sRGB Centroids for the ISCC-NBS Colour System

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Abstract

The ISCC-NBS colour system specifies 267 colour categories with non-technical names such as "light purplish pink." Computer monitors typically specify colours by red-green-blue (RGB) coordinates, standardized in the sRGB system. This paper presents a detailed technical description of conversions between the two systems. Many sRGB triples fall in a particular ISCC-NBS category; the centroid of all such triples, calculated with respect to a Euclidean metric on sRGB space, is taken as the most representative sRGB for that category. The conversion uses the Munsell system as an intermediary. ISCC-NBS categories, which apply to object colours, are not immediately compatible with sRGB coordinates, which apply to light sources. To achieve compatibility, it is assumed that an sRGB monitor is viewed under Illuminant C (the standardized illuminant for Munsell and ISCC-NBS), at intensity levels that make the monitor's colours appear as object colours. The paper's practical results include a simple lookup table for the centroids, and some open-source code for further development.

1 Introduction

Colour specification is an important practical problem, for which many systems have been developed. In industrial settings, colour specification can be very technical, requiring instrumented measurements and trained personnel; likely some version of the tristimulus coordinates[2] recommended by the Commission Internationale de lÉclairage (CIE) would be used. In design settings, on the other hand, such as fashion or interior decoration, non-technical staff would use everyday terms like "light purplish pink," describe colours informally rather than specifying them exactly, Specification systems differ in their level of precision: less precise systems rely on common words, while more precise systems use numerical coordinates.

To account for less formal situations, the Inter-Society Color Council (ISCC) and the National Bureau of Standards (NBS, now NIST), in 1955, standardized the ISCC-NBS colour system.[3] To be accessible to non-technical people, the ISCC-NBS system uses only common English words. Basic hues like yellow or green are combined with modifiers like "pale" or "vivid" to produce 267 colour categories; some examples are "light greenish gray" and "deep blue." The term "deep blue" is not one particular colour, but rather encompasses many different colours. This level of precision, in which a recognizable colour range is defined rather than one exact colour, would be suitable, for instance, for clothing designers who are choosing colours for next season's skirts. Although the ISCC-NBS system is intended for non-technical situations, it still has a rigorous technical definition: each category is a well-defined subset of the Munsell system,[4] and every Munsell colour belongs to a unique ISCC-NBS category.

In recent decades, much design, including colour decisions, has become digital. Computer monitors are now routinely used to display and evaluate colours. The standard red-green-blue (sRGB) system[1] is an international colour specification that defines what colours an electronic display emits in response to RGB coordinates. Colour problems can occur, however, when a design on a computer screen is produced in the physical world—the physical colours look noticeably different from the screen colours. Colour translation from a monitor to the physical world is difficult because the sRGB system used for the screen applies to coloured *light sources*, while the ISCC-NBS or Munsell system used for the product applies to coloured *objects*. This distinction matters because (by mechanisms not yet understood) human colour constancy identifies object colours correctly regardless of illumination, but colour constancy does not apply to coloured light sources.

A way around this difficulty is proposed, in order to convert between sRGB colours and ISCC-NBS categories. The central assumption is that a computer monitor is viewed under ambient illumination that is consistent with Illuminant C, which is the illuminant assumed by both the Munsell and ISCC-NBS systems. From a practical point of view, this assumption can be satisfied, at least approximately, if the monitor is viewed in indirect daylight, which Illuminant C models . If the monitor's brightness is adjusted correctly, then the monitor's colours, even though they are physically light sources, will be perceived as object colours, and their Munsell coordinates, and then their ISCC-NBS categories, can be calculated.

A sort of inverse calculation is also presented, involving centroids. An ISCC-NBS category contains a multitude of sRGB triples (that is, sRGBs which, when converted, are within that category). The sRGB triples for a particular category fill a limited, contiguous, approximately convex, region of sRGB space. sRGB space can be visualized naturally as a cube; furthermore, a Euclidean metric, that is locally compatible with human perception, can be imposed on that cube. To visually display a category on a monitor, we would like to choose one sRGB, out of the many contained in that category, that best represents that category. A natural choice is the region's sRGB centroid, which is roughly in the middle of the region, and averages out colour variations over the region. The Euclidean metric allows us to calculate such centroids. The main practical result of this paper is a lookup table that lists sRGB centroids for ISCC-NBS categories, and that designers and programmers can use to display or work with the ISCC-NBS system.

The paper is organized as follows. First, three colour specifications (the Munsell system, the ISCC-NBS system, and the sRGB standard) are described. Second, conversions between these specifications are derived. The assumption of Illuminant C is important for the conversions, so it is discussed in some detail. Gamut mismatch, which occurs because the Munsell and sRGB colour spaces do not agree perfectly, and which affects the conversions, is also discussed. Third, the sRGB centroid calculations are described, and lookup tables of the results are given. Finally, some data files and computer routines are presented, which are being released as open source. Others are welcome to use and modify them, with the understanding that any modifications will be similarly publicly released.

2 Colour Specifications

2.1 The Munsell System

At the start of the 20th century, the American painter and teacher Albert Munsell developed the Munsell colour system, as an educational tool for painters. It has since become common in many visual fields, such as graphics and fashion. It applies to the colours of physical objects, rather than to the colours of lighting. The Munsell system is helpful because it classifies surface colours by three natural perceptual attributes that are basic to design: 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. Figure 1, for example, shows the "hue leaf" for 10R, a set of colours all of which have hue 10R. 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 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 blacks, such as the black ink used by printers, are about N1, rather than N0. Similarly, common whites are 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 instance, 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 to encounter 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

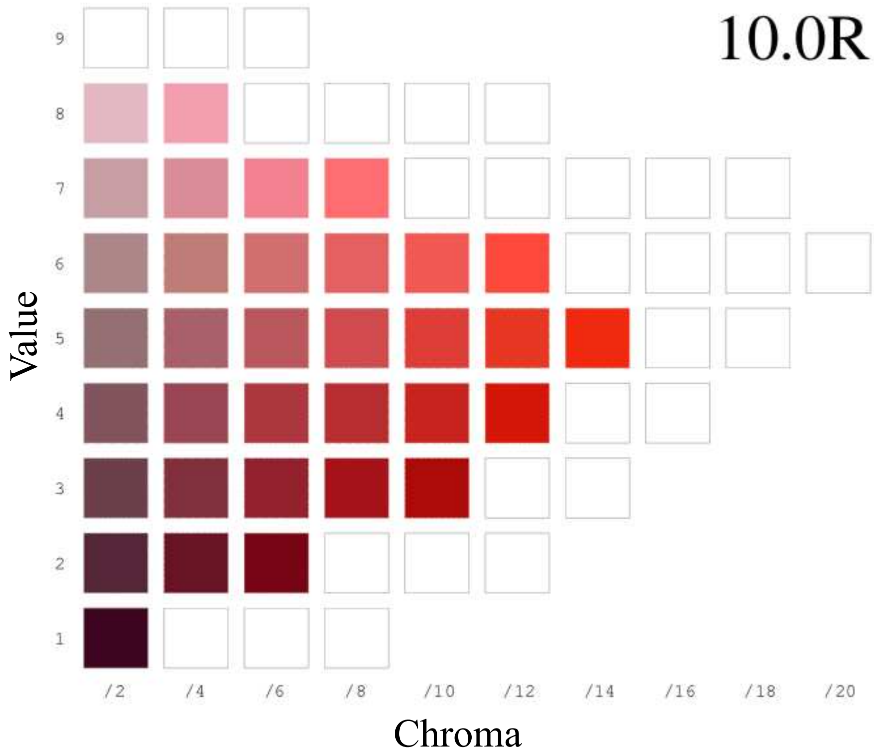

Figure 1: The Hue Leaf for 10R in the Munsell System

orange. The hue of high-chroma colours, by contrast, can easily be identified. Each hue leaf increases in chroma as one moves to the right, and decreases as one moves to the left. The left edge of each hue leaf, in fact, transitions smoothly into a vertical neutral axis, consisting solely of greys, whose chroma is 0.

