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Imaging Soundscapes: Identifying Cognitive Associations between Auditory and Visual Dimensions

Kostas Giannakis and Matt Smith

Introduction

The extent to which we can represent musical information in computers, in a way that matches our mental images, is one of the most intriguing and compelling questions in music research. Leman (1993) distinguishes three kinds of musical representation:

1. Acoustical, i.e. based on the physical properties of sound (e.g., sonograms, spectrograms).
2. Subsymbolic, i.e. based on the known behaviour of the human hearing system and how the human brain processes auditory information (e.g., auditory models).
3. Symbolic, i.e. based on the manipulation of symbols (e.g., Common Music Notation).

Our research focuses on the mapping between a symbolic (or abstract) system (in this case a colour model) and the perceptual dimensions of musical sounds. The postulate here is that it is possible to devise a visual approach to sound design based on human cognitive associations between auditory and visual percepts. Empirically derived auditory-visual associations can contribute to the design of more cognitively useful sound design tools that support the externalisation of composers' internal *auditory images*.

By auditory percepts we mean the following perceptual dimensions of sound:

1. *Loudness*, i.e. a psychoacoustic variable that refers to the subjective perception of sound intensity.
2. *Pitch*, i.e. a psychoacoustic variable that refers to the subjective perception of sound frequency.
3. *Timbre*, i.e. 'that attribute of sensation in terms of which a listener can judge that two steady complex tones having the same loudness, pitch and duration are dissimilar', Plomp (1976).

By visual percepts we refer to elements such as: colour, shape, and texture. In the present study we focus on the perception of colour. Colour has three perceptual dimensions (Fortner & Meyer, 1997):

1. *Hue*, i.e. the dominant wavelength in the power spectrum of a colour.
2. *Saturation*, i.e. the degree to which hue is perceived to be present in a colour.
3. *Light intensity*, i.e. how light or dark a colour is.

We have designed and conducted an experiment in order to examine the associations between pitch, loudness and the above colour dimensions. The results are presented and discussed.

Related work

Colour spaces for sound

An important concept in colour research is the concept of *colour space*. The latter is a formal method of representing the visual dimensions of colour (Jackson et al., 1994). There are various examples of colour spaces ranging from purely physical models (e.g., RGB) to more perceptually based models (e.g., CIELUV, CIELAB, HSL, HSV, NCS).[1] Colour spaces present a number of important features that are also highly desirable in the area of sound design. For example, by arranging colours in a three-dimensional space it is easy to understand concepts such as colour complementarity, similarity, and contrast. In a similar manner, it may be possible to structure timbre relations in terms of similarity, difference, etc. Various empirical studies (e.g., Bismarck, 1974; Grey, 1975; Plomp, 1976; Slawson, 1985; McAdams, 1999) have shown that timbre is a multidimensional attribute of sound and have proposed a small number of prominent dimensions (e.g., sharpness, compactness, roughness, etc.) for the qualitative description of timbre.

Barrass (1997, pp. 96-97) cites Caivano (1994) and Padgham (1986) as the first attempts to model sound using colour spaces. The auditory-visual associations that were proposed by these studies are summarised in Table 1 on the next page. However, these studies are based on correspondences that may exist between the physical dimensions of sound and colour. For example, in Caivano's approach, hue is associated with pitch since both these dimensions are closely related to the dominant wavelengths in colour and sound spectra respectively. In the same manner pure (or high-saturated) colours are associated with pure (or narrow bandwidth) tones whereas low-saturated colours (those that involve wider bandwidths of wavelengths) are associated with complex

Table 1. Studies that attempt to model sound using colour dimensions.

Studies	**Colour Dimensions**		
	Hue	Colourfulness	Lightness
Padgham (1986)	Formants	Timbre	Loudness
Caivano (1994)	Pitch	Timbre	Loudness
Barrass (1997)	Timbre	Brightness	Pitch

tones and noise. Finally, light intensity is associated with loudness (black and white represent silence and maximum loudness respectively with the greyscale representing intermediate levels of loudness). It is of further interest to investigate whether the above associations can be supported by empirical studies.

Synaesthesia

One useful source of information for auditory-visual associations may be a closer investigation of the phenomenon of synaesthesia. In one of the most detailed accounts for synaesthesia to date, Marks (1997, p. 47) defines synaesthesia as '...the translation of attributes of sensation from one sensory domain to another...'. The association between visual and sonic stimuli (i.e. coloured-hearing synaesthesia) is one of the most common synaesthetic conditions and manifests itself in two different but very related phenomena:

1. Coloured vowels, i.e. visual sensations produced by the sound of vowels.
2. Coloured music, i.e. visual sensations produced by musical sound.

