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Physical and Psychophysical Relations

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Color and Sound: Physical and Psychophysical Relations*

Many artists and scientists have been concerned, throughout time, with the correspondences between color and sound. Numerous studies on the subject have been written. There are approaches based on intuition as well as approaches based on psychology, psychophysics, physics, and physiology. The classical comparison relies on the fact that the stimuli for the sensations of pitch in sound, and hue in color, are mainly determined by the wavelength of the auditory energy and the visible energy, both taken as undulatory phenomena. On this basis, a comparison is usually drawn between the chromatic scale of sounds and the hue circle. This criterion has been followed to such extent to relate a sound of specific frequency with a determined spectral color. The comparison can be expanded and refined by considering the other variables of sound and color, too. This article relates luminosity of color with loudness of sound, saturation of color with timbre of sound, and size of color with duration of sound. There are psychological and physical arguments to support such a comparison. © 1994 *John Wiley & Sons, Inc.*

Key words: music and color, sound and light, comparative analysis, physical variables, perceptual variables, scales, audition and vision

INTRODUCTION

Among the artistic and scientific personalities who have been interested in the relations between color and sound, Aristotle, Newton, Goethe, Helmholtz, Skryabin, Ostwald, Munsell, Kandinsky, and Gombrich can be mentioned, just to take the most familiar names.

Aristotle, in his book *De Sensu et Sensibilia*, assumes that the aesthetics of the color groupings is governed by the same rules that govern the musical consonances.

Newton compares the vibrations of the light rays, which according to their "bigness" (wavelength) excite the different sensations of color, with the air vibrations, which according to their length also excite the sensations of the different sounds. He speculates on the question that the harmonies or disharmonies of color depend on the proportions among the vibrations propagated through the optical nerve, in the same way as the harmonies or disharmonies of sounds are derived from the proportions among the air vibrations.[1] In the light spectrum, he defines seven colors and marks their boundaries, establishing among the segments corresponding to each color a series of proportions, which coincide with the proportions of the intervals of a diatonic musical scale (Fig. 1).[2]

Goethe, who at every moment manifests his disagreement with Newton's theories, denies any possible direct comparison between color and sound, but maintains that both phenomena can be referred to a superior formula (the text is ambiguous; apparently he alludes to physics), from which both are derivable following different courses.[3]

Munsell understood that just in the same way as music is equipped with a system by which every sound is defined in terms of pitch, intensity, and duration (his words), so should color be provided with a similar appropriate system. In fact, this is the kind of system of variables he proposes for his color notation and atlas.[4]

Egbert Jacobson, in a book about the Ostwald system, considers that the basis to create harmony, both in music and color, relies on the disposition of the visual or auditory stimuli according to a certain order, as in the series of octaves and the keyboard of a piano. He feels that the analogy between color and music is accidental, but that thinking in terms of a color "keyboard" (say, a system such as the Ostwald one in which colors are definitively established) is very useful.[5]

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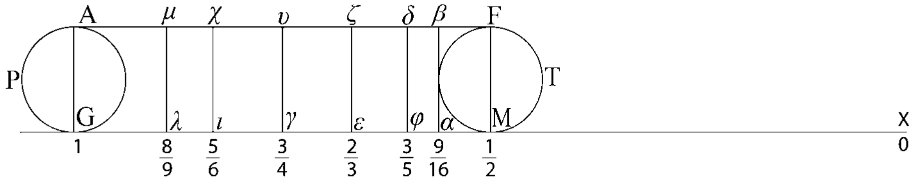

FIG. 1. Division of the spectrum of visible radiation, according to Newton. The spectrum is comprised in *AFGM*. Line *MX* has a length equal to *GM*. Fractions indicate the proportions of each segment, as measured from *X*, in relation to segment *GX*, which constitutes the unity. These fractions are the reciprocal of the ones between the frequencies of sounds in a diatonic minor natural scale with the VI degree raised (after Newton *Opticks*).