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 instance, the colour 10R 7/6 would be a fairly light (V is 7), 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.

A three-dimensional *Munsell tree*, shown in Figure 2, can be constructed by placing the far left, or neutral, edges of all the hue leaves along a common vertical axis. Since the hue leaves have different shapes, the Munsell tree as a whole is irregular, extending out to different distances at different heights, depending on the leaf. The leaves are placed sequentially by hue (red, yellow-red, orange, etc.), forming a smooth circle. The fact that object colours form a continuous solid, without any holes, is not only an important theoretical result, but will also be useful later as a practical result, when we define transformations from the Munsell solid to the solid sRGB cube or three-dimensional tristimulus space.

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,[4] which superseded previous versions, and is the standard today. The renotation used 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

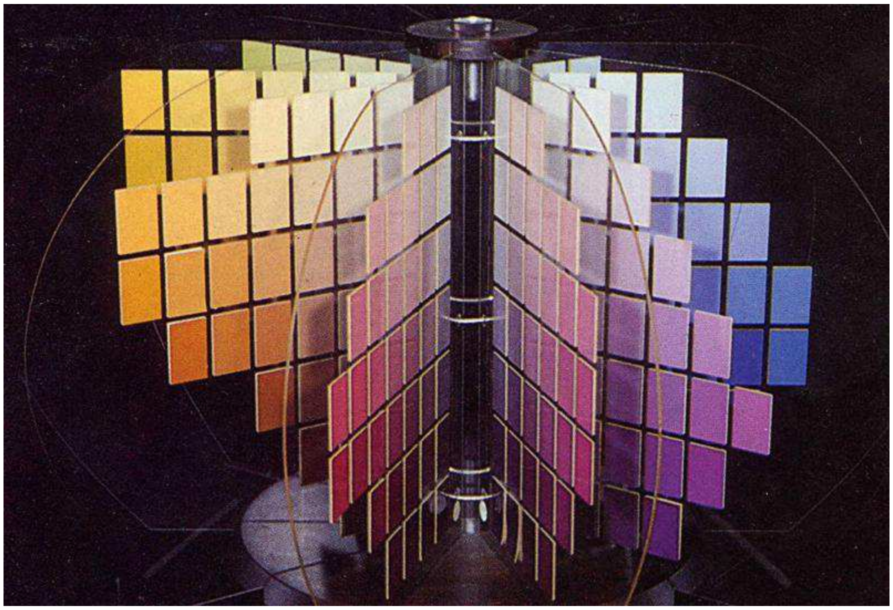

Figure 2: The MunsellTree

set of 2,745 Munsell colours scientifically, in terms of tristimulus coordinates. For greater consistency, the renotation also standardized viewing conditions, requiring that samples be judged under Illuminant C lighting, which models indirect daylight.

The Munsell system encompasses every possible object colour; each object's surface has a reflectance spectrum which, when viewed under Illuminant C, has a Munsell specification. Furthermore, a Munsell specification can be calculated for *any* reflectance spectrum. Any colour with a particular hue and value, however, has a maximum attainable chroma, which occurs at the rightmost end of the horizontal bar of colours of that value, in that hue leaf. Figure 1 shows, for instance, that the maximum chroma for hue 10R at value 5 is about 18. Taken as a whole, these maximum chromas bound the three-dimensional Munsell colour tree, and are referred to as the *MacAdam limits*. The renotation transforms the Munsell tree into a solid in tristimulus colour space, so the MacAdam limits can equally well be seen as applying there.

In fact, the MacAdam limits were originally calculated in tristimulus space, and only later transferred to Munsell space. These limits are theoretical. They represent colours that could be produced physically if surfaces with the right reflectance spectra could be found. In practice, actual colorants, such as pigments or printing inks, extend somewhere between one-half and two-thirds of the way to the MacAdam limits, for any particular hue and value. Colours near the neutral axis are well-represented, but there are no physical examples of many high-chroma colours. While the renotation provides chromas for colours at the MacAdam limits, these chromas were extrapolated from colours nearer the neutral axis. The more neutral colours had actually been produced in paint, and human subjects assessed their chromas, so there is more confidence in chroma assignment for lower-chroma colours.

It should be noted that the MacAdam limits apply only to surface colours, and not to coloured lights. Both surface colours and coloured lights can be assigned tristimulus coordinates, and in fact a particular surface colour and coloured light can have identical coordinates. Coloured lights, however, can have coordinates that are outside the MacAdam limits. Such lights can produce colours that are more saturated than any paint or ink. An example is the colour given by RGB coordinates $[0, 255, 255]$, which is a very intense blue-green. This gamut mismatch, in which one space contains colours that another space doesn't, will become relevant later on when converting between computer colours and the Munsell system.

The 1980 Pointer gamut[8] provides more realistic bounds to the Munsell system than the MacAdam limits. The Pointer gamut was calculated by measuring the reflectance spectra of a wide variety of actual colour samples, especially samples with high chromas. Every colour in this gamut is a "real" colour in that an example of it has been produced. As more colorants, especially very saturated colorants, are developed, the Pointer gamut is gradually expanding beyond its original 1980 boundaries.

2.2 The ISCC-NBS System

While the Munsell system is conceptually useful and scientifically accurate, its notation can put off non-technical workers. Furthermore, a physical exemplification, such as a printed book or poster, is needed to assign Munsell coordinates with any confidence. In many situations, everyday colour terms, such as "reddish grey" or "pale pink," though not as precise as the Munsell system, are sufficiently descriptive, and have the advantage of being universally understood. The ISCC-NBS colour system[3] formalizes such common colour names, and defines them rigorously as subsets of Munsell space. Like the Munsell system, the ISCC-NBS system applies only to object colours (not to light sources), and assumes Illuminant C viewing. It is particularly appropriate in a product's design stage, where precise colour specification would be premature and distracting. Rather than an exact colour, like 5B 3/4, a colour category, like "dark grayish blue" is often easier to work with. In a digital environment, lookup tables to be presented later could provide sRGB coordinates that correspond to dark grayish blue; this application in fact motivated this paper.

The ISCC-NBS system formalizes the idea of "sufficiently descriptive" with three levels of precision. Each level offers a list of colour names, also called colour categories. A colour category can be thought of as a subset, or block, of the Munsell system. Any particular colour within a block is within that category, so a category represents a broad range of colours. As the level of precision increases, the blocks get smaller.

Level 1 is the simplest and most approximate level. At this level, every object colour is described by one of the following 13 names: pink, red, orange, brown, yellow, olive, yellow green, green, blue, purple, white, gray, or black. Each of these 13 categories covers a plethora of colours; for instance, an apple and a cardinal would both be described as red at Level 1, even though their reds are distinct.

Level 2 contains 29 names or categories, allowing finer descriptions than Level 1. The right half of Table 1 lists the Level 2 names. Each Level 2 category is contained completely within one Level 1 category, although the official description is not quite clear on the relationships: page A-13 of Ref. 3 states "In level 2, the whole color solid is divided into 29 blocks; four of the level 1 blocks remain unchanged while 9 are divided into two or three parts," but does not specify the divisions. Table 1 lists a reasonable set of divisions which is compatible with this statement, and which will be used in this paper.