Marks examined a large number of reported synaesthesia studies related to coloured vowels and combined the results in order to identify general characteristics and consistencies among synaesthetes. The opponent colour model (see Fairchild, 1998; Jackson et al., 1994) was used with the opponent colour axes being: black-white, red-green, and yellow-blue. Marks found that the black-white axis predicts vowel pitch and that the red-green axis predicts the ratio of the first two formants in the vowel spectra (the first two formants are considered to be the most important ones for vowel discrimination). In further studies (Marks, 1997, p. 72) with musical tones, Marks reports experiments with non-synaesthete subjects that have shown associations between pitch and light intensity as well as loudness and light intensity. Although these associations are in agreement with earlier synaesthesia studies, Marks' overall conclusion was that it is neither pitch nor loudness that is related to light intensity, but auditory *brightness*. This conclusion is based on an assumption that auditory brightness is the same as auditory *density*, a dimension that increases when both pitch and loudness increase. However, auditory brightness has been shown to be a dimension of timbre that is determined by the upper limiting frequency and the way energy is distributed over the frequency spectrum of a sound (see Bismarck, 1974; Grey, 1975). Furthermore, a problem lies

Table 2. Current computer music systems for sound design that employ auditory-visual associations.

Applications	**Colour Dimensions**			**Description**
	Hue	Colourfulness	Lightness	
Metasynth Wenger (1998)	✓	✘	✔	Red - Yellow - Green scale for spatial position. Dark - Light for Soft - Loud.
Phonogramme Lesbros (1996)	✘	✘	✔	Light - Dark for Soft - Loud

in the method behind the above-described experiments. Marks investigated only the dimension of light intensity, therefore hue and saturation were not considered. It is not very surprising to suggest that when people are asked to relate either pitch or loudness to a dark-light scale, they will succeed in both pitch and loudness. The question that arises is what happens when there are multiple visual and auditory dimensions for the subjects to associate.

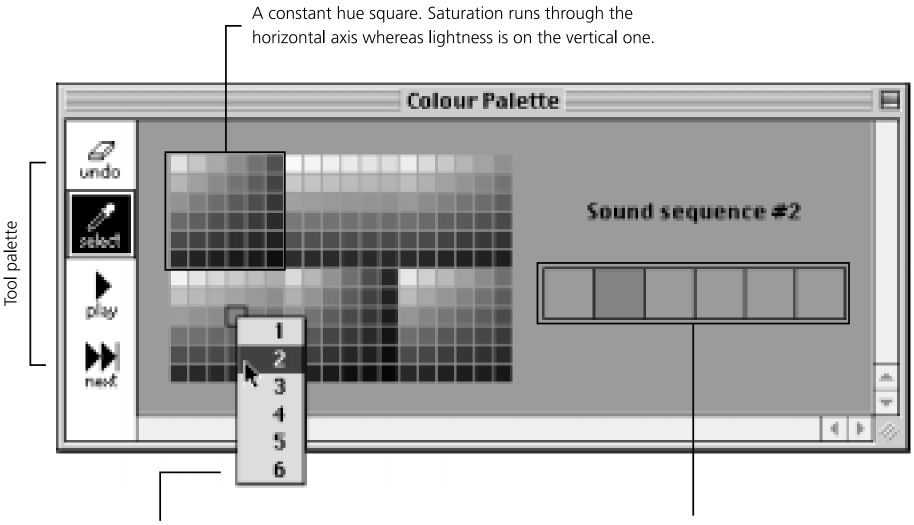
Sound design systems

Colour dimensions have been incorporated in a number of current computer music systems for sound design (see Table 2). The most common association is between light intensity and loudness. The level of light intensity (how dark or light a colour is) specifies the loudness for a sound with black and white usually being the minimum and maximum values respectively. Hue and saturation have been neglected with the exception of *Metasynth* (Wenger, 1998) where a red-yellow-green hue scale is used to determine the spatial position of sound. Furthermore, there is no general agreement on the use of dark (or light) as soft or loud, although in conventional sound representations (e.g., sonograms, correlograms, cochleagrams[2]) darker areas represent higher levels of amplitude whereas light areas represent the lower levels.

Summary of reviewed work

The reviewed attempts to create colour spaces for sound lack empirical evidence to support the proposed physical correlations between auditory and colour dimensions. Similarly, none of the reviewed computer music systems for sound design are based on empirical studies to support design strategies. This has resulted in a number of different approaches that in certain cases are very different and inconsistent. The majority of synaesthesia related studies have suggested an association between pitch and light intensity. Although this association is empirically supported, various methodological problems have been identified (e.g., other colour dimensions have not been investigated in the reported experiments).

In general there is no theoretical framework for auditory-visual associations based on empirical studies and that can be used for intuitive sound descriptions. The lack of such a framework forms the motivation behind the research we have conducted.



A constant hue square. Saturation runs through the horizontal axis whereas lightness is on the vertical one.

Clicking on a colour chip displays a poup menu with the numbers 1-6 corresponding to the six sounds in a sequence and the six slots in the display area (from left to right).

Display area. Selecting a number from the popup menu will cause the selected colour to be displayed in the appropriate slot.

Figure 1. The Colour Palette.

Experimental design

An experiment was designed to investigate the matching of pure tones with colours. The main objective was to provide results to help answer the following questions:

1. To what extent can a colour model based on hue, saturation, and light intensity provide a useful metaphor to describe loudness and pitch?
2. Which of these colour dimensions are associated with loudness and pitch?
3. To what extent do different sound frequency ranges influence colour selections?

A prototype computer application was designed for use in this experiment comprising a custom colour palette and three series of sound sequences.

