A Study of Temporal Visual Composition

by

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ABSTRACT

With the rapid growth of digital art, the temporal dimension is becoming a more and more important aspect of visual creations. This thesis is an effort to contribute to the construction of a disciplined basis for the composition of visual creations along the temporal dimension. It studies new perceptual phenomena and compositional issues introduced by temporal visual composition; it proposes and develops a set theory-based composition approach; it also presents the applications of this approach in compositional experiments at different levels of abstraction. As another aspect of contributing to the temporal visual composition research, this thesis designs and develops a temporal visual composition interface and a system for color generation and manipulation based on spectral information. This interface and system serve as an indispensable support for the composition experiments in this study. They also present to artists a new level of control over both graphical materials and the composition process. Furthermore, they suggest new creative potentials in temporal art.

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Table of Contents

Chapter 1. Introduction

1.1. Motivation

Time, movement, and the process of change have preoccupied visual artists for centuries. With the advent of moving pictures, time is finally added to the artists' palette. The development of digital art further made the temporal dimension an increasingly important aspect of visual creations. However, for the design and composition along this new dimension, we lack the theoretical repertory as we have for spatial composition. In order to fully take advantage of the temporal dimension in creating a dynamic visual experience, new visual perceptual phenomena introduced need to be studied, methods for constructing the work along time so as to engage the audience need to be explored, and structural elements and vocabularies for the temporal composition also need to be analyzed. This thesis is such an effort to contribute to this long-term development of temporal visual composition.

Another aim of this thesis is to present to artists the level of control we have in temporal visual composition under the current technology. At different period of time in the history, it is the technology available at that time that affected the process of composition and the type of composition that can be achieved. It is thus important to update artists on the latest technology supporting temporal visual composition and point out the artistic potentials it opens up.

1.2. Background and the Role of this Study

Throughout history, there have been many attempts by artists to represent or induce the perception of time, motion, and the process of change in painting. Limited by the static nature of the medium, their passion for temporal transformation and development is only communicated to the viewer through passive means, with which some perceptual or cognitive processes within the viewer have to be involved in order to close the loop.

With the advent of moving pictures, the temporal dimension is finally in the hand of the artists physically and artists were excited about that painting finally "get rid of its last principle shackle – immobility" and "become as supple and rich as a means of expressing out emotions as music is" (Survage). To manifest the similarity between music composition and this newly acquired capability for structuring along time, many works used musical terms in their titles, such as "Colored Rhythm", "Diagonal Symphony", and "Rhythm 21". However, in spite of the great enthusiasm those artists had for this new means of artistic expression, the technology available at that time tremendously hindered the process of composition. The enormously long period of time needed for the artist to get some visual feedback renders this process not a process of composition in the normal sense. Instead, it is mostly a one shot recording of the imagination in the mind of the experienced artists.

The development of computer graphics and the computer technology in general eventually made time an element in artists' "palette", as handy as form, color, depth and other traditional materials. Valuing the great potentials brought by this new dimension and exploring sensible ways to better utilize it in artistic creation is what lies ahead for artists these days.

In the following part of this section, attempts to introduce time to static visual art works and the early explorations of temporal visual composition by experimental animators are introduced. The subject, approach and achievement of some studies in the computer era concerning the general topic of temporal visual composition are discussed. The intention, scope, and property of this study are then stated in comparison with those early researches.

To provide an overview, Fig. 1 displays a timeline view of related artists under the three main stages in the exploration (painting, experimental animation, computer art). Their relevance to current study is hinted by the tone value (the darker the more relevant). The year following each name marks the time around which works related to the current study are created. There is an overlap between the experimental animation and the computer art stages.

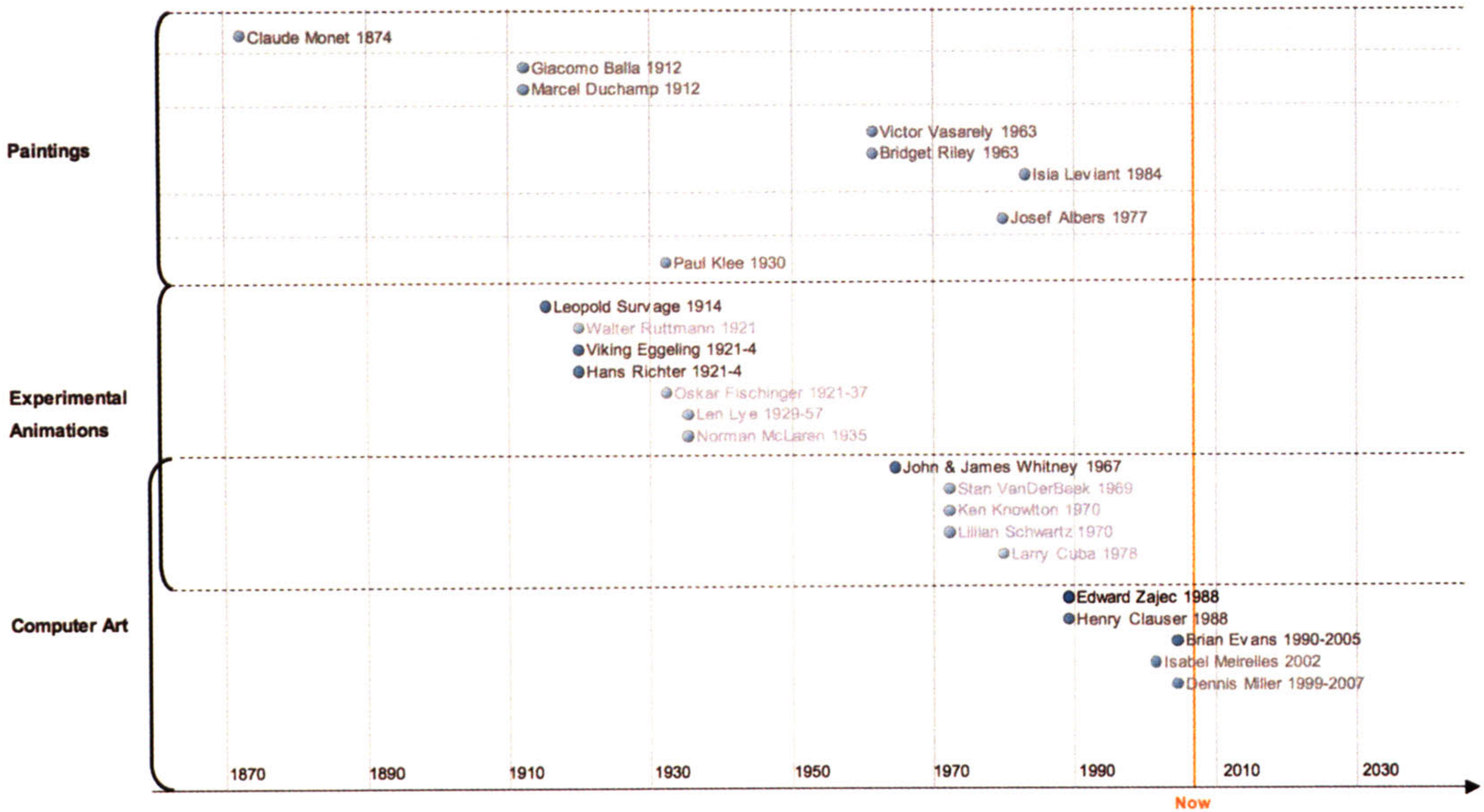

Figure 1. Background timeline.

1.2.1. The Long Standing Interest in Time, Motion and Process of Change in the Visual Arts

The idea of communicating the sense of time and motion through painting has occupied many artists in the history. Various approaches had also been carried out to realize this seemingly impossible idea of creating motion out of static images. Impressionists utilized unique painting techniques to create the illusory sense of motion. Marcel Duchamp and others explored ways of using sequences of static images or explicit trace lines to suggest motion. Optical artists played with perceptual response of the spectators and generated the illusion of motion in their works. Albers' linear creations also evoke dynamic feelings from those otherwise impossible spatial configurations. Controversially, Gombrich and others claimed that the successive scanning and temporal integration involved in picture reading suggests that visual art is by nature not only an art of space but also an art of time. Examples of attempts belonging to each of these categories are listed below.

Figure 2. The Poppy Filed outside of Argenteuil, 1873, by Claude Monet.

Sense of Motion in Impressionist Paintings[1]

Many of the impressionist paintings by Monet express a strong sense motion. In *Vision and Art: The Biology of Seeing*, Margaret Livingstone analyzes, based on the latest research in science of vision, the possible reasons underlying this visual phenomena. In *The Poppy Field outside of Argenteuil* (Fig. 2), the bright but equiluminant colors of the flower and the grass allow the "what" visual system to easily distinguish the flowers from the grass, but give trouble to the "where" system in telling the position of the flowers. This causes an illusory instability that gives the painting a lively quality.

In *Rue Montorgueil in Paris* (Fig. 3), the low spatial precision in the painting evokes the spatially imprecise peripheral vision to make illusory conjunction and complete the picture differently at each glance. This gives the painting vitality and a transient feeling.

Figure 3. Rue Montorgueil in Paris, Festival of June 30, 1878, by Claude Monet.

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[1] This section about the perceptual principles underlying some of the impressionist paintings is based on Margaret Livingstone, *Vision and Art: The Biology of Seeing* (New York: Harry N. Abrams, Inc., 2002).

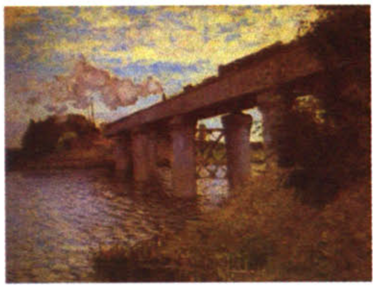


Figure 4. Railway Bridge at Argenteuil, 1874, by Claude Monet.

According to the so-called McKay illusion, repetitive high contrast lines will induce motion perpendicular to their orientation. In *Railway Bridge at Argenteuil* (Fig. 4), the juxtaposition of high luminance contrast with equiluminance regions in the painting leads to an illusory motion, which makes the water look shimmering and to seem to be flowing underneath the bridge.

Implied Motion in Sequential Images

Figure 5. Dynamism of a Dog on a Leash, 1912, by Giacomo Balla.

To depict motion is one of the primary objectives of the Futurist movement. In *Dynamism of a Dog on a Leash* (Fig.5), Balla attempted to recreate speed and flight by showing the forms as a repeated sequence of superimposed images.

Figure 6. Nude Descending a Staircase No. 2, 1912, by Duchamp.

Nude Descending a Staircase (Fig. 6) by Duchamp is a painting made up of around 20 abstract pictures of a nude in the successive act of descending. Static terms are used here to suggest movement.

Motion Illusion in Optical Art

Many of the Optical Art creations revolved around motion illusion. *Enigma* (Fig. 7) by Isia Leviant is an example of the McKay, or Venetian Blind, illusion. A streaming effect is perceived in the colored circles moving perpendicular to the high contrast black and white lines. The equiluminance of the two colors in the circles enhances this illusory motion.

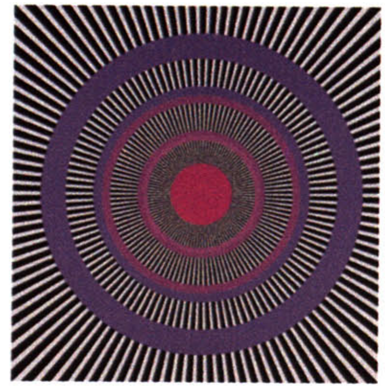


Figure 7. Enigma,1984, by Isia Leviant.

In *Fall* (Fig. 8) by Bridget Riley, high-contrast repetitive lines both induce strong illusory motion and generate illusory stereo-depth.

Figure 8. Fall,1963, by Bridget Riley.

Cognitive Factors

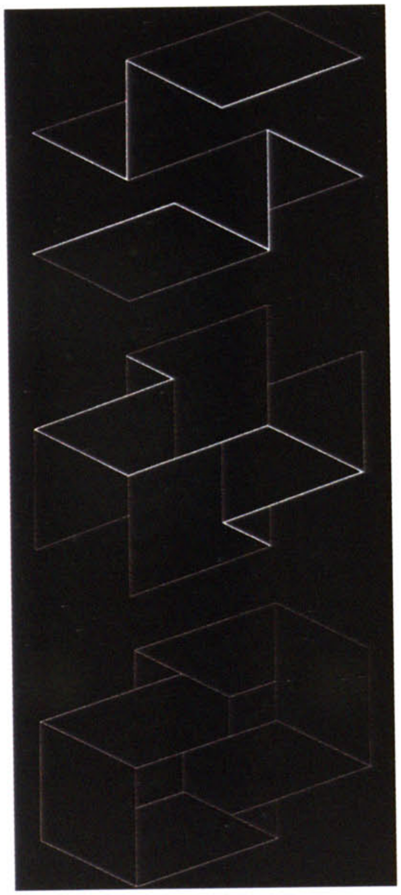
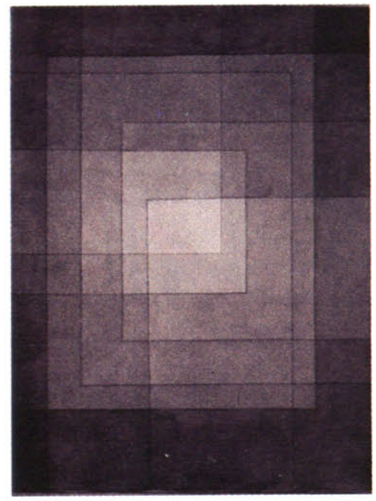


Figure 9. Linear constructions from *Despite Straight Lines*, 1977, by Josef Albers.