A confusing feature of the ISCC-NBS system is that every Level 1 name also appears as a Level 2 name, but (apart from the names white, gray, black, and yellow green) denotes a more restricted colour set at Level 2. An apple, depending on its particular coloration, might be described as a Level 1 red, but as a Level 2 purplish red rather than a Level 2 red. A cardinal, on the other hand, would likely be described as both Level 1 red and Level 2 red. Every Level 2 purplish red is also a Level 1 red, but not vice versa; similarly, every colour in Level 2 red is also in Level 1 red, but not vice versa. To be technically correct, the term red should only be used along with the qualifier "Level 1" or "Level 2." To avoid this ambiguity, this paper proposes using the same sRGB centroid for Level 1 and 2 categories with the same name; later analysis will show that any loss of accuracy is insignificant.

Level 1	Level 2
1. Pink	1. Pink 3. Yellowish pink 25. Purplish pink
2. Red	2. Red 26. Purplish red
3. Orange	4. Reddish orange 6. Orange
4. Brown	5. Reddish brown 7. Brown 9. Yellowish brown
5. Yellow	8. Orange yellow 10. Yellow 12. Greenish yellow
6. Olive	11. Olive brown 13. Olive 15. Olive green
7. Yellow green	14. Yellow green
8. Green	16. Yellowish green 17. Green 18. Bluish green
9. Blue	19. Greenish blue 20. Blue 21. Purplish blue
10. Purple	22. Violet 23. Purple 24. Reddish purple
11. White	27. White
12. Gray	28. Gray
13. Black	29. Black

Table 1: Containment Relationships between ISCC-NBS Levels 1 and 2

Level 3 is the finest level of the ISCC-NBS system, and contains 267 names. Each

Level 3 category is formed by subdividing a Level 2 category, using modifiers such as "light" or "grayish." For instance, Level 2 pink is subdivided into ten Level 3 categories: vivid pink, strong pink, deep pink, light pink, moderate pink, dark pink, pale pink, grayish pink, pinkish white, and pinkish gray. Table 10.1 of Ref. 5 contains a complete listing of the Level 3 categories. Again, there is some confusion in the names when relating Level 2 to Level 3. For instance, pinkish gray should arguably be classed as gray at Level 2, rather than as pink. The aforementioned Table 10.1, which this paper follows, indicates not only each Level 3 category, but also the Level 2 category that contains it.

The three ISCC-NBS levels are levels of the *precision* of a colour description. An object colour can be described at all three levels simultaneously, depending on the degree of accuracy required. For instance, the artist's pigment burnt sienna (PBr7) would be described at Level 3 as moderate reddish brown, at Level 2 as reddish brown, and at Level 1 just as brown. The Level 1 category of brown contains many browns that are definitely not burnt sienna, such as tans or yellow ochers. The Level 2 category of reddish brown is a smaller subset, that contains no tans or yellow ochers. The Level 3 category of moderate reddish brown is even more descriptive, indicating that a red component is noticeable but not very strong. Designers move naturally between the levels, sometimes lumping burnt sienna with browns in general, and other times focusing not just on its brownness, but also on its reddish shade.

The ISCC-NBS system deliberately uses non-technical language, so that anyone can understand it. The ISCC-NBS distinctions, though not as fine as Munsell distinctions, are usually adequate for the early stages of a project. For instance, a furniture manufacturer might need some colour schemes for next year's living room sets. In that case, Level 3, and possibly even Level 2, provides clear enough descriptions for the designers to communicate, even remotely, without requiring technical expertise.

Even though the ISCC-NBS system appears somewhat informal, it is defined rigorously in terms of the Munsell system. Ref. 3 contains a series of 31 charts, which can be overlaid on various Munsell hue leaves. Figure 3 shows one such chart, for hue leaves 9R through 1YR. Figure 4 shows that chart overlaid on the 10R hue leaf from Figure 1. The chart divides the hue leaf into regions that correspond to different Level 3 categories. Suppose one is interested in burnt sienna. Then its Munsell coordinates, about 10R 3/4, can be located on the appropriate hue leaf, as shown in the figure. Then the Level 3 category, in this case moderate reddish brown, can be read directly from the chart. The Level 3 category completely determines the Level 1 and 2 categories. The 31 charts span all the hue leaves, and adjacent charts tend not to vary much, because similar hues are likely to fall in the same ISCC-NBS category. For instance, any colour with value 3 and chroma 4, as long as its hue was between 6R and 3YR, would be a moderate reddish brown.

A weakness of the ISCC-NBS system is its uncertain empirical basis. While the Munsell renotation incorporated numerous human assessments of physical colour samples, the historical record for the ISCC-NBS system is unclear on to what extent human judgements were involved. Ideally, subjects would have judged how well the proposed colour names described the colours they represent, and names and overlay charts would have been adjusted accordingly. Despite this uncertainty, the well-established ISCC-NBS system seems reasonable, and fills a needed niche, so using it makes sense.

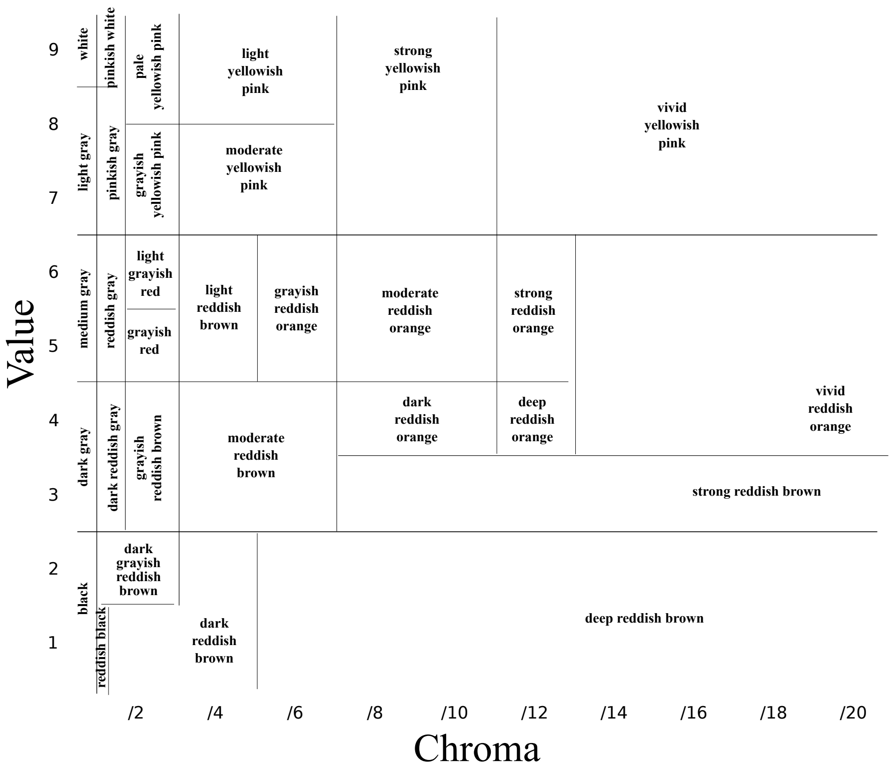

Figure 3: The ISCC-NBS Chart for Munsell Hue Leaves 9R through 1YR

2.3 The sRGB Standard

The Munsell and ISCC-NBS systems apply only to object colours. The standard red-green-blue (sRGB) specification,[1] by contrast, applies only to light sources, and defines a display device's colour behavior in device-independent terms. The sRGB standard aims to maintain colour consistency across electronic displays, such as computer monitors, which produce a wide gamut of colours by combining red, green, and blue light of different intensities.