Colour palette

We used a computer implementation of the well known HSV (Hue, Saturation, Value) (see Jackson et al., 1994) colour model in order to select six hues: red (R), yellow (Y), green (G), cyan (C), blue (B), magenta (M) - in other words the three primary (RGB) and three secondary (YCM) hues. Value is the correlate of the dimension of light intensity in the HSV colour space (Fortner and Meyer 1997). The saturation and value levels were subdivided into six equal steps thus producing thirty-six different saturation-value combinations for each hue (6x36 = 216 colours in total). The HSV values were then translated into their RGB equivalents encoded in the *MacProlog32* programming environment in order to display the custom colour palette (see Fig. 1).

Table 3. The sound sequences used in our experiment.

Sequence	1	2	3	4	5	6	7	8	9	10	11
Complexity	1				2		3				4
Loudness	⬉	⬋	•	•	↯	•	⬉	⬋	⬉	⬋	↯
Pitch	•	•	⬉	⬋	•	↯	⬉	⬋	⬋	⬉	↯

Sound sequences

The auditory dimensions under examination in this experiment were loudness and pitch. We used pure tones, i.e. sounds with a single sinusoidal frequency component, in order to neutralise the effect of timbral richness (sound complexity) on subjects' responses. All sequences consisted of six sounds whose frequency content was a single fundamental frequency. The individual tones were designed with *PowerSynthesiser* (Russell, 1995), a computer application for the design of psychoacoustical experiments involving sound. Although PowerSynthesiser provides adequate control over amplitude and frequency, mention should be made that these objective physical properties of sound are closely related to loudness and pitch, which in contrast are subjective perceptual measures.

Three series of eleven sound sequences were designed - one series for each of the following frequency ranges: 110Hz - 220Hz (Low), 440Hz - 880Hz (Mid), and 1760Hz - 3520Hz (High). Each sequence consisted of six tones. The sequences were designed and classified according to their level of complexity (Table 3 depicts the content of each sequence in a series).

The first complexity level comprised sequences where tones were either increasing or decreasing linearly in one auditory dimension while keeping the other constant. The second level was an extension to the previous case with tones varying in a non-linear way. The third level incorporated sequences with both loudness and pitch varying simultaneously either in the same or opposite linear direction. Finally, the fourth level extended the previous case with non-linear variation of loudness and pitch. It should be mentioned that during the experiment, sequences were not introduced in the same order as depicted in Table 3. Instead, they were shuffled and their order was the same for all subjects within a subject group but in all cases sequences started with low complexity and progressed to higher complexity.

Subjects

We had twenty-four subjects in total and all were given a screening questionnaire about their experience in both traditional and computer music. The exact composition of the twenty-four subjects was:

1. twelve undergraduate students studying sonic arts (11) or other fields (1) with average music experience,
2. five individuals with a great deal of computer music experience,
3. seven individuals with no musical background.

Subjects were randomly assigned into three groups of eight (one group for each series of sound sequences) and screened with an Ishihara colour plates test to detect colour vision deficiencies (one subject failed the Ishihara test). The purpose of the colour vision test was not to disqualify subjects but to test the effect(s) of colour blindness on subjects' colour selections.

Experimental environment

The experiment was conducted in a room with normal 'office' lighting and sounds were presented binaurally through headphones. Due to hardware limitations the experiment was designed and run on an Apple PowerMacintosh capable of representing thousands of colours, a limitation that in some cases produced less uniform colour variation in our Colour Palette. Subjects sat approximately 80 cm away from the computer screen and the components of the interface were sized for comfortable viewing and manipulation at that distance.

Experimental task

The experimenter demonstrated how to use the sequence player and the colour palette. This was followed by a short practice period of one tone sequence. The practice sequence was part of the series but reintroduced later in the experiment. The experimental task was: for the current sequence of six tones to create a sequence of six corresponding colours. Subjects could listen to the current sequence as many times as they wished, at any point during the task. Each subject completed the task for eleven sequences. Subjects performed the experiment at their own pace and times ranged from thirty to forty-five minutes. The experimenter was present throughout the experiment recording observations that formed the basis for post experiment interviews with subjects. Finally, a data collection program logged colour selections in terms of hue, saturation, and value, as well as completion time per sequence.

Results

We now present the results obtained from the above-described experiment. The presentation is based on a qualitative method supported by quantitative data. The major qualitative variable is the colour selection strategy followed by subjects. With three colour dimensions there are $2^3 = 8$ possible strategies. In order to identify a strategy we assigned a score to each strategy based on the correlation with the corresponding variation in pitch and/or loudness. Tables 6–13 on pages 59ff. show the results after the processing of the raw data obtained from subjects' colour selections. It must be noted here that each colour chip in the palette was a discrete step (the same held for loudness and pitch values). This allowed for the classification of sounds and colours also in discrete steps. As an example let us assume that the six colour selections (raw data) for a sequence of six tones with varying loudness and constant pitch were those depicted in Table 4 on the following page. These are translated to the discrete steps shown in Table 5.