Arthur Pope, though recognizing certain analogy between color and music, sets forth the difference that exists between the combinations of sounds and the combinations of colors. If we play a chord with several simultaneous sounds, each of them keeps its individuality and can be distinguished from the others by the ear, whereas the superposition of colors destroys the individuality of the components generating a new, different color.[6] This holds true whether the combination of colors is an additive mixture (color–light) or a subtractive one (color–pigment).

Vernon describes the relation as a psychological phenomenon known as synesthesia, by which stimuli of different sensory modes, for instance visual and auditory, are associated. She reports that, according to various studies, it has been verified that 20–40 percent of persons claim to “see” colors while listening to music, generally making a rigid association between specific series of musical notes or tonalities and specific color images.[7]

Kandinsky assumes a relationship between bright colors (such as yellow) with high sounds, and dark colors with low sounds.[8]

The case of Alexander Skryabin, who established a parallel between sounds and colors on spiritual bases and applied it to his music, specially in his Fifth Symphony *Prometheus*, is mentioned in nearly all the bibliographies on the subject.

Let’s now proceed to a more specific correlation between both phenomena, analyzing each of the variables and comparing them.

HUE IN COLOR AND PITCH IN SOUND

Hue is the aspect that we distinguish when discriminating colors by the names red, orange, yellow, green, blue, violet, etc.

Pitch is the variable of sound that enables us to discriminate low from high sounds. It depends on the frequency of the undulatory movement but, as Stevens and Davis have demonstrated,[9] there is no linear relationship between frequencies and the sensations of pitch. Although increasing the frequency leads to the perception of higher sounds, the increment of the sensation does not bear a constant proportionality to the increment of the stimulus.

Maitland Graves[10] quotes Sir James Jeans, who refers to the physical relationship between colors (given by their wavelengths) and pitch of sounds (given by their frequencies). As a sound having a frequency twice the frequency of another produces the same note, though an octave higher, the extremes red and violet in the spectrum of visible radiation can be said to cover an octave, because they are in relation of two to one, between 760 and 380 nanometers of wavelength (Fig. 2).

The same observation is made by Garner,[11] who conceives that the eye works in octaves like the ear, and that it is possible to translate exactly an octave of sound into an octave of light. As a demonstration, he divides the spectrum into twelve colors and makes this correspond with the chromatic musical scale, making the extreme red (800 nm) coincide with a *C* note of 125 cycles per second.

Alan Wells[12] presents a table (credited to R. Lang), which compares different historical proposals for correspondences between chromatic or diatonic musical scales and hue scales or the sequence of spectral colors. According to this table, four proposals (Newton, Finn,

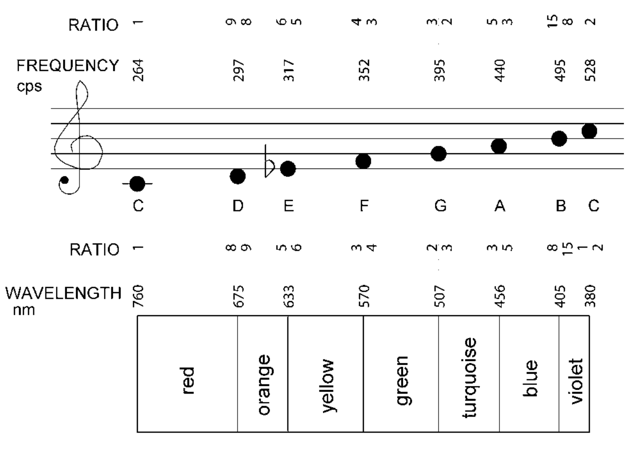

FIG. 2. Comparison of an octave of sound with an “octave” of light. The frequency of each sound and the fractions obtained by dividing each one by the frequency of the first degree of the scale are indicated. In the light spectrum, the wavelengths (reciprocals of frequencies) marking the separation among colors are given beside the fractions obtained by dividing each one by the wavelength of the extreme red. Note that these ratios are the inverse of the ones for sounds.

