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Harmonic Content Influence on Colour-Choice Association with Unaccompanied Tones

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Abstract

This study investigated simultaneous auditory and visual sensory processing. It was hypothesized that visible spectrum colours ROYGBIV (red, orange, yellow, green, blue, indigo, violet) would specifically map to tones of the 88 note piano keyboard, and presence/absence of harmonic content would manifest as measurable variability differences regarding colour choice associations between sine and harmonic tones. A sinusoidal wave colour-picker image was presented upon which participants subjectively defined borderlines between colours ROYGBIV, and then listened to 77 sine or harmonic tones/semi-tones ($G^{\#}_1$-C_8) while clicking on the colour-picker image to render colour choices. Results indicate: 1) A consistent colour-across-octaves pattern demonstrating piano keyboard mapping of pitch with colour; 2) Presence of harmonic content in tones manifests via increased variability for colour-choices—choices tending toward 'blended' colour borders such as yellowish-green, or greenish-blue.

1. Introduction

There are few natural stimulus relationships that fascinate us more than the relationship of sound and colour. A brief inquiry to an internet search engine will yield hundreds, if not thousands, of references to sound-colour, music-colour associations —associations endorsing everything from therapeutic facilitation benefits via proper colour-sound combination exposure, to potential architectural/décor-design applications.

For thousands of years, scientists and laypersons alike have sought the joining of these two stimuli in some harmonious and substantive way. From Pythagoras to Sir Isaac Newton to the present, theories promulgating the marriage of the visible range of electromagnetic spectrum radiation colours red, orange, yellow, green, blue, indigo, violet (ROYGBIV), with the physical environment of sound conduction via air pressure change have arisen—all thus far, resulting in lack of empirical validation.

2. Research and the Sound-Colour Relationship

Perhaps the most profound influence upon the ongoing sound-colour fascination was Newton's (1704) prismatic light spectrum experiments whereby he parsimoniously decomposed visible white light into its individual spectrum components ROYGBIV by sending it through a prism, and subsequently engineered the recombinant inverse using a second prism to create white light again. Newton himself, reflecting on his knowledge of music, assigned the seven notes A, B, C, D, E, F, and G within an octave (while ignoring sharps and flats) with the ROYGBIV spectrum (Levenson, 1994). Heralded as one of the most elegant and profound discoveries within the field of optics, this decomposition of the visible light spectrum and Newton's subsequent attempt at tonal correspondence with colours set off a wave of associative inquiry that has continued for 300 years. Thus was born the assumed relationship of "do, re, mi, fa, so, la, ti" with the seven visible spectrum colours ROYGBIV—a relationship that even Newton himself never fully explained (Figure 1).

Figure 1. Newton's "colour wheel" (Newton, 1704)

In line with the theory of Newton is that of Russian composer Alexander Scriabin, who also theorized the association of colors and piano tones (Galayev, B.M., & Vanechkina, I.L, 2001). Scirabin's 'color organ' (Peacock, K., 2001) led to his own theoretical mapping of tones across the piano keyboard, and seemingly builds upon the foundation of Newton's work using a circle-of-fifths type of design. Scriabin actually manifested his theory in a 1915 live performance titled *'Prometheus: A Poem of Fire'* by utilising audience members as a sort of musical 'canvas' for the projection of colors simultaneously with his music (Moritz, W., 1997; Peacock, K., 2001).

The importance of such a relationship cannot be underestimated, as it is likely that such a relationship would extend well beyond that of theoretical purposes to potentially clarify the way in which colour is responded to and utilized (West-Marvin & Brinkman, 2000). Interestingly, much of the research continues to associate the seven member musical octave with the seven member visible light spectrum octave. The Newtonian-driven attempt to assign constant hues to all occurrences of a single categorical variable (i.e., a musical note) identically across all octaves, seemingly self-perpetuates and has yet to be defeated.

Though there exist few empirical studies directly addressing the association of colour with sound/music, there are some which do deviate from the static Newtonian perspective of the last couple of centuries. One such study by Sebba (1991), though lacking in statistical analyses beyond that of simple descriptive statistical comparison, provided interesting results. Sebba's inquiry addressed questions such as: In what way does one express, via choice of colours, their impression of a piece of music? What are the characteristics of ‘colour’ scales that are shaped according to a musical scale and what is the visual effect of a colour scheme that was built according to the formation of notes of a musical piece? Sebba found apparent commonality in the expression of music using colour, via correspondence between hierarchical organization of hues and hierarchical organization of sounds. Additionally, Sebba’s findings indicated a ratio between the width of coloured areas and choice of hues, to be similar to ratios of tone duration to pitch—that level of contrast between adjacent hues creates an effect similar to the level of contrast between adjacent tones—and that the arrangement of colour areas creates an expressive whole, similar to that of tone groupings.

In a simple paradigm that investigated brief musical passages and colour association, Cutietta and Haggerty (1987) looked at the subjective music-colour associations rendered by 1256 participants aged 3 to 78—perhaps one of the largest studies to date. Participants listened to three musical excerpts, and then indicated what colour they thought each excerpt was best associated with. Results indicated strong music-colour associations that were consistent across all the musical excerpts and all represented generations from age 9 and beyond.

Marks (1987) used a visual and auditory processing paradigm aimed at addressing how cross-modal similarities between sensory attributes in vision and hearing reveal themselves in speeded, two-stimulus discrimination. Marks found a prevalent cross-modal influence and interaction within pairing presentations of stimuli such as dim/bright lights, and dark/light colours accompanied by high/low pitched tones. Results indicated concurrence with findings on cross-modal perception, synesthesia, and synesthetic metaphor, by indicating direct similarity between cross-modal combinations such as pitch and lightness, pitch and brightness, and loudness and brightness.

In a meta-analysis, Marks (1975) addresses ‘coloured-hearing’ synesthesia, as manifest by numerous collective reports of synesthete colour experiencing with English language vowels. Marks’ paper provides specific list containing forty-four such studies from history regarding this colours-vowels association/experience alone.

In addition, and perhaps most telling, forty-seven entries from this list contain the words colour, music, pitch, and brightness, or some combination thereof. This investigation by Marks also develops an insightful methodology of meta-analyzing the results from a large number of these studies. Ultimately, the fruits of Marks' labor here effectively show the indisputable relationship of brightness to pitch in visual-auditory synesthesia. This paper by Marks also provides evidence of the association of colour and music for the non-synesthete (as per his own empirical research; see Marks 1974) whereby he graphically shows sound frequencies in Hertz as a function of Munsell Value of colour composition.

In another study by Marks (1974), participants matched the brightness of gray surfaces with pure tones. Varied results indicated increasing loudness to be associated with increasing brightness—with some participants associating it to increasing darkness. Further results indicated that when brightness of surface was held at a constant, most participants offset increasing pitch by decreasing loudness of tones. Marks indicated these results to be mimicry of a synesthesia effect, suggesting that most participants will match auditory brightness to visual brightness.

Taking this line of research a bit further, Hubbard (1996) investigated this synesthetic-type effect by addressing visual lightness vs. auditory pitch along with visual lightness vs. melodic interval. Ratings elicited from participants regarding how visual lightness and auditory pitches "fit together" indicated that lighter stimuli fit better with higher pitches, and darker stimuli fit better with lower pitches. Additionally, Hubbard's investigation found that larger melodic intervals produced more extreme (lighter or darker) choices by participants.