A single pixel of a typical monitor actually consists of three tiny primary light sources, side by side. One primary is red, one is green, and one is blue. The intensity of each primary can be varied independently, from zero, in which no light at all is emitted, to some maximum. When seen together, the various combinations of intensities make a wide range of colours, including whites, grays, and many hues. The set of all colours that a monitor can produce is called its *gamut*. The intensity of each primary is often scaled from 0 to 255. Users can specify a pixel's colour in RGB coordinates, by giving the intensities of the three primaries. For example, RGB$= [225, 225, 40]$ is a greenish yellow.

Any two sRGB-compliant monitors should produce the same colour from the same sRGB coordinates. To achieve this device-independent colour, the standard specifies the colours of the primaries in CIE tristimulus coordinates, and also the primaries' physical intensities as a function of the sRGB coordinates. Without such a specification, different manufacturers could use different primaries, or the same manufacturer could use different primaries in different monitors, resulting in unpredictable colours. For ease of use, sRGB coordinates are designed to be perceptually linear. For instance, a human will perceive the sequence

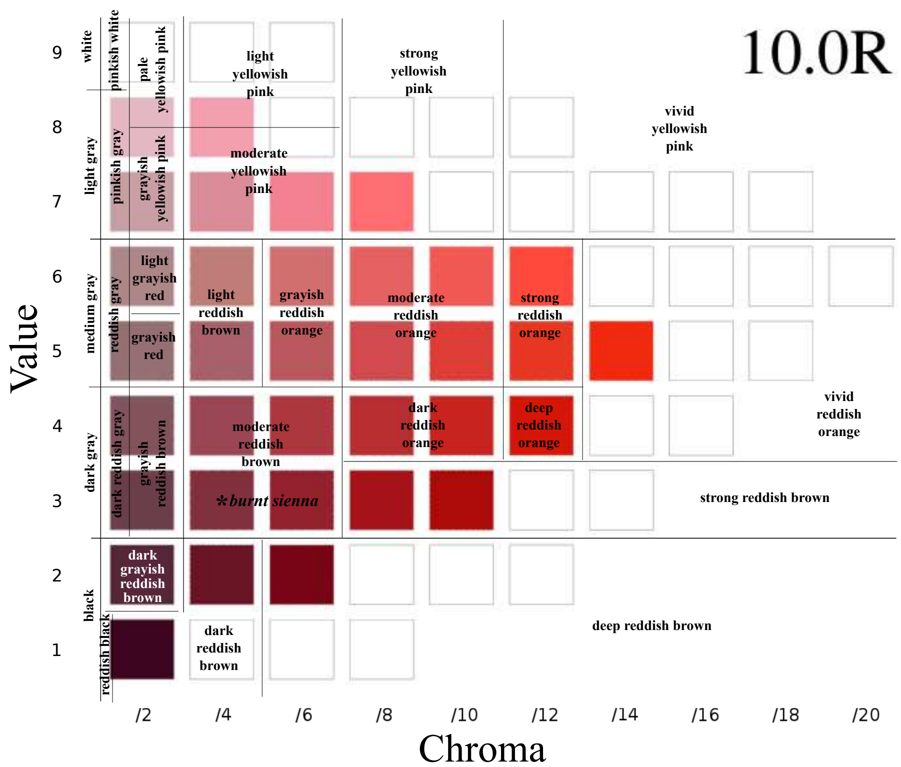

Figure 4: The ISCC-NBS Chart for 9R-1YR, Overlaid on the Munsell Hue Leaf for 10R

[50, 0, 0], [100, 0, 0], [150, 0, 0], [200, 0, 0], [250, 0, 0] as a set of equally spaced reds. The *physical* intensities, however, for a linear *perceptual* sequence are far from linear. The standard uses piecewise transformations, some involving a "gamma" correction, to transform perceptual quantities to physical quantities.

In practice, the sRGB standard is a rarely achieved ideal. To satisfy the standard, not only must the monitor's hardware produce primaries with the required tristimulus values, but the monitor must also be colour-calibrated. Furthermore, the RGB images displayed on the monitor must have been created in (or converted to) sRGB space; otherwise, they are likely to show a colour cast on an sRGB monitor. Another factor that affects colour is the ambient lighting in which a monitor is viewed; our conversions from sRGB to Munsell and ISCC-NBS will fix this lighting to be consistent with Illuminant C, to eliminate this factor. A known, though not very important, shortcoming is that RGB= [0, 0, 0] should be an ideal black, which reflects and emits no light; in practice, of course, even a monitor that emits no light reflects some ambient light, enough to reach a Munsell value of about 1. Even though, as a result of these factors, the sRGB requirements are rarely met, the standard is still a helpful guideline.

3 Conversions between Colour Specifications

The previous section presented the Munsell and ISCC-NBS systems, and the sRGB standard. A main result of this paper is a method of converting between the three specifications, which will allow the calculations of sRGB centroids for ISCC-NBS categories. This conversion is conceptually difficult because the sRGB system applies to light sources, while the other two systems apply to object colours. The difficulty is resolved by assuming that an sRGB monitor is viewed under Illuminant C, which is the illuminant used for the Munsell and ISCC-NBS systems. Once the illuminant is fixed, the colours produced by an sRGB monitor, provided the monitor is not unduly bright, are perceived as object colours. The sRGB standard defines sRGB colours by tristimulus coordinates, and the 1943 renotation[4] defines the Munsell system by tristimulus coordinates, so Munsell coordinates can be calculated for sRGB coordinates, and vice versa. Since the ISCC-NBS system is defined in terms of the Munsell system, the conversion from sRGB to ISCC-NBS is immediate. This section presents the details of the conversions.

3.1 Illumination

Surface colours, also called object colours, are classified by the Munsell and ISCC-NBS systems. They are produced when a light shines on a physical substance such as paint; the light is modified as it reflects off the substance, after which it enters a human eye. Surface colours are defined by their reflectance properties, which are independent of any light source. Light sources, such as traffic signals, can also be perceived directly by the human eye, without reflecting off any surfaces. The pixels on an sRGB monitor are light sources, while paintings are composed of surface colours.

The distinction between sources and surfaces seems superfluous physically, since both result when a visual stimulus enters a human eye. In practice, however, humans process these two kinds of stimuli differently. *Colour constancy* makes the colour of a particular *object* appear the same, even when illuminated by different light sources; this result is unexpected, since the resulting visual stimuli are very different. A related effect is that prevailing illumination usually appears white or neutral, even when it has a colour bias.

Humans do not always consciously distinguish between light sources and object colours. A computer monitor, which is actually a light source, is perceived as a coloured surface, much as if it were a printed brochure. This effect is intended: graphic artists and photographers use complicated colour management techniques to make images on their monitors look very much like images produced by their printers. In effect, they are translating between coloured lights and coloured surfaces. Such translation can be achieved when a monitor is viewed under sufficiently bright ambient illumination (about the level of indirect daylight), and the monitor itself has the right brightness level. A monitor that is too bright looks like a spotlight, and is interpreted as a light source. Ideally, the monitor should be just luminous enough that its white (when RGB=$[255, 255, 255]$) produces as much light as a white surface would reflect, under the ambient illumination.