Lind, and Maryon) begin by relating the note *C* with the color red, while only one (Castel) relates the note *C* with blue.

Ralph Pridmore[13] also intends to establish an exact correspondence but he goes even beyond others, converting the frequency of sound into wavelength (he uses the velocity of light in the transposition, recognizing that this election is arbitrary) and making successive divisions by two until reaching the range of the wavelengths of visible radiation. As a result of this, he determines a correspondence between a *C* note of 261.6 cycles per second and a green of 521 nanometers.

$$\text{wavelength} = \frac{\text{velocity}}{\text{frequency}} = \frac{299\ 699\ 947 \text{ m/sec}}{261.6 \text{ c/sec}}$$

$$= 1\ 145\ 642 \text{ m/c} \qquad (1)$$

1 145 642 m after 41 divisions by 2 gives 0.000000521 m = 521 nm

This idea can be traced back to Thomas Young, who says:

> If a chord sounding the tenor C, could be continually bisected 40 times, and should then vibrate, it would afford a yellow green light: this being denoted by C_{41}, the extreme red would be A_{40}, and the blue D_{41}.[14]

Personally, I do not find the procedure employed by Pridmore to transpose tones to hues fully convincing. I do not think that the fact that a wavelength of one stimulus is multiple of the other is a guarantee to experience any relationship. Both phenomena stand completely apart, are physical waves of different natures (one mechanical, the other electromagnetic), and are perceived by different senses.

However, there is a salient aspect in Pridmore's paper. His system allows for the distinction between tone and pitch in sound. The tone is cyclical and is repeated at intervals of octave (it is what we identify through the names of the notes) while the pitch is not, because it varies continuously in one direction. A *C* tone keeps its identity of *C* in different octaves, despite the fact that the pitch changes. This feature is adequately represented by means of a spiral, where in each cycle we return to the same position but on a different level.

Rachel Sebba[15] does not admit that a parallel exists between a certain hue and a specific sound. Nevertheless, she assumes the hypothesis that there is a correspondence between the ratios of a musical scale and the ratios of a scale of color (as in the case of Newton).

In the book by Villalobos-Dominguez[16] there is a curious example of color transposition. A certain color composition is transported to other tonalities with different hues, keeping the internal relationships. This idea is clearly taken from music, where a motive can be played in different tonalities (*C* major, *D* major, *E* major, minor tonalities, etc.), which, though changing the motive's character, does not take away its identity.

There is a correspondence between the different hue scales, organized in a circular fashion, and different musical scales, in regard to the quantity of hues and sounds, respectively. Thus, we have:

Color circles		Musical scales
Munsell	5 hues	Pentatonic scale (e.g., Incaic music)
Küppers	6 hues	Whole-tone scale (e.g., Debussy)
Newton	7 hues	Diatonic scale (tones and half-tones)
Itten	12 hues	Chromatic scale (e.g., Bach, tempered music)
Pope	12 hues	Chromatic scale (e.g., Bach, tempered music)
Ostwald	24 hues	Quarter-tone scale (e.g., microtonal music)

(See also Fig. 3).

Beside these analogies, there are also some noticeable differences between hue and pitch. Perhaps the most striking one is the fact that the auditory range comprises around ten octaves while the visible range hardly covers one "octave". Helmholtz[17] points out other differences between audition and vision. He even notes that, according to Fraunhofer's measurements, the visible spectrum is shorter than an octave. These observations and the fact that the divisions of colors in the spectrum are more or less arbitrary, lead him to the conclusion that "this comparison between music and colour must be abandoned." Nevertheless, one of the dissimilarities Helmholtz points out seems not to be so. He refers to the differential sensitivity of the eye and ear when he says that

> at both ends of the spectrum the colours do not change noticeably for several half-tone intervals [of pitch], whereas in the middle of the spectrum the numerous transition colours of yellow into green are all comprised in the width of a single half-tone [of pitch]. This implies that . . . the magnitudes of the colour intervals are not at all like the gradations of musical pitch . . .[18]

This is due to the fact that he is comparing the whole visible range with only one octave of the auditory range. If one takes the full auditory range, it can be observed that the sensitivity of the ear also decreases when approaching the very high or very low frequencies.

In some fields the comparison has practical consequences and should not be discarded as proposed by Helmholtz. Yilmaz[19] found certain analogies between color and whispered speech (especially in regard to the perception of vowels) and predicted the possibility of

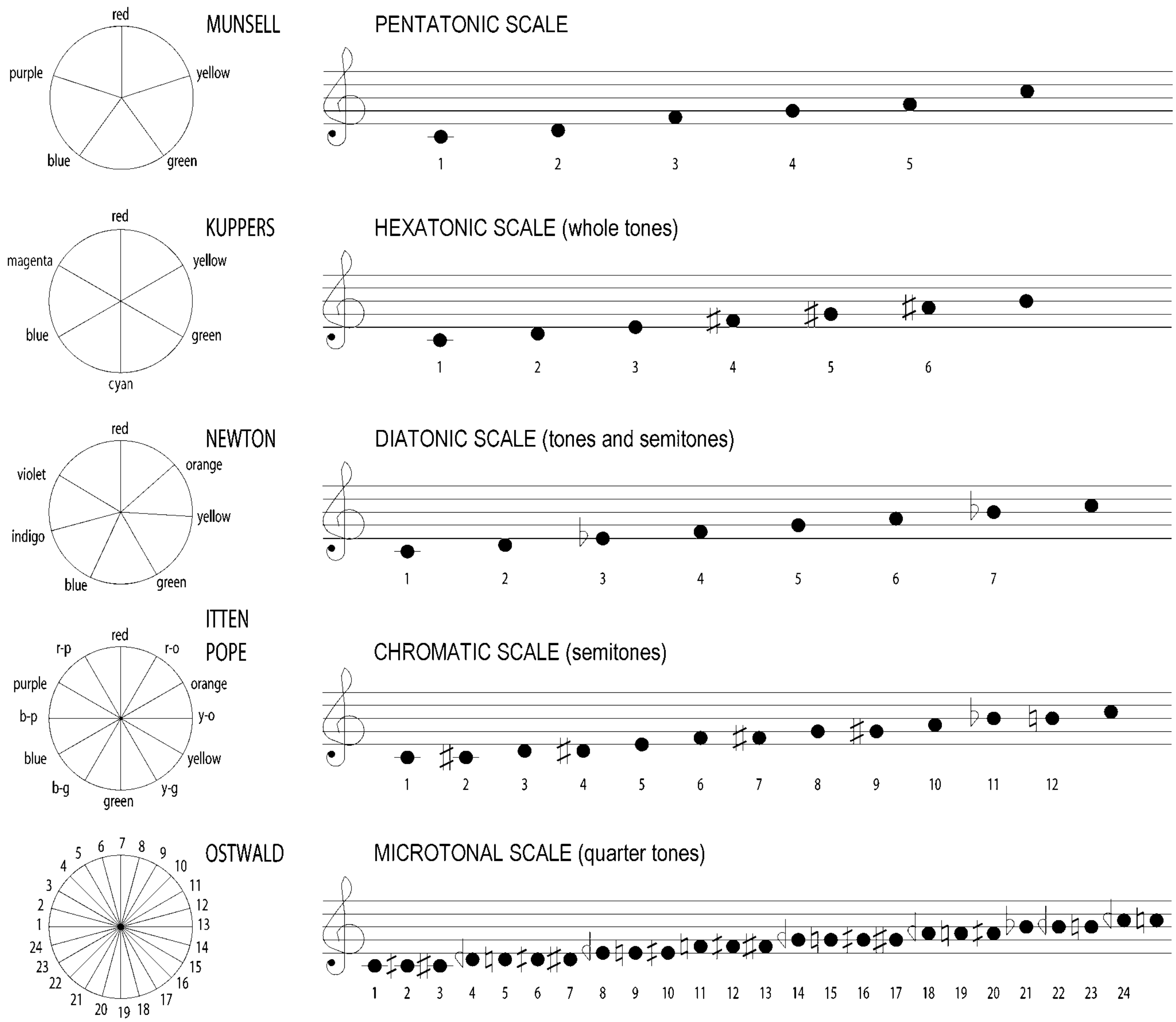

FIG. 3. Correspondence between some color wheels and some types of musical scales. The 5 main hues of Munsell correspond with the 5 sounds in a pentatonic scale, generally used in Indian American music. However, a difference should be noted, in that Munsell proposes 5 equal intervals and the pentatonic scale has nonequal intervals (intervals in tones: 1-1½-1-1-1½). The 6 hues of Küppers adequately correspond with the hexatonic or whole-tone scale, composed of 6 equal intervals (6 tones), profusely used by Debussy. The 7 colors of Newton and his proportional division of the chromatic circle (with unequal sectors) correspond with a diatonic minor natural scale with the VI degree raised (having unequal intervals of whole tones and semitones). The 12 hues in which both Itten and Pope divide the color circle in perceptually equal intervals correspond with the 12 sounds in a tempered chromatic scale, with intervals of semitones, which has been in use from Bach to the present. The 24 hues of the Ostwald's chromatic circle correspond with the 24 sounds in a quarter-tone scale, used in twentieth century microtonal music.

sensory substitution by which the deaf could be taught to speak and the blind to read.

We must conclude then, that a kind of relation between hue and pitch does exist. However, we should consider this as a general analogy, not attempting to take it in all aspects.

LUMINOSITY IN COLOR AND LOUDNESS IN SOUND

The physical magnitude of luminous intensity has its sensorial correlate in the luminosity or brightness, which is found in the scale of grays in most color order systems.

The physical magnitude of intensity in sound has its sensorial correlate in loudness, that aspect we refer to when speaking of strong or weak sounds. However, it is necessary to make it clear, as Stevens and Davis demonstrate,[9] that such a relationship is not a linear one. A certain increment of the intensity does not correspond with an equal increment in the perceived loudness.

Here it is assumed that luminosity in color has a strong correlate with loudness in sound. Both sensations are derived from the same kind of physical variable: intensity. Logic indicates that light colors must correlate with loud sounds, while dark colors with weak sounds. In the ex-

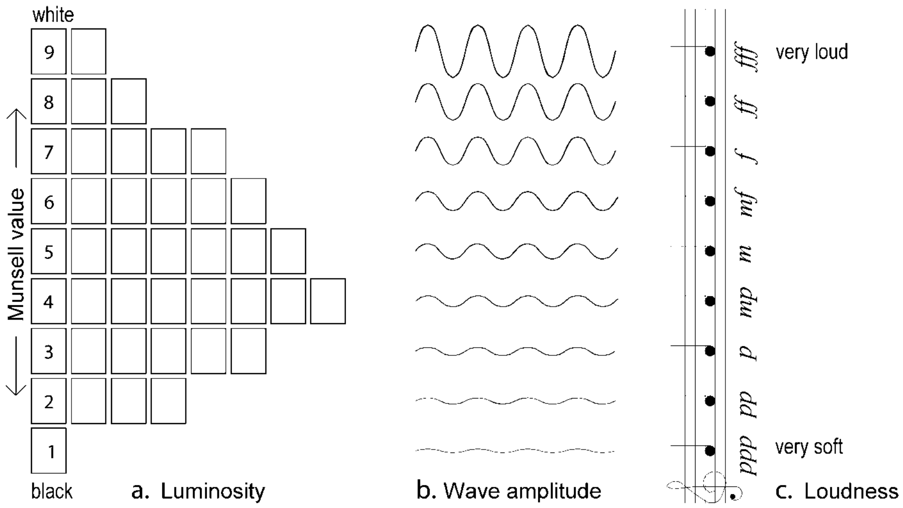

FIG. 4. Comparison between luminosity in color and loudness in sound. (a) A plane of constant hue from the Munsell atlas, with the variation of value (or luminosity), which increases upward. (b) Representation of the increase in sound intensity by means of wave amplitude. (c) Traditional musical notation for a scale of loudness. In traditional musical notation, the sign "m" is not used as a dynamic marking to represent an intermediate step between "mp" and "mf". It has been introduced here simply to make the scale of loudness correspond with the steps of Munsell's scale of values.

treme cases, black (the absence of light) would parallel silence (the absence of sound), and white (the highest sensation of luminosity) would parallel the highest perceptible loudness. Some other investigations can be taken to support this proposed relationship.

Stevens and Guirao[20] describe an experiment in which a group of observers were instructed to use the apparent length of a line as a variable to represent loudness and luminosity. Although the authors do not explicitly establish a relationship between loudness and luminosity, in fact they take a certain association for granted. On the other hand, the observers obviously represented a greater loudness and luminosity by a greater length of the line. From this, we can directly infer that an increase of loudness is also associated with an increase of luminosity.

Ralph Pridmore[13] has built a transducer, which transforms auditory stimuli into colored luminous stimuli. In this device, loudness is represented by luminosity.

Summing up, to give an example, we can compare a series of sounds where loudness varies (keeping pitch constant) with the variation of value (luminosity) in the Munsell atlas (keeping hue constant) (Fig. 4).

SATURATION IN COLOR AND TIMBRE IN SOUND

As far as I know, no one has gone deeply into the correlation between the variables of saturation (or chroma) in color and timbre in sound. It seems to me that such a correlation is conceivable and has been anticipated in a previous work,[21] where shape configurations and auditory organizations were mainly compared. Recently, I have found that this analogy did not pass unnoticed by others, too. Woodworth and Schlosberg[22] have made the same correlation (saturation with timbre) in addition to the other more usual ones: hue with tone (or pitch) and brightness (or luminosity) with loudness. However, these authors merely mention the correspondences without providing arguments, references, or other sources on this subject.

Timbre is the dimension of sound that depends on the way in which the harmonics are grouped around a fundamental sound; it has to do with the quantity and relative intensity of these harmonics; we can say that this is what makes the "complexity" of the sound.* Timbre is the variable by which we can recognize the sound of the different musical instruments or human voices, even when they emit exactly the same tone. Timbre has been called the "color" of sound.[23] In the musical jargon it is usual to talk of pure, rough, piercing, soft, smooth, velvety timbres, and so on.

A pure sound is the one that does not have harmonics, such as the sound produced by a tuning fork. In physical terms this sound is an undulatory simple movement and is represented by a perfect sine-wave (Fig. 5b, right sector). All the traditional musical instruments produce sounds with harmonics, that is to say, relatively complex sounds where the vibrations of the harmonics overlap the undulatory movement of the fundamental sound. The representation of this is a periodic wave of complex shape. The complex shape appears repeated at certain periods (Fig. 5b, middle sector). If the complexity is such that no pattern is repeated, then what we perceive is a

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* Any person can perform the following simple experiment on a piano: Keep the tonal pedal (the middle pedal in grand pianos) pressed down; hold down, without producing any sound, the keys corresponding to notes C_2, G_2, C_3, E_3, G_3, and B_3 flat, which are the first ones of the series of harmonics; then, play with strength the lowest C note (C_1). In a few seconds the series of harmonics overlapping that C_1 will be heard.