Cuddy (1987) looked at the manner in which colour principles might operate within musical melody, hypothesizing that such principles occur at higher levels of auditory organization rather than at the level of the individual tone. In addition, Cuddy theorized and found support for the idea that higher-order processing of tonal information would follow colour mixture principles at a general level.

Musical keys (e.g. major/minor) have also been tied to colour association—particularly as colour relates to that which can be assigned to 'darkness' and/or ‘brightness’—such as human emotion (e.g. happy vs. sad), or even atmospheric ambiance (e.g. gloomy vs. pleasant). Steblin (1983) presents an example of this via her translation of Schubart’s work on colour and musical key associations (Schubart, C., 1806) —a relationship that goes beyond simple colour-tone associations and hints at the manner in which elements such as colour, mood, and music might be seen as inextricably intertwined.

In a study by West-Marvin and Brinkman (2000), the effect of key colour (black and white keys) and timbre, on absolute pitch recognition was the focus. It was found that the colour of the key was an integral part of identification response time and thus suggests a cognitive relationship between response times and expected frequency of occurrence of black and white key pitches. Additionally, West-Marvin and Brinkman found that timbre presentations of piano vs. a string instrument had little effect on participants’ performance within all presented experimental paradigms, and suggest the pervasiveness of piano tones in western culture may well have an effect on their expected frequency. The simple fact that colour (albeit simple black and white) is an inherent part of a piano keyboard stirs curiosity that colour and sound/music may have a far more intimate relationship than was once thought.

These types of studies, whereby an attempt is made to show a relationship between a stimulus processed within a specific modality with another stimulus processed within a different modality, are often called “mappings”—with one of the more commonly studied synesthetic mappings being that between visual lightness and auditory pitch. Thus, a piano keyboard is an excellent example of the physical manifestation of “mapping” in that specific pitches “map” directly to specific keys in specific locations on the keyboard.

In another study by Marks (1982) using synesthetic metaphors (e.g., “the dawn comes up like thunder”), it was found that language metaphors are able to influence perception of the music/sound and colour connection. Across a series of four experiments, participants utilized loudness, pitch, and brightness scales in evaluating the meanings of a variety of synesthetic auditory-visual metaphors. Results indicated loudness and pitch were expressed metaphorically as greater brightness; in turn, brightness expressed itself as greater loudness and as higher pitched. This type of scientific investigation of semantic influence related to sound/music colour connectedness perpetuates the Newtonian ideology of matching the seven major note names with the seven prismatic rainbow colours ROYGBIV across all octaves. Though valuable and interesting in its own right, this Newtonian ideology perpetuates a scientific endeavor that has yielded little if any palatable scientific 'fruit' over several centuries.

With linguistic/semantic study results in line with Newton's first assignation of tone names to colours, it is no wonder then that the bulk of most available information, scientific or otherwise, on the music/sound colour relationship seemingly continues to disseminate the ideology of seven principal tone names corresponding somehow to the seven prismatic colours of the rainbow—a mere categorical marriage of nominal variables.

It seems that the music-colour correspondence quest has taken a form parallel to that of Johannes Kepler's search for symmetry in planetary orbits—a decade long search in which Kepler all but exhausted potential circular orbital pathway combinations only to find that the simple elegance and symmetry of a circle had obscured any consideration for the simple elegance and symmetry of an ellipse. With respect to music-colour correspondence, here too nature appears to require a different 'elegant' explanation. In attempting to break free from the Newtonian ideology, one must consider that correct and incorrect solutions may have nearly equivalent parsimony—that nature is perhaps compelled toward such illusory occurrences. It therefore appears the answer to the 'Newtonian driven' music-colour correspondence enigma may lie elsewhere.

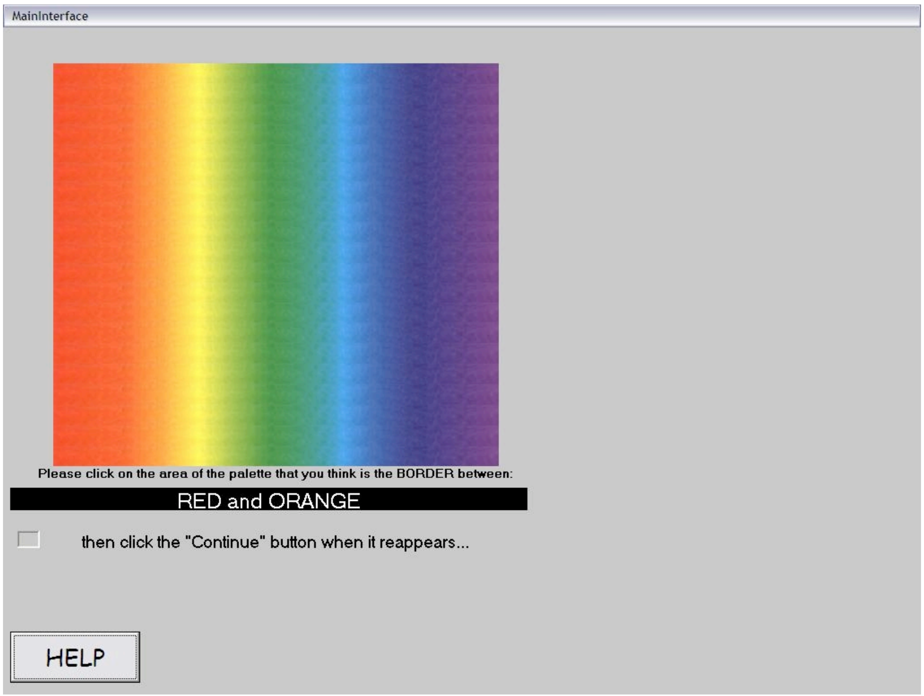
Despite the range and relatively comprehensive nature of pitch and colour investigations to date, these studies have omitted the main thrusts of the current investigation—1) the direct mapping of ROYGBIV spectrum colours to the notes of a standard piano keyboard; and 2) investigating the influence of presence or absence of harmonic content with respect to pitch-colour associations.

3. Hypotheses

An experiment was conducted with the intent of testing the hypotheses that ROYGBIV visible light spectrum colours would systematically map to a piano keyboard via a 77 tone sine/harmonic tone sequence. Additionally, it was hypothesized that between sine tones and tones containing harmonic content, there would be measurable response variability regarding colour choice.

4. Method

The experimental design directive was four-fold: 1) testing the influence of harmonic overtone content based upon colour borderline definitions as rendered uniquely by each participant; 2) presenting highly related but subtly different auditory stimuli in the form of tones and semitones, so as to reveal any natural affinity for colour-tone matching which might be prevalent at differing levels of pitch sensitivity; 3) testing any influence on the part of natural harmonic content and natural amplitude content of harmonic tones vs. sine tones; and 4) presenting a 'blended' ROYGBIV sinusoidal-wave grating colour-picker (Figure 2), which might best reflect response subtleties to the aforementioned harmonics and amplitude content of tones.



Please click on the area of the palette that you think is the BORDER between:

RED and ORANGE

☐ then click the "Continue" button when it reappears...

Figure 2. Screenshot of main interface showing "colour-picker" visual stimulus

Thus, there were two groups that differed only with respect to auditory stimulus exposure to either sine tones or harmonic content tones. The continuous scale colour-picker stimulus enabled participants to actually speficy their own borderlines between colours of the colour spectrum ROYGBIV, and allowed exposure to a more natural and complete range of hue options.

4.1 Participants

Seventy-eight graduate and undergraduate students (60 females and 18 males) participated and received partial course credit.

4.2 Materials and Apparatus

The experiment was presented on-screen as a computer program written using the Microsoft Visual Basic 6.0. Program elements included sequentially: 1) demographic information collection; 2) instructions to participants; 3) participant defining of colour borders on the colour-picker stimulus; 4) practice stimulus trials/samples; 4) experimental stimulus trials; 5) completion screen; and 6) debriefing information.

Computers utilized were Dell Dimension model 4100 with Windows XP-Pro software, a 1 GHz Pentium-3 processor, and 256 MB RAM capacity. The monitor display was a Dell Ultra-Scan P991 in conjunction with an NVIDIA RIVA TNT2 Model-64 32 MB graphics card. The screen resolution for stimulus presentation within all three experiments reflected a factory default setting of 1024 x 768 pixels, 32-bit colour quality, 96 DPI display setting. A standard mouse and QWERTY keyboard were available for data entry of demographics information and responses. Participants listened to the tones through Aiwa HP-X222 model stereo headphones with an externally accessible volume control available to them for any preferred adjustment.

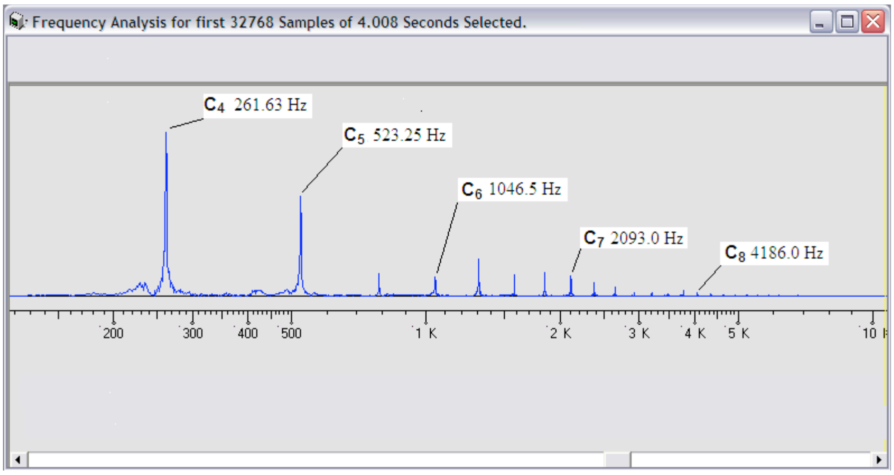
4.3 Auditory Stimuli

Two types of auditory stimuli were presented, sine tones and harmonic tones. Sine tones were generated by mathematical equation using GoldWave version 4.25 audio waveform editing program. Audio stimuli were created as .wav files and subsequently converted via Microsoft Windows Media Converter compression formatting to .wma files so as to decrease file size and possibly eliminate any potential latency in the auto-start loading process of the Windows Media Player as demanded by the software program code. Audio samples were not constructed for equivalent amplitude presentation and the natural sound energy/amplitude of each individual tone was present. All sine tones were audible for 3 seconds. Sine tone stimuli encompassed a full range of 77 tones and semi-tones from the $G^{\#}_1$ to C_8 frequency range of 51.91 Hz to 4186.0 Hz. The 11 tones and semi-tones below $G^{\#}_1$ were not utilised because of concern that the greater vibrational energy of lower frequency notes, and their ability to transmit this vibration physically to participants via the headphones, might influence color choice contrary to the hypotheses. It has been shown that vibrational frequencies, via controlled application of proprioceptive stimuli, can also influence systematic association of color with vibrational stimuli (Howard, J., 2006).

Creation of harmonic tones consisted of recording a series of waveform samples of an acoustic grand piano (program number "000 AcGrandPno") from an Alesis QSR 64-voice synthesizer default General Midi sound bank. The harmonic tone set also included 77 tones and semitones for the range $G^{\#}_1$ to C_8. Sampling rate was 44.1 KHz for all tones which were then converted from .wav file format to CD quality 128 mbps .mp3 file compression format using dBpowerAmp music converter program. Each harmonic tone was approximately 3-4 seconds long and merely varied in length as a function of the natural decay of the differing frequencies. It should be added that although highly realistic, this type of waveform sample would most likely fall short of full natural harmonic overtone production as would be provided by a real instrument influenced by the acoustical properties of a more natural listening environment.

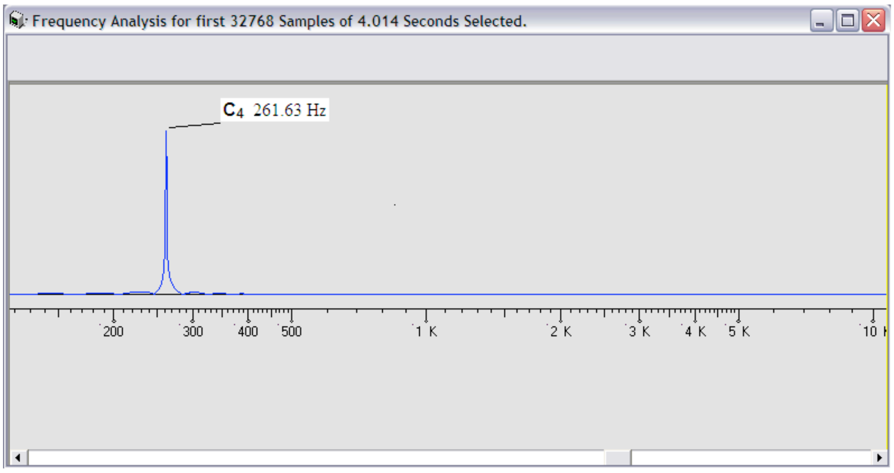
It would be helpful here to add basic and brief clarification of harmonic overtone content so as to further clarify its role. Middle C (C_4) on an acoustic piano will vibrate at 261.63 Hz when the key is struck, thus producing the 'fundamental frequency' for this note. Different segments of a string will also 'sub-vibrate' at different frequencies. For example, the C_4 string will vibrate as a whole entity at

261.63 Hz; each half of the string also vibrates creating the 'first overtone'; each third of the string vibrates to create the second overtone, as will each quarter of the string vibrate to create the third overtone and so on (Seashore, 1938). Therefore harmonic overtones are directly related to their fundamental frequency, and certain overtones are simply even multiples of this fundamental frequency. A frequency analysis comparison of actual 261.63 Hz (C_4) tones utilized for the harmonic tone and sine tone conditions of these two groups is presented in Figure 3 and Figure 4 emphasizing presence and absence of harmonic overtones for C_4, which clearly shows the differences in harmonic content between these two types of tones.



Frequency Analysis for first 32768 Samples of 4.008 Seconds Selected.

Figure 3. Harmonic tone C_4 (261.63 Hz) with harmonic content. Note how equally spaced harmonics are even multiples of the fundamental frequency (Bryan, 2002)



Frequency Analysis for first 32768 Samples of 4.014 Seconds Selected.

Figure 4. Sine tone C_4 (261.63 Hz). Note total absence of any harmonic frequency content (Bryan, 2002)

4.4 Visual Stimulus

The visual stimulus was a sinusoidal –wave grating replication of the visual light spectrum colours ROYGBIV, and was presented via a “colour-picker” tool comprised of continuous colour gradations similar to that found on a graphics design program (see Figure 1). Participants would render their colour choices by clicking on the colour-picker image, which allowed varying shades of colour to be chosen. On-screen dimensions of the colour-picker itself were 168mm in width by 152mm in height. The colour-picker was positioned in the upper left-hand corner of the screen, 25mm from the top, 19mm from the left, 162mm from the right, and 88mm from the bottom.

To record responses at a high level of sensitivity, horizontal ‘X’ axis and vertical ‘Y’ axis coordinates representing horizontal and vertical cursor position over the colour-picker image were captured and recorded. These values are ‘pixel-distance’ values reported by the program, and provide a means by which to track cursor movement direction and position over an image stimulus. Thus, having participants initially specify where the lines were that divided the colours on the colour-picker, allowed for any ‘X’ axis coordinate value obtained after a mouse click to register as a specific colour having been chosen on the colour-picker image.

The colour-picker stimulus was not neutralized for presentation of equal “perceived brightness” (albedo), allowing for those perceived as seemingly brighter (such as yellow) to be perceived as such. This is due to the fact that any positive results of an experiment such as this would likely garner greatest attention from the domain of real-world multimedia interface design/applications. Of the simultaneous audio-visual experiences of the average person, few if any would be ‘isoluminant’ in their nature. Human everyday audio-visual experience is variable in its nature and is not highly controlled on-screen for albedo equivalency across colours—and evidence exists that perceptually isoluminant colours are not optimal as a design choice—that there is increased difficulty in separating figure-ground elements when both are presented in isoluminant colours (Hoffman 1998; Livingstone & Hubel 1988).

4.5 Procedure

Upon entering the lab, participants were randomly assigned to either the sine tone or harmonic tone condition via roll of the die—odd numbers were assigned to the sine tone group, and even numbers assigned to the harmonic tone group. Thus, there were 39 participants in the sine tone group and 39 participants in the harmonic tone group.

The experiment was comprised of six stages: demographics information collection; experiment instructions; practice tones; the 'colour-defining' task; 77 experimental trials; and debriefing screen. The instruction phase presented a screen where participants read instructions regarding the task. For the practice trial phase, participants listened to two randomly selected tones from their assigned tone set. During the colour-defining phase, participants were sequentially prompted to choose the dividing lines between the various colours of the colour picker (ROYGBIV). Participants would define the area for a colour by clicking the place on the colour-picker where they thought the "dividing-line" between any two colours should be placed (e.g., the dividing line between red and orange). When a participant clicked on the colour-picker, a black line would be placed on the colour-picker. This black line would move to wherever they clicked, and when a participant was satisfied with the position of the line, they would click the 'continue' button which would "anchor" this line and then prompt them to place a new line to define the next colour in the sequence. After defining the six borderlines between all ROYGBIV colours was completed, participants entered the experimental trial phase. The 77 experimental trials were comprised of either sine tone or harmonic tone auditory stimuli presented randomly by the software program, along with the presence of the on-screen colour-picker that allowed a colour choice to be made after hearing a tone. In this phase, participants would choose a colour on each trial that they felt was most 'representative' of the tone they had heard.

Upon completion of the experiment, participants were presented the on-screen debriefing statement. All participant responses along with all demographic information were collected automatically by appending to a text file that was created by the program and stored with the program files for later retrieval. This text data from participant responses was then inspected and 'set-up' where necessary so that a comma delimited import of the text file data could be effectively completed to place the data into a Statistical Package for the Social Sciences (SPSS) file for analysis.

5. Results

Chi Square analyses were conducted so as to identify any tones associated with specific spectrum colours. In addition, the experiment provided unique insight via captured horizontal 'X' axis cursor position values from mouse movement and mouse clicks on the colour-picker image, which according to their value reported, would indicate exactly where the colour-picker image had been clicked and could be directly associated with specific colours. These 'X' axis values are reported by the Visual Basic program in 'twips', whereby one twip equals 1/1440th or .0006944 inches ('X' axis value range = 0 to 7440). Capturing these values on the colour-picker gave a more heightened level of measurement sensitivity regarding subtleties of colour-blending and potential influence over colour choice by presence or absence of harmonic content. Figure 5 and Figure 6 present Chi Square analyses results for all harmonic and sine tones presented across the 77 tone sequence, as mapped to an 88 note piano keyboard.

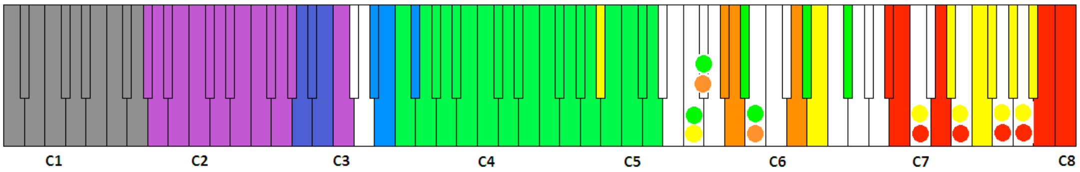


Figure 5. Harmonic tone Chi Square analyses results as mapped to standard 88 note piano keyboard.

Solid gray = not used in study

Solid colors = single colors as associated with specific notes

White keys = not significant at/below .05 level for any colour

Double dots = pitches with dual colour association

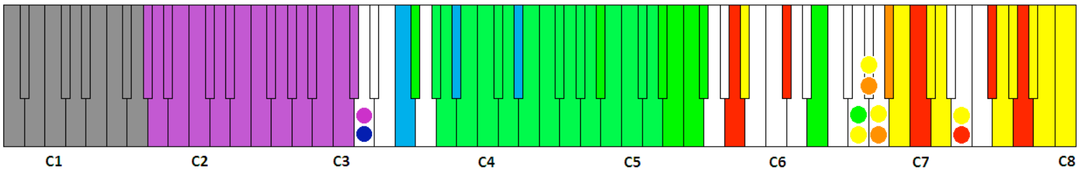


Figure 6. Sine tone Chi Square analyses results as mapped to standard 88 note piano keyboard.

Solid gray = not used in study

Solid colors = single colors as associated with specific notes

White keys = not significant at/below .05 level for any colour

Double dots = pitches with dual colour association

Note the clustering of specific colours for specific octaves, as well as long-wavelength/bright colours mapping to high-frequency bright pitches, and vice versa. Individual tone frequency counts, Chi Square statistics, and significance values for the harmonic tone group can be seen in Tables 1 through 14 with gray shaded cells indicating highest response frequency.

Table 1. Harmonic and Sine group colour-choice frequency counts for G#1 through G2

Hue	**G#1**	**A1**	**A#1**	**B1**	**C2**	**C#2**	**D2**	**D#2**	**E2**	**F2**	**F#2**	**G2**
R	5	5	5	3	4	5	8	1	4	3	4	4
O	0	0	0	2	1	0	1	4	1	2	1	1
Y	0	0	0	0	0	1	0	0	0	1	1	0
G	0	0	0	2	0	0	2	0	5	2	1	0
B	1	1	5	1	2	2	0	0	1	3	1	3
I	5	7	7	5	5	8	8	12	10	10	13	15
V	28	26	22	26	27	23	20	22	18	18	18	16
R	2	1	0	2	1	1	0	2	2	2	1	2
O	1	0	1	0	1	1	1	0	2	0	2	0
Y	0	2	1	1	1	1	1	1	2	0	1	1
G	2	3	3	3	2	2	2	2	3	3	4	2
B	0	0	0	0	1	1	3	2	3	0	2	7
I	6	4	7	6	5	4	3	6	7	8	6	7
V	28	29	27	27	28	29	29	26	23	26	23	20
Total	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**

Table 2. Harmonic and Sine group χ^2 values and significance for tones G#1 through G2

	G#1	**A1**	**A#1**	**B1**	**C2**	**C#2**	**D2**	**D#2**	**E2**	**F2**	**F#2**	**G2**
χ^2	46.64	38.03	20.79	71.61	60.35	40.87	29.33	27.15	32.84	41.94	53.07	26.00
p	<.000	<.000	<.000	<.000	<.000	<.000	<.000	<.000	<.000	<.000	<.000	<.000
χ^2	67.28	72.66	62.15	60.87	107.6	116.2	94.07	72.53	53.15	38.23	67.07	39.00
p	<.000	<.000	<.000	<.000	<.000	<.000	<.000	<.000	<.000	<.000	<.000	<.000

Table 3. Harmonic and Sine group colour-choice frequency counts for G#2 through G3

Hue	G#2	A2	A#2	B2	C3	C#3	D3	D#3	E3	F3	F#3	G3
R	2	2	6	1	1	2	4	4	1	9	6	5
O	0	2	1	4	0	4	2	3	3	2	0	1
Y	0	2	0	1	1	0	2	2	3	1	1	2
G	7	7	4	6	1	6	10	6	8	10	10	12
B	7	4	6	7	10	12	10	13	11	8	13	9
I	9	12	14	12	8	9	6	7	7	4	2	6
V	14	10	8	8	11	6	5	4	6	5	7	4
R	3	2	1	3	0	2	3	4	3	3	1	4
O	0	0	1	0	0	0	0	0	0	0	3	0
Y	0	2	0	2	3	1	0	0	1	4	1	3
G	2	5	4	3	5	7	4	6	7	8	11	10
B	2	2	5	1	6	6	8	10	9	14	6	6
I	10	9	11	12	12	10	12	9	10	5	10	7
V	22	19	17	18	13	13	12	10	9	5	7	8
Total	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**

Table 4. Harmonic and Sine group χ^2 values and significance for tones G#2 through G3

	G#2	A2	A#2	B2	C3	C#3	D3	D#3	E3	F3	F#3	G3
χ^2	9.59	18.61	14.69	16.82	15.00	9.76	12.15	14.66	12.87	13.23	16.23	16.10
p	.048	.005	.012	.010	.010	.082	.059	.023	.045	.040	.006	.010
χ^2	38.05	34.69	30.69	36.53	10.10	16.23	9.33	3.69	10.38	12.53	17.89	5.76
p	<.000	<.000	<.000	<.000	.039	.006	.053	.449	.065	.028	.006	.329

Table 5. Harmonic and Sine group colour-choice frequency counts for G#3 through G4

Hue	**G#3**	**A3**	**A#3**	**B3**	**C4**	**C#4**	**D4**	**D#4**	**E4**	**F4**	**F#4**	**G4**
R	4	3	2	5	7	6	6	2	5	6	3	2
O	3	2	2	0	1	4	2	2	3	3	7	4
Y	1	1	2	4	4	0	2	3	3	5	7	4
G	13	19	16	19	14	15	13	18	20	19	12	20
B	9	9	11	6	9	10	8	9	0	5	6	8
I	5	2	4	3	2	2	4	3	5	1	1	1
V	4	3	2	2	2	2	4	2	3	0	3	0
R	1	3	0	3	3	6	1	6	2	3	5	4
O	2	0	0	0	2	2	2	1	4	3	3	2
Y	2	1	3	1	1	2	3	4	2	1	3	2
G	12	15	11	17	15	13	18	12	16	17	18	19
B	11	9	12	8	11	7	8	13	9	9	8	10
I	6	5	10	7	2	8	3	0	2	2	0	2
V	5	6	3	3	5	1	4	3	4	4	2	0
Total	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**

Table 6. Harmonic and Sine group χ^2 values and significance for tones G#3 through G4

	G#3	**A3**	**A#3**	**B3**	**C4**	**C#4**	**D4**	**D#4**	**E4**	**F4**	**F#4**	**G4**
χ^2	17.89	45.17	34.41	30.38	24.00	20.23	16.46	39.07	34.38	31.30	14.30	38.07
p	<.000	<.000	<.000	<.000	.001	.001	.011	<.000	<.000	<.000	.026	<.000
χ^2	21.12	19.00	10.10	25.76	30.82	19.69	37.64	18.69	29.38	34.41	27.92	36.23
p	.002	.002	.039	<.000	<.000	.003	<.000	.002	<.000	<.000	<.000	<.000

Table 7. Harmonic and Sine group colour-choice frequency counts for G#4 through G5

Hue	G#4	A4	A#4	B4	C5	C#5	D5	D#5	E5	F5	F#5	G5
R	7	9	2	5	3	2	6	5	6	5	3	10
O	4	7	7	4	11	8	3	5	7	5	11	7
Y	4	3	12	4	5	7	6	7	8	10	7	5
G	17	15	11	20	12	16	14	10	10	10	12	7
B	5	4	4	5	5	3	8	6	5	6	4	7
I	2	0	2	0	0	2	0	3	2	2	2	1
V	0	1	1	1	3	1	2	3	1	1	0	2
R	5	6	2	4	8	8	4	6	6	9	10	5
O	4	5	7	2	4	2	5	5	7	9	9	9
Y	2	5	4	7	7	9	8	6	7	2	5	7
G	16	14	16	19	11	12	13	14	13	13	12	9
B	8	5	6	4	6	6	7	5	4	4	2	6
I	2	2	1	2	2	1	0	1	1	1	1	3
V	2	2	3	1	1	1	2	2	1	1	0	0
Total	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**

Table 8. Harmonic and Sine group χ^2 values and significance for tones G#4 through G5

	G#4	A4	A#4	B4	C5	C#5	D5	D#5	E5	F5	F#5	G5
χ^2	22.38	19.61	21.84	35.30	12.23	30.46	14.07	6.41	11.07	13.23	13.76	10.71
p	<.000	.001	.001	<.000	.032	<.000	.015	.379	.086	.040	.017	.097
χ^2	27.94	17.53	27.59	41.94	13.23	20.41	11.30	18.97	18.61	24.35	15.61	4.23
p	<.000	.007	<.000	<.000	.040	.002	.046	.004	.005	<.000	.008	.517

Table 9. Harmonic and Sine group colour-choice frequency counts for G#5 through G6

Hue	**G#5**	**A5**	**A#5**	**B5**	**C6**	**C#6**	**D6**	**D#6**	**E6**	**F6**	**F#6**	**G6**
R	8	8	5	5	9	8	4	7	5	6	8	9
O	10	13	7	11	4	6	11	6	9	9	8	9
Y	5	3	8	6	7	6	9	8	11	8	6	6
G	9	7	9	11	7	6	7	12	6	6	12	6
B	4	6	8	4	8	7	4	3	4	7	2	2
I	1	1	1	1	2	4	3	2	1	0	1	2
V	2	1	1	1	2	2	1	1	3	3	2	5
R	8	13	6	9	7	12	11	7	8	11	11	6
O	9	1	10	8	10	8	9	7	9	10	6	9
Y	8	8	13	8	9	6	4	6	5	7	9	10
G	6	11	3	9	8	9	7	11	12	5	8	10
B	6	4	6	3	4	3	6	3	3	5	3	2
I	2	2	1	2	1	1	0	2	2	1	2	1
V	0	0	0	0	0	0	2	3	0	0	0	1
Total	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**

Table 10. Harmonic and Sine group χ^2 values and significance for tones G#5 through G6

	G#5	**A5**	**A#5**	**B5**	**C6**	**C#6**	**D6**	**D#6**	**E6**	**F6**	**F#6**	**G6**
χ^2	13.23	20.05	12.15	18.61	8.92	4.25	13.59	16.10	12.87	3.308	17.89	8.92
p	.040	.003	.059	.005	.178	.642	.035	.013	.045	.653	.006	.178
χ^2	4.84	18.69	15.00	7.61	8.84	12.53	8.23	10.71	11.30	10.38	9.46	18.97
p	.435	.002	.010	.179	.115	.028	.144	.097	.046	.065	.092	.004

Table 11. Harmonic and Sine group colour-choice frequency counts for G#6 through G7

Hue	G#6	A6	A#6	B6	C7	C#7	D7	D#7	E7	F7	F#7	G7
R	9	11	14	12	12	11	12	10	11	12	12	10
O	8	6	4	4	4	10	3	3	3	3	4	7
Y	8	6	6	11	12	6	9	14	11	13	14	10
G	6	6	7	2	5	3	3	3	4	2	3	3
B	4	5	3	6	3	5	5	5	4	4	3	4
I	4	2	2	3	0	0	3	1	3	2	2	2
V	0	3	3	1	3	4	4	3	3	3	1	3
R	6	4	9	9	10	10	11	12	13	12	13	12
O	11	12	11	7	9	7	5	5	7	8	6	5
Y	10	13	7	10	9	12	12	9	13	11	10	15
G	6	5	9	8	4	4	6	7	2	3	5	3
B	2	3	1	2	5	3	3	6	3	5	3	4
I	3	2	2	2	1	2	2	0	1	0	1	0
V	1	0	0	1	1	1	0	0	0	0	1	0
Total	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**	**78**

Table 12. Harmonic and Sine group χ^2 values and significance for tones G#6 through G7

	G#6	A6	A#6	B6	C7	C#7	D7	D#7	E7	F7	F#7	G7
χ^2	3.61	8.92	18.25	20.41	14.38	8.23	13.59	23.64	15.02	24.71	29.02	12.51
p	.606	.178	.006	.002	.013	.144	.035	.001	.020	<.000	<.000	.051
χ^2	16.10	17.46	12.84	15.38	15.74	18.97	13.15	3.94	22.69	7.53	22.20	14.71
p	.013	.004	.025	.017	.015	.005	.022	.413	<.000	.110	.001	.005

Table 13. Harmonic and Sine group colour-choice frequency counts for G#7 through C8

Hue	**G#7**	**A7**	**A#7**	**B7**	**C8**
R	12	11	14	14	15
O	2	2	2	1	0
Y	13	11	15	12	13
G	4	4	0	2	2
B	3	6	3	4	4
I	2	1	0	2	1
V	3	4	5	4	4
R	10	13	13	14	11
O	3	6	4	4	4
Y	21	11	14	15	20
G	3	2	4	3	2
B	1	5	2	1	0
I	1	0	1	1	0
V	0	2	1	1	2
Total	**78**	**78**	**78**	**78**	**78**

Table 14. Harmonic and Sine group χ^2 values and significance for tones G#7 through C8

	G#7	**A7**	**A#7**	**B7**	**C8**
χ^2	24.71	17.53	19.84	29.38	27.30
p	<.000	.007	.001	<.000	<.000
χ^2	47.30	16.23	33.33	41.59	30.87
p	<.000	.006	<.000	<.000	<.000

The hypothesis that the 77 tones would be systematically associated with colour choice appears to garner support at this point as evidenced by the sequence of Chi Square analyses in Tables 1-14. In addition, Figure 7 presents a graphic that approximates this relationship—a seemingly inverse relationship between ROYGBIV visible light spectrum colours and sound frequencies, as represented also via the harmonic and sine tone keyboard mappings in Figure 5 and Figure 6.

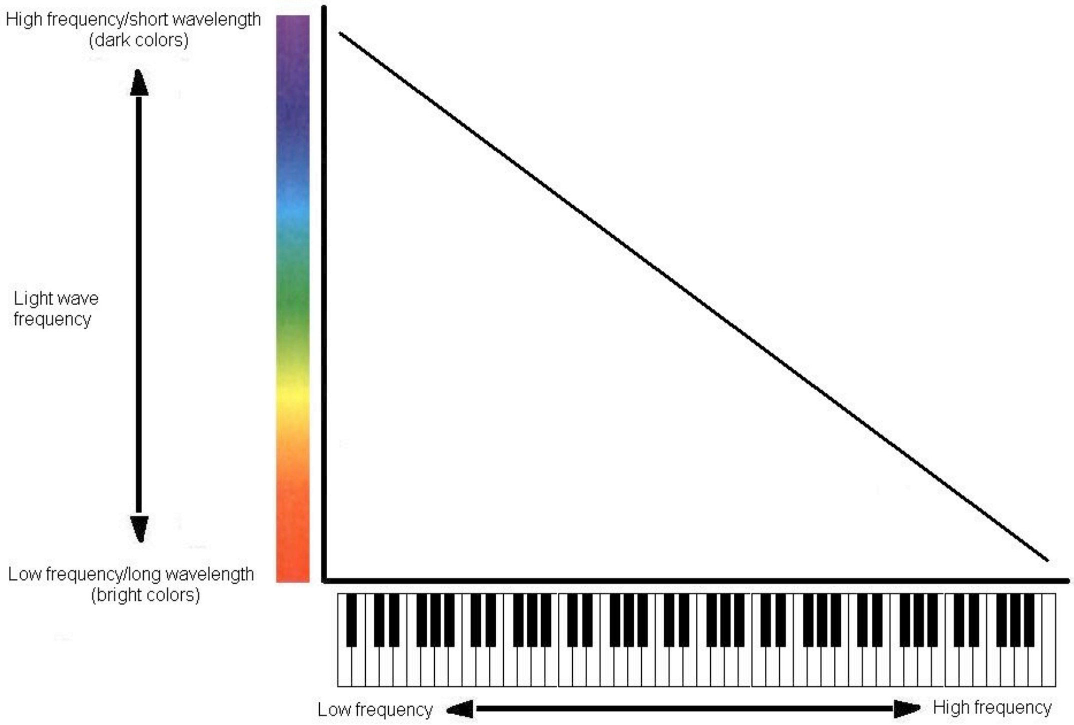


Figure 7. Theorized inverse relationship between wavelength frequency of light and wavelength frequency of sound for single tone presentations

Another interesting result of these data analyses involved that of comparing variability differences displayed by the sine vs. harmonic groups regarding the captured 'X' axis values for all ROYGBIV colour choices, as derived from mouse clicks on the colour-picker. As previously mentioned, these colour-picker image 'X' axis values representing the left-to-right distance on the colour-picker image itself, allowed blended colours, such as 'bluish-green' or 'reddish-orange' to play a role in the analyses, and examines how these subtle colour blends might be associated with the presence or absence of harmonic content. In support of this, the data do appear to indicate that overall harmonic tone colour-choice variability on the 'X' axis of the colour-choice stimulus does vary from overall sine tone colour choice variability on the 'X' axis of the colour choice stimulus. A test for sine vs. harmonic tone 'X' axis values was conducted (Table 15) to compare these standard deviations of colour-choice 'X' axis values of both groups against one another—the hypothesis again being that presence of harmonic content should influence variability of colour choice across all notes. Thus all 77 sine tones, and the standard deviation of the 'X' axis value garnered by each, were t-tested against these same 'X' axis value standard deviations for all 77 harmonic notes. The results of this comparison, t (113.49, df adjusted) = -5.63, $p < .00$, indicates significant differences—albeit results assume non-equal variance due to a Levene test statistic indicating violation of the homogeneity of variance assumption. It must be emphasized that a violation of homogeneity of variance would be in order for a test on these data—sine and harmonic tones are not homogeneous—harmonic tones contain greater variability (e.g. harmonic overtones). Thus a manifestation of color choices that demonstrate this same lack of homogeneity for X-axis values on the color stimulus places these color-choice data points in line with the hypotheses as stated—that color choice variability would be influenced by presence or absence of harmonic overtone content.

Table 15. Independent samples t-test: Standard deviations of mean ‘X’ axis values for 77 sine tones vs. Standard deviations of mean ‘X’ axis values for 77 harmonic tones

	Harmonic tones	Sine tones	*t*	df
Means of the standard deviations of mean ‘X’ axis values	1739.62 (290.16)	1530.31 (149.04)	1.97*	152

Note. * = $p \leq .01$. Standard deviations appear in parentheses below means.

Thus the indication is that ‘X’ axis variability between the two groups for all 77 tones is significantly different, and that perhaps the harmonic content of notes could have contributed to this discrepancy. It is important to mention that the resulting variability differences could also be due to amplitude differences between harmonic tones and sine tones as the sine tones presented were natural and thus contained their natural sound energy. The influence of such amplitude differences on colour selection was not analysed separately as extracted variance in the analysis of the data, and could clearly have contributory influence on the results. Albeit the nature of the experiment was to analyse the naturally occurring association of color with the presented tones, further research should indeed look at extraction of qualitative components of variability so as the further clarify the full extent of the relationship.

Additionally, the analysis of variability differences between groups revealed another interesting pattern in the data. Calling attention to this pattern is Table 16 and Table 17, which present the mean sine group and harmonic group ‘X’ axis values for all ROYGBIV colours, and the standard deviations of these dependent measures.

Table 16. Mean sine group 'X' axis values for all ROYGBIV colours

Sine tone colour choice	N	Minimum	Maximum	Mean	Standard Deviation
Red	39	294.75	1440.00	704.04	299.72
Orange	36	1251.82	2185.91	1692.91	210.77
Yellow	39	2187.27	2992.86	2406.64	135.77
Green	39	3200.36	4968.89	3530.98	281.30
Blue	39	4383.33	6172.50	4865.76	265.15
Indigo	36	4877.86	6105.00	5645.04	279.60
Violet	39	6176.25	7233.00	6705.36	286.15

Table 17. Mean harmonic group ‘X’ axis values for all ROYGBIV colours

Harmonic tone colour	**N**	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
Red	38	110.00	1296.00	689.55	279.61
Orange	36	1134.00	2378.57	1645.72	246.02
Yellow	38	2035.00	3033.33	2399.49	186.04
Green	39	397.50	4155.88	3414.81	544.52
Blue	39	2691.20	5170.00	4792.79	403.92
Indigo	38	4899.55	6416.25	5712.81	324.19
Violet	39	5886.59	7248.00	6679.72	322.49

Upon closer examination, one will note the unusual ‘ratio’ relationships between the standard deviations of colours YGBI (yellow, green, blue, indigo) for these groups, as demarcated by the shaded numerical values in Table 16 (sine) and Table 17 (harmonic). These values appear to reveal a systematic relationship regarding the ratio of variability between harmonic and sine standard deviations of ‘X’ axis values. Figure 8 shows this ratio relationship as derived by dividing the harmonic tone standard deviation for each colour by its corresponding sine tone standard deviation.

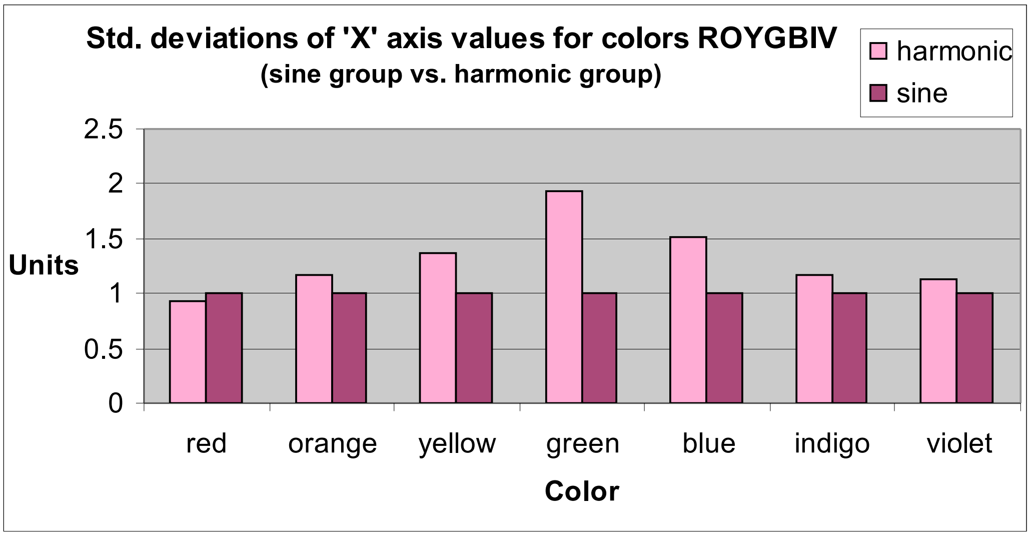


Figure 8. Ratio of harmonic tone ‘X’ axis variability to sine tone ‘X’ axis variability

Additionally, the colours YGBI that show differences in Figure 8 were virtually the only colours to be associated with specific tone clusters as per the earlier sequences of one-sample t-tests. Note how the colours red, orange, and violet have nearly equivalent variability ratios of 1:1 between sine and harmonic tones, as opposed to the comparisons of colours YGBI.

The ratio sequence for Figure 8 was derived by dividing each harmonic standard deviation for the colours YGBI by its colour-matching sine tone standard deviation. These calculations indicate that the amount of harmonic variability for every 1 unit of sine variability equals .933 to 1 for red; 1.167 to 1 for orange; 1.36 to 1 for yellow; 1.936 to 1 for green; 1.523 to 1 for blue; 1.159 to 1 for indigo; and 1.127 to 1 for violet. This relationship appears to reflect the hypothesized influence that harmonic content may have on participant colour choice however, as mentioned earlier, there are clear amplitude differences at work within the two groups. The natural sound energy of the sine tones changes at the higher frequencies and thus there may be an interaction of several effects that facilitates varied responses.

It is also important to address a discrepancy in standard deviation sizes in Tables 16 and 17 with respect to the colour red and the remaining six colours. For example, in Table 16 the colour red garners a standard deviation of 299.72—nearly half the size of its mean 'X' axis value of 704.04. The remaining six colours do not show such drastic variability between their means and standard deviations. A plausible explanation for this is the fact that within the visible light spectrum, the colour red occupies the greatest bandwidth or 'range' with respect to the colours ROYGBIV—130 nanometers in width for red, as opposed to 20 nanometers in width for a colour such as yellow—a more than six-fold difference (Hyperphysics, 2010). As presented earlier, the Figure 2 screenshot of the main interface showing the "colour-picker" visual stimulus provides an excellent visual example of this red-yellow visible spectrum bandwidth difference. Thus the colour red not only has wider representation on the sinusoidal wave colour visual stimulus, but it also has greater bandwidth representation within the human visual system as per the visible light spectrum. Therefore it is possible that this greater bandwidth perception for the colour red translates into greater variability in 'X' axis clicks on the part of participants.

6. Discussion

The experiment produced all indications that there is a consistent pattern of responding regarding association of basic colour with harmonic and sine tones. In addition, it strongly corroborates previous research indicating high tones being associated with bright colours, and low tones being associated with dark colours (see Marks 1975; 1987). Also, the fact that the experiment utilized a sequence of tones and semi-tones was of great importance in that it allowed for a precise tone content analysis and thus a more sensitive measure of any occurring effects. Similarly, the inclusion of tones with harmonic content allowed a more precise measurement of how colours and tones might be associated—a relationship that is perhaps more indicative of 'real-world' music listening and tone exposure.

For several hundred years Newton's mapping of tones to a wheel representing an octave of sound has persisted—the result s of this study directly challenge this Newtonian theory. The results of this investigation appear to indicate that dispersion of colour association with tones occurs contrary to that which Newton theorized, and seemingly occurs linearly *across* octaves rather than repetitively *within* octaves. In addition, the current investigation utilized a colour sinusoidal wave stimulus that is strongly in concert with Newton's early experiments revealing prismatic decomposition of the visible light spectrum results in a sinusoidal waveform.

As per the hypotheses as stated, the result s of this experiment do support an observable systematic mapping of tones to the piano keyboard and do support the hypothesis that sine and harmonic tones would manifest measureable variability—with both hypotheses as stated being confirmed at levels of statistical significance. Serendipitously, it was found that the relationship of the sine and harmonic tones manifests not only as simple measurable variability, but as a clearly defined ratio-related systematic patterned relationship that actually reflects the physical differences between these different types of tones.

The results as garnered by this experiment appear to indicate that human colour vision, when coupled with a tone presentation paradigm, responds to colour stimuli differently—that is, in a very systematic way with with respect to presence or absence of tonal harmonic content. Thus the converse idea that a presentation of specific colours could lead to accurately mapped specific tonal responses on the part of individuals, is a very plausible reality. Such a relationship would not only be interesting, but could be a relationship that could be exploited to assist in everything from music composition to strengthening brain pathways that share the common processing of such information. The idea that a system of colour presentations could one day be used to assist those with damaged auditory pathways would bring new meaning to the sound-colour relationship by taking it further out of the artistic realm and placing it within the treatment realm. In addition, such a system could lend itself to the treatment of visual system deficits via reverse application.

Albeit, this experiment provided insight in how this relationship of tones and colours may be founded, it cannot provide full support for the definitive relationship of tones and colours. Further research should look into other tone sequences to determine exactly where the borderlines of this tone/colour relationship effect truly lie. For example, a set of tones that do not reflect natural or 'obvious' tones that one would be exposed to, would be of great interest.

Perhaps the human ear is naturally tuned to the tones that are indeed reflected on the piano keyboard, and that the historical development of the piano keyboard and its tones was unconsciously guided by this natural response attunement. This experiment may be a furthering of what constitutes a truly systematic relationship that can be capitalized upon. It is also important to acknowledge the role that timbre might play in results such as those generated here. One cannot distinctly or remotely draw the conclusion that these results will generalize to other instruments or listening environments. As the oboe yields a different sound and listening experience from that of the flute, so might colour association vary across the multiplicity of musical timbres (e.g., West-Marvin & Brinkman, 2000). As equally important would be the dynamic qualities of tones, such as sound envelope parameters of attack, decay, sustain, and release. It may well be the case that combinations of envelope parameters themselves can influence colour choice—or perhaps variation of timbre in concert with variation in envelope parameters has a distinct influence on synesthetic experience and response.

Analyses within this series of experiments provide clear indication that a greater spread of tones via larger intervals on the keyboard, gives the best insight into how the association of colour with pitch is manifest—a parallel to that found by Hubbard (1996). Additionally, as per Hubbard (1996), Marks (1975), this experiment gives precise support for the existence of 'mappings' between visual lightness, visual darkness, and auditory pitch—and more specifically via colour-tone mapping to a universally recognized instrument, bolsters this relationship with far greater empirical evidence.

One could also consider the appearance of this type of result as the potential revealing of a new direction regarding auditory and visuo-sensory mappings/associations. In fact, Figure 10 is an intended visual representation of this potential tone-colour mapping relationship in its basic form. Additionally, and as important as any pure psychophysical result derived from this experiment, this investigation appears to reveal additional insight into the apparent relationship between the visible light frequency spectrum and the sound frequency spectrum.

But, as is always the case, one must approach new findings, no matter how enlightening, with cautious optimism and the attitude that further investigation will always clarify things to a greater degree. By having participants individually define the colours beforehand, this experiment was susceptible to what could be termed as 'differential perceptual agreement'—that is, although people may actually 'perceive' colours differently, as long as there is consensual agreement (e.g., categorical and descriptive) between people despite these differences, these differences go unnoticed and unchallenged. Thus, additional individual differences can clearly exist, but are perhaps masked by participants' personal categorical nomenclature of the perceptual world.

7. Conclusion

The purpose of the current investigation was to reveal the association of basic tones with colours, and to determine any influence that the presence/absence of harmonic content may have on such a relationship. Experimental results as per this study do indicate that there is a systematic relationship between tones and colour as well as a systematic relationship between harmonic content and participant colour response. Such results confirm the hypotheses as stated and are highly intriguing in that they are clearly contrary to the relationship of sound and colour as Newton put forth several hundred years ago. However, it is difficult to fully conclude this relationship is definitive without more in-depth studies inclusive of the relevant perceptual and processing areas of the human brain.

Cross-sensory modality processing and its influence on human behaviour is an extremely important research endeavor for a future of computerized virtual interaction between machine and man. It is without doubt that there remain a plethora of discoveries to be made in the field of cross-sensory modality studies—as of yet we have only scratched the surface. Perhaps one day such studies will reveal the manner in which we can use auditory information to treat vision problems; proprioceptive information to treat auditory deficits; or multi-sensory combinations of vision and audition to strengthen damaged neuro-motor pathways. Ultimately, the importance and urgency of understanding cross-sensory modality relationships is underscored by our ever-increasing reliance on technology itself, and its value to science across all endeavors of human exploration.

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