Albers created in his works visual events of motion within planes and into space. The constantly changing relationship of shapes in space and the reversible images break down the objective reality and create an unexpected ambiguity and perception of movement. (Fig. 9)

Temporal Aspect from Eye Movement

Our eyes are not able to see the whole field of vision with equal sharpness all at once. The process of viewing inevitably involves fast scanning of the scene and the integration of this successive information in the brain. If Gombrich's discussion about the temporal nature of visual art based on this factor is too philosophical, Klee's works are great examples of how a painter can purposefully lead the beholder's eye. His idea was to create regions with different pictorial energy through contrasts of hue, value, and other means, and arrange them based on certain designed path for the eye to follow. Such a path in *Polyphonic Setting for White* is described by Klee both in schematic form, and in words: "The eye moves slowly from center 1 to the successively weaker values 2, 3, 4, 5, 6 (movement), then leaps back to the strongest energy (countermovement)." (Fig. 10)



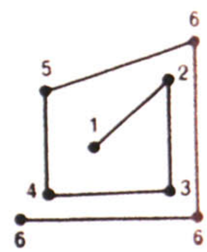


Figure 10. Polyphonic Setting for White,1930, by Paul Klee. (Black and white version of the painting along with path of eye movement in schematic form)

1.2.2. Early Explorations of Temporal Visual Composition by Experimental Animators

When a series of still images of an object are presented rapidly enough, the difference between the depictions of that object in successive images will be perceived as movement of it along time. This is the principle under the invention of those optical toys in the 17th~19th century, and of the later film technology. It is also the utilization of this illusory motion that evolutionarily added a temporal dimension to visual creations. This upgrade of human visual experience is no less breathtaking than the experience of the "Square" from Flatland getting into the Spaceland (Abbott). The huge gap with previous experience even made some people have difficulty in "seeing" the movement at first. The perceptual, psychological and thus aesthetic properties of the visual experience after introducing this new dimension is a fundamentally different one. Unlike scanning around the scene at will while appreciating a static artwork, the rhythm of seeing in animation and film is mostly forced upon the spectator. "Thus memory becomes involuntary ... the rapid succession of images "collage" our memory, and instinctive process are brought to play. The sharp, exact image before us is maintained in an ambiguous sea of remembering and forgetting." (O'Doherty,1968)

Facing this new cinematic technology, a group of pioneer artist-animators enthusiastically embraced the great artistic potential it opens up and seriously studied the nature of visual experience and creation with this new medium.

Leopold Survage was the first known artist who saw the meaning of the temporal dimension for visual art and experimented with the idea of temporal composition in his work. He wrote in a document the idea of color orchestration: "Painting, having liberated itself from the conventional forms of objects in the exterior world, has conquered the terrain of abstract forms. It must get rid of its last and principal shackle – immobility – so as to become as supple and rich a means of expressing our emotions as music is. Everything that is accessible to us has its duration in time, which finds its strongest manifestation in rhythm, action and movement, real, arranged, and unarranged. I will animate my painting, I will give it movement, I will introduce rhythm into the concrete action of my abstract painting, born of my interior life; my instrument will be the cinematographic film, this true symbol of accumulated movement. It will execute the 'score' of my visions, corresponding to my state of mind in its successive phase. I am creating a new visual art in time, that of colored rhythm and of rhythmic color."

He wrote about his work *Colored Rhythm*: "Colored rhythm is in no way an illustration or an interpretation of musical work. It is an autonomous art ... It is the mode of succession of their elements in time which establishes the analogy to music, sound rhythm, and colored rhythm,... The fundamental element of my dynamic art is COLORED VISUAL FORM which plays a role analogous to that of sound in music."

He also wrote about the role of time for artistic expression: "An immobile abstract form is still not expressive enough....Only when it begins to move, when it transforms itself and meets other forms is it able to arouse a FEELING....Psychologically, it is neither color nor sound, absolute, isolated, which touch and influence us, bit the alternating series of color and sounds. Thanks to its principle of mobility, the art of colored rhythm increases this alternation which exists already in ordinary painting, but only as a group of colors simultaneously fixed on an immobile surface and without changing relationships. By means of movement, the character of these colors acquires a force superior to that of immobile harmonies."

Viking Eggeling is another artist who had been rigorously searching for principles of plastic expression and "rules of a plastic counterpoint". Laszlo Moholy-Nagy thought of Eggeling as "one of the most lucid thinkers and creators" and wrote about him in book *Painting, Photography and Film*: "Not only was he first to discover the all-prevailing, revolutionary importance of an aesthetic of time in film, he set forth its principles with scientific precision and attempted to carry them over into his creative work. His experiments at first leaned upon musical frames of reference, such as the division of time, regulation of tempi, and over-all structure. Slowly, however, his perception of optical timing asserted itself, and so his first work, based upon form-drama, became a veritable ABC of the phenomena of movement, as expressed by light-dark and by variations in direction."

In collaboration, Eggeling and **Hans Richter** explored through their works the orchestration of form and movement in scroll painting and the orchestration of time in film. They had searched for a "universal language", a self-expressive principle, by clarifying and purifying the basic visual material – form and color.

Using the scroll painting medium, they sketched transformation of form element as "themes" or "instruments" and "orchestrated" the "instruments" through different stages. They discovered from this process a dynamic relationship that invites the eye and a sensation the easel painting cannot offer. Richter described it: "This sensation lies in the stimulus which the remembering eye receives by carrying its attention from one detail, phase or sequence, to another that can be continued indefinitely. This is because the aesthetic theme is just that: the relationship between every part and the whole. In so following the creative process, the beholder experiences it as a process, not as a single fact. In this way, the eye is stimulated to an especially active participation, through the necessity of memorizing; and this activity carries with it the kind of satisfaction which one might feel if one were suddenly to discover new or unusual forms of one's imagination." Eggeling wrote about the perception in this intermediate medium that: "Every form occupies not only space but time. Being and becoming are one.... What should be grasped and given form are things in flux."

When orchestrating time with film, Richter studied rhythm, the new sensation special to this medium. He also invented a notation system on graph paper to score his work *Rhythm 25*. This suggested the method of using scores to compose temporal visual creations, which provides a common ground for both musical and visual materials to come into play.

1.2.3. Research on Temporal Visual Composition in the Computer Era

Despite the great passion among the early pioneers for the temporal dimension, the frame-by-frame painting and filming process available at that time had tremendously constrained their explorations. The advent of computer greatly improved the conditions for structuring time with visual materials. However, only few artists in the computer era have explored general concepts and theories about temporal visual composition. These artists all see the importance of building structures or grammars for temporal composition and approached this task through their own theoretical and artistic creations.

John Whitney was the first in the computer era who attempted to establish a compositional grammar and syntax for temporal visual creations. He believes that “only structured motion begets emotion” and he sees the importance of building an instrumentality similar to scale in music to help coping with the composition problem in a precise and accurate way. In order to control the inner structural elementals, he chooses to create motion out of basic graphical elements, consciously design the details in each frame, and compose motion forward in time by transforming the details from frame to frame. He investigated essential components of time and temporal organization in prior arts and studied how music engages people by following “time’s rule upon human experience”, which is “to anticipate the next moment and to gratify expectations raised by the moment just past”. With his ‘differential dynamics’ system, Whitney explored in a number of works the development of visual tension/release and harmonic resonance with graphical patterns.

Edward Zajec expresses in his writing his concern for the lack of a theoretical framework for temporal visual composition: “Contemplating such possibilities of controlled action and duration on the plane is evidence of the meagerness of our color-structuring principles in comparison to music. While the spatial aspects of color dimensionality have been codified systematically, the temporal aspects of color remain almost completely uncharted...... With the computer we now have acquired the technical means to control time and light as music control time and sound. In contrast to music, however, we do not have a theoretical body of rules and conventions that would allow us to communicate visual ideas unrelated to narrative and figurative representations within a temporal framework.”

Zajec sees his exploration as a search for “new codes of visual communication”, for “a guiding principle on which to base an active autonomous visual line of development.” To emphasize his focus in the temporal development of visual statement and themes, he explicitly states in many places that in the context of his research, “to animate means to orchestrate the flow of color passage in time, rather than to choreograph the motions of objects in space.”

In his work *Chromas* and *Color-Based Time*, he developed the method of dimensional upgrades, which transits one voice, such as a series of colors, to many voices and thus extend the linear series into a visual plane. For the upgrade, he uses rules similar to permutations in serial music to ensure the specific color series retains its signature and preserves its structural identity. In *Chromas,* Zajec use the method thematic dissolves to realize the temporal development. Besides the basic modulation like transition from one image to another, it is also possible to "intertwine and unify different interlocking shapes that reveal hidden patterns as well as unexpected color harmonies that are not part of either transparency but surface only for the duration of a thematic dissolve."

As a composer investigating the temporal visual composition, **Brian Evans** always values the role of compositional methods and languages from his music experience. He writes: "The study of codified music theory helps the composer through the decision-making process in music composition. An understanding of what has worked in the past can minimize the number of wrong turns down the road to solving aesthetic problems. The same is true of visual composition."

Various explorations by Evans are guided by the compositional concept of using visual consonance and dissonance to create tension release over the development of the work. He studied the visual consonance and dissonance from proportion, color and elemental weight and the generation of consonance/dissonance through mathematical mechanisms. In one study he also experimented with a method of building temporal structure through creating contrapuntal relationships between visual materials and further creating motivic development through repetitions and variations, in a manner similar to harmonic/thematic development in music.

Henry R. Clauser thinks one of the premises for the development of a dynamic visual art "is the establishment of a formalism, which as in the musical arts, would be didactic and would have common acceptance by visual art composers, performers and the public. Analogous to music, it would have a specified structural format and a symbolic language. As Abraham Moles has said: 'there is no art without constraint. To say that music is an art is to say that it obeys rules. Pure chance represents total liberty, and the word construct means precisely to revolt against chance. An art is exactly defined by the set of rules it follows.'"

Through a series of works Clauser worked on a formal generative system governed by the differential function of a logarithmic grid and the progression of discrete color values. He also looked for compositional structures that would provide the framework or format for articulating dynamically the visual components and produce complex thematic, symphonic-like compositions. He outlined a system called "visone", which has a pictorial space (visone space), shape elements (visones), and the dynamics of the visones in the visone space, such as color modulation, position change, orientation change and image transformation. The visone space could be of a Field format or a Set format similar to musical scale. A fourth dimension representing the trajectory of successive states of visone space is available for temporal composition.

Isabel Meirelles's research on dynamic visual formation touched some fundamental issues about temporal visual language and spatio-temporal structures, such as interval, duration, velocity, rhythm, identity and synchronization. However, the focus of this research is about time on a relatively local scale and has not reached the level of form development and composition.

1.2.4. This Study as Theoretical Thinking and Technical Consolidation for Temporal Visual Composition

Theory

As already pointed out by those pioneers in experimental animations, the process of seeing in film or temporal visual creations is fundamentally different from what is involved in appreciating static paintings. Consequently, the process of creation with temporal visual art also needs to deal with issues that never existed in traditional art, such as rhythm, temporal context, and temporal development. However, as revealed from the earlier review of research or artistic explorations on temporal visual creation, there isn't a solid theoretical basis for this new format of art like what we have for traditional visual art. This is true for both the perceptual and creative aspects.

The current thesis is an effort to contribute to the theoretical study of both aspects in order to support the creation of temporal visual art works. This is achieved through the design of an approach for temporal visual composition, and through series of studies on perceptual and compositional issues performed while experimenting with this approach.

Instead of creating a single piece of work, the aim of this study is to provide support to artists in a broader sense. This is exemplified both through the study of general issues related to temporal visual composition and through the way the composition approach is proposed. Instead of serving as grammars or rules for composition, the approach suggests many compositional ideas, the use of which could contribute to a rich and coherent creation. And it invites the creation of compositional grammars or rules, at the artists' discretion, as an integral part of their creative production.

