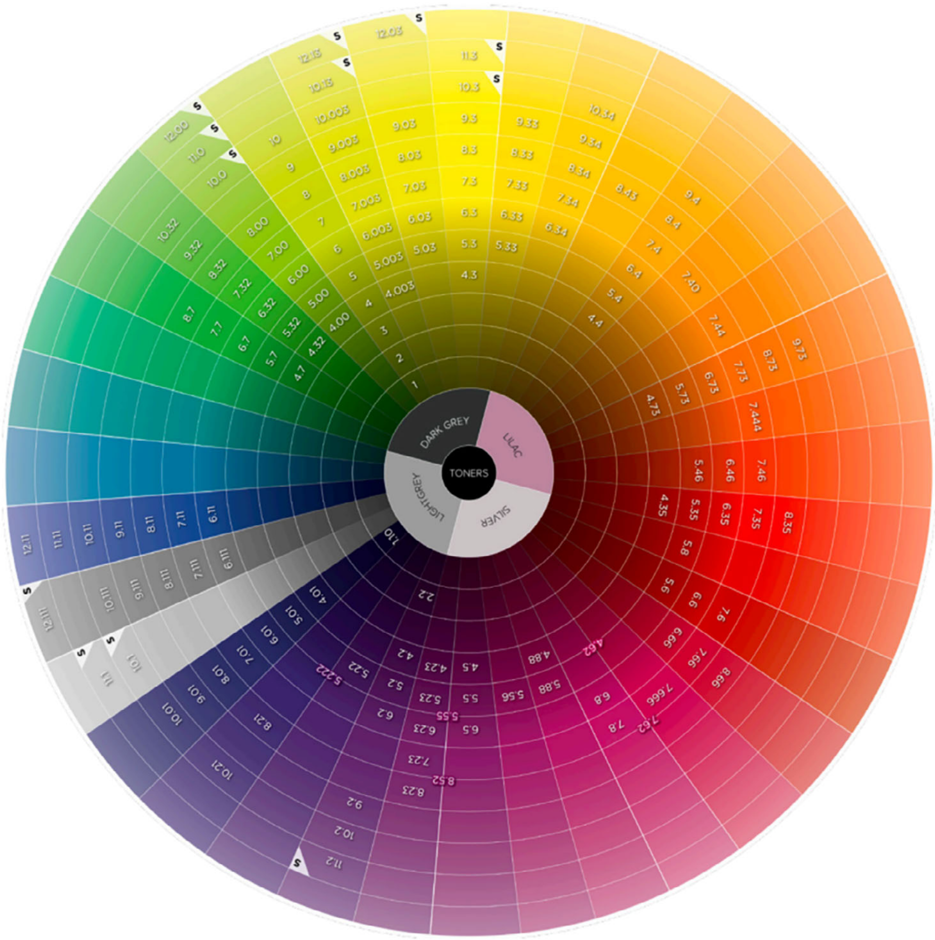

FIGURE 8 Example of a colour wheel as found on a hair colour chart. Here, hair level is shown radially, hair tone along the circumference. Notice the inconsistent scaling of levels. Also, tone positioning is arbitrary since oxidizing pigments do not actually possess the suggested hue. Finally, gray slices for the ash series have no place on a hue circle since gray is achromatic

> with white and becomes sharply altered in character. Yellow is cooled by white[.] A colour may be diluted with black. [...] By admixture of black, carmine acquires a timbre in the direction of violet. [...] Vermilion diluted with black gives a kind of burnt red-brown pigment.[13]

This suggests perceived hue changes at the very least both in light and dark clear series. Let us examine, for instance, the clear white series of Ostwald's hue 7 triangle (a red) and compare it to the closest Munsell Hue (Figure 9A). Such comparison has been made available by Granville[5] and was carried out through the common reference of chromaticity and luminance coordinates of Ostwald's third version of the Manual and Munsell Renotations.[14] From the pure red on the outermost tip of the colour triangle, toward the topmost pure white, Munsell Hues for Ostwald chips are: 5R–5R–4R–3R–3R–2.5R–2.5R. On a modern Munsell Book of Colours matte edition, this entails a well perceived Hue shift amounting to an entire page toward a colder red.