If we now examine the above step sequences, we can conclude that the variation in saturation correlates perfectly with the linear step variation in loudness (i.e. from soft to loud: 1 2 3 4 5 6) while hue and value steps remained constant. Thus, our colour strategy for this example sound sequence was to associate saturation with loudness

Table 4. Raw data for six colour selections. Hue is expressed in angle degrees around the HSV colour wheel.

Dimension	**Colour 1**	**Colour 2**	**Colour 3**	**Colour 4**	**Colour 5**	**Colour 6**
Hue	0°	0°	0°	0°	0°	0°
Saturation	16%	32%	48%	64%	80%	96%
Value	64%	64%	64%	64%	64%	64%

Table 5. The discrete colour steps based on the raw data in Table 4.

Dimension	**Step 1**	**Step 2**	**Step 3**	**Step 4**	**Step 5**	**Step 6**
Hue	1	1	1	1	1	1
Saturation	1	2	3	4	5	6
Value	4	4	4	4	4	4

within the same hue and value confines. Furthermore, Figures 3–10 one pages 63–67 are based on the patterns obtained from subjects and display average levels for each colour dimension relative to pitch and/or loudness. Note that floating point numbers were not actually part of the experiment. For example, a saturation step of 2.3 was not a possible selection. Thus, the figures should be interpreted as showing the trend in the patterns and not actual steps.

Discussion

Table 6 on the next page shows the overall results for sequences where the only varying (linear and non-linear) auditory attribute was loudness. In single dimension terms (i.e. varying one dimension while keeping the remaining dimensions constant), hue varied in 1/72, saturation in 38/72, and value in 9/72 sequences. Furthermore, hue remained constant in 55/72, saturation in 15/72, and value in 49/72 sequences. These results suggest that the majority of subjects from all three groups varied the saturation level while keeping hue and value at constant levels. This correlation between saturation and loudness can also be seen in Figure 3 on page 63. Quiet sounds were associated with weak colours while louder sounds evoked stronger colour selections.

Table 7 on the next page shows the overall results for sequences where the only varying (linear and non-linear) auditory attribute was pitch. In this case the results are not as clear as for loudness. There was no dominant colour selection strategy as well as a high number of selections that involve variation in all three colour dimensions. The results for strategies that involve variation in only one colour dimension show that subjects varied hue in 10/72 sequences, saturation in 15/75, and value in 11/72. However, these figures are relatively small to support safe conclusions although Figure 4 on page 63 hints at a possible pitch-value association. Furthermore, we can suggest that hue doesn't seem to have any immediate role in colour selections since hue remained

Table 6. Overall results for sequences with varying loudness (linear and non-linear) and constant pitch.

Strategy			Frequency Range			Total
H	**S**	**V**	**Low**	**Mid**	**High**	
✘	✘	✘	0	3	0	3
✓	✘	✘	1	0	0	1
✘	✓	✘	**13**	**14**	**11**	**38**
✘	✘	✓	5	1	3	9
✓	✓	✘	1	3	3	7
✓	✘	✓	0	0	2	2
✘	✓	✓	2	1	2	5
✓	✓	✓	2	2	3	7
Total			**24**	**24**	**24**	**72**

Table 7. Overall results for sequences with varying pitch (linear and non-linear) and constant loudness.

Strategy			Frequency Range			Total
H	**S**	**V**	**Low**	**Mid**	**High**	
✘	✘	✘	1	0	0	1
✓	✘	✘	5	3	2	10
✘	✓	✘	4	4	7	15
✘	✘	✓	6	3	2	11
✓	✓	✘	3	2	3	8
✓	✘	✓	1	0	0	1
✘	✓	✓	0	11	3	14
✓	✓	✓	4	1	7	12
Total			**24**	**24**	**24**	**72**

constant in 41/72 sequences, saturation in 23/72, and value in 34/72.

Table 8 on the next page shows the overall results for sequences where both loudness and pitch were varying simultaneously in a positively correlated fashion. Here, the dominant colour selection strategy (17/48 sequences) was to vary both saturation and value while hue remained constant (33/48 sequences). This supports the point made before that saturation and value are the key dimensions for differences in loudness and pitch. However, since both loudness and pitch follow the same pattern (either soft-loud/low-high or loud-soft/high-low), we cannot immediately tell which of the two corresponds to which auditory dimension.

Table 8. Overall results for sequences with linear (ascending or descending) variation in both pitch and loudness.

Strategy			**Frequency Range**			**Total**
H	**S**	**V**	**Low**	**Mid**	**High**	
✘	✘	✘	0	0	1	1
✓	✘	✘	1	0	5	6
✘	✓	✘	1	5	4	10
✘	✘	✓	3	0	2	5
✓	✓	✘	1	0	1	2
✓	✘	✓	1	0	0	1
✘	✓	✓	**7**	**8**	**2**	**17**
✓	✓	✓	2	3	1	6
Total			**16**	**16**	**16**	**48**

Table 9. Overall results for sequences with descending loudness (linear) and ascending pitch (linear).

Strategy			**Frequency Range**			**Total**
H	**S**	**V**	**Low**	**Mid**	**High**	
✘	✘	✘	0	0	1	1
✓	✘	✘	0	0	2	2
✘	✓	✘	1	2	1	5
✘	✘	✓	0	0	1	1
✓	✓	✘	0	1	1	2
✓	✘	✓	1	0	0	1
✘	✓	✓	**5**	**5**	**1**	**11**
✓	✓	✓	1	0	1	2
Total			**8**	**8**	**8**	**24**

In order to address this issue we examined the subjects' responses for the third level of sequence complexity, i.e. sequences with negatively correlated levels of loudness and pitch. Tables 9 and 10 contain the results for these two cases. The results suggest that in both cases saturation and value were again the varying colour dimensions (hue remained constant in 17/24 and 16/24 sequences respectively). Table 11 on the facing page (left side) breaks down the results for this colour selection strategy in sequences where loudness descended linearly from loud to soft and pitch followed the reverse pattern. The dominant strategy was to decrease saturation and increase value levels. Based on these results we can suggest that saturation and value predict

Table 10. Overall results for sequences with ascending loudness (linear) and descending pitch (linear).

Strategy			Frequency Range			Total
H	S	V	Low	Mid	High	
✘	✘	✘	0	0	0	0
✓	✘	✘	0	1	2	3
✘	✓	✘	1	1	1	3
✘	✘	✓	1	0	2	3
✓	✓	✘	0	1	1	2
✓	✘	✓	1	0	0	1
✘	✓	✓	**4**	**4**	**2**	**10**
✓	✓	✓	1	1	0	2
Total			**8**	**8**	**8**	**24**

Table 11. (Left) Breakdown of results for the saturation-value strategy based on the results in Table 9. (Right) Breakdown of results for the saturation-value strategy based on the results in Table 10.

Strategy		Frequency Range			Total
S	V	Low	Mid	High	
↖	↖	1	1	0	2
↖	↙	1	1	0	2
↙	↙	0	0	0	0
↙	↖	**3**	**3**	**1**	**7**
Total		**5**	**5**	**1**	**11**

Strategy		Frequency Range			Total
S	V	Low	Mid	High	
↖	↖	0	0	0	0
↖	↙	**4**	**3**	**0**	**7**
↙	↙	0	1	2	3
↙	↖	0	0	0	0
Total		**4**	**4**	**2**	**10**

Table 12. Overall results for sequences with non-linear variation in both loudness and pitch.

Strategy			Frequency Range			Total
H	S	V	Low	Mid	High	
✘	✘	✘	1	0	0	1
✓	✘	✘	1	0	0	1
✘	✓	✘	0	1	2	3
✘	✘	✓	1	0	0	1
✓	✓	✘	0	0	3	3
✓	✘	✓	0	0	0	0
✘	✓	✓	**2**	**4**	**3**	**9**
✓	✓	✓	3	3	0	6
Total			**8**	**8**	**8**	**24**

Table 13. Compiled results for all the sequences that hue remained constant.

Hue Pairs	**Low**	**Mid**	**High**	**Total**
Red - Yellow	16	20	**28**	64
Green - Cyan	20	**28**	10	57
Blue - Magenta	**26**	19	8	51
Total	**62**	**67**	**46**	**175**

loudness and pitch respectively. However, this would hold only if the same applied to sequences where pitch descended linearly from high to low and loudness followed the reverse pattern. This is clearly demonstrated from the results shown in Table 11 (right side).

The results for the fourth level of complexity are shown in Table 12 on the page before. Once again, subjects varied saturation and value as a response to the non-linear simultaneous variation in both pitch and loudness. As it can be seen in Figures 8, 9, and 10 on pages 65–67 the variations in saturation and value seem to match the variations in loudness and pitch respectively, however, the complexity of the sequences clearly affected the accuracy of colour selections.

Finally, we examined the colour selection strategy that involved no variation in any colour dimension, i.e. subjects selected the same colour for all the tones in the sequence despite the variation in loudness and/or pitch. These results are shown in the first row of figures for the tables discussed above (except Table 11). Summing up these figures results in six such cases which, surprisingly, belong only to the subject that failed the Ishihara test. However, since there was only one colour-blind subject, the above observation has no significant statistical value.

As previously mentioned the vast majority of subjects kept hue at constant levels. It is of further interest to examine to what extent these levels are related to sound characteristics. In Table 13 we have compiled the results for all the sequences that hue remained constant. The hues are organised in pairs and in the same order as they appear in the HSV colour space. For sequences of low frequency tones, chosen hues appear to fall most often in the *blue-magenta* region. For sequences of middle frequency tones, chosen hues appear to fall most often in the *green-cyan* region. Finally, for high frequency tones, chosen hues appear to fall most often in the *red-yellow* region. Therefore, although hue does not seem to have any immediate effect on pitch-colour selections, there seems to be an effect in terms of general frequency ranges. This means that subjects associated hue with certain frequency ranges and varied value with the various frequencies that fall in those ranges.