Technology

Technology is an important factor for the creation of temporal visual art. It directly affects the composition process and affects to some extend the artistic quality of the work and the type of compositional thinking that could be used.

In the early years of animation creation, huge numbers of drawings were needed to animate a visual idea of a short time. In some cases, draftsmen had to be involved in finishing up all the drawings. Even though the artist can give instructions to the draftsmen as to the intention of the design and the number of drawings needed for interpolating between the key frames provided, this split of the creative process into two stages still imposed difficulties on the improvement and modification of design ideas, especially for an art in which the temporal pattern is an important ingredient. In other cases, such as when Oskar Fischinger was creating Motion Painting No.1, in order to keep technical conditions consistent and avoid unexpected variations in image quality, he had to paint every day for over five months without being able to see how it was coming out on film. This is far from an ideal condition for visual creation, for which visual feedback is very important for the development of the work. Furthermore, after having the drawings, another process of filming has to be involved to animate the drawings. The process of creation is further split as a three-stage process involving the artist, the draftsmen and the film technician. This is obviously not a good process which could let the artistic minds work at its best. Richter once described his experience: "It had taken an UFA technician more than a week to animate a single drawing of my scroll, 'Prelude.' The technician was not very encouraging to begin with, and I felt like a blind man being led by another blind man."

With the advent of computers and the computer graphics technology, many of these problems have been alleviated. However, at different stages of computer technology development, there have still been different constraints for artists. In the early years of computation, even access to computers was a problem - not to mention their graphics generation capabilities. John Whitney wrote about this in his book: "A question remained: what computer, whose computer? Despite the continuing annual renewal of grants from IBM, I envisioned a time when, by the rapid growth of the electronics industry and the diminution of the size and cost of the components, I might own my own computer. However, for the present, despite the generosity of my sponsor, my work at computer facilities was assigned the lowest priority. I longed for a workable relation with the world of technology other than by intermittent, short-term grants of support."

When computer access was no longer a problem, the development of the computer graphics and image processing technology started to play the role in defining the condition for temporal visual creation. When Zajec was creating his work *Chromas* from 1984 to 1987, to output the work into movie format he had to transfer the video images to videotape and there were unavoidable color distortions and loss of resolution during this process.

After looking at these examples from history, one will naturally ask what are the current technological conditions available for temporal visual composition. This leads to another part of this thesis, which aims at providing an overview of the current technology and developing tools for temporal visual composition taking advantage of the latest technology. Similar to the nature of the compositional approach, the tools developed are not only for the creation of one single piece of work. They are designed with the consideration of general issues in temporal visual composition in mind, and are intended to provide other artists a more intuitive environment for artistic creation.

1.3. Overview of the Thesis

The content of this thesis is organized into five chapters. Chapter 2, *Early Steps in the Research,* describes how the current research is developed from a case study in a comprehensive framework of study about the temporal dimension of visual art. It presents the problems encountered in the early stage and shows how the process of solving these problems leads the original research to the current thesis - the development of a set theory-based approach for temporal visual composition. The study of precise control of color on the computer and the study of the relationship between color and music play an important role in this process and are thus described in detail in a separate section.

Chapter 3, *Development of a Set Theory-Based Temporal Visual Composition Approach,* presents the development of a set theory-based approach for color composition. The compositional use of this approach is discussed; the basic concepts of the system are defined; visual and compositional properties of the set materials are further analyzed.

Chapter 4, *Experiments,* documents the experimentation of the set theory-based approach in a series of graphical experiments and digital art creations. The five experiments started from characteristic graphical materials in Klee's paintings, and cover various aspects of employing this approach in temporal graphical composition. Perceptual and compositional issues unique to temporal visual composition introduced during the experiments are also discussed. The three ongoing digital art works are designed to show the applicability of this approach in large-scale art works of various compositional characteristics.

Chapter 5, *Interface and System Developed for Temporal Visual Composition*, introduces the development of a temporal visual composition interface designed by considering important aspects in the composition process. It also introduces a system designed for generating and manipulating color through spectral information, and discusses new artistic potentials brought by this system.

Chapter 6, *Conclusion,* summarizes the contributions of this research to the discipline of temporal art; lists my next steps for continuing the current study; and points out suggestive issues for temporal visual composition research.

Chapter 2. Early Steps in the Research

2.1. Steps Leading to the Current Study

2.1.1. As a Case Study in a Bigger Framework of Research

The current study was originally part of a bigger framework of research about the temporal dimension of visual art. To guide the study, major aspects related to the temporal dimension are first identified. Those aspects are categorized into three types, the ones intrinsic to the temporal dimension, the factors influencing the temporal dimension, and the aspects induced by the temporal dimension. Temporal context, temporal composition, and direct crafting of motion belong to the first category; influence from music and influence from psychological, cultural, and historical factors belong to the second category; and emotion evoked along the temporal development of the work is under to the third category.

Two directions of thinking are then employed to discover principles in temporal visual art creation. One is a rational thinking by going through lists of basic parameters for motion and majors categories and parameters in visual perception. The other one is an empirical process of getting inspirations from perceptual phenomena and from other temporal arts, such as music, dance and film. Some of the principles are directly identified and then further studied through their variations in temporal visual art creation. Some are discovered in a reverse way: rich variations under one subject are well studied first; principles are then discovered from characteristics common to all the variations.

In order to carry out the study in depth, four case studies are designed to show how principles are discovered and realized in creation with rich variations. The first study, *Iridescent: In & Out of Phase*, addresses the topic of temporal composition. The second study, *In Harmony*, brings to conscious the effect of temporal context. The third study, *Ocean of Luminance*, takes motion instead of moving graphics as the subject matter of study. The fourth study, *ME-RROR: Me in Mirror*, introduces the psychological, cultural, and historical dimensions to the temporal visual art. Besides studying how other factors affect the temporal dimension, this case study also shows how principles discovered under all of the intrinsic aspects can work well together within one piece of creation.

By being organized in this way, the research has both an overall framework and thorough studies with sensible creations. From the root to branches, there are many levels to be flexibly zoomed into. The general framework is outlined in the following table:

<table>
<tr><td>Subject</td><td colspan="9">Temporal dimension</td></tr>
<tr><td rowspan="2">Aspects</td><td colspan="4">Intrinsic</td><td colspan="3">Influencing</td><td colspan="2">Induced</td></tr>
<tr><td>Composition</td><td>Context</td><td>Motion</td><td>...</td><td>Culture</td><td>Music</td><td>...</td><td>Emotion</td><td>...</td></tr>
<tr><td>Case Studies</td><td>Iridescent: In & out of Phase</td><td>In Harmony</td><td>Ocean of Luminance</td><td></td><td>ME-RROR</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Principles</td><td>In/out of Phase</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="5">Variations</td><td>Abstract: form</td><td rowspan="5"></td><td rowspan="5"></td><td rowspan="5"></td><td rowspan="5"></td><td rowspan="5"></td><td rowspan="5"></td><td rowspan="5"></td><td rowspan="5"></td></tr>
<tr><td>Abstract: color</td></tr>
<tr><td>Direct: pattern from wave lines</td></tr>
<tr><td>Indirect: surface movement under wavy forces</td></tr>
<tr><td>Rules from light physics</td></tr>
</table>

Figure 11. Table of the framework of study for the temporal dimension of visual art.

The research in this thesis grew out of the case study "In Harmony" (marked in orange in the table above). The original idea was to study the importance of temporal context in visual composition by referencing the harmonic progression in music.

Music as an art of time has well-developed theories about temporal development. In a research about the temporal dimension of visual art, it is very natural to look into music for inspiration. Harmonic progression provides a vivid example for the study of temporal context. The role of a chord in the progression can only be determined after looking at the overall compositional context it sits in. My plan was to first construct a system where the basic functions, such as tonic, dominant, and subdominant, could be defined for colors on the color wheel. After establishing the basic conventions, rich temporal compositions could then carried out with same colors placed in different progression contexts. It is my wish that with the conventions just defined, these different contexts would render the same color with different roles in the composition and evoke different sets of emotions.

2.1.2. Change from Harmonic Progression to Set Theory

Puzzles

As the first step, I started to research about color harmony, which would be the correspondence to the concept of chord in music. Of the many studies and experiments on this topic across history, the color harmony album created by Wilhelm Ostwald is the most systematic one. The Ostwald color system provides a solid ground for his rules for obtaining harmonious color combinations.

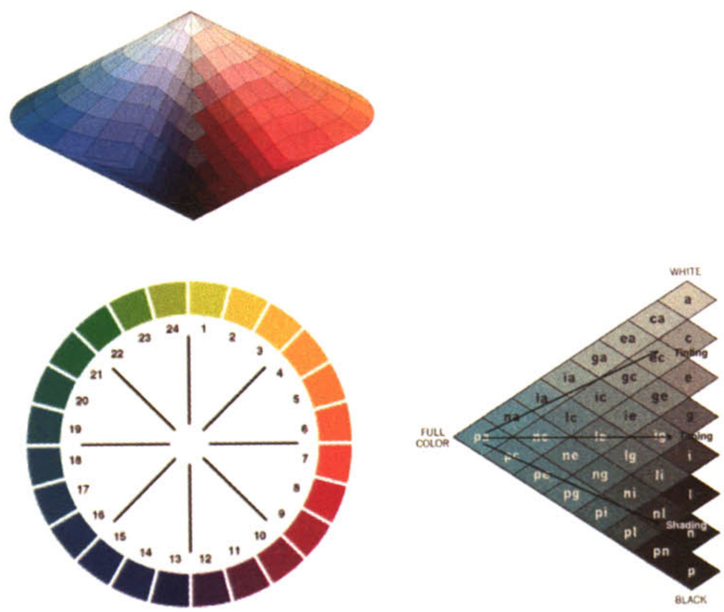


Figure 12. Ostwald color system and rules for obtaining harmonious color combinations.

As shown in Fig. 12-1, the system is designed as a double cone. Fig. 12-2 and Fig.12-3 display the hue circle and one slice of the structure. Harmonic combinations could be obtained from colors with equal intervals in the isotint series, the isotone series, the shadow series, and the isovalent circle. One color could also form harmonic combination with two monochromatic colors or with colors from more than one of the color series mentioned above.

After a thorough study of the Ostwald color system, I planned to write an interactive Java application to show all his ways of harmonious color generation. Problems came right away.

What are the RGB values of all the colors in his system?

What are the numerical relationships between colors along the major dimensions in the system?

What is the digital correspondence of adding white or black to a color?

I then realized that these are problems I would have as well with many other traditional color systems designed for manual instead of digital creations. Those color systems are normally composed of a set of color cards created following certain relationships based on perceptual measurement and used for color comparison in art practice. There are no ready numerical values for the colors. Even if one can measure and get RGB values for individual colors, there are no systematic numerical relationships between these color values.

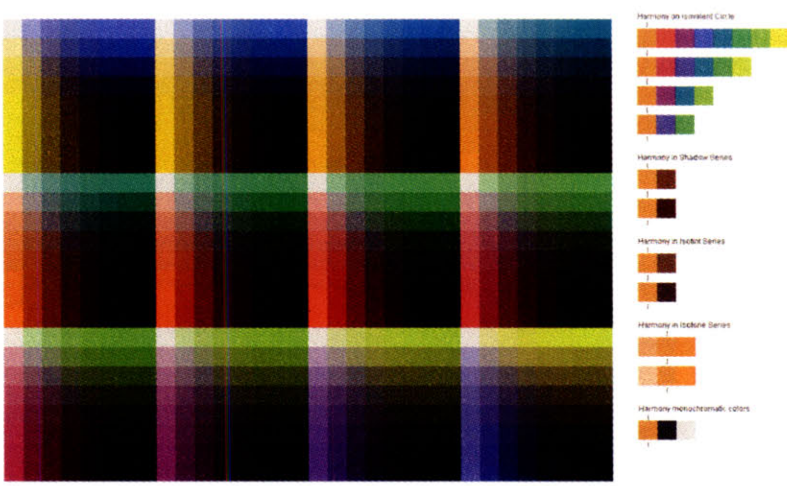


Figure 13. Screen shot of an interactive application intended to generate harmonic combinations based on the Ostwald system.

Problems also arose from my attempt to map musical structure to color. In order to borrow the harmonic progression concept, I thought of defining in color the tonic, dominant, subdominant and leading tone relationship starting from different color keys. But there doesn't seem to be a strong sense of ordering among colors like what could be found with

Figure 14. Brightness tendency of 24 pure colors in Ostwald system.