Apart from luminosity, chromaticity is also an important consideration. Suppose that Illuminant D65 is the ambient light when viewing an sRGB monitor, and that every pixel is set to its maximum: $[255, 255, 255]$. According to the sRGB standard, $[255, 255, 255]$ has the same chromaticity as D65. Now place a well-lit piece of white paper, which diffusely reflects 100 percent of each wavelength in the visible spectrum, next to the monitor. The spectral distribution of the reflection off the white paper is then the spectral distribution of D65, which has the same chromaticity as $[255, 255, 255]$. If the monitor's luminosity is adjusted correctly, then [255, 255, 255] will look like a white surface. Now change the ambient lighting to Illuminant A, which has a reddish cast. Then the spectral distribution of the paper will be consistent with Illuminant A. The monitor's output is consistent with D65, which does not have a reddish cast, so [255, 255, 255] will not appear quite white, because its chromaticity differs from that produced by actual white objects.

These examples show that ambient illumination must be considered when converting between light sources and object colours. In the case at hand, both the Munsell and ISCC-NBS systems are standardized on Illuminant C, so Illuminant C will be assumed for our conversions. Since Illuminant C models indirect daylight, viewing a monitor indoors during the day, without any artificial light, should approximate Illuminant C.

3.2 Conversion Algorithms

Illuminant C lighting makes it possible to convert between sRGB and Munsell colours; since the ISCC-NBS system is defined in terms of Munsell colours, conversion from sRGB to ISCC-NBS then becomes possible (although the inverse conversion is not unique). The following conditions are assumed for such conversions:

1. The ambient illumination is diffuse Illuminant C lighting, at levels characteristic of indirect daylight,
2. The display device is sRGB-compliant,
3. The display device is colour-calibrated, and
4. The display device's luminosity is adjusted so that the display output appears as object colours rather than a light source.

This section gives the details of the conversion when these conditions are met. Gamut mismatch is an unavoidable issue: some sRGBs have no Munsell specification, and vice versa. Fortunately, the effects of gamut mismatch on this paper's results are minimal.

In the first step in the conversion, the sRGB standard gives CIE tristimulus coordinates for an sRGB triple; these coordinates are independent of the illuminant. Since the monitor has been adjusted to make its output appear as object colours, a viewer judges the colours on the screen in the context of the ambient lighting, which is assumed to be Illuminant C. A pixel on the screen will have the same colour as a painted surface if and only if the tristimulus coordinates of the pixel and the painted surface are identical. Since Illuminant C is assumed, the Munsell specification of the painted surface can be found by calculating the surface's tristimulus coordinates, and then inverting the 1943 renotation[7] to find hue, value, and chroma. Similarly, the second step uses the renotation to transform a pixel's tristimulus coordinates into Munsell notation; the Munsell notation is of course the converted value of that pixel's sRGB. The inverse conversion follows the same steps in reverse: Munsell to tristimulus coordinates by the 1943 renotation, followed by tristimulus coordinates to sRGB by the sRGB standard.

Gamut mismatch can occur when transforming between sRGB and Munsell. The set of all possible sRGB triples is naturally visualized as a cube, three of whose sides, originating at a common point, are red, green, and blue axes, each scaled from 0 to 255. This cube as a whole can be transferred to tristimulus space—where it will no longer be a cube, but rather a bounded, irregular solid, called the *sRGB gamut*. Similarly, the entire Munsell system, out to the MacAdam limits, can be expressed in tristimulus space, in this case giving a zonohedral *object-colour solid* called the *Munsell gamut*.

While these two gamuts largely overlap in tristimulus space, each one also extends somewhat outside the other. The triple $[0, 0, 255]$, for instance, is a very saturated blue—more saturated than any paint or ink could produce. It lies outside the MacAdam limits, so it is in the sRGB gamut, but not in the Munsell gamut. Likewise, many Munsell colours, especially highly chromatic ones, cannot be produced on an sRGB monitor, so they are in the Munsell gamut, but not in the sRGB gamut. One consequence of this mismatch is that it is impossible to produce a complete exemplification of the Munsell system on an sRGB monitor; likewise, it is impossible to print a complete exemplification of all the colours of an sRGB monitor. Fortunately, these mismatch cases only have a small effect on the calculations in this paper.

Once an sRGB colour has been converted to a Munsell specification, overlay charts like the one in Figure 4 can be used to place it in an ISCC-NBS category; combining these two steps, of course, allows a transformation from sRGB to ISCC-NBS. Since one category can contain a multitude of Munsell colours, and therefore a multitude of sRGBs, the inverse transformation is not unique. A major result of this paper, however, will be a calculation of the centroids of all the sRGBs that belong to a given ISCC-NBS category. This centroid can be thought of as the most characteristic sRGB colour for that category, and so can serve as an inverse.

As a result of the gamut mismatch between the sRGB and Munsell solids, seven Level 3 categories of the ISCC-NBS system contain no sRGBs at all, and so cannot be displayed on an sRGB monitor. Since 260 of the 267 Level 3 categories can still be expressed as sRGBs, however, the loss of these seven is not of much consequence.

4 Centroid Calculations

For digital applications, such as displaying a palette that is comprehensive but not overwhelming, it would be helpful to represent each ISCC-NBS category by a single, most typical, colour—a natural candidate for which is the centroid of all the colours in that category. Such centroids have already been calculated in Munsell space;[6] this section presents similar centroid calculations, in sRGB space. A useful practical result is a lookup table of sRGB centroids, that can be used by technical and non-technical workers alike.

4.1 Munsell Centroids

In 1958, Kelly[6] calculated Level 3 ISCC-NBS centroids in the Munsell system. The overlay charts were used to find the region of Munsell space that defines each category. Such a region is a three-dimensional subset of the Munsell tree. By design, Munsell hue, value, and chroma are each equally spaced perceptually, so the tree has sufficient metric structure to calculate a centroid for that region. As Kelly notes, 120 of the 267 Level 3 categories are *peripheral* subsets of Munsell space, that extend to the MacAdam limits. The centroids of the 120 peripheral categories were estimated graphically, not by the integral expressions used for the non-peripheral blocks. The graphical approach, combined with Munsell uncertainty near the MacAdam limits, result in less confidence in the peripheral centroids.

Had it been available when he was working, Kelly might have done better to calculate centroids over the 1980 Pointer gamut, rather than the Munsell system. Kelly's centroid for strong reddish brown, for example, is 0.5YR 3.0/11.2. Figure 4 shows the hue leaf for 10R, which is very near 0.5YR, and the centroid 10R 3.0/11.2 cannot be produced, i.e. it is outside the Pointer gamut. Assigning that centroid to 10R 3/9 instead, which is near the center of the *real* colours for strong reddish brown, would have been more useful. We will see later that similar issues do not arise for sRGB centroids, because every colour in sRGB space is producible by construction.

4.2 sRGB Centroids

Centroids for ISCC-NBS categories can be found not only in Munsell space, but also in sRGB space. A lookup table of such sRGB centroids is a major result of this paper. This section presents details of the centroid calculations. A Euclidean structure, that is perceptually reasonable for small regions, is first developed for the sRGB cube; some such structure is needed if centroids are to be calculated at all. Unlike Kelly's Munsell calculations, problems with peripheral categories are avoided, because every colour in the sRGB cube can be physically produced. Gamut mismatch causes a new, but fortunately minor, problem: seven of the 267 Level 3 categories cannot be represented in sRGB space. To avoid confusion in terminology, such as the fact that Level 1 blue and Level 2 blue are different sets, no Level 1 centroids are recommended; analysis will show, furthermore, that a Level 1 centroid can be replaced by the Level 2 centroid with the same name, with no significant loss of accuracy.