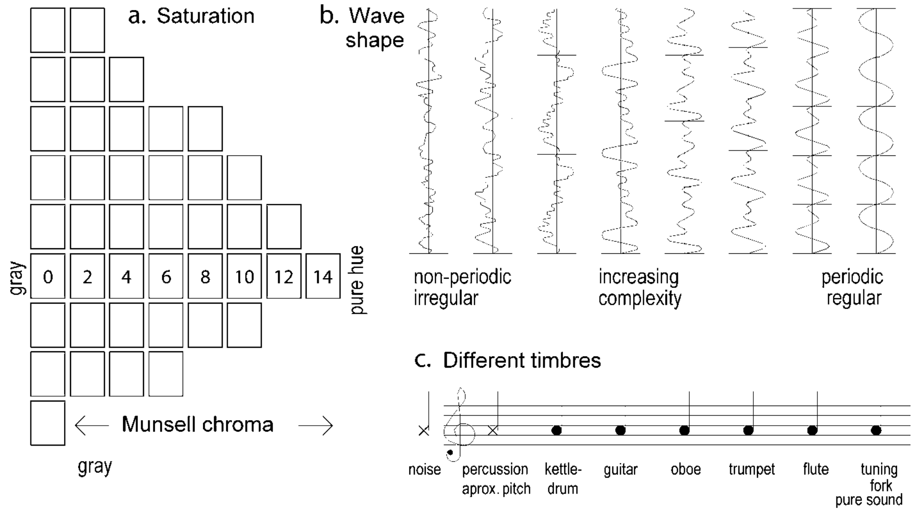

FIG. 5. Comparison between saturation in color, and timbre in sound. (a) A plane of constant hue from the Munsell atlas, with the variation of chroma (or saturation), which increases from left to right. (b) Representation of different timbres by means of oscillograms; the difference is given by the complexity and periodicity of waves. (c) Diverse musical instruments, which produce different timbres, placed in correspondence with the oscillograms.

noise (Fig. 5b, left sector). The feature making the difference between sound and noise is that the vibrations of the sound are periodic, while those of the noise are nonperiodic. Nevertheless, this division cannot be exactly determined when one approaches the extremes of what could be considered noise or sound; it would be better to understand this as a phenomenon with different degrees of complexity in the periodicity. In simple terms, we can say that if a scale of timbres is possible, then we would have a pure tone in one extreme and a noise in the other.

Saturation, on the other hand, is the dimension of color that enables us to discriminate a pure tone from a grayed one, even when both possess the same hue. Saturation is sometimes referred to as color purity or degree of chroma. Purity describes an objective physical aspect and is applied to light sources or stimuli. Monochromatic light (that is, light taken from a very narrow portion of the spectrum, having a single wavelength) has 100% purity, whereas white light (composed of all the wavelengths of the spectrum) has 0% purity. Saturation is the subjective correlate of purity; it is a term applied to sensations. In a saturation scale we have a strong color in one extreme and a gray color in the other (Fig. 5a).

Kandinsky[8] points out that some colors are described, in a tactile sense, as rough or prickly, while others as smooth and velvety. We have just seen that these or similar adjectives are also applied to the timbres of musical instruments.

As previously stated, a complex sound is a compound of various related vibrations (corresponding to the different harmonics) and a pure sound is made up of a single vibration. Likewise, white, or any achromatic color, is the result of various combined wavelengths (a wide portion of the spectrum) and a pure color is made up of a single wavelength (a very narrow portion of the spectrum). Thus, from the physical point of view, the correlations are: a noise with an achromatic color, an intermediate complex sound (typical of traditional instruments) with an intermediate nonsaturated color, and a pure sound (the one from a tuning fork) with a saturated or pure color.

We can compare a scale of chroma (or saturation) from the Munsell atlas with a series of sounds: a pure one, some of certain complexity, and a noise (Fig. 5).

Psychologically, the pure sound is perceived as limpid while the noise as dirty. We can say that the pure sound is saturated while the noise is nonsaturated. The pure sound is experienced as being smooth and so is the pure hue, while the noise is felt as being rough and so is the gray color.