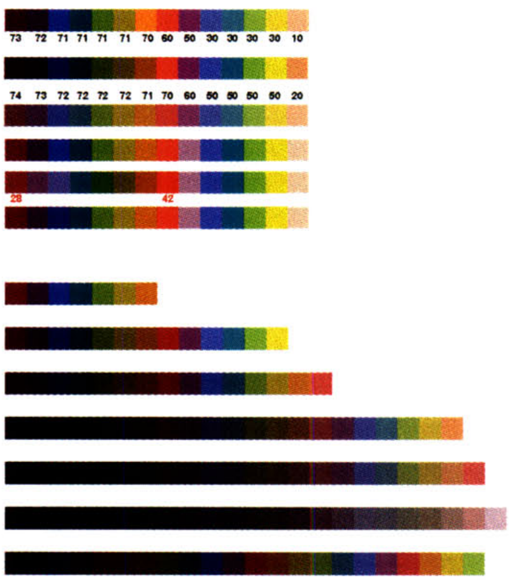


Figure 15. Color wheel with increasing brightness.

pitches. The perceptual meaning of the relationship between tonic, dominant, subdominant and leading tone in music no longer exists here. Albers wrote in his book *Interaction of Color*: "If one is not able to distinguish the difference between a higher tone and a lower tone, one probably should not make music. If a parallel conclusion were to be applied to color, almost everyone would prove incompetent for its proper use. Very few are able to distinguish higher and lower light intensity (usually called higher and lower value) between different hues…" Here he is mapping the luminance of colors to pitches. Intuitively, this seems to be a correct mapping, brighter color, higher pitch, darker color, lower pitch. I then turned to analyze the brightness relationship among colors. Besides the difficulty in analyzing this numerically, there is no direct connection between the RGB values and the brightness values. From the analysis, no meaningful relationship could be found among the brightness values of colors in the traditional color wheel. There is only a general direction of brightness change as displayed in Fig.14. In order to build a perceptually meaningful relationship analogous to music, I even started building a new color wheel with continuously increasing brightness (see Fig. 15) and also tried to expand the color wheel to be color helix with rounds of same hues having continuously increasing luminance. Of cause, because of its imprecise and non-numerical nature, this new color wheel does not have any value for further use in digital visual creation.

Study of the Precise Control of Color and the Relationship between Color and Music

Facing all these problems, I began to question whether my original design of the study is approachable, whether there is a way to generate and manipulate colors on computer along perceptually meaningful dimensions, and whether it is appropriate to borrow the harmonic progression concept from music. A very broad study quickly grew out of these questions. It mainly falls into two topics: 1) color perception and measurement; and 2) relationship between color and music. (A detailed description of facts and thoughts under each topic pertinent to the development of the current study is included in next section of this chapter, *Studies of Color*.)
From studies around the first topic, I got a clear idea of how to control color precisely on the computer along perceptually meaningful dimensions and how to connect to color systems in

history. This enables color use from an artistic point of view and color use grounded in art history. A system to generate and manipulate color based on spectral components is also developed. Being able to control color at spectral level opens up new dimensions for composing color numerically and brings the possibility of creating a new type of color, temporal color, which has temporal change as one of its intrinsic properties. These findings and design not only serve as a support for current study but also made available to other artists the knowledge about precise color control on the computer for artistic purpose and color generation and manipulation unique to digital media.

In the study about the relationship between music and color, I analyzed the correspondence between the fundamental aspects of color and sound, the correlation between the increase of frequency and perceived loudness of sound, and the luminance change of monochromatic colors across the visible range. I also did a conceptual octave calculation and found that the visible range occupies exactly the frequency range of one octave. The results from the study of color music relationship suggests that it is impossible to set up a perceptually meaningful mapping between color and sound for using the harmonic progression concept analogously. Instead, the musical set theory in which individual pitches are boiled down into pitch-classes turn out to be a better source for inspiration.

The emphasis on classes of pitches with octave equivalence goes well with the fact that color has only one octave. The pitch class concept also echoes with the way we think about and work with color: when we talking about color, instead of referring to a specific color, we normally refer to all the colors within a range of hue with different saturation and luminance. Furthermore, the correspondence of pitch class set, color scheme, is a concept well grounded in visual art. The fact that numerical manipulation plays an important role in the set theory-based composition also fits well with this study as an exploration on the computer.

All these factors suggest that the musical set theory is a more appropriate template to look into for the objectives of this research. The original purpose of studying temporal context in visual composition (inspired by the prominent property of harmonic progression) also changes to be the exploration of general approaches for temporal visual composition.

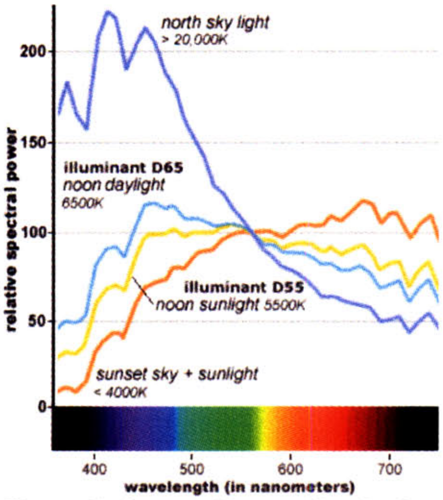


Figure 16. Spectral Power Distribution Curves.

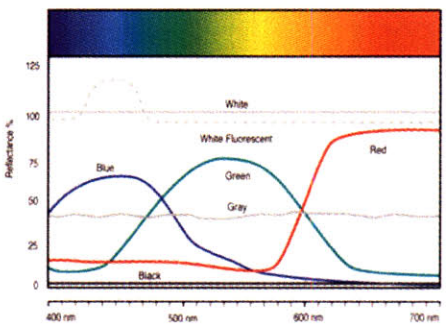


Figure 17. Spectral Reflectance Curves.

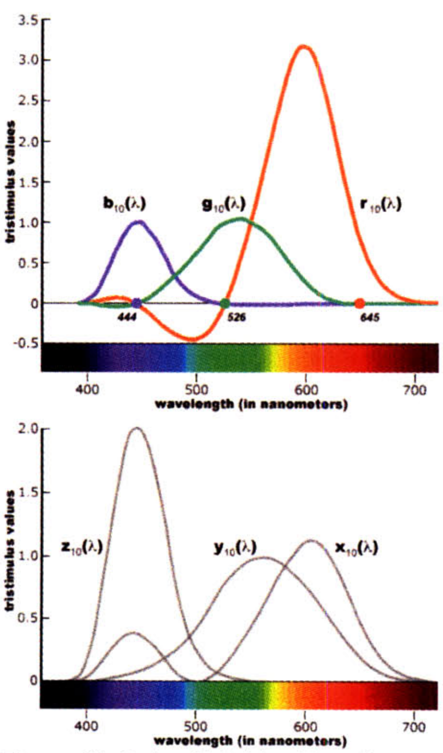


Figure 18. Color Matching Functions.

2.2. Studies about Color

The two studies about color in this section are very important to this research. The first study about color perception and measurement enables me to carry out this research on the computer. The second study about the relationship between color and music leads to the change from using harmonic progression to using set theory as source of inspiration from music composition. They are thus introduced here in a separate section to provide the background knowledge for understanding the design and implementation of the set theory-based compositional approach developed in this thesis.

2.2.1. Study about Precise Control of Color on the Computer

Color Perception and Color Measurement

Color is a visual sensation formed depending on three components: light source, reflectance or refraction object, and the human visual system. The visible electromagnetic energy from the light source initiates the process, the reflectance or refraction object modulates the energy based on its physical and chemical properties, and the human visual system detects and processes the modulated energy and forms the perception of color.

The light source is quantified by its spectral power distribution, which shows the relative intensity of light radiation at each wavelength compared to a standard or peak wavelength. (Fig. 16)

The property of the material is specified by its spectral reflectance or transmission curve, which shows the proportion of the energy which is reflected or refracted by the surface at each wavelength. (Fig. 17)

The visual system is quantified through its color matching properties, which are defined by the spectral responsivities of the three cone types, L(λ), M(λ), and S(λ).

Since any color can be matched by certain amount of *RGB* primaries, these amount, also called the tristimulus values, are used to specify a color. As displayed in the following equations, the tristimulus values of any stimulus can be obtained by multiplying the color matching functions by the amount of energy in that stimulus at each wavelength and integrating the multiplication results across the spectrum.

$$R=\int_{\lambda}\Phi(\lambda)\,\bar{r}(\lambda)\,d\lambda$$

$$G=\int_{\lambda}\Phi(\lambda)\,\bar{g}(\lambda)\,d\lambda$$

$$B=\int_{\lambda}\Phi(\lambda)\,\bar{b}(\lambda)\,d\lambda$$

The color matching functions $\bar{r}(\lambda)$, $\bar{g}(\lambda)$, $\bar{b}(\lambda)$ are spectral tristimulus values for the complete spectrum, which are estimated averages of the population of observers with normal color vision. In early 1930s the Commission Internationale de l'Eclairage (CIE) established a standard set of color matching functions based on the mean results of the experiments completed by Write and Guild to estimate average color matching functions. In order to eliminate the negative values in the color matching functions and to force one of them to equal the CIE 1924 photopic luminous efficiency function V(λ), the CIE shifted from the *RGB* to the XYZ primaries. (Fig. 18)

$$X=\int_{\lambda}\Phi(\lambda)\,\bar{x}(\lambda)\,d\lambda$$

$$Y=\int_{\lambda}\Phi(\lambda)\,\bar{y}(\lambda)\,d\lambda$$

$$Z=\int_{\lambda}\Phi(\lambda)\,\bar{z}(\lambda)\,d\lambda$$

The corresponding color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$, known as the color matching functions of the CIE 1931 standard colorimetric observer are used as the international standard.

Derived from the XYZ tristimulus values, the CIE chromatic diagram provides a convenient two-dimensional representation of colors. (Fig. 19)

$$x=\frac{X}{X+Y+Z} \qquad y=\frac{Y}{X+Y+Z} \qquad z=\frac{Z}{X+Y+Z}$$

$$z=1.0-x-y$$

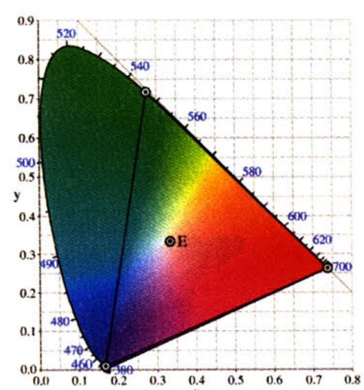


Figure 19. CIE Chromatic Diagram.

Y tristimulus value represents the luminance information and is normally used together with the chromaticity coordinates x and y to specify a colored stimulus.

CIE color spaces, CIELAB and CIELUV, extend the tristimulus colorimetry to three-dimensional spaces with dimensions approximately correlate with the perceived lightness, chroma, and hue of a stimulus. CIELAB defined by the following equations is now universally used for color specification and particularly color difference measurement.

$$L^*=116(Y/Y_n)^{1/3}-16$$

$$a^*=500[(X/X_n)^{1/3}-(Y/Y_n)^{1/3}]$$

$$b^*=200[(Y/Y_n)^{1/3}-(Z/Z_n)^{1/3}]$$

$$C^*_{ab}=\sqrt{(a^{*2}+b^{*2})}$$

$$h_{ab}=tan^{-1}(b^*/a^*)$$

In these equations, X, Y, Z are the tristimulus values of the stimulus, X_n, Y_n, Z_n are the tristimulus values of the reference white. L* represents lightness, a* approximate redness-greeness, b* approximate yellowness-blueness, C^*_{ab} chroma, and h_{ab} hue.

The L*, a*, b* coordinate construct a Cartesian space; the L*, C^*_{ab}, h_{ab} coordinates forms a cylindrical representation of the same space. (See Fig. 20)

The above outline and much others information about color measurement and color spaces allow me to find the way to control color precisely along perceptually meaningful dimensions, especially the luminance dimension which is normally intertwined with hue and saturation in traditional color systems. During the research, I developed an application called "explicit control of luminance" to test the possibility of precise control of color and experimented with various meaningful perceptual effects enabled by direct manipulation of luminance (see Fig. 21). Based on this background research, the CIELab color space was selected to be the basic framework to organize color generation and manipulation in my study.

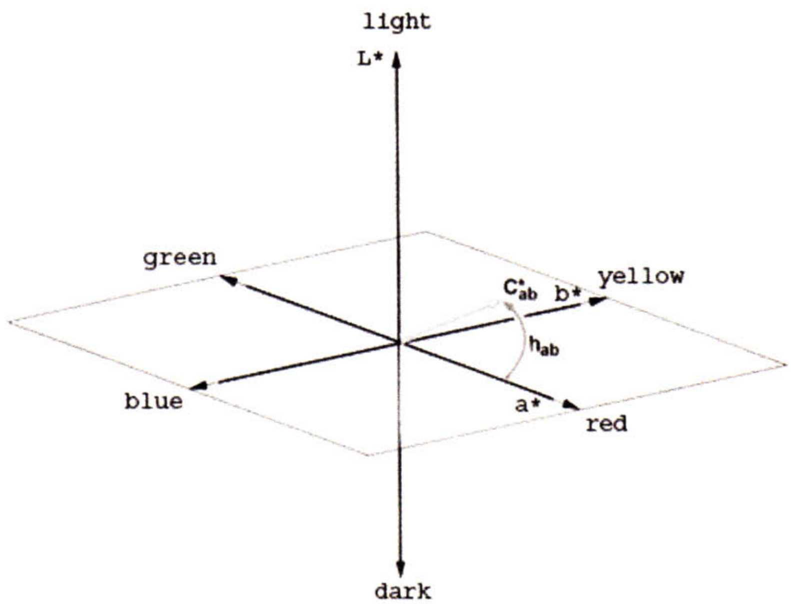


Figure 20. CIELAB and CIELCH Color Space.