Conceptually, the calculations for sRGB and Munsell centroids follow the same lines. All the sRGBs in a particular ISCC-NBS category form a contiguous region in the sRGB cube; the centroid of that region is the sRGB centroid for that category. Centroid calculations in sRGB space require some metric or linear structure on the sRGB cube. Ideally, this structure should reflect perceptual properties. By design, the standard's transformations from coordinates to luminosities make the R, G, and B coordinates of sRGB space perceptually linear. In a sequence such as $[40, 60, 35], [40, 80, 35], [40, 100, 35], ...$, for example, where the G value increases by 20 at each step, the difference between any two adjacent colours appears about the same. The red, green, and blue directions in the sRGB cube were also chosen to be independent, to span a reasonably wide gamut. These two facts justify imposing, at least locally, the standard Euclidean metric on sRGB space: the distance d between two sRGB triples is

$$d\left([R_1, G_1, B_1], [R_2, G_2, B_2]\right) = \sqrt{(R_1 - R_2)^2 + (G_1 - G_2)^2 + (B_1 - B_2)^2}. \quad (1)$$

This metric would likely be questionable if applied to distant points in the sRGB cube, but it is reasonable for small subsets, such as the set of sRGB colours that define a single ISCC-NBS category. Furthermore, the metric does not need to be perfect, because any sRGB that is reasonably near the centroid should represent a particular category well enough.

The centroids for the ISCC-NBS categories were calculated numerically from a fine, discrete grid. The grid consisted of all sRGB triples, 140,608 in total, such that each coordinate was a multiple of 5. Each triple was converted to a Munsell specification, using the algorithm described earlier, and then placed in an ISCC-NBS category for each of the three levels. sRGB triples that were outside the MacAdam limits could not be expressed in the ISCC-NBS system. In all, 135,465 sRGBs were assigned ISCC-NBS categories.

The set of sRGB points in any particular ISCC-NBS category was used to approximate the sRGB region for that category. The sRGB centroid for that category is then the centroid of that set of points, calculated with the Euclidean structure. As a result of gamut mismatch, seven Level 3 categories contained no sRGB points at all: brilliant orange, vivid orange yellow, deep olive green, deep green, deep bluish green, vivid greenish blue, and strong greenish blue. For these seven cases, no centroids were calculated. The seven empty regions occur because of limitations in the sRGB system, which cannot produce some sufficiently saturated green-blues and orange-yellows.

As long as there are a fair number of sRGB points in a particular category, the centroid calculation should be plausible. In addition to the seven empty regions, eight Level 3 categories had ten sRGB points or fewer in their centroid calculations. One category, brilliant orange yellow, only had one point in its centroid calculation. Brilliant orange yellow is a small region in Munsell space, extending from hues 7YR to 1Y, chromas 10 to 14, and values 8 and over. The sRGB gamut just overlaps the brilliant orange yellow region, at a single point; although not very accurate, this centroid was retained, to have at least some representation for that category. The other categories with fewer than 10 points were: reddish black, brownish black, olive black, greenish black, and purplish black (4 points each), then blackish red (6), and bluish black (7). The overlay charts show that all these regions are small, usually spanning no more than one chroma step and one-and-a-half value steps. Furthermore, they cluster near N0, while monitors' Munsell values are rarely less than 1. With such a small extent, the maximum colour difference within any of these regions is barely perceptible, so any point would represent the category adequately. The centroid results were therefore retained. All the other regions had 14 or more sRGB points; many regions had hundreds, and a few had thousands (the largest, vivid yellow green, had over 13,000). Such large numbers of points, dispersed evenly, give confidence that the calculated sRGB centroids are characteristic of the ISCC-NBS Level 3 categories.

Tables 2 through 4 give the sRGB centroids for Level 3. Each row has been coloured with the sRGB for that row. As a whole, the tables can serve as a reasonably sized palette, from which graphic designers and others can choose digital colours.

While Level 3 is the most commonly used ISCC-NBS level, centroids were also calculated for Levels 1 and 2. The categories at Levels 1 and 2 are larger, so there were no empty regions, and only a few sparsely populated regions. The smallest categories, white and black, had 22 and 25 points respectively. (Level 1 white is identical with Level 2 white, and the same holds for black and gray.) The next smallest category, gray, had 148 points, and each remaining category, at either level, had well over 500. The centroids for the Level 1 and Level 2 categories are therefore typical representatives. Tables 5 and 6 show the sRGB centroids for these two levels.

As mentioned earlier, using the same name, such as blue, for categories in both Level 1 and Level 2 can be confusing. Each of the 13 Level 1 names also appears as a Level 2 name, although Level 2 adds in 16 intermediate categories. In four cases (yellow green, white, gray, and black) the Level 1 and Level 2 categories contain exactly the same colours. In the other

	ISCC-NBS Level 3 Name	sRGB
1	Vivid pink	253,121,146
2	Strong pink	244,143,160
3	Deep pink	230,105,128
4	Light pink	248,195,206
5	Moderate pink	226,163,174
6	Dark pink	197,128,138
7	Pale pink	239,209,220
8	Grayish pink	203,173,183
9	Pinkish white	239,221,229
10	Pinkish gray	199,182,189
11	Vivid red	213,28,60
12	Strong red	191,52,75
13	Deep red	135,18,45
14	Very deep red	92,6,37
15	Moderate red	177,73,85
16	Dark red	116,36,52
17	Very dark red	72,17,39
18	Light grayish red	180,136,141
19	Grayish red	152,93,98
20	Dark grayish red	83,56,62
21	Blackish red	51,33,39
22	Reddish gray	146,129,134
23	Dark reddish gray	93,78,83
24	Reddish black	48,38,43
25	Vivid yellowish pink	253,126,93
26	Strong yellowish pink	245,144,128
27	Deep yellowish pink	239,99,102
28	Light yellowish pink	248,196,182
29	Moderate yellowish pink	226,166,152
30	Dark yellowish pink	201,128,126
31	Pale yellowish pink	241,211,209
32	Grayish yellowish pink	203,172,172
33	Brownish pink	203,175,167
34	Vivid reddish orange	232,59,27
35	Strong reddish orange	219,93,59
36	Deep reddish orange	175,51,24
37	Moderate reddish orange	205,105,82
38	Dark reddish orange	162,64,43
39	Grayish reddish orange	185,117,101
40	Strong reddish brown	139,28,14
41	Deep reddish brown	97,15,18
42	Light reddish brown	172,122,115
43	Moderate reddish brown	125,66,59
44	Dark reddish brown	70,29,30
45	Light grayish reddish brown	158,127,122
46	Grayish reddish brown	108,77,75
47	Dark grayish reddish brown	67,41,42
48	Vivid orange	247,118,11
49	Brilliant orange	NaN,NaN,NaN
50	Strong orange	234,129,39

	ISCC-NBS Level 3 Name	sRGB
51	Deep orange	194,96,18
52	Light orange	251,175,130
53	Moderate orange	222,141,92
54	Brownish orange	178,102,51
55	Strong brown	138,68,22
56	Deep brown	87,26,7
57	Light brown	173,124,99
58	Moderate brown	114,74,56
59	Dark brown	68,33,18
60	Light grayish brown	153,127,117
61	Grayish brown	103,79,72
62	Dark grayish brown	62,44,40
63	Light brownish gray	146,130,129
64	Brownish gray	96,82,81
65	Brownish black	43,33,30
66	Vivid orange yellow	NaN,NaN,NaN
67	Brilliant orange yellow	255,190,80
68	Strong orange yellow	240,161,33
69	Deep orange yellow	208,133,17
70	Light orange yellow	252,194,124
71	Moderate orange yellow	231,167,93
72	Dark orange yellow	195,134,57
73	Pale orange yellow	238,198,166
74	Strong yellowish brown	158,103,29
75	Deep yellowish brown	103,63,11
76	Light yellowish brown	196,154,116
77	Moderate yellowish brown	136,102,72
78	Dark yellowish brown	80,52,26
79	Light grayish yellowish brown	180,155,141
80	Grayish yellowish brown	126,105,93
81	Dark grayish yellowish brown	77,61,51
82	Vivid yellow	241,191,21
83	Brilliant yellow	247,206,80
84	Strong yellow	217,174,47
85	Deep yellow	184,143,22
86	Light yellow	244,210,132
87	Moderate yellow	210,175,99
88	Dark yellow	176,143,66
89	Pale yellow	239,215,178
90	Grayish yellow	200,177,139
91	Dark grayish yellow	169,144,102
92	Yellowish white	238,223,218
93	Yellowish gray	198,185,177
94	Light olive brown	153,119,54
95	Moderate olive brown	112,84,32
96	Dark olive brown	63,44,16
97	Vivid greenish yellow	235,221,33
98	Brilliant greenish yellow	233,220,85
99	Strong greenish yellow	196,184,39
100	Deep greenish yellow	162,152,18

Table 2: sRGB Centroids for ISCC-NBS Level 3 Categories (Page 1 of 3)

	ISCC-NBS Level 3 Name	sRGB
101	Light greenish yellow	233,221,138
102	Moderate greenish yellow	192,181,94
103	Dark greenish yellow	158,149,60
104	Pale greenish yellow	230,220,171
105	Grayish greenish yellow	190,181,132
106	Light olive	139,125,46
107	Moderate olive	100,89,26
108	Dark olive	53,46,10
109	Light grayish olive	142,133,111
110	Grayish olive	93,85,63
111	Dark grayish olive	53,48,28
112	Light olive gray	143,135,127
113	Olive gray	88,81,74
114	Olive black	35,33,28
115	Vivid yellow green	167,220,38
116	Brilliant yellow green	195,223,105
117	Strong yellow green	130,161,43
118	Deep yellow green	72,108,14
119	Light yellow green	206,219,159
120	Moderate yellow green	139,154,95
121	Pale yellow green	215,215,193
122	Grayish yellow green	151,154,133
123	Strong olive green	44,85,6
124	Deep olive green	NaN,NaN,NaN
125	Moderate olive green	73,91,34
126	Dark olive green	32,52,11
127	Grayish olive green	84,89,71
128	Dark grayish olive green	47,51,38
129	Vivid yellowish green	63,215,64
130	Brilliant yellowish green	135,217,137
131	Strong yellowish green	57,150,74
132	Deep yellowish green	23,106,30
133	Very deep yellowish green	5,66,8
134	Very light yellowish green	197,237,196
135	Light yellowish green	156,198,156
136	Moderate yellowish green	102,144,105
137	Dark yellowish green	47,93,58
138	Very dark yellowish green	16,54,26
139	Vivid green	35,234,165
140	Brilliant green	73,208,163
141	Strong green	21,138,102
142	Deep green	NaN,NaN,NaN
143	Very light green	166,226,202
144	Light green	111,172,149
145	Moderate green	51,119,98
146	Dark green	22,78,61
147	Very dark green	12,46,36
148	Very pale green	199,217,214
149	Pale green	148,166,163
150	Grayish green	97,113,110
151	Dark grayish green	57,71,70
152	Blackish green	31,42,42
153	Greenish white	224,226,229
154	Light greenish gray	186,190,193
155	Greenish gray	132,136,136
156	Dark greenish gray	84,88,88
157	Greenish black	33,38,38
158	Vivid bluish green	19,252,213
159	Brilliant bluish green	53,215,206
160	Strong bluish green	13,143,130
161	Deep bluish green	NaN,NaN,NaN
162	Very light bluish green	152,225,224
163	Light bluish green	95,171,171
164	Moderate bluish green	41,122,123
165	Dark bluish green	21,75,77
166	Very dark bluish green	10,45,46
167	Vivid greenish blue	NaN,NaN,NaN
168	Brilliant greenish blue	45,188,226
169	Strong greenish blue	19,133,175
170	Deep greenish blue	NaN,NaN,NaN
171	Very light greenish blue	148,214,239
172	Light greenish blue	101,168,195
173	Moderate greenish blue	42,118,145
174	Dark greenish blue	19,74,96
175	Very dark greenish blue	11,44,59
176	Vivid blue	27,92,215
177	Brilliant blue	65,157,237
178	Strong blue	39,108,189
179	Deep blue	17,48,116
180	Very light blue	153,198,249
181	Light blue	115,164,220
182	Moderate blue	52,104,158
183	Dark blue	23,52,89
184	Very pale blue	194,210,236
185	Pale blue	145,162,187
186	Grayish blue	84,104,127
187	Dark grayish blue	50,63,78
188	Blackish blue	30,37,49
189	Bluish white	225,225,241
190	Light bluish gray	183,184,198
191	Bluish gray	131,135,147
192	Dark bluish gray	80,84,95
193	Bluish black	36,39,46
194	Vivid purplish blue	68,54,209
195	Brilliant purplish blue	128,136,226
196	Strong purplish blue	83,89,181
197	Deep purplish blue	42,40,111
198	Very light purplish blue	183,192,248
199	Light purplish blue	137,145,203
200	Moderate purplish blue	77,78,135

Table 3: sRGB Centroids for ISCC-NBS Level 3 Categories (Page 2 of 3)

	ISCC-NBS Level 3 Name	sRGB
201	Dark purplish blue	34,34,72
202	Very pale purplish blue	197,201,240
203	Pale purplish blue	142,146,183
204	Grayish purplish blue	73,77,113
205	Vivid violet	121,49,211
206	Brilliant violet	152,127,220
207	Strong violet	97,65,156
208	Deep violet	60,22,104
209	Very light violet	201,186,248
210	Light violet	155,140,202
211	Moderate violet	92,73,133
212	Dark violet	52,37,77
213	Very pale violet	208,198,239
214	Pale violet	154,144,181
215	Grayish violet	88,78,114
216	Vivid purple	185,53,213
217	Brilliant purple	206,140,227
218	Strong purple	147,82,168
219	Deep purple	101,34,119
220	Very deep purple	70,10,85
221	Very light purple	228,185,243
222	Light purple	188,147,204
223	Moderate purple	135,94,150
224	Dark purple	86,55,98
225	Very dark purple	55,27,65
226	Very pale purple	224,203,235
227	Pale purple	173,151,179
228	Grayish purple	123,102,126
229	Dark grayish purple	81,63,81
230	Blackish purple	47,34,49
231	Purplish white	235,223,239
232	Light purplish gray	195,183,198
233	Purplish gray	143,132,144
234	Dark purplish gray	92,82,94
235	Purplish black	43,38,48
236	Vivid reddish purple	212,41,185
237	Strong reddish purple	167,73,148
238	Deep reddish purple	118,26,106
239	Very deep reddish purple	79,9,74
240	Light reddish purple	189,128,174
241	Moderate reddish purple	150,88,136
242	Dark reddish purple	95,52,88
243	Very dark reddish purple	63,24,60
244	Pale reddish purple	173,137,165
245	Grayish reddish purple	134,98,126
246	Brilliant purplish pink	252,161,231
247	Strong purplish pink	244,131,205
248	Deep purplish pink	223,106,172
249	Light purplish pink	245,178,219
250	Moderate purplish pink	222,152,191

	ISCC-NBS Level 3 Name	sRGB
251	Dark purplish pink	198,125,157
252	Pale purplish pink	235,200,223
253	Grayish purplish pink	199,163,185
254	Vivid purplish red	221,35,136
255	Strong purplish red	184,55,115
256	Deep purplish red	136,16,85
257	Very deep purplish red	84,6,60
258	Moderate purplish red	171,75,116
259	Dark purplish red	110,41,76
260	Very dark purplish red	67,20,50
261	Light grayish purplish red	178,135,155
262	Grayish purplish red	148,92,115
263	White	231,225,233
264	Light gray	189,183,191
265	Medium gray	138,132,137
266	Dark gray	88,84,88
267	Black	43,41,43

Table 4: sRGB Centroids for ISCC-NBS Level 3 Categories (Page 3 of 3)

	ISCC-NBS Name	sRGB	DE00
1	Pink	231,141,170	4.8
2	Red	186,42,94	8.3
3	Orange	217,89,45	12.5
4	Brown	131,75,44	1.1
5	Yellow	215,182,74	1.7
6	Olive	94,94,9	5.6
7	Yellow green	160,194,69	0.0
8	Green	73,193,114	8.5
9	Blue	66,114,195	1.8
10	Purple	158,66,189	3.8
11	White	231,225,233	0.0
12	Gray	147,142,147	0.0
13	Black	43,41,43	0.0

Table 5: (Discarded) sRGB Centroids for ISCC-NBS Level 1 Categories

	ISCC-NBS Level 2 Name	sRGB		ISCC-NBS Level 2 Name	sRGB
1	Pink	230,134,151	16	Yellowish green	74,195,77
2	Red	185,40,66	17	Green	79,191,154
3	Yellowish pink	234,154,144	18	Bluish green	67,189,184
4	Reddish orange	215,71,42	19	Greenish blue	62,166,198
5	Reddish brown	122,44,38	20	Blue	59,116,192
6	Orange	220,125,52	21	Purplish blue	79,71,198
7	Brown	127,72,41	22	Violet	120,66,197
8	Orange yellow	227,160,69	23	Purple	172,74,195
9	Yellowish brown	151,107,57	24	Reddish purple	187,48,164
10	Yellow	217,180,81	25	Purplish pink	229,137,191
11	Olive brown	127,97,41	26	Purplish red	186,43,119
12	Greenish yellow	208,196,69	27	White	231,225,233
13	Olive	114,103,44	28	Gray	147,142,147
14	Yellow green	160,194,69	29	Black	43,41,43
15	Olive green	62,80,31			

Table 6: sRGB Centroids for ISCC-NBS Level 2 Categories

nine cases, the Level 2 category is a proper subset of the Level 1 category. To avoid confusion, it is recommended that the centroids in Table 5 not be used; instead, each Level 1 category will be assigned the sRGB centroid of the Level 2 category with the same name.

To show that this recommendation does not make a significant difference, the last column of Table 5 displays the colour difference (calculated with respect to Illuminant C, using the DE00 formula[2]) between the centroid for the Level 1 category and the centroid for the Level 2 category of the same name. Two chromatic colours whose DE00 is 2 or less are often considered indistinguishable for practical purposes, and offset presses do not often achieve DE00's less than 4. Since eight of the thirteen Level categories have DE00's less than 4, the Level 1 and Level 2 centroids would serve equally well. Three categories (red, orange, and green) have rather high DE00's, but it is probably not worth distinguishing between the two levels for just those three cases. Another argument for discarding the Level 1 calculations is that they cover much larger sRGB regions than Level 2, so the Euclidean metric is less plausible, and thus the Level 1 centroids are more questionable. As a practical matter, then, the centroids in Table 5 will be discarded, and a Level 1 category will be assigned the same centroid as the Level 2 category of the same name.

To compare with previous work, the sRGB centroids for the ISCC-NBS Level 3 categories were converted to Munsell coordinates, and DE00 values were found between them and Kelly's 1958 Munsell centroids. The Munsell centroids for the 120 peripheral categories, which include the seven categories for which sRGB centroids are not available, are less certain, and often outside the Pointer gamut, so no DE00's were calculated in those cases. In all, 147 DE00's were found: 133 of the DE00's were 2 or less, nine were between 2 and 3, and five were considerably higher (4.5, 5.7, 5.7, 7.2, and 9.4). A DE00 of 2 or less, or even of 3, is not significant in this case, because two centroids with such small differences appear nearly identical.

The five higher DE00's all have green-blue hues and likely occur when the boundary of the sRGB cube cuts across a category's region, leaving some of the region inside the cube, and some outside. The centroid calculation is then biased toward the inside part. This explanation is supported by the fact that, In all five cases, the chroma of the sRGB centroid is less than the chroma of the Munsell centroid, which would occur if the higher-chroma section of a region were outside the sRGB cube. From another point of view, the high DE00's result from gamut mismatch—sRGB space does not include some colours that Munsell space does. The comparison of sRGB and Munsell centroids provides a sanity check on both calculations, and allows us to conclude that our sRGB centroids represent the ISCC-NBS categories reasonably well.

5 Open-Source Resources

Some data files and Octave/Matlab routines that others might find useful have been released in open-source form. They can be downloaded from the author's website, www.MunsellColourScienceForPainters.com/. The Octave/Matlab routines have been incorporated into the author's Munsell and Kubelka-Munk Toolbox, and use many other routines from that toolbox. Other workers are welcome to use and modify the following files, with the understanding that they will make any modifications publicly available:

1. **ISCCNBSdesignators.txt.** A listing of the names and numbers of all ISCC-NBS categories, at all three levels.
2. **MunsellCentroidsForISCCNBS.txt.** A digital version of Kelly's 1958 Munsell centroid calculations.[6]
3. **sRGBcentroidsForISCCNBS.txt.** This text file lists the sRGB centroid for each category of the ISCC-NBS system, at all three levels.
4. **MunsellRenotationTosRGB.txt.** This file converts (the in-gamut colours in) the Munsell renotation into the sRGB system.
5. **sRGBToMunsellAndISCCNBS.txt.** This file lists the Munsell specification and ISCC-NBS categories for each of the 135,465 sRGB triples that were converted.
6. **ConvertsRGBtoISCCNBS.ods/xlsx.** The first spreadsheet in this workbook uses nearest-neighbor interpolation over the data in sRGBToMunsellAndISCCNBS.txt to

find the ISCC-NBS categories for a user-entered sRGB. The second spreadsheet lists the sRGB centroid for each ISCC-NBS category along with the Munsell coordinates for the sRGB centroid (which differ slightly from Kelly's Munsell centroids). This file is suitable for non-programmers who are interested in a small number of sRGBs.

7. **sRGBtoISCCNBS.m.** Given an sRGB triple, this Octave/Matlab routine returns the ISCC-NBS category that contains that triple.

6 Summary

This paper has found sRGB centroids for ISCC-NBS categories, and made them available in both digital and printed tables. Others can use these centroids to produce digital presentations of the ISCC-NBS system, such as a computer palette of 260 evenly spaced colours, with easily understood names. The centroid calculations used the Munsell system as an intermediate step. An important assumption, which made the calculations possible, is that the sRGB triples are viewed under ambient lighting that is consistent with Illuminant C. This assumption will be approximately satisfied if indirect daylight is the light source for the room in which the sRGBs are displayed. Open-source code has been provided, along with some spreadsheets, that others are free to use and modify.

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