Paul Centore

Controlling Colour with the Munsell System

With 41 Spectrophotometrically Accurate Colour Plates

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Suggested Cataloging Data
Centore, Paul
Controlling Colour with the Munsell System/P. Centore
56 p., 29.2 by 25.2 cm
Includes bibliographical references
ISBN 978-1-63227-012-2
1. Munsell Color System 2. Color—Study and Teaching 3. Plates of Color Standards
I. Centore, Paul, 1968- II. Title
ND1493.M8 2014
751.4

Printed in the United States of America

ISBN 978-1-63227-012-2

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1 Introduction

Controlling colour and using it well is an important concern for painters and other visual professionals. Such control requires a coherent language, ideally one that is rooted in objective criteria. For the last century, the Munsell colour system has provided such a language. Its key concepts of hue, value, and chroma comprise a basic, natural framework for colour decisions. The system was originally defined by physical samples, but the 1943 Munsell renotation,[1] which is now the standard, uses quantitative definitions that depend on scientific measurements.

In addition to clear definitions, working artists also need physical exemplifications: colour samples that can be viewed and compared with the colours on palettes and canvases. Historically, such samples have been labor-intensive, and often prohibitively expensive. An industry standard for many years has been X-Rite's "Big Book of Color." While an excellent resource, X-Rite's book currently costs nearly $US 1000, beyond the budgets of most painters. In the last decade, Jim Long and Joy Turner Luke have produced a student Munsell book that retails for well under $US 100. This helpful resource is affordable, but only offers a limited set of 235 standard Munsell colours.

The current book offers an affordable Munsell set, with a much wider gamut, of over 1500 standard Munsell colours. Such a presentation has only become possible recently, with the advent of cheap (but very capable) printers, spectrophotometers, and computers. In fact, this entire book was produced in the author's home, with equipment bought at retail stores. For those who are interested, the final section gives some technical details. Unlike the two other books mentioned, this book's colour swatches cannot be removed. Its gamut and accuracy, however, are comparable.

This book was motivated by the author's desire to use the Munsell system in his own painting, and the lack of comprehensive, affordable references. It is hoped that its publication will benefit other artists, too. Any suggestions, criticisms, comments, and questions are welcome, and should be sent to centore@99main.com, or paul@isletech.net.

2 Description of the Munsell System

The Munsell colour system is a colour classification and specification system that is tailored for painting and the visual arts. It was developed by the American painter and teacher Albert

Munsell, at the start of the 20th century, as an educational tool. The system is effective because it is based on natural colour perception. The Munsell colour system classifies surface colours by three perceptual attributes that are basic to painting: hue, value and chroma.

Hue is universally understood. It says whether a colour is red, yellow, purple, etc. Munsell designates 10 basic hues: R (red), YR (yellow-red, or orange), Y (yellow), GY (green-yellow), G (green), BG (blue-green), B (blue), PB (purple-blue), P (purple), and RP (red-purple). Each basic hue is further subdivided into 4 steps, denoted with a prefix. For example, the four greens are denoted 2.5G, 5G, 7.5G, and 10G. 2.5G is a yellower green, that is closer to GY than it is to BG. 10G is a bluer green, that is closer to BG than it is to GY. A prefix of 10 is sometimes replaced with a prefix of 0 and the next hue. For example, 10G is sometimes written 0BG. In all, then, the Munsell system specifies 40 hues (4 steps for each of the 10 basic hues). These 40 hues are equally spaced perceptually. For example, the hue difference between 2.5G and 5G is the same size as the hue difference between 5G and 7.5G. The 40 hues are discrete stopping points on a continuous hue circle. One could interpolate any desired amount between two adjacent hues. For example, the hue 6GY is a yellowish green that is between 5GY and 7.5GY, but closer to 5GY. White, black, and greys are not considered hues in the Munsell system. An N, for "neutral," is used to designate them.

Many different colours can have the same hue. For example, the second colour plate shows the "hue leaf" for 2.5R, a set of colours all of which have hue 2.5R. The different colours within a hue leaf are specified further by value and chroma. The empty boxes indicate colours that are in the Munsell system, but that are beyond the gamut of the printing process used to produce the figure.

Munsell value designates how light or dark a colour is. The theoretically darkest black has a value of 0, and is denoted N0. The theoretically lightest white has a value of 10, and is denoted N10. N0 and N10 are theoretical ideals, that actual paints approach, but have so far not reached. Most artists' blacks, such as carbon black, are about N1, rather than N0. Similarly, titanium white is just below N10. Between N0 and N10 are 9 progressively lighter greys, denoted N1, N2, and so on up to N9. The spacing between the greys is perceptually equal. All colours have a Munsell value, not just the neutrals. For example, there are light blues and dark blues. A blue with value 8.5 has the same lightness as N8.5.

Munsell chroma refers to how intense, or saturated, a colour is. For example, a lemon is an intense yellow, while masking tape is a dull yellow. A dull colour is closer to a neutral grey than an intense colour. The Munsell system denotes chroma numerically. Greys have chroma 0. A colour with a chroma of 10 is generally perceived as saturated, and it is rare for paints to have chromas greater than about 16. Colours of low chroma, say 4 or less, are perceived as subdued, with a high grey content. It is often difficult to distinguish the hue of low-chroma colours. For example, one cannot say readily whether masking tape is more yellow or more orange. The hue of high-chroma colours, by contrast, can easily be identified.

The Munsell notation for a colour takes the form H V/C, where H stands for hue, V stands for value, and C stands for chroma. For example, the colour 10R 9/6 would be a very light (V is 9), moderately intense (C is 6), orangish red (H is 10R). A colour with chroma 0 is a neutral grey, which is denoted NV, where V stands for value. For example, N5 is a grey that is midway between white and black. Liquitex acrylic paints typically give Munsell notations directly on their tubes, at least on some lines. Other manufacturers, such as Golden, list Munsell notations on their websites.

The 41 colour plates in this book are a physical exemplification of the Munsell system. The first plate shows the neutral greys. The remaining 40 plates show leaves for all 10 basic hues, in the order listed above. There are four plates for each basic hue, with the numerical prefixes running from 2.5 through 10.0.

The Munsell system is important to painters for several reasons. First, the attributes it identifies (hue, value, and chroma) are all basic to art. A painter should see his paintings in those terms. Value is the most important. A black and white reproduction of an image retains the Munsell values, but discards all hues and chromas, yet there is no trouble "reading" the black and white reproduction. A painter should similarly learn to look at paintings solely in terms of lights and darks. Classically, a tonal underpainting served to make sure the light and dark structure was sound. Chroma is also important. Colours whose chromas are too high (in the context of a painting) tend to be "loud" and jarring, calling undue attention to themselves. Colours whose chromas are too low will not provide sufficient emphasis.

Second, the Munsell system provides a language for colour communication. One painter, for example, might see that another painter's work suffers because the range of chromas is too narrow. The Munsell terminology allows him to articulate that insight clearly and helpfully. In a forum such as the Internet, where painters cannot easily show one another accurate colours, or when catalogues' colour reproductions are inadequate (which is usually the case), a Munsell specification can describe a colour precisely.

Thirdly, general rules, such as the relationship of colours in light to those same colours in shadow, are also naturally expressed in the Munsell language. The Reilly method for mixing paints requires that a desired colour have the correct hue and value, before adjusting its chroma. Such general procedures rely on core Munsell concepts.

3 How to Use the Munsell System

3.1 Colour Identification

Colour identification is the process of determining what a particular colour's hue, value, and chroma are. This task sounds simple, but can be surprisingly tricky without a physical Munsell set. The difficulty arises from Josef Albers' famous dictum that "Color is the most relative medium in art." The same colour, seen in a painting, on a palette, or in a Munsell book, can look very different, because it is strongly influenced by nearby colours. For accurate judgement, the colour of interest should be judged directly against Munsell samples, with no intervening colours or white space. A simple way to do this is to paint a small bit of the colour of interest on the edge of a sheet of disposable canvas paper, and then lay that section of the edge directly on top of a colour square on one of the colour plates. This comparison will emphasize colour differences: two colours that look the same when held an inch apart can look distinctly different when placed side by side. For similar reasons, it is best to use opaque colours: a paint that is transparent or translucent can have different colours, depending on how thickly it is applied.

A convenient colour identification procedure first estimates the hue, then the value, and finally the chroma. It is simple to identify a hue family, such as green, G. Once that family is found, consider the two adjoining hues, in this case GY and BG. Decide whether the sample tends more toward yellow (in which case GY is the basic hue), towards blue (in which case BG is the basic hue), or is a true green (in which case G is the basic hue). Once a basic hue is identified, refine it further, deciding whether the hue prefix is closer to 2.5 or 10.0, or somewhere in between. Of course, looking at the relevant colour plates will help in making these decisions. The result should be a hue leaf, such as 2.5G, that most closely matches the colour of interest. The agreement will probably not be perfect. For example, the true hue might be something like 1.5G, which is between 10.0GY and 2.5G. Nevertheless, settle on the closest hue leaf.

Now estimate the value of the colour. A simple method is to hold a swatch of the colour directly against the greys in the first colour plate. When held against a grey of the same value, the dividing line between the colour and the grey will disappear, and there might be an apparent vibration. This vibration results because value (how light or dark a colour is) is perceptually the most important Munsell coordinate. At a first pass, two colours of the same value will seem equivalent. Only after a closer look will their differences become apparent. The vibration is a double take, as the viewer tries to reconcile the difference with the equivalence.

If the first grey attempted is too light, then try again with a darker grey. If the first attempt is too dark, then try again with a lighter grey. Likely, no grey will match the colour's value perfectly. Rather, there will probably be two adjacent greys, one of which is slightly lighter than the swatch, and the other of which is slightly darker. A visual judgement can then be made as to whether it is about halfway between the two, or nearer to one of them. This degree of accuracy is adequate, because the just-noticeable-difference (JND) for greys is about a quarter of a value step: if the two greys' difference is less than a quarter of a step, they cannot be distinguished.

Once the hue and the value have been estimated, the chroma can be determined. Turn to the hue leaf that was chosen earlier, and find the row (or rows) that have the same value as the colour of interest. Move the swatch along those rows, comparing it to each of the different chromas. If the swatch is more saturated than the current square that it is being compared to, then move it to the right. If it is duller, then move it to the left. Likely, there will not be a perfect fit for chroma, but it will be possible to identify two adjacent chromas that bound the swatch. The chroma can then be numerically estimated to within half a step, which is adequate for practical purposes. The final result of this procedure will be a Munsell specification for a colour of interest, in the form H V/C.

3.2 Establishing Colour Guidelines

These specifications can be used to suggest guidelines for future effort. It is helpful for a painter to have a stock of effective colour combinations, that can serve as starting points for paintings. For example, a painter, after many experiments, might arrive at a set of colours for a figure painting that is realistic and interesting. After identifying the major colours as suggested above, he might realize that the colours for Caucasian skin, when viewed in light, have a Munsell value of about 7. Convincing highlights might be half a value step lighter and of a slightly cooler hue than the skin itself. If the shadows have value 4, the figure will appear to be in a light that is directional rather than diffuse, and at some distance. These lights and darks can serve as a template for later figure paintings. It should be understood that such templates are not strict rules, but rather starting points that should be adapted as needed.

This method is especially helpful for painters who produce many paintings with similar subjects. A landscape artist, for example, might determine a set of sky colours, for different weather and lighting conditions. The sky colour for his next painting could then be chosen by interpolating between the colours in this set, or by adjusting the hue, chroma, or value of one colour in the set. Regardless of the choice, a large stock of Munsell specifications will help insure repeatable results.

3.3 Colour Mixing

Frank Reilly used the Munsell colour system to develop a systematic paint mixing method, now called the Reilly method.[2] The method allows a painter to control hue, value, and chroma, in isolation from each other. A painter would refer to the colour plates when employing the method. The method assumes that the Munsell specification of the target colour is known—of course, this condition is always satisfied when the target colour has been chosen directly from one of the colour plates.

The first step in the Reilly system is to obtain a grey value scale, such as occurs in Colour Plate "N." For this purpose, Golden Acrylics manufactures a set of neutral greys in acrylics, spanning from N2 to N8, that are spectrophotometrically tested to conform to the Munsell standard. Williamsburg makes a similar set in oils, though just for greys N2, N4, N6, and N8. If needed, approximate greys can be mixed by combining burnt umber and titanium white, and matching to the grey values in a Munsell chart. While such mixtures are only approximate, they are usually adequate. From the value scale, select the grey which has the same value as the target colour (or mix two adjacent greys to produce an intermediate value if needed).

The second step is to mix a saturated colour of the same hue and value as the target. The chroma of this colour should equal or exceed the chroma of the target colour . A saturated colour will usually involve a paint, or perhaps two paints of related hues, that are taken straight from the tube, probably lightened to the correct value by adding some titanium white. Mixing paints of unrelated or distant hues, such as blue and orange, tends to give a mixture of lower chroma than either of the constituents. Mixing closer hues, such as blue and green, might give intermediate hues (in this case turquoises) of comparable chroma. Adding white might be necessary to achieve the same value as the target, if the hue colour is too dark. This step can be tricky, because white can sometimes cause a hue shift. For example, a mixture of cadmium red and titanium white tends to be more purplish than straight cadmium red. Adding white can also cause significant chroma changes. For example, pure Prussian blue is a very dull colour that by itself appears nearly black, yet a brilliant blue is produced when white is added. On the other hand, an intense pigment such as pyrrole orange will be considerably desaturated by adding white. The variability in hue mixtures makes it hard to give simple rules for this step; practice and experimentation are needed.

The third step is to adjust chroma. Mixing the grey from the first step with the saturated colour from the second step, in various proportions, will produce colours of different chromas. The higher the proportion of grey, the less chroma the mixture will have. Since the grey and the saturated colour have the same value, their mixtures should have about that value, too.

The mixtures should form a chroma scale (that is, a scale which varies only in chroma, but not in hue or value), from which a painter can choose a mixture with the same chroma as the target. Since the hue and value of that mixture already matches the target, that mixture must be the target colour. In practice, difficulties can occur with the chroma step because of unexpected hue shifts. For example, mixing a yellow paint with a grey of the same value can produce an unwanted greenish tint. Some experimentation with pigments might be needed to overcome these difficulties.

3.4 Colour Understanding

A complete Munsell set can be useful for visualizing and familiarizing oneself with the entire gamut of available colours. While one knows intellectually, for example, what a dark, dull purple is, visualizing such a colour can be difficult—and visualization is important for any practitioner. A Munsell set lets an artist literally see what different colours look like. When executing a painting, an artist is continually making colour decisions. Every time a colour is selected, its suitability can be evaluated in terms of hue, value, and chroma. The artist should mentally ask whether the colour should be lighter or darker (a value adjustment), duller or more saturated (a chroma adjustment), or warmer or cooler (a hue adjustment). With experience, these adjustment decisions become automatic. When learning, however, a Munsell book is an excellent aid for visualizing the directions in which a colour can vary. In fact, many painters and designers enjoy thumbing through a Munsell set, or a similar assortment such as Color-Aid cards, just to acquaint themselves with the wide variety of colours.

4 Technical Production Details

While the Munsell system is often used as an approximate guide rather than as an exact specification, it in fact has been given a precise scientific definition, called the *Munsell renotation*. In order to satisfy that definition, a technical process, involving measuring instruments and a custom colour reproduction algorithm, was used to produce the colour plates in this book. This section gives an overview of that process, for those who are interested. A more detailed description is contained in the write-up "How to Print a Munsell Book," available at the author's website, www.99main.com/∼centore; relevant open-source software is also available there.

4.1 The Munsell Renotation

Early versions of the Munsell system were collections of hand-painted swatches, which were used as physical standards for judging other colours. A major advance was the 1943 Munsell renotation,[1] which superseded previous versions, and is the standard today. The renotation analyzed thousands of visual assessments of paint samples, by 41 human observers, to provide a firm empirical basis for the system. In addition, the renotation specified a set of 2,745 Munsell colours scientifically. A paint swatch can be measured with a spectrophotometer, and its colour can be specified objectively, in terms of three coordinates defined by the

Commission Internationale de l'Éclairage (CIE).[3] Any two swatches with the same CIE coordinates, even if they are made from different paint mixtures, will have identical colours if viewed under the same conditions. By interpolating between the 2,745 specified colours, any surface colour can be located. Furthermore, inverting[4] the Munsell renotation allows a Munsell specification to be assigned to a measured paint swatch.

The scientific specification allows physical exemplifications such as the colour plates to be assessed quantitatively. In 2000, the CIE defined a perceptual difference[3,5] between two colour stimuli. This difference, denoted DE2000 and commonly referred to just as a "DE," is actually the latest revision in a series of difference expressions. The lower the DE between two colours is, the more similar those colours appear. When the DE is small enough, even though it might not be 0, two colours are indistinguishable to a human viewer. The threshold of distinguishability, called the just noticeable difference (JND), varies for different colour combinations, and no general rule can be found for it. In many settings, a DE of 2 is a usable estimate of the JND, but for comparing greys or very neutral colours, the JND is likely nearer 1.

Ideally, the physical Munsell colours in the colour plates should match the specifications in the Munsell renotation. Of course, there is actually some deviation, which can be quantified by calculating the DE between the CIE coordinates of the physical sample, and the CIE coordinates in the renotation. The physical sample is first measured with a spectrophotometer, which finds the sample's reflectance spectrum. The reflectance spectrum gives the percentage of each wavelength of light (in the visible spectrum) that the sample reflects. The sample's CIE coordinates can be calculated from this spectrum, under the renotation assumption that the sample is viewed in Illuminant C, and that the observer is the CIE 1931 2° Standard Observer.[3] The renotation gives the target CIE coordinates, so the DE between the sample and its target can be calculated.

A sample colour was considered sufficiently accurate for this Munsell book if the DE between the sample and the target was 2 or less. One colour, 7.5PB 1/12, was slightly above this threshold with a DE of 2.3, but was included anyway, to avoid a gap. In all, about 1,530 acceptable reproductions were found, out of 2,745 renotation colours.

Figure 1 shows a histogram of the DEs attained by this book. The average and median DE were both about 0.6. These seemingly excellent accuracies should be taken with a grain of salt. Multiple potential samples were printed and measured for almost all Munsell aimpoints. When repeated measurements are made, and the measuring device shows some variability, a printed sample's DE will occasionally be very low, just because of random variation. Furthermore, measurements with a different spectrophotometer,[6] or even repeated measurements with the same spectrophotometer,[7] could plausibly differ by perhaps as much as 1 DE. Nevertheless, even if every measurement in Figure 1 should have an additional error of 1 DE, the DEs would still be almost all less than 2. This accuracy will later be seen to compare favorably with other Munsell products.

The Munsell renotation extends to theoretical limits, called the *MacAdam limits*, providing specifications for some very intense colours that are well beyond the gamut of any paints or inks. The many colours that are not included in this book tend to be very saturated, and thus out of gamut. The colour plates indicate a colour that is within the MacAdam limits, but outside the printing gamut, with an empty square.

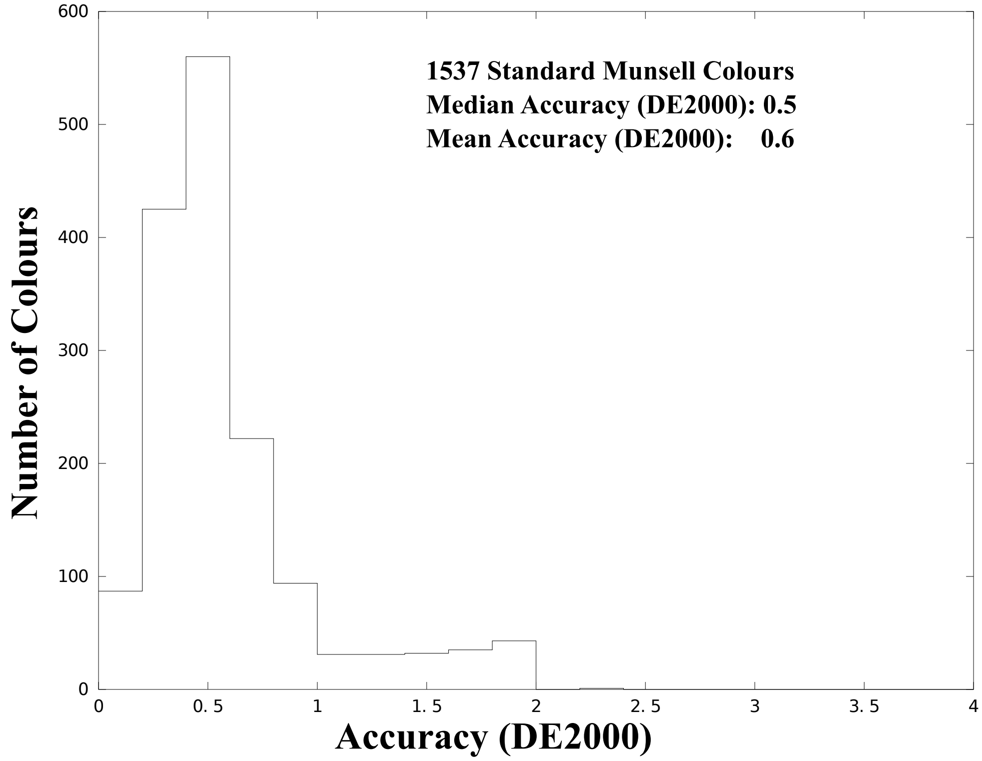

Figure 1: Histogram of Accuracies of Algorithm Output

4.2 Production

A major motivation for this book was the desire for an affordable, wide-gamut exemplification of the Munsell system. As of 2013, only two such products were available: a book by Jim Long and Joy Turner Luke,[8] and a book produced by the X-Rite Corporation.[9] Long's book is reasonably priced at about $65 US, but only contains about 235 standard colours. X-Rite's book presents a wide colour gamut, but its cost is approaching $1000 US.

In recent years, printer and colour measurement equipment have not only become considerably more sophisticated, but also much less expensive. As a result, the author can now produce this reasonably accurate Munsell book, from his own home. The equipment used is readily available at retail stores, and not too costly:

1. A higher-end printer. An Epson Stylus Photo R2880 was used, which cost $600 US,
2. Higher-quality photographic paper. Kirkland Signature Pro Glossy Inkjet Photo Paper (Item #503626) was used, at a cost of about 15 to 20¢ per sheet,
3. A spectrophotometer. An X-Rite ColorMunki was used, which cost $450 US (later an X-Rite i1 Pro 2 was used, costing about $1200 US), and
4. A computer, equipped with Octave or MATLAB. MATLAB is expensive, but Octave is an open-source MATLAB clone that can be downloaded for free.

Although the equipment was not a major investment, considerable effort went into developing and implementing an algorithm to print colours that matched the renotation sufficiently accurately. The write-up "How To Print A Munsell Book" gives details of this development. The algorithm that was developed is iterative. It starts by measuring the gamut of the colours the Epson R2880 can produce. Interpolation is then used to estimate the RGB specifications for the renotation colours. These estimates are themselves printed and measured. If an estimate matches its renotation aimpoint to the desired DE, then no further attempts are made for that aimpoint. If an estimate is not a good enough match, then further RGB specifications around the estimate are printed and measured, to give more precise information. Further estimates for the remaining aimpoints were calculated from this additional information. These estimates were printed and measured. These iterations continued until the aimpoints were matched sufficiently closely.

4.3 Comparison With Other Munsell Books

The DEs of the colour plates were compared with the DEs of the two other Munsell books, and found to be about on par. The two books contain both standard and non-standard Munsell colours. A Munsell colour is considered standard if it appears in the Munsell renotation data. Standard colours have integer Munsell values, even Munsell chromas, and hues prefixed with 0.0, 2.5, 5.0, 7.5, or 10.0. Non-standard colours are interpolations between the standard colours. For example, the X-Rite book contains many colour samples with chroma 1; since 1 is not an even number, these samples were discarded as non-standard. To eliminate variability in the comparisons, all three books were measured with the same brand of spectrophotometer, an X-Rite ColorMunki.

The New Munsell Student Color Set, 2nd ed. contains swatches that a student sorts himself, and glues onto Munsell sheets. This book is affordable, but limited in its gamut. Only hues prefixed with 5.0 are presented, and the chromas stay near the neutral axis. Figure 2 is a histogram of the differences between the printed samples and their renotation aimpoints. Out of 235 printed standard colours, the median DE was 1.6, and the mean DE was 1.8. A very large DE of 10.2, occurs for the colour N9, which is printed far too light. Removing this point makes the mean error slightly less. A third edition of this book has just become available recently; the DEs might be different for the newer book.

X-Rite's "Big Book of Color" is an industry standard, that has been produced for many years. An extensive set of inks is used, to attain a wide gamut. More recent versions have over 1600 removable printed samples. For the current analysis, the 2007 glossy edition was measured, with results shown in Figure 3. In the 2007 book, 1301 samples were standard Munsell colours. Their median DE, when compared to renotation aimpoints, was 1.9, and the mean DE was 2.1. Overall, then, this Munsell book achieved a DE accuracy of about 2.0, not much different from *The New Munsell Student Color Set.* New editions of the Big Book of Color are produced regularly, in both matte and gloss versions; possibly the DEs will be different in different editions.

The histograms in Figures 1 through 3 show that the current colour plates compare favorably in accuracy with both the student set and X-Rite's industry standard: overall, the plates seem to about one DE more accurate. As mentioned previously, of course, the colour plate DEs might be optimistically low, because of selection bias and spectrophotometer variability. Still, even accounting for that optimism, the colour plates' accuracy seems to be at least on par with the other two books, and can therefore be used with confidence.

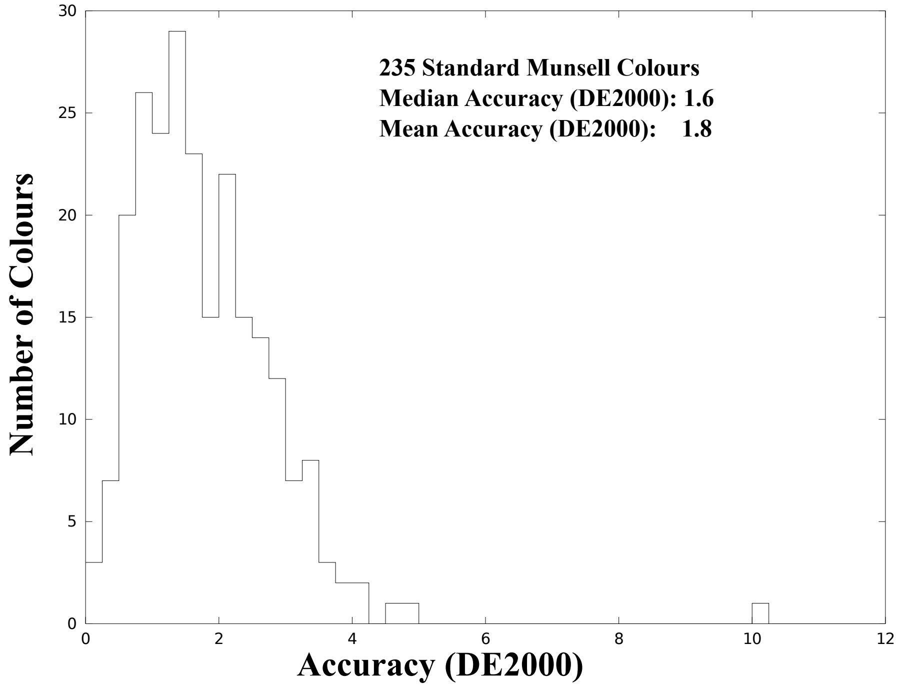

Figure 2: Histogram of Accuracies for *The New Munsell Student Color Set, 2^{nd} ed.*

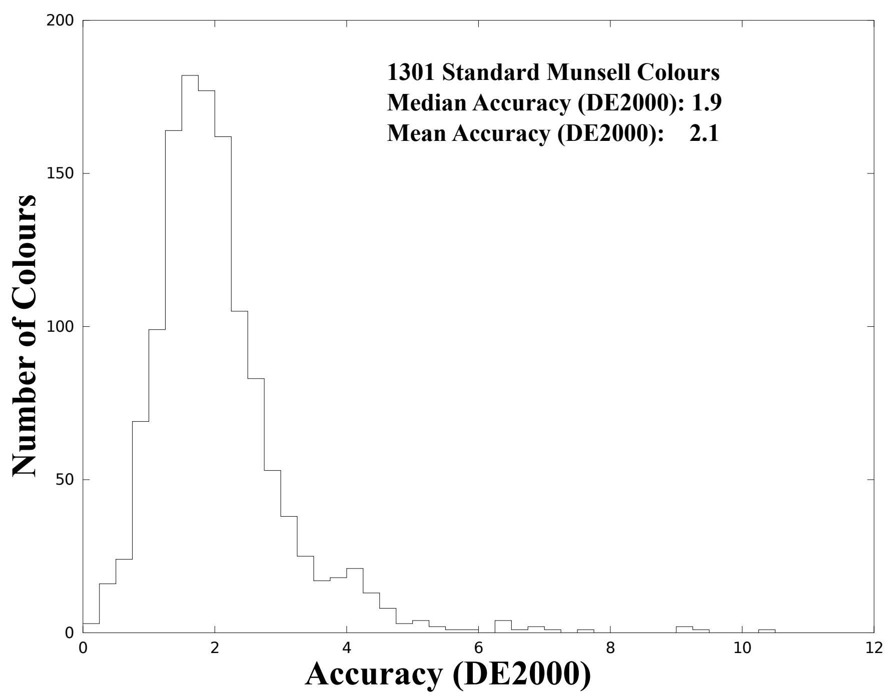

Figure 3: Histogram of Accuracies for the 2007 Glossy "Big Book of Color"

4.4 Limitations

The current Munsell book produced is accurate, affordable, and wide-gamut, but still has some limitations which should be kept in mind. In particular, manufacturing variability and unknown permanence could be important issues.

Manufacturing variability means that individual items, though produced by the same equipment and process, can still have differences. Consistently printing the Munsell book requires that the printer, inks, and paper, do not change over time. In fact, of course, physical equipment and materials can change over time, causing the output Munsell colours to vary. The current production chain relies on paper and ink that are supplied by outside parties, so there is no direct control over their properties. Even without changes in the physical equipment, production conditions, such as humidity when printing, can cause variability. These factors are particularly difficult to control in a home environment. This variability is believed to be small, but it has not been quantitatively assessed.

Permanence is another issue. Any printed colours, including the colour plates, have an uncertain permanence, especially when used as a working tool. It is likely that the colours will fade sooner or later, or otherwise alter. Testing every few years would be needed to see how long the colours maintain the desired DE.

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Colour Plates