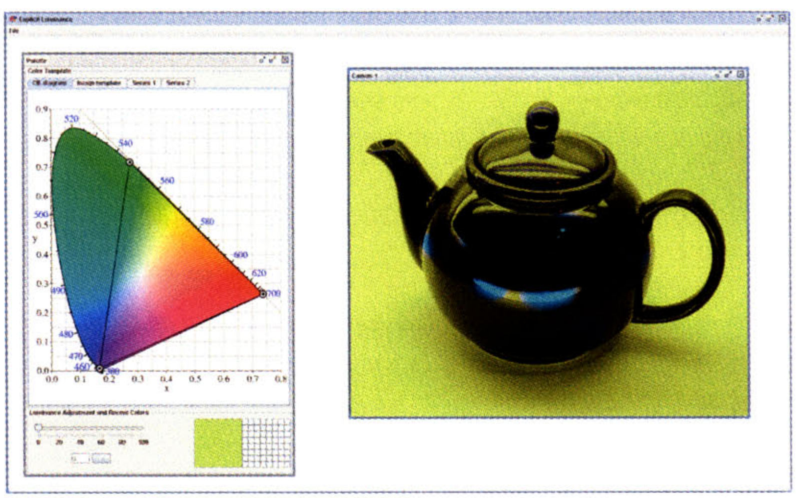


Figure 21. Interface for explicit control of color.

JColor System

An idea of controlling color at spectral level also came from this study of color perception and measurement. As explained above, the formation of color perception is triggered by energy from light source specified by it SPD curve, that energy is then modulated by the reflection or refraction object before being detected by the eye. The modulated energy could be obtained by multiplying the values on the SPD curve and the values on the spectral reflection or refraction curve at each wavelength and integrating multiplication results across the spectrum.

Since in my study, what I need are means to generate colors through perceptually meaningful algorithms, instead of strictly following the physical and chemical conventions involved in the measurement of the modulated energy, I designed two ways to virtually generate and manipulate colors at the spectral level.

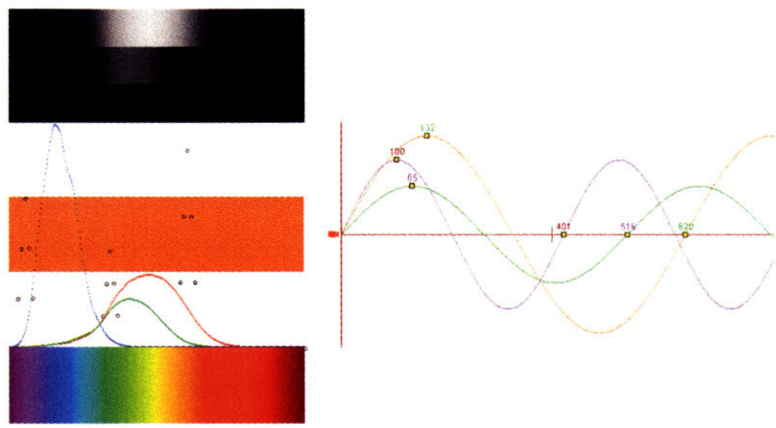


Figure 22. Interface for color generation and manipulation at the spectral level.

The first one is to generate color by defining the value at each wavelength. For the reason mentioned above, the curve formed by these values could either be thought of as the SPD curve of a light source being fully reflected or refracted to the eye, or be thought of as the spectral reflectance curve of a reflecting surface with an artificial white light, a light which contains all visible wavelengths in equal amounts, as the light source. It could also be thought of as the curve of the modulated energy.

This idea of using component waves to generate color and changing color by manipulating its component waves was inspired from computer music. Echoing CSound, a programming language designed and optimized for sound rendering and signal processing, I developed an interactive system called JColor (Java Color) for color generation and composition through manipulation of the spectral components (Fig.22). Besides used together with the interface, algorithms in the JColor system could be linked to and used separately in any graphics programming and rendering environment. The structure and functions of this system is described in detail in Chapter 9.

The second one is to use spectral reflectance curve of pigments as material in color generation (Fig.23). By following the subtractive color mixing principles in the calculation of the combinatory color, these reflectance curves could be used in digital visual creation with the same way of thinking as mixing paints on the palette. Here we can add white to make a color brighter and add black to make a color darker in the digital environment.

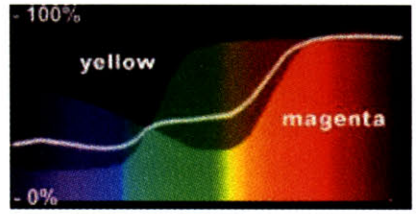


Figure 23. Subtractive Mixture through Spectral Reflectance Curves.

The spectral reflectance curve could be measured using spectrometer. For experimental purpose, I started with spectral reflectance curve images from the handbook series *Artists' Pigments – a Handbook of Their History and Characteristics*.

2.2.2. Study about Relationship between Color and Music

Even though from the physics perspective, sound is composed of longitudinal waves (alternate compressions and expansions of matter) and light is composed of transverse waves in an electromagnetic field, they are both forms of wave motion and are both detected by the perceptual system as energy from waves. Since my study focuses on the perceptual response, it is thus appropriate to compare sound and light on aspects common to all wave motions.

A wave consists of successive troughs and crests. The distance between two adjacent crests is called the wavelength, which can be calculated according to the equation:

$$\lambda = v/f$$

where λ is the wavelength, v is the speed of the wave, and f is the frequency. (Fig. 24)

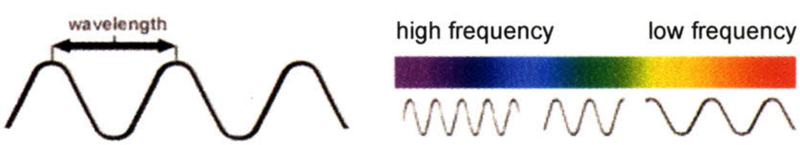


Figure 24. Wave illustration.

Frequency is the rate of oscillation of the wave and is measured in hertz. It is an important aspect of both sound and light wave. For sound, frequency is perceived as pitch, for visible light, it is perceived as color.

Wavelength is the common way of describing light waves, but the wavelength normally used actually refers to a specific conversion of the frequency when the wave travels under the speed of light in a vacuum.

Wavelength = Speed of light in vacuum / Frequency

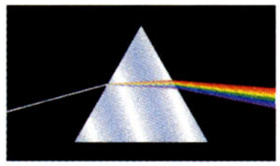


Figure 25. Steady frequency.

As shown in the Fig. 25, when light travels from one media to another, its speed changes, its frequency remains the same and as a result, its wavelength undergoes change. Thus, frequency instead of wavelength is the property which decides the color of a visible light wave.

It is possible to look at sound and light as waves fall into different wavelength ranges in a continuum of spectrum. Many insights could be gained into the property of color and the relationship between color and sound through this unified perspective.

Octave is a type of interval in music, frequencies of notes at this interval is at the ratio of powers of 2. Because the human ear tend to hear notes an octave apart as essentially the same (octave equivalence), in western music notation system, they are given the same note name and considered as part of the same pitch class. What would it be if we use the same rule to calculate the frequencies of an abstract higher octave all the way to the vicinity of visible light? I was amazed by the result that the visible range covers exactly one octave starting from Fig. 26. If the octave equivalence is also applicable for visual perception, we are fortunate to be able to see all the classes of colors. This also shows that it would be impossible to make perceptually meaningful mapping between pitches across multiple octaves and colors which spread out only one octave.

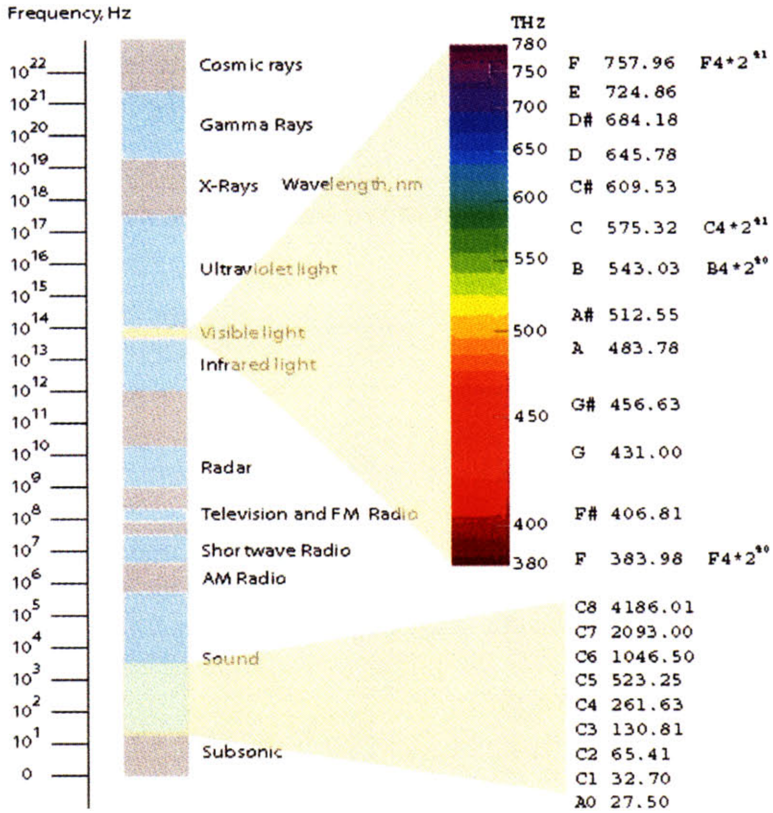


Figure 26. Sound and light waves.

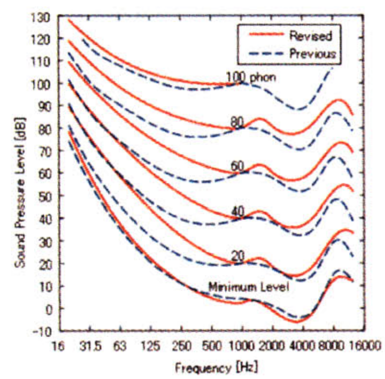


Figure 27. Equal-Loudness Curves.

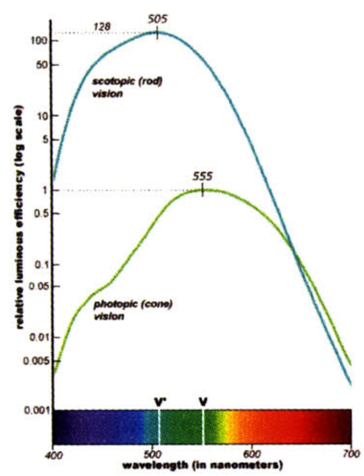


Figure 28. Sensitivity Curves.

The intensity of sound (the power in a sound that actually contacts the eardrum) corresponds to the modulated light energy the eye detected. Similar to luminance, loudness is a subjective measurement factored by the ear's sensitivity to particular frequencies in the sound. However, there are major differences between the two types of sensitive curves. As displayed in the equal-loudness level image (Fig. 27), in the frequency range of music notes, 27Hz to 4186Hz,, except for a small uprising segment after 1000Hz, the higher the frequency, the more sensitive we are to it. Thus, given same amount of energy, we hear pitches with higher frequency to be louder. Whereas, as discussed before and displayed in the photopic & scoptopoc sensitivity functions (Fig. 28), the sensitivity curve for different light frequencies is bell-shaped across the visible range. There is no consistent frequency-luminance relationship and thus no clear sense of ordering across color frequencies.

It is also obvious that comparing our capability in differentiating higher pitch vs. lower pitch and our capability in differentiating higher luminance vs. lower luminance is a mismatching. The correlation between pitch increase and

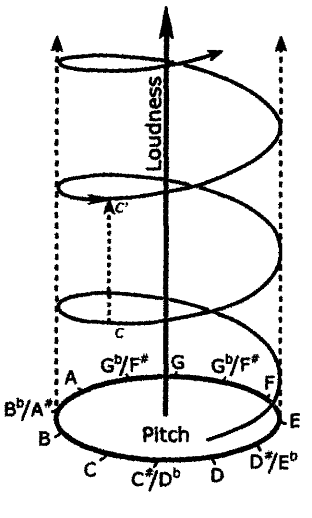


Figure 29. Perception of pitches across octaves.