A comparison for the remaining Munsell attributes for all chips belonging to the same Ostwald page is also shown where Ostwald chips are positioned within a Munsell Value versus Munsell Chroma frame of reference (Figure 9B). This graph highlights yet another issue. Let us consider, for instance, all H 5/C Munsell chips, that is, all chips at Value 5, any Hue, any Chroma. Munsell Value is, reportedly, the most accurate attribute even when physical samples are accounted for. Spectrophotometric measurements of the Munsell Book of Colour matte edition at our disposal show an average $L^* = 51.90$. SD is only 0.51, less than 1% of the average. Thus, Munsell Value is demonstrably reliable, in that it is both accurate and consistent. By considering Munsell Values of Ostwald chips it is apparent that tonal equality suggested by the perfectly triangular shape is deceitful when perceptual uniformity is accounted for, as chips do not line up horizontally. Furthermore, Ostwald has all pure colours stand on the very same level, the colour equator. Munsell notices that colours reach their purest at different Values: highly chromatic yellows also have higher values, whereas highly chromatic Blue have lower values,

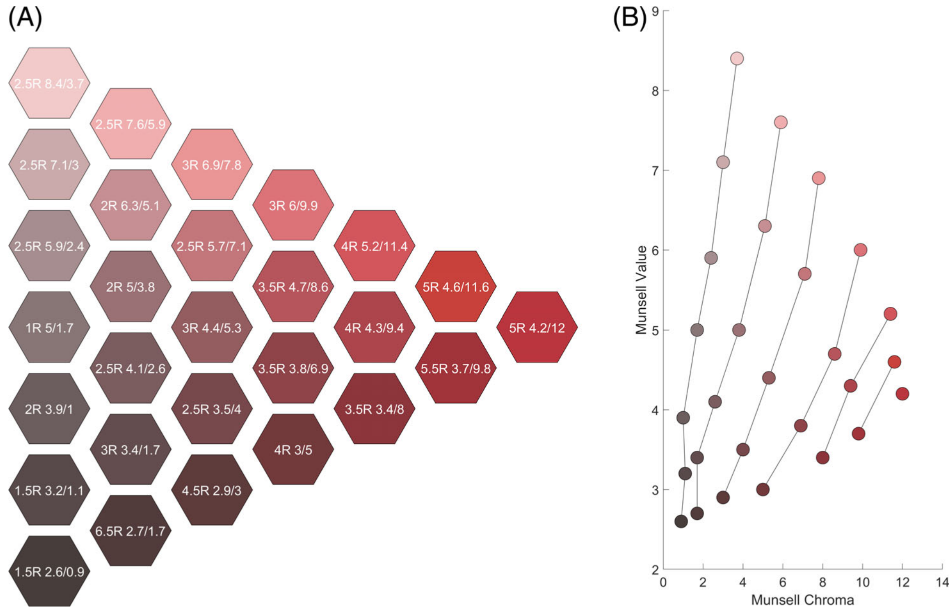

FIGURE 9 (A) Representation of Ostwald hue page 7 (as per his Manual, third edition), with Munsell counterparts superimposed. Hue varies inconsistently from a minimum of 1R to a maximum of 6R. (B) Scatterplot on a Munsell Value versus Munsell Chroma frame of reference

because pure blue is intrinsically darker than pure yellow.