Summary and conclusions

Based on the above analysis and discussion we can argue that the loudness and pitch of pure tones can be predicted by saturation and light intensity respectively (see Fig. 2 on the next page). In general, quiet tones were associated with low levels of saturation while louder tones with increasing levels of saturation. Furthermore, low-pitched

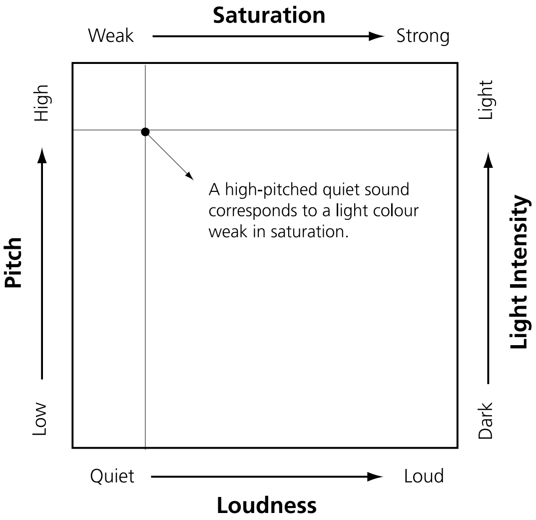


Figure 2. Proposed space for the associations between pitch-light intensity and loudness-saturation.

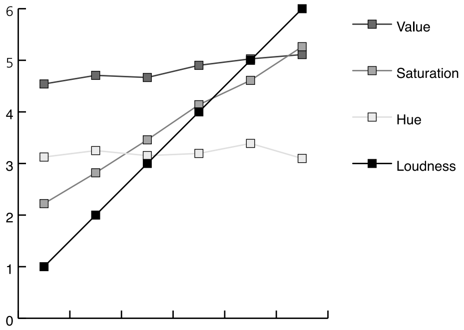


Figure 3. Trends for each colour dimension based on the results in Table 6.

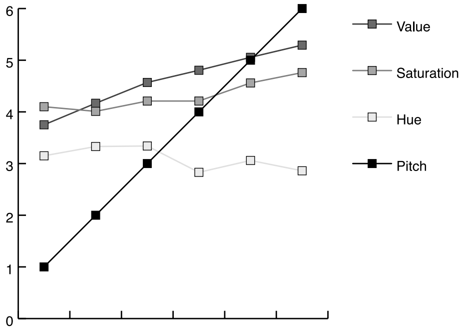


Figure 4. Trends for each colour dimension based on the results in Table 7.

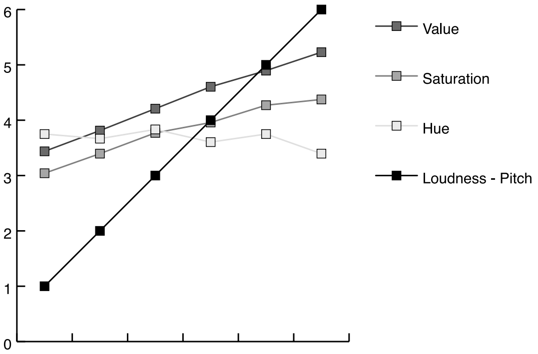


Figure 5. Trends for each colour dimension based on the results in Table 8.

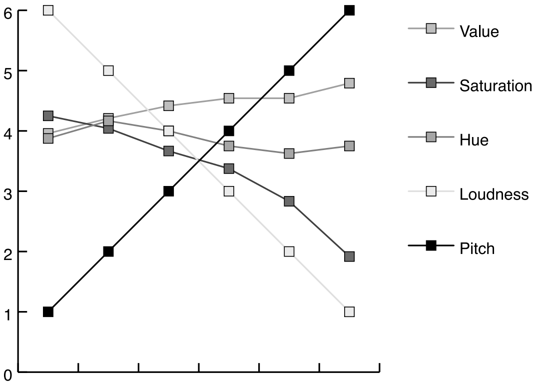


Figure 6. Trends for each colour dimension based on the results in Table 9.

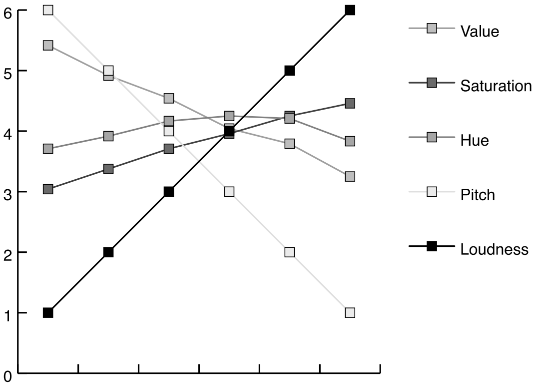


Figure 7. Trends for each colour dimension based on the results in Table 10.