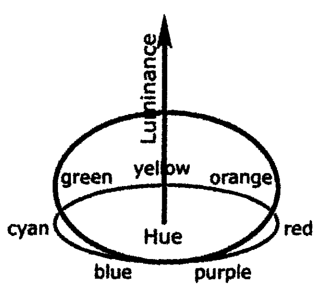


Figure 30. Perception of color.

loudness increase might be the reason that causes this confusion.

Considering of the octave equivalence and the correlation between the frequency and loudness increase, the perception of pitch across octaves could be represented as in Fig. 29. The corresponding picture for color would be Fig. 30.

Different octave spans and different perceived intensity curves make it impossible to create a perceptually meaningful mapping from the harmonic progression in music to color. The identity of each individual pitch plays a very important role in tonal music. Without the possibility to find the correspondence of individual pitch in color, it would be hard to borrow tonal composition theory systematically.

Musical set theory in which individual pitches are boiled down to pitch classes seems to be a better candidate. In set theory-based music, pitch class is the basic element of composition. The general characteristic of all the pitches in a pitch class is of first consideration. Technically, this helps to avoid the problem of finding in color the counterparts of individual pitches across octaves. Perceptually and historically, the correspondence of pitch class, all variations of a color with different saturation and luminance, is a very natural concept when people think about and work with color. The "color class" concept is actually far more typical in color use than pitch class in music.

The use of set theory in atonal music has an even stronger correspondence in color use. "Color-class sets", color combinations or schemes, is a well-studied topic that has been widely employed in visual art creations. The existence of visual correspondences deeply grounded in visual art tradition would further ensure the visual meaning of compositions guided by methods inspired by music.

Chapter 3. Development of a Set Theory-Based Temporal Visual Composition Approach

Based on the my early research described in previous chapter, set theory in atonal music is chosen to be a source for inspiration in the exploration of temporal visual composition. This chapter describes in detail the development of a set theory-based temporal visual composition approach. The compositional characteristics and ideas of this approach are first introduced. Basic concepts and mechanisms are then systematically defined. On top of this, the essential building block of this approach, color-class set, is further analyzed both in terms of the set content and in terms of the use of the set material in composition.

3.1. Set Theory-Based Temporal Visual Composition

Set theory in mathematics is a theory of sets, which represent collections of abstract objects. It provides the language in which mathematical objects are described and constructed formally from the undefined terms of "set" and "set membership". [2]

In the mid-1940's, Milton Babbitt wrote an influential essay "*The Function of Set Structure in the Twelve-Tone System*".
The idea of analyzing set structures in music presented in this essay was then actively developed and expanded by a growing group of musicians into a theory about defining sets of pitches and organizing music around these sets and their transformations. This is what is generally referred to as the musical set theory. It shares some common concepts, such as pitch class, with twelve-tone system or serialism, but it has its own focus on the identification and classification of pitch-class combinations and the systematic analysis of possible set relationships. Musical set theory has been widely used in both music analysis and music composition. Under these two different conditions, the points of view and the approaches of utilizing the fundamental concepts and methods could be very different.

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[2] Descriptions about mathematical set theory are based on materials on Wikipedia.

Inspired by musical set theory, a set theory-based approach for temporal visual composition is designed in this thesis. It utilizes color sets as the basic component and organizes the composition based on the sets and various set relationships. During the development of this approach, sets and set relationships are defined with the consideration of traditions in visual culture. It is not a literal mapping of the musical concepts to the visual domain. What is learned from music is the approach of using sets to achieve rich but coherent overall effects, the idea of manipulating set materials to evoke esthetic response, and the concept of using numerical control to achieve high perceptual payoffs.

In the following part of this section, basic concepts of musical set theory and compositional characteristics of set theory-based works are first introduced to provide the necessary background knowledge. The value of introducing this set theory approach to temporal visual composition is then presented through the discussion of its unique properties and some compositional ideas. Since composition is the focus of this thesis, in the introduction of musical set theory, a compositional point of view is assumed in most cases.

3.1.1. Set Theory in Atonal Music[3]

Concepts and Definitions

1) Pitch Class

To introduce basic concepts of set theory in music, we will need to start from the concept Pitch Class. This refers to a group of pitches with the same name, or in other words, pitches one or more octaves apart. These pitches are usually perceived as in some sense equivalent (octave equivalent). Different from tonal music, in atonal music, pitches that are enharmonically equivalent are also functionally equivalent. Thus we have twelve different pitch classes with different

[3] This section about set theory in atonal music is based on Joseph N. Straus, *Introduction to Post-Tonal Theory* (Upper Saddle River, NJ: Prentice-Hall, Inc., 2000), chapter 1-3; and Robert Morris, *Composition with Pitch-Classes: A Theory of Compositional Design* (New Haven: Yale University Press, c1987). Some of the analyses are tentative speculations based on my own understanding of the materials.

content. Fig. 31 displays a list of the pitch-classes referred to by integers from 0 through11.

Integer Name	Pitch-class Content
0	B#, C, Dbb
1	C#, Db
2	C##, D, Ebb
3	D#, Eb
4	D##, E, Fb
5	E#, F, Gbb
6	F#, Gb
7	F##, G, Abb
8	G#, Ab
9	G##, A, Bbb
10	A#, Bb
11	A##, B, Cb

Figure 31. 12 Pitch-classes.

Based on the definition of pitch classes, besides the linear relationship displayed above, the 12 pitch-classes also form a circular relationship as shown in the figure below.

0
11 1
10 2
9 3
8 4
7 5
6

Figure 32. Circular relationship among pitch-classes.

2) Interval Class

The distance between two pitch-classes is called the pitch-class interval. Since every pitch belongs to one of the 12 pitch-classes, pitch-class intervals are always less than 11 semitones. There are two types of pitch-class intervals: ordered pitch-class interval and unordered pitch-class interval. For ordered pitch-class intervals, the interval for two pitch-classes counted upward is different from counted downward. And these two numbers add up to 12. For example, the ordered pitch-class interval from A to C# is (1-9=-8(mod 12)=4). The interval from pitch-class C# to A is (9-1=8). 4 and

8 add up to 12. For unordered pitch-class interval, we take the shortest one, either counting upward or downward. Since on a circle with 12 pitch-classes we never need to count more than 6 semitones, there are only 7 different unordered pitch-class intervals including the unison, 0.

Those 7 different unordered pitch-class intervals are also call interval classes. Each interval class contains both corresponding pitch intervals larger than an octave and pitch intervals belonging to the ordered pitch-class interval that adds up to 12 with this interval class. The following is a table of the 7 interval classes and some on the contents of each.

Interval class	0	1	2	3	4	5	6
Pitch interval	0, 12, 24	1, 11, 13	2, 10, 14	3, 9, 15	4, 8, 16	5, 7, 17	6, 18

Figure 33. Interval classes and pitch interval contents of each interval class.

3) Interval-Class Content

Interval-class content describes the occurrence of each of the six interval classes (interval class 1 to 6) contained in a sonority. It is usually presented as an interval vector, a string with 6 numbers indicating the occurrence of the corresponding interval classes. Interval-class content can roughly summarize the quality of a sonority. It provides a convenient way to describe the basic sound of the huge variety of music ideas in atonal music.

4) Pitch-Class Sets

A pitch-class set is an unordered collection of pitch-classes. It represents the pitch-class and interval-class identity of a musical idea and is the basic building block for most atonal music. With pitch-class sets, the identifying characteristics in tonal music, such as register and order, are no longer a factor of consideration.

Pitch-class sets are normally written in their *normal form*, a format which helps to show the essential attributes of a sonority. It takes several steps to write a pitch-class set into its normal form. As part of the application, I created a JavaScript object in Jitter to take care of the calculation.

5) Transposition

Pitch-class transposition is very different from the transposition of a line of pitches. When transposing a line of pitch-class, the contours of the two lines are no longer the same. They still sound similar for the following reasons: 1) for each pitch-class, the corresponding member in the second melody lies the same pitch-class interval away; and 2) the ordered pitch-class interval between adjacent elements in one line is the same as in the other. When transposing a set of pitch-classes, besides the contour, the order is not preserved either. The two sets will be both different in pitch and different in pitch-class content. What makes them still sound similar are: 1) when written in normal form, there is a one-to-one correspondence between their elements. 2) they have the same unordered pitch-class intervals. Transposition of a set of pitch-classes preserves interval-class content, "as a result, it is an important compositional means of creating a deeper unity beneath a varied musical surface." (Straus)

6) Inversion

Inverting a line of pitch-classes is by convention an inversion around pitch-class 0. It preserves the ordered pitch-class intervals, only in a reversed direction. Inverting a set of pitch-classes makes the intervals in the normal forms of the two sets mirror images of each other. This also means that those two sets will have the same interval-class content. As mentioned above, this helps to create deeper unity under seemingly rich musical surfaces.

7) Set Class

Another important musical structure for atonal music is set class. It is a collection of pitch-class sets that are all related to each other either by transposition or by inversion. "As a result, they all have the same interval-class content. By moving from set to set within a single set class, a composer can create a sense of coherent, directed musical movement" (Straus).

Every pitch-class set belongs to a single set class. To obtain the other members of this set class, one can first find the 11 transpositions of the current pitch-class set, and then find its inversion and the 11 transpositions of its inversion. The number of members in a set class is normally 24. Because of duplication, that number could be from 2 to 24. One common way to represent a set class is using its prime form, a member in the set class that begins with 0 and is most packed to the left.

8) Additional Relationships

Besides the above basic concepts and definitions, there are some other relationships also commonly employed during the composition. Some examples are transpositional symmetry, inversion symmetry, z-relation, complement relation, subset and superset relations, contour relations, transpositional combination, and voice leading. The properties of these relations and how they could be employed in the composition will be introduced along with design of using these relationships in the temporal visual composition of color.

Compositional Characteristics

1) Deep Coherence under Rich Musical Surface

Pitch class sets could be used melodically as successive tones, harmonically as simultaneous chords, or as a combination of these two. A pitch-class set always retains its pitch-class and interval-class identity no matter how it is manifested. This provides the composer a structural unit to unify the composition and ensure a coherent appearance. At the same time, different transformations and various relations add rich variations to the musical surface.

2) Composed of Multiple Streams

Pitch-class sets in a set class all share the same interval-class content, a strong factor to distinguish one sonority from another. Progression involving members of the same set class can create a deep sense of coherence under the rich musical surface. The transposition and inversion of these sets form multiple paths which intersect, diverge, or run parallel to each other during the progression of the music. Straus metaphorically describes this type of music as a "rich and varied fabric, comprised of many different strands". He further pointed out that during the comprehension of this music "it is our task to tease out the strands for inspection, and then to see how they combine to create the larger fabric".

For this type of music there is no single principle which could be used to explain the whole composition. What's characteristic is the network formed from all the paths. Some of them stand out, some of them form the overall context in the musical tapestry, and others flicker between these two roles depending on subjective interpretation.

3) Guided by Musical Ideas

For the analysis of such a seemingly complex composition, it is important to grasp the fundamental and recurring musical ideas. Notes grouped together must be associated under certain musical idea and share some distinctive quality such as proximity, highness, lowness, longness (Straus). This analysis principle is also suggestive for composition. At the same time making the composition less mechanical and adding complexity to the musical surface, certain musical ideas should always clearly exist in the mind of the composer and be used to purposefully direct the musical movement. Even though in certain places these ideas might not be that obvious, their existence provides a framework to keep composition musically meaningful.

For both analysis and composition, there are many ways one could think of to create musically meaningful groupings.

1) Melodically, the grouping could break the constraints of the phrase structure. For example, for a melody with 5 notes, 1-2-3, 2-3-4, 3-4-5, and 4-5-6 could all be considered for three-member sets.

2) Harmonically, not only notes attacked at the same time but also notes that sound simultaneously could be grouped into sets.

3) Notes could be associated by register.

4) Notes could be associated rhythmically by certain rhythmic pattern or rhythmic features such as successive downbeats, the beginning of a recurring rhythmic figure, or notes that are given the longest durations.

5) Notes could also be associated by timbre, such as being produced by a single instrument, or by a certain kind of articulation.

3.1.2. Set Theory in Temporal Composition of Color

Compositional Properties

1) Ensure Coherence under Rich Variations

   Same as with music, using variations of colors of one set could bring to the work an overall coherence under the rich visual surface.

2) Provide Building Block at Structural Level of the Composition

   The design of set content, set operations and change between different sets forms a comprehensive framework of composition along time. From this point of view, sets function as the basic building block for temporal composition.