It is worth noting here that some people feel the sound produced by an instrument more colorful than the sound of a tuning fork, making the analogy in a direction opposite to the one proposed here. These opinions must be taken into account, since there is no guarantee that the physical analogy must coincide with the psychological one. Recently, I have begun experiments presenting people with series of sounds and series of colors, asking them to relate both sensations. One pair of these series involves sounds of different timbre and colors of different saturation. Though the experiments are not complete yet, the tendency shows that about 80% of the people relate pure sounds with saturated colors, complex sounds with duller colors, and noise with gray or achromatic colors (these results coinciding with the physical correlation), while only about 20% of the people make the opposite choice.

The work of Yilmaz[19] can also be cited to support the correlations proposed to this point. He depicts a tridimensional cone-shaped space representing speech sounds, which has the same kind of organization that a color space has.

SIZE IN COLOR AND DURATION IN SOUND

There is, both for color and sound, a fourth variable or dimension, without which none of these phenomena could exist for perception. For color, this dimension is the size or spatial extension (whether it be an area or volume) that a color stimulus occupies. For sound, it is the temporal extension (duration) that an auditory stimulus lasts.

Color is a spatial sign; without a certain development in space it cannot be perceived. Whether it be color-pigment or color-light, the stimulus needs to be present in a certain surface in relation to the distance of the observer for him to be able to perceive it as a color stimulus and discriminate the other variables of hue, luminosity, and saturation.

Sound is a temporal sign; without a certain development in time it cannot be perceived. The auditory stimulus needs to have a determined duration for a hearer to be able to perceive it as such and discriminate the other variables of pitch, loudness, and timbre. In general, with a duration of 1/20 of a second we can already have a clear sensation of pitch. However, the subject is not simple, since the minimal duration needed can vary between 1/20 and 1/100 of a second, according to the frequency of the sound involved. This and other aspects of duration of sound in relation to pitch are developed by Stevens and Davis.[24]

From the foregoing facts, it seems evident that a correlation between the size of color and the duration of sound can be proposed on some logical basis.

FINAL REMARKS, GUIDELINES, AND APPLICATIONS

After all these correlations, an important difference between color and sound, which is more general than the dissimilarities indicated specifically for hue and pitch, must be acknowledged. It is found in the relation between stimuli and sensations. Color stimuli can differ in spectral composition while eliciting identical color sensations, constituting what is known as the phenomenon of metamerism. For instance, the yellow color produced by a homogeneous light can be matched by many compounds of different red and green lights at different intensities. This phenomenon, which has appeared at the basis of the science of colorimetry from its beginning,[25] does not happen with acoustic stimuli and sound sensations.

More than establishing conclusions, this article offers lines to be further investigated. For instance, experiments could be designed to test the psychological correlations and to see in which cases they coincide with the physical ones.

As a matter of fact, some such experiments are being carried out. Series of auditory stimuli are presented to listeners/observers together with series of color stimuli. They have to decide, exclusively on the basis of their sensations (without employing much reasoning or previous knowledge), if they find any correspondence at all, and also to quantify these correlations. The details about the methods employed and the results obtained will be presented in a future article.

The psychological correlations may or may not coincide with the physical ones; and may even be different for diverse cultural groups. In this regard, there are no universal correlations, just as there are no universal meanings for any kind of sign. Being aware of this, we can use the correlations according to a certain purpose. A composer who aims at affecting the feelings of an audience may address the psychological associations, but an engineer who intends to make a machine convert light stimuli into auditory stimuli, or vice versa, will have to think on the basis of physical correlations.

Physical interactions between light and sound have found practical applications over the years, ranging from devices such as the photophone built by Graham Bell and Tainter[26] (which modulated light intensity in response to the vibrations of a speaker's voice and sent these signals to a distant point where light was converted again to sound so that a listener could hear the voice of the distant speaker) to the more recent field of acousto-optical imaging based on laser and high-frequency acoustic techniques.[27]

Applications with artistic or educational purposes[28] can also be conceived, for instance, systems to learn music with the aid of colors, or methods to improve musical notations.

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