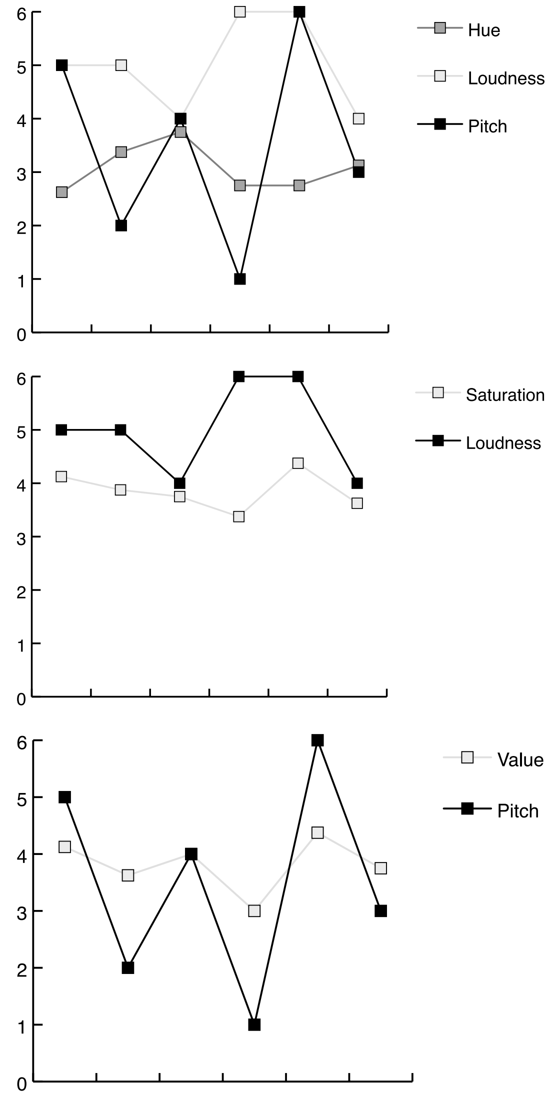


Figure 8. Trends for each colour dimension based on the results in Table12 (low frequency).

tones evoked dark (low levels of light intensity) colour selections while high-pitched tones were associated with lighter colours. Hue was not found to have any immediate association with pitch or loudness. However the experimental results suggest an association between hue and certain sound frequency ranges. Finally, our experimental design suggests that the use of a three-dimensional colour space can provide a more useful framework for the investigation of auditory-visual associations than the use of single dimension scales by previous studies.

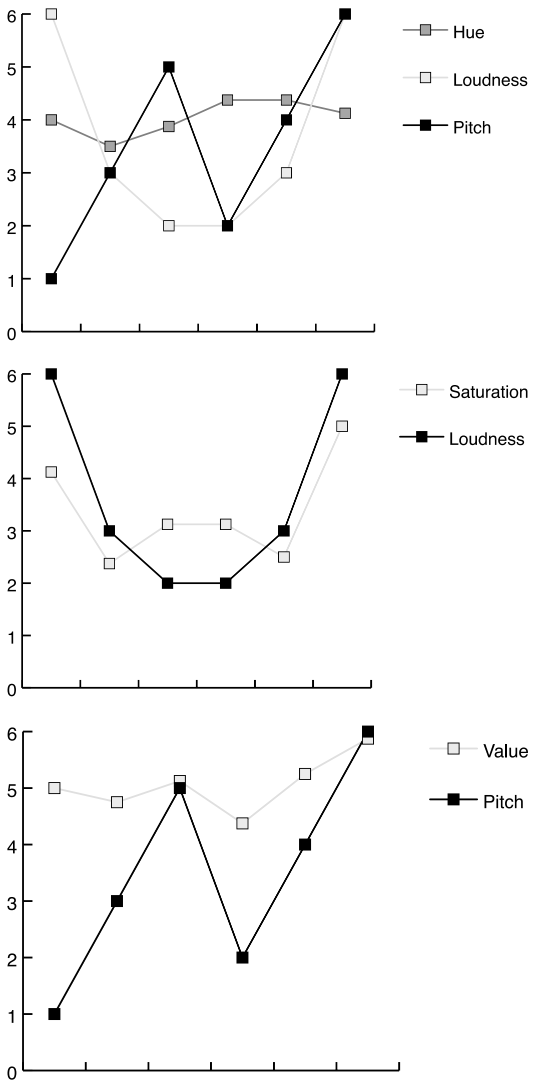


Figure 9. Trends for each colour dimension based on the results in Table 12 (mid frequency).

Further work

We should point out that this research did not attempt to derive perceptual scales for the associations between auditory and visual dimensions. To develop such scales would require rigorous psychophysical experiments – such experiments would be a natural extension leading from the research we describe here. A limitation of our experiment is that it focused on pure tones. However, in order to design effective sound design tools we must deal with the dimension of timbre. As we discussed earlier, the

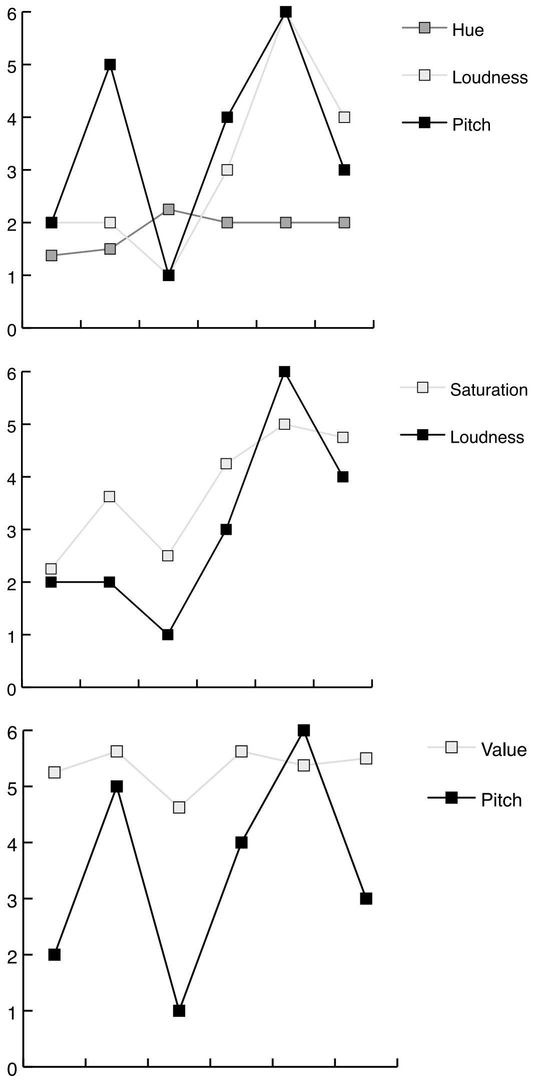


Figure 10. Trends for each colour dimension based on the results in Table 12 (high frequency).

perception of timbre is a more complex and multidimensional phenomenon. Recently, visual texture has been proven effective when used in the visualisation of multidimensional data sets (e.g., Ware & Knight, 1992; Healey & Enns, 1998). In another study (Giannakis & Smith, 2000), we have also identified a number of important similarities between timbre and visual texture that suggest further investigation of the potential cognitive associations between these sensory percepts.

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Notes

1. The CIELUV and CIELAB colour spaces are based on a system of colorimetry developed by the Commision Internationale de l'Eclairage (CIE). The Hue, Saturation, Lightness (HSL) and Hue, Saturation, Value (HSV) colour spaces are based on the perceptual dimensions of colour described above and are widely used in computer systems due to their ease of implementation. Finally, the Natural Colour System (NCS) is based on the opponent theory of colour that is described later in this chapter. For a more detailed description of these colour spaces, see Jackson et al. 1994.
2. For a more detailed description of these visual representations of sound, see Roads (1996).

References

Barrass, S. (1997). *Auditory information design*. PhD Thesis. Camberra: The Australian National University.

Bismarck, von G. (1974). Timbre of Steady Sounds: A Factorial Investigation of its Verbal Attributes. *Acustica*, *30*, 146-159.

Caivano, J. L. (1994). Colour and Sound: Physical and Psychophysical Relations. *Color Research and Application*, *19(2)*, 126-132.

Fairchild, Mark D. (1998). *Colour Appearance models*. Reading Massachusetts: Addison Wesley Longman.

Fortner, B. and Meyer, T. (1997). *Number by Colors*. New York: Springer-Verlag.

Giannakis, K. and Smith, M. (2000). Towards a Theoretical Framework for Sound Synthesis based on Auditory-Visual Associations. In *Proceedings of the AISB 2000 Symposium on Creative and Cultural Aspects and Applications of AI and Cognitive Science* (pp. 87-92). University of Birmingham, UK.

Grey, J. M. (1975). *Exploration of Musical Timbre*. PhD Thesis, Report No. STAN-M-2. Stanford, California: CCRMA, Stanford University.

Healey, C. and Enns, J. (1998). Building Perceptual Textures to Visualize Multidimensional Datasets. In *Proceedings of the IEEE Visualization 1998* (pp. 111-118). Los Alamitos, Calirfornia: IEEE Computer Society Press.

Jackson, R. et al. (1994). *Computer Generated Colour: A Practical Guide to Presentation and Display*. Chichester: John Wiley & Sons.

Leman, M. (1993). Symbolic and Subsymbolic Description of Music. In G. Haus (Ed.), *Music Processing*. Oxford: Oxford University Press.

Lesbros, V. (1996). From Images to Sounds, A Dual Representation. *Computer Music Journal*, *20(3)*, 59-69.

Marks, L. E. (1997). On colored-hearing Synesthesia: Cross-modal Translations of Sensory Dimension. In S. Baron-Cohen, J.E. Harrison (Eds.), *Synesthesia: Classic and contemporary readings* (pp. 49-98). Oxford: Blackwell Publishers Ltd.

McAdams, S. (1999). Perspectives on the Contribution of Timbre to Musical Structure. *Computer Music Journal*, *23(3)*, 85-102.

Padgham, C. (1986). The Scaling of the Timbre of the Piping Organ. *Acustica*, *60*, 189-204.

Plomp, R. (1976). *Aspects of Tone Sensation*. London: Academic Press.

Roads, C. (1996). *The Computer Music Tutorial*. Cambridge Massachusetts: MIT Press.

Russell, P. (1995). *PowerSynthesiser Manual*. Brighton: University of Sussex.

Slawson, W. (1985). *Sound Color*. Berkeley California: University of California Press.

Ware, C. & Knight, W. (1992). Orderable Dimensions of Visual Texture for Data Display: Orientation, Size, and Contrast. In *Proceedings of the 1992 CHI – ACM Conference on Human Factors in Computing Systems* (pp. 203-209). New York, N.Y.: ACM Press.

Wenger, E. (1998). *Metasynth Manual*. I & U Software (`http://www.uisoftware.com/`).