3) Enhance Integration with Music

   As a composition method inspired from the use of set theory in atonal music, it has an innate connection with music. This will enhance the integration between the graphics and music. They could be controlled directly by the same set parameters; they could be used as composition material equally in a set theory-based work composed cross music and graphics; they could also follow their own set theory-based composition and present a coherent appearance acquired from the same composition method. In this case, the music and graphics could either totally run parallel, or intersect at certain points controlled by the numbers in the set progression behind both of them.

4) New Way of Using Color

   In this specific study of using set theory-based method for the temporal visual composition of color, instead of being the property of shapes, color by itself becomes a compositional element. Using set to control color change and application numerically at both spectral and schematic level, along both the spatial and temporal dimension, also shows a new way of color use in visual art creation.

5) A Method Unique to Digital Art

Using sets in the temporal visual composition for digital art works is also a good way to take advantage of the computational power of the digital media. Compositions generated based on complex result of set combination and transformation can create innovative visual effects which cannot be achieved by handmade process or even effects which cannot be imagined.

Compositional Ideas

1) Color Timbre

Working together with the JColor system, set theory could be used in the generation and manipulation of colors at spectral level. Set members could be used either as "chords" to form chromatic color or be used "melodically" in the formation of the temporal color, a new type of color with temporal change as part of itself.

In Morris's idea of joining pitch-class-based composition with timbre composition, the nature and perception of pitch are only used when pondering upon how the context would affect the pitch-class relations. In color composition, this contextual thinking is still valid. At the same time, set theory, the theory pitch-class-based composition is based upon, can be used in timbre composition in the same way as it is used in pitch-class-based composition. The set content, the transformations, and the numerical relationships can all be used in the generation of color timbre at the spectral level.

Even though this is not the way of using set familiar to composers, it is actually an approach ready to be picked up for doing timbre compositions using computer music. It will fit the signal processing nature of computer music very naturally and its advantage will be further displayed through the calculation power of the computer.

2) Color scheme

More commonly, the correspondence of the pitch-class set and set class in color would be color schemes, the combination of certain colors classes or color classes with certain intervals on the color wheel. Color schemes will thus be an important starting point for this composition method. Similar to the search for a musically meaningful set, color schemes are analyzed from the point of view of preparing for set materials. Aspects analyzed include the perceptual, psychological, and cultural properties of different schemes and their compositional characteristics such as reaction to spatial and temporal context.

Since the use of set theory in atonal music is only an inspiration for the design of this method, many visually meaningful color schemes which have no correspondence in the music set theory notions are also used as fundamental set materials. For example, the Primary, Secondary, and Tertiary schemes share the same interval content, but are composed of colors with different roles in color mixture and perception. In the design of this method, these schemes belonging to the same color-class set are used as basic sets parallel to other content independent schemes for their special visual properties.

3) Multithreading

As one way for voice leading in atonal music, multithreading is also a main characteristics of set theory-based composition. Multiple paths of transformation weave sets in a set class into a complex tapestry throughout time. In temporal visual composition, the dimension perpendicular to time is displayed in a format perceptually more dominant than in music, where the combination of the multiple paths heard is a transient mental task. With temporal visual composition, one can see the tapestry spatially and temporally at the same time.

Given this extra power of display, there is also an extra challenge for the multithreading in temporal visual composition. Both the spatial and temporal context need to be considered at equally important levels. Rich spatial fabrics need to be created to satisfy the eye and to enhance the multithread under deep coherence characteristics of set theory-based composition.

4) Miscellaneous Design Considerations and Ideas

- Small sets can repeat. The overall impression of small sets is achieved through their frequency of appearance. Similarly, certain set relationships need to be presented multiple times in order to be discerned and memorized.

- Long and special sequences are better to be presented not many times. Long sequences are normally used to defined the main character of the work. The longer the sequence, the smaller the range of variation.

- Choose one set as the major set; choose a loose set as the supporting material which forms a contrast or affinity with the major set.

- Use different transformations of the prime form or normal form to emphasize different intervals. The intervals could be treated equally or use some of them to provide context for others

- Emphasize the combination and separation both spatially and temporally.

- Play with a set, its subset, its superset, and the combination of this set or its subset with other sets.

- Use different sets of the same size or change the size of a set, add or remove members from it. This is similar to using subset and superset, except that the members removed or added don't lead to the formation of smaller or larger groups.

- Luminance change is normally a change on a large scale, be it either raising up or lowering down. It is not appropriate to make too many individual colors too strong or too weak. It is normally a good strategy to sacrifice some local contrast in order to enhance the effect of the overall luminance change. This would be applicable to the luminance change both spatially and temporally.

- Use high contrast sets for different parts of an image spatially; use low contrast soft set to control the color progression temporarily.

- Certain video content could be used to control the overall color change along time. High contrast or harmonic visual effect created from the set could be used spatially in the local graphics grown on top of the video.

3.2. Basic Concepts

In this section, basic concepts of this set theory-based approach are defined. The overall structure of the system is similar to that of musical set theory. The component concepts are defined either based on color use deeply rooted in visual culture or from my own design thinking of temporal color composition. Analogous musical notions are also mentioned at corresponding places in order to set up the connection for understanding this approach in light of musical set theory.

3.2.1. Color Class

Similar to the way that pitch class is introduced at the very beginning before any other notions in musical set theory; the concept of color class is also introduced first. Both the pitch class and the set class are the most basic elements in a set theory-based system. They function as members of a set.

Pitches in a pitch class all share some properties in common because of the universal auditory sense of octave equivalence. Defining the concept of pitch class and basing the composition on top of pitch class instead of individual pitches reflect one of the fundamental objectives of musical set theory, which is to construct compositional relationships out of abstract entities representing the common properties of each pitch class and thus achieve deep unity and coherence under a rich musical surface.

Under the same purpose, two different types of color class are designed. Individual colors in these two types of color classes share common properties either along the hue dimension or along the luminance dimension. The objectives for defining these two types of color classes and the specific definitions for each of them are presented below.

Hue-Based Color Class

From the light and sound physics point of view, the hue of a color corresponds to the pitch of a note. Both of them refer to frequency. Based on my early study of looking at light and sound as part of a continuum of spectrum, visible light only occupies the frequency of one octave. If a literal mapping is to be used, the hue of colors is already a counterpart of pitch class.

However, from the artistic point of view, what is closest to the meaning of pitch class in composition are **groups of colors with hues in a certain range and with all the different variations of luminance and saturation**. Instead of being an abstract concept as in the case of pitch class, this hue-based color class actually reflects the natural way we think about color. No matter in everyday life or in design, when we talking about colors, what we think about first are pretty close to the color class concept defined here. For example, when we say the color red, what we have in mind is a whole group of colors with all the different variations of luminance and saturation, and with hue around the frequency of the 405~480THZ. In a less scientific way, what we have in mind are all the different variations of the reddest red. When Albers wrote about color recollection, he made a more vivid illustration about this class concept of color: "If one says 'Red' (the name of a color) and there are 50 people listening, it can be expected that there will be 50 reds in their minds. And one ca be sure that all these reds will be very different." He further analyzed two reasons for this phenomenon. One is that our visual memory, which is poor compared with our auditory memory, makes it hard to remember distinct colors. The other is the inadequacy of color nomenclature. (Albers, 1971)

The 12-hue color circle is the most widely accepted model in visual history. It nicely represented the relationship among the primary, secondary and tertiary colors, which is the core of traditional color theory. In the current system, 12 color classes are defined around the 12 colors on the 12-hue color circle. This both ensures the continuation of color used familiar to artists and also goes well with the number of pitch classes in musical set theory. This makes it possible to take advantage of the well-defined set operations and relationships in musical set theory.

Luminance-Based Color Class

Even though the hue-based color class echoes with the natural way we think about color and is an analogy of pitch class people would naturally think of because of the correspondence between hue and pitch, a luminance-based color class concept is also proposed for a different set of considerations.

Let's look again at the diagram of the correlation between pitch increase and perceived loudness increase and the luminance change of monochromatic colors across the visible range. As displayed in Fig. 34, along with the pitch change within or across octaves from C to B, the perceived loudness also increases continuously. However, in color, along with the change of the hue from purple through red, yellow, green to blue, the luminance of colors rise and then falls back, with the highest value around the greenish yellow.

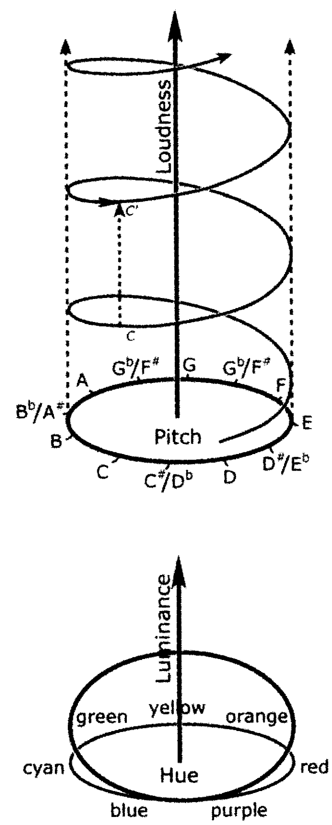


Figure 34. Comparison of the perception of sound and color (same as Fig. 29, 30).

Perceptually, people might be more sensitive to the order in luminance or loudness than to the order in frequency. The strong sense of order we perceive out of pitches might come from the correlation between pitch change and perceived loudness change. This could explain the apparent mismatching between pitch and luminance (light intensity or value in his words) in Albers' comparison about people's sensibility in music and in color.[4] When he talked about the higher and lower light intensity as in parallel with higher and lower pitch, he might actually refer to the impression of higher and lower perceived loudness through correlation. While, since this correlation indeed exists there, this seemingly mismatching from the physics point of view might not really be a

[4] "If one is not able to distinguish the difference between a higher tone and a lower tone, one probably should not make music. If a parallel conclusion were to be applied to color, almost everyone would prove incompetent for its proper use. Very few are able to distinguish higher and lower light intensity (usually called higher and lower value) between different hues..." (Albers, 1971)

mismatching. Since both the hue and the luminance aspect of color only share partial properties in common with the perception of pitch (hue in terms of frequency, luminance in terms of intensity through the correlation with the perceived loudness), from the perceptual point of view it is hard to say which one is a more appropriate counterpart of pitch.

Putting aside the discussion about whether hue or luminance is a more appropriate counterpart of pitch, it is the luminance aspect of color that resembles pitch of tones in evoking the sense of order. In a system for composition, this property of luminance makes it worth being considered as one dimension along which to define one type of color class.

Comparable to hue-based color class, the definition of luminance-based color class is: **groups of colors with luminance in certain range and with all the different variations of hue and saturation.** 12 luminance-based color classes are created, echoing the order of intensity evoked by 12 equal tempered tones in one octave.

3.2.2. Color-Class Sets

In a set theory-based approach, it is the property of the set (either pitch-class set or color-class set) used in a composition that defines its general characteristics. A clear understanding of the visual meaning of the color-class set is thus very important. In this system, color-class sets formed out of the hue-based color class coincide with the long-standing concept of color schemes. Color-class sets formed out of luminance-based color class are closely connected to another concept deeply rooted in visual literature - tonal grouping. In the context of temporal visual composition, both types of color-class sets also acquire compositional functions that have counterparts from music composition other than from static visual art creations. In the following writing, color scheme, tonal grouping and their relationships with the two types of color-class sets are discussed in detail.

Color Scheme & Hue-Based Color-Class Sets

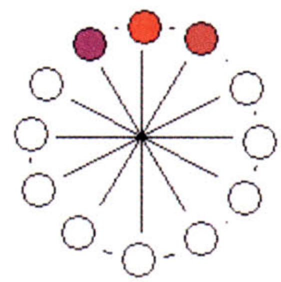
Even though the major and minor scale in music could also be thought of as seven member sets, the use of set in music in the set theory sense actually occurred much later than the use of color scheme in visual composition.

Color scheme is a group of colors designed to express certain emotional, psychological or cultural meanings and is employed to keep the overall coherence of the visual creation. This echoes with the role of sets in music composition.

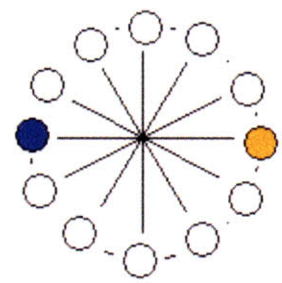
Infinite numbers of color schemes could be created out of colors with subtle differences. However, they can be categorized into a limited number of basic color schemes represented by colors on the color circle, or color class in the set theory-based system.