A distinction should perhaps be made regarding Saturation and Chroma. Saturation is defined as "colorfulness of an area judged in proportion to its brightness," whereas Chroma as "colorfulness of an object relative to the brightness of a white object similarly illuminated."[15] An analysis of these two quantities is shown in Table 1 for the Munsell Book of Color matte edition, Hue page 2.5R. Saturation is computed as the difference between the maximum and minimum RGB channel values, divided by the maximum, while Chroma is simply the difference. In order to keep colour constancy when depicting objects under different lighting conditions, realist landscapists and portraitists must change object colours accordingly. Ostwald's shadow series are collections of coloured samples precisely endowed with this property: every sample on the same vertical line represents an identical surface colour viewed in full light (at the top) and in full shadow (at the bottom). Vertical lines on Ostwald's colour charts are therefore lines of equal Saturation. Not so much Chroma, as can be seen again looking at Figure 7—right, where shadow series show a consistently skewed pattern. By moving along constant Saturation lines, both Munsell Value and Chroma must change at the same time, and in the same fashion.[15]

A case could be made for the use of Ostwald in hair colouring since his system relies explicitly on the mixture of pigments, apparently much like hair colourants. However, in the case of artistic pigments the result on canvas is for the most part coherent with the appearance of the mixture. This is not true for hair colourants, which are often comprised of other chemical compounds such as ammonia, and then mixed with oxidizing agents. Artists want their pigments to be stable and *not* to chemically react when mixed, while hair colour is meant from the start to interfere with hair melanin, in fact denaturing it. In other words, hair colour is not contained in the tube. For example, the colourant for black is originally a whitish cream that only darkens hair after a few minutes, by means of an addition of hydrogen peroxide and provided the necessary basic pH is reached for cuticles to open.[16]

Munsell colour attributes lend themselves very well to the description of hair colour. The latter is traditionally defined by means of a two-part numeral figure: level, and tone (not to be confused with tone according to artists: level is to hair colourists what tone is to artists, while tone is hue). Level broadly classifies hair into 10 subsequent steps of lightness, ranging from pure black (1) to platinum blonde (10) through increasingly lighter browns and blondes. Tone, or nuance, represents a hue shift at any given level: 6.1 is ash (/.1) dark blonde (6./), whereas 6.3 is golden (/.3) dark blonde (6./); 7.1 is ash (/.1) blonde (7./, one level higher than 6./), et cetera. Usually, tones are coded as per the following: /.0 natural; /.1 ash; /.2 irisé (a purplish hue); /.3 golden; /.4 copper; .5 mahogany; /.6 red. Other nuances exist that are for the most part inconsistent among brands. Mixed nuances are notated with two different decimal digits, the first being the dominant tone: ./34 is a copper red, while /.43 is a red copper. Finally, intense versions also exist which are notated by doubling, or even tripling, the same digit after the decimal point: /.66 is an intense red; /.666 is an ultra-intense red. Not every level has all tones, in a way that is again strictly dependent on the brand at hand. Thus, a

TABLE 1 Tristimulus coordinates of Munsell Hue page 2.5R gained from spectrophotometric measurements of The Munsell Book of color, matte edition

Tristimulus and RGB (D65) values, plus saturation and chroma, of The Munsell Book of Color 2.5R chips									
Chip	**X**	**Y**	**Z**	**R (D65)**	**G (D65)**	**B (D65)**		**Saturation**	**Chroma**
2.5R 2.5/2	5.6788	4.9389	5.3359	0.3162	0.2204	0.2465		30.28	9.57
2.5R 3/2	8.2335	7.2009	7.6563	0.3780	0.2682	0.2951		29.04	10.98
2.5R 4/2	13.1475	12.0087	13.0303	0.4571	0.3546	0.3820		22.42	10.25
2.5R 5/2	21.4010	20.0911	22.1933	0.5602	0.4598	0.4907		17.92	10.04
2.5R 6/2	32.6374	31.0384	34.5343	0.6714	0.5660	0.6012		15.70	10.54
2.5R 7/2	45.2845	43.7186	49.0045	0.7681	0.6664	0.7043		13.24	10.17
2.5R 8/2	61.2013	59.6178	67.1792	0.8713	0.7693	0.8110		11.71	10.20
2.5R 9/2	79.8052	78.3953	89.2544	0.9713	0.8726	0.9203		10.17	9.87
2.5R 3/4	9.0866	6.9926	6.6461	0.4286	0.2371	0.2741		44.68	19.15
2.5R 4/4	15.1835	12.4419	12.2406	0.5269	0.3342	0.3695		36.57	19.27
2.5R 5/4	23.1017	19.8965	20.3134	0.6193	0.4338	0.4697		29.95	18.55
2.5R 6/4	34.1728	30.3208	31.6358	0.7244	0.5378	0.5763		25.76	18.66
2.5R 7/4	48.2276	43.4658	45.3219	0.8371	0.6397	0.6780		23.59	19.75
2.5R 8/4	64.8664	59.5262	62.8402	0.9423	0.7446	0.7852		20.98	19.77
2.5R 3/6	10.0294	7.1340	6.3593	0.4657	0.2188	0.2677		53.02	24.69
2.5R 4/6	16.0609	12.0213	10.8906	0.5670	0.3023	0.3484		46.69	26.47
2.5R 5/6	25.6347	20.2601	18.9721	0.6834	0.4093	0.4535		40.10	27.40
2.5R 6/6	36.3906	29.6948	28.1895	0.7871	0.5022	0.5446		36.20	28.49
2.5R 7/6	52.5100	44.4376	43.5494	0.9070	0.6203	0.6644		31.61	28.67
2.5R 4/8	17.1124	12.0087	10.4572	0.5994	0.2801	0.3416		53.27	31.93
2.5R 5/8	26.7893	19.2686	16.1324	0.7297	0.3632	0.4184		50.23	36.65
2.5R 6/8	39.2033	29.9488	26.3290	0.8427	0.4763	0.5262		43.47	36.64
2.5R 7/8	56.1950	44.8454	40.5027	0.9684	0.5956	0.6406		38.50	37.28
2.5R 4/10	19.3564	12.2432	9.6475	0.6583	0.2377	0.3278		63.90	42.07
2.5R 5/10	29.0659	19.4677	15.1007	0.7781	0.3314	0.4046		57.41	44.67
2.5R 6/10	42.0236	30.0183	24.4493	0.8955	0.4442	0.5070		50.39	45.12
2.5R 7/10	57.4082	42.8602	35.5030	1.0107	0.5491	0.6011		45.67	46.15
2.5R 4/12	22.0438	12.7080	9.0662	0.7178	0.1846	0.3175		74.28	53.32
2.5R 5/12	32.8825	20.4211	14.8690	0.8420	0.2945	0.4014		65.02	54.75
2.5R 6/12	44.4806	29.7870	22.2929	0.9417	0.4058	0.4842		56.91	53.59

Note: RGB conversion (reference white: D65). And finally, Saturation and Chroma series. Saturation is computed as the difference between the maximum and minimum RGB channel values, divided by the maximum, while Chroma is simply the difference. While the latter remains approximately constant, the former changes. Colour depictions are only approximations of true Munsell chips.

parallel can easily be traced: hair level as Munsell Value, hair tone as Munsell Hue, and, perhaps to a lesser extent, intensity as Munsell Chroma.

The issue with Chroma is easily explained: contrary to Munsell neutral axis, natural hair, that is: the backbone of hair colours, is not gray (except when spontaneous depigmentation occurs due to advanced age or albinism). Apart from black 1.0 (which is by definition an achromatic colour), browns and blondes, irrespective of level, have an intrinsic chromatic component. Regardless, we deem Chroma more suitable to describe hair intensity as opposed to Saturation. By looking at a 7.666, a hair colour professional will know conceptually that a very "strong" version of a fixed level (Value) and fixed tone (Hue) is being employed, that is: only one facet of the colour is being acted on. If, on the contrary—because of the intrinsic limits of colour wheels—hair tone, level and intensity are being confused (as is often the case, see

Figure 10) having three attributes separately influencing colour appearance is also a very desirable property from an educational point of view.

At least two further practical considerations can be made, again considering both level and tone. First, it must be remembered that Munsell provides perceptually uniform colour intervals. In sample colour charts, it is apparent that the series of naturals is not equally spaced. Its lower half, comprised of black and browns, moves in very short steps, so short in fact that swatch 2.0 is often entirely omitted due to its close proximity both to 1.0 and 3.0. On the contrary, from 6.0 up to 10.0 these steps are far wider, disproportionately so with respect to the bottom half of the series. By providing Munsell Values for hair swatches, the non-uniform scaling is made quantitatively apparent (Figure 11A).[17] Because Munsell Values are perceptually linearly scaled, a perfectly balanced series of naturals would ideally fit on a straight line connecting black to platinum blonde. More likely, a matching could be established between hair level and Munsell Value in order to have a more reasonable scaling, if not entirely linear. This would then transfer to other nuances. Albeit all swatches sharing the same level digit, for example, 8./, are supposed to be equally light, it is very much not the case for the majority of real charts and colour lines. Despite not being expected to, tonal shifts do often tamper with levels. A Munsell Value analysis could then provide a quantitative insight on such differences.

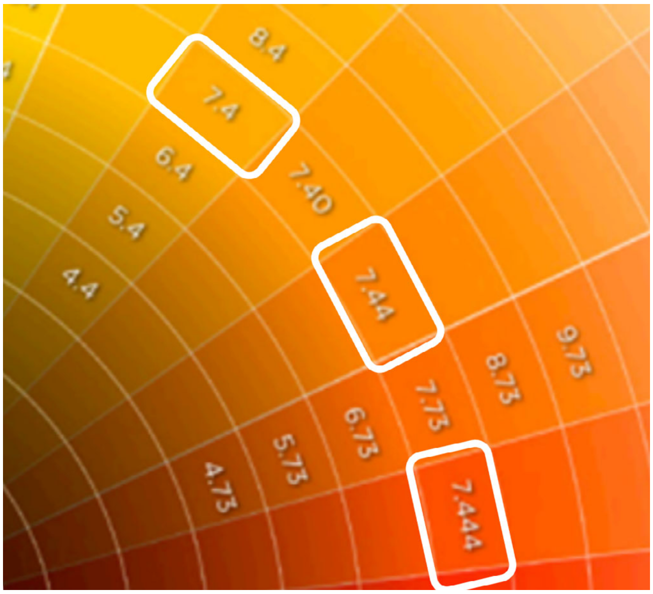

FIGURE 10 Figure 8, magnified. Because colour wheels are two-dimensional, not all colour attributes can be shown adequately. Here, different colour intensities for a copper blonde (7.4, 7.44, and 7.444) are assigned different hues, wrongly suggesting different tones for the three versions

Regarding tone itself, a further consideration is needed. When dealing with customers, hair colourists must often resort to bleaching: before a product is applied, natural melanin must be removed, especially in the case of dark hair. The remaining colour is sometimes

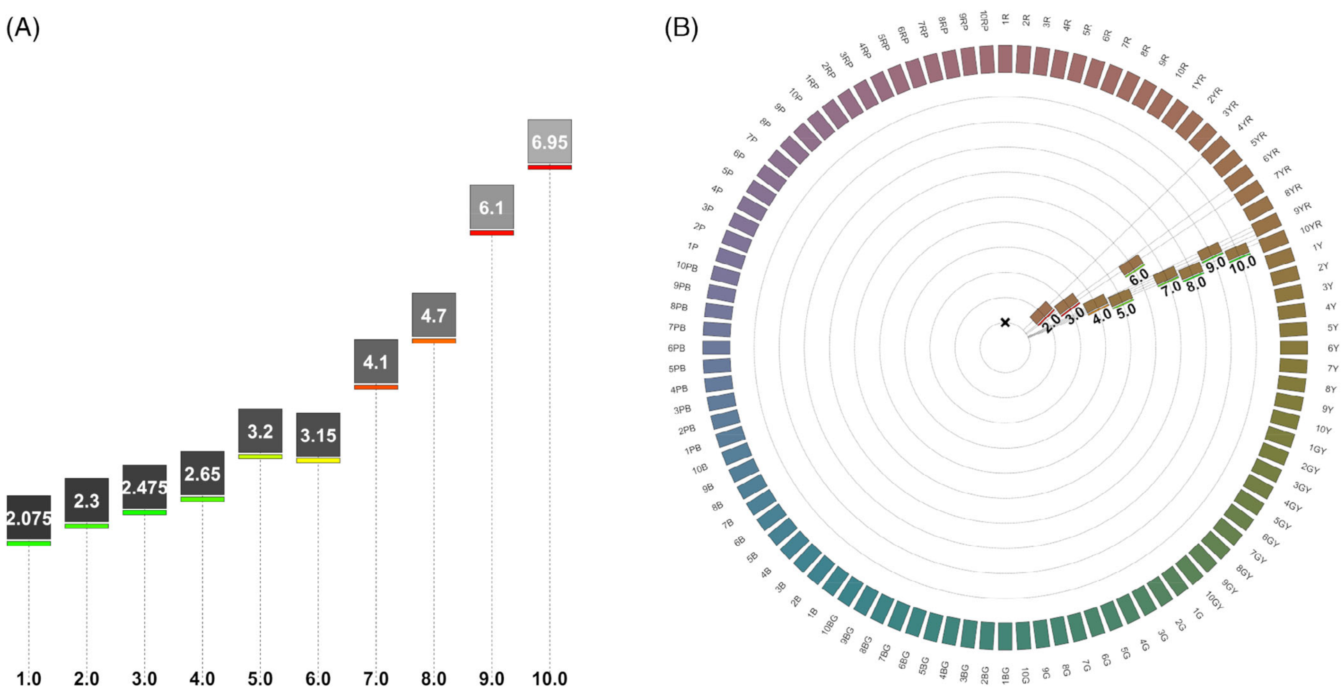

FIGURE 11 Example of a numerical Munsell analysis of the natural series: (A) Munsell Value for hair level; (B) Munsell hue for hair tone

referred to as natural remaining pigment, which is known to shift according to the amount of bleaching: less intense bleaching products, and shorter application thereof, result in a reddish appearance which turns more and more yellow the stronger the product, the longer the processing time. All intermediate hues are possible, comprised of those with red prevailing over orange, and vice versa, and orange prevailing over yellow, and vice versa. When trying to dull a red-orange natural remaining pigment, professional hair colourists need to balance out red first, and orange second. When trying to dull an orange-red instead, a product must be applied with the reverse order of priorities. Also, because colour wheels incorrectly claim that any given tone fits entirely within a homogenous hue, subtler distinctions go all but lost. When pairing Munsell chips to hair swatches, their perceived Hues are also quantified (Figure 11B), so that a more accurate evaluation of their tone, and/or natural remaining pigment, can better serve the colourist.

Finally, we propose Munsell colour-ordering system, and the Munsell Book of Colour for all practical intents and purposes, as a tool for measuring hair colour appearance in light of the medium's unsuitability with respect to spectrophotometric measurements. Because human hair are scatterers, light shone on them is very likely to be reflected in unpredictable ways, more so for blondes.[18] This is unsuitable for all instruments that rely on light bouncing off surfaces for colourimetric determinations. But what matters the most is that we deem Munsell colour-order system to be extremely well suited to make *relationships* between colours stand out, as opposed to colours in and of themselves. In other words, not only can Munsell system help build a perceptually defined hair colour line. It can also provide a tool for hair colourists to make of a set of products something more than the simple sum of its parts.

6 | CONCLUSIONS

Colour-order systems represent a compromise between the world of art and science. They are usually well suited to practical applications, because a physical version can be realized for direct comparison with surface samples. Despite a ubiquitous use of a simplified version of Ostwald system within the hair colouring industry, we make a case for the use of Munsell system instead. The latter's "agnostic" approach to colour, and his choice of colour attributes, make his Book a very versatile device, and one quintessentially compliant with human perception of colours, whichever object they belong to.

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AUTHOR CONTRIBUTIONS

Simone Liberini: Writing and editing. **Alessandro Rizzi:** Conceptualization, formal assessment and reviewing.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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