Many of the basic color schemes are defined solely based on the intervals between scheme members on the color circle. These basic color schemes already cover all the transpositions and inversions of a specific color-class set and are the same as set classes in musical set theory. Fig. 35 displays four of such schemes. The Analogous scheme is composed of three members next to each other; the Complementary scheme has two members facing each other across the circle; the Split Complementary is composed of one color and two colors on both sides of its complementary; the Clash scheme has one color and another color on either side next to its complementary. In these schemes, it is the intervals (interval-class content) that decide the characteristic appearance of the color combinations, no matter which exact colors are in the group. The color-class sets indicated in Fig. 35 could be rotated or inverted along the circle, which is an operation same as transposition for pitch-class sets in a set class. More schemes like these include the Triadic scheme (044), the Tetradic (Rectangle) (Double-Split Complementary) scheme (0246), the Square scheme (0336), the Double Complementary scheme (0156), and the Related scheme (01).

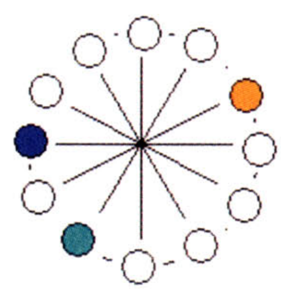
Besides those defined based on intervals, there are also content specific schemes such as Primary, Secondary and Tertiary color schemes; and property specific schemes such as Neutral scheme, Cool color scheme, Warm color scheme. These basic schemes are less subject to set manipulations.



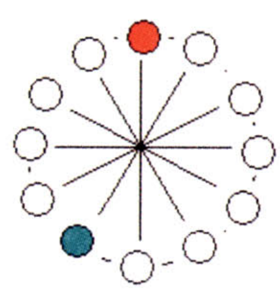
Analogous Scheme (012)



Complementary Scheme (05)



Split Complementary (046)



Clash Scheme (04)

Figure 35. Color schemes based on the distance between colors on the color wheel (labeled following the same conventions as set class prime form).

Two other characteristic scheme categories are Monochromatic scheme and Achromatic scheme. Monochromatic color schemes are composed of colors with the same hue but different luminance and/or saturation. Achromatic schemes are composed of achromatic colors. These two actually belong to luminance-based color-class sets.

Tonal Grouping & Luminance-Based Color-Class Sets

Grouping colors into different tonal planes is very important for keeping the order, clarity and vigor of a composition. This understanding has guided the creation of both abstract visual compositions and traditional paintings throughout history. During the process of creation with tonal grouping in mind, several principal tones are first chosen; graphical components are then assembled into chief planes or groupings around the principal tones. The tone of individual graphical component in each plane might have minor difference from the principal tone of that plane but not to the extent of blurring the distinction across the main groupings. This process is very similar to set theory-based composition using luminance-based color-class sets. The set members play the same role as the principle tones; the composition around the set members also forms a clear sense of tonal grouping. These shows the visual meaning of luminance-based color-class set and the composition out of it.

Even though tonal grouping has been a long-standing concept, it is not an easy task to accomplish a visual composition under this guideline using traditional media. Johannes Itten wrote about this in *The Art of Color*: "An eye for hues of equal brilliance is necessary to the observation of this rule." However, it is commonly known that differentiating luminance of two colors with different hue or finding equiluminant colors is very difficult. As Albers wrote in *Interaction of Color*: "…'equal values' are more spoken about than realized – than actually seen… very few people – including many colorists and painters – have ever seen 2 adjacent colors of true equal light value …"

With digital media, we acquire direct control over the luminance of color. This eliminates the difficulty in finding the accurate luminance value of colors and makes it possible to create colors with desired luminance value. Because of this, a set theory-based composition of luminance color-class set in digital art not only continues the tonal grouping concept, but also make it a guideline practical to approach in visual creation.

The following figure displays a simple experiment using sets to control four principal tones (luminance) in a polytone composition. Set content and operations could be set interactively. Using the color swatch on the right, one can experiment with colors of different hues following the same luminance relationship defined through set transformations.

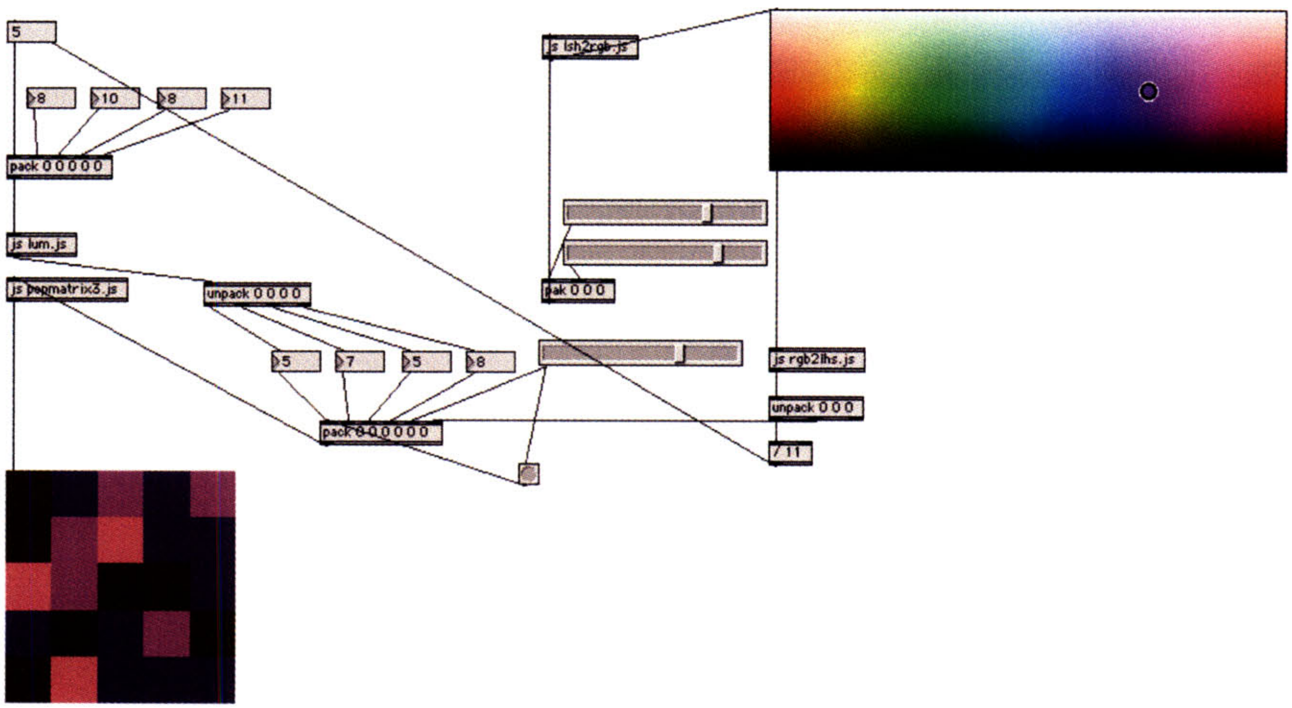


Figure 36. Set-based tone planes (experiment in Jitter).

3.2.3. Operations

Operations transform a set systematically and function as fundamental means in the development of set theory-based composition. Just as in musical set theory, two types of operations are defined: transposition and inversion.

Transposition

In traditional music, transposition refers to transposing a line of pitches in order by certain pitch intervals. By this way the contour of the line is preserved and it is obvious to recognize the connection between a line of pitches and its transposition. For a sequence (spatial or temporal) of colors, this type of transposition could refer to changing to another sequence with same hue and saturation before but raising or lowering the luminance same amount for each color. It could also refer to changing the hue of each color for the same amount around the color circle. Both methods of transformation are easy to recognize because of the same value in hue or luminance between the original and transposed sequence.

In musical set theory, transposition refers to adding pitch-class intervals to each pitch class in a line or in a set. Under such transpositions, neither contour nor order is preserved. The transposed set still sounds similar to the original set because they share the same interval-class content. This fact is easy to discern when transposing color-class set in the same way. For hue-based color-class set, the visual display of a set and its transposition on the color circle reveals this deep relationship between them immediately; the transposed set is simply a rotation of the original set on the circle. Different from in the traditional type of transposition, the luminance of the set members might not be the same as its correspondence. The similarity between the two sets comes from the same intervals along the color circle between their set members. Their visual similarity is exemplified by the existence of interval-based basic color schemes. This kind of scheme is composed of all the transpositions and inversions of a hue-based color-class set. The fact that they are identified as a group provides a strong evidence of the visual similarity between them. Beyond similarity, each interval-based basic color scheme also has its characteristic visual property. For example, the Clash scheme has a brash and surprising effect; the Analogous scheme on the other hand is harmonious and pleasing. For luminance-based color-class sets, during transposition, what is preserved is the luminance interval between the set members, no matter what hue or saturation values they assume. Using terms from the tonal grouping concept, it is the interval between the tonal planes which is preserved. However, because of the non-circular nature of luminance-based color-class, transformation and many other operations or relationships could only be applied within certain ranges.

Inversion

Similar to transposition, inversion of a line of pitches in traditional music keeps the contour of the line and is easy to recognize. Inversion in musical set theory normally involves both an inversion of the set members around 0 and a transposition of the inverted set by the desired pitch-class interval. Same as pitch-class set transposition, the pitch-class set inversion also only preserves the interval-class content. In both transposition and inversion, it is this deep unity brings to set theory-based composition one of its main characteristics: deep coherence under rich musical surfaces.

The property and visual effect of color inversions corresponding to these two types of inversions in music are similar to that of the transposition.

3.2.4. Characteristic Set Relationships[5]

Employing characteristic set relationships to realize compositional ideas forms a major part of the set theory-based composition process. In the following writing, six characteristic set relationships are introduced in groups based on their attributes suggestive to composition.

Common Tones: Transpostional Symetry and Inversional Symetry

Similar as the role of common tones in music, colors held in common between a set and its transposition or inversion can help provide a visual continuity during the transformation. On the other hand, when a contrast effect is intended transformations of a set with no or few common colors could be employed.

Set can also be purposely designed in order to get the desired common color relationships with all its transformations. The properties of the major scale and whole tone scale in music can help illustrate this idea. The interval vector for the major scale is 254361. It has a different number of occurrences for

[5] The descriptions about characteristic set relationships in this section and the use of set in linear development discussed in next section are based on Joseph N. Straus, *Introduction to Post-Tonal Theory* (Upper Saddle River, NJ: Prentice-Hall, Inc., 2000), chapter 3;

each interval class and thus a rich variation of common tone numbers at each transpositional level (following the rules for finding common tones that will be introduced a little later). This creates a hierarchy of closely and distantly related keys, in which the transposition a perfect fifth up has the 6 tones in common and the transposition a semitone down has only 2. In contrast to the major scale, the transpositions of the whole tone scale (interval vector 060603) either has 6 common tones or 0. The rich hierarchical closeness relationship between a set and its transpositions no longer exists here. This example suggests that the common color relationship with a set's transpositions could be factor to consider during the design of the set for the composition.

The general rule for finding out the number of common colors between a set and its transposition is: when a color-class set is transposed by interval n, the number of common colors is equal to the number of times the interval n occurs in the set. The procedure for figuring out the common colors with a set's inversion is similar. For an inversion of (T_nI) (invert, then transpose for interval n), the number of common colors equals to the number of times an index number is formed by summing each pair of elements in a set.

Considering the common colors after transformation, there are two types of characteristic sets. One is transpositionally symmetrical; the other is inversionally symmetrical. A transpositionally symmetrical set can map entirely onto itself through transposition. An inversionally symmetrical set can map entirely onto itself under inversion. This also means that these types of sets can have the highest number of common colors with one of their transformations.

Interval-Class Content: Z-Relation and Complement Relation

As discussed in the previous section, it is the common interval-class content that makes sets related by transposition or inversion sound similar despite the different contours they have. Here are two other relationships, members of which sound similar for interval-class content related reasons.

The first one is the Z-relation. It refers to the relationship between sets that have the same interval-class content but are not transposition or inversion of each other. The second one is the complement relation. It refers to the relationship between a set and the set formed out of pitch or color classes not included in the first set. The interval-class content of a set and its complement are proportionally related. In other words, a set and its complement have similar distribution of intervals. The difference in the number of occurrence of each interval is equal to the difference between the sizes of the sets. Sets in both relationships are not as closely related to each other as sets in a set class.

Two examples of employing complement relationship in music composition are suggestive for color compositions. At the beginning of Schoenberg's String Quartet No.3, similar sound between the melody and the accompaniment is achieved by using the complementary of the melody to form the accompaniment. At the very end of the second of Schoenberg's Little Piano Pieces, the final four-note chord and the last eight notes of which it is a part form a complement relation. This makes the chord reside in a harmonious context.

Inclusion Relations: Subset and Superset Relations and Transpositional Combination

Inclusion relation refers to the relationship between two or more sets, some of which are part of others. If a set is included in another set, then the first set is a subset of the second and the second is a superset of the first. This kind of relationship is not as strong as Z-relation or complement relation, but can be compositionally interesting. A dynamic and fluid visual effect can be achieved when smaller sets are frequently combined into larger ones and larger ones fall apart again. It would be more interesting if those smaller sets were related by transposition or inversion. Transpositional combination is an operation preparing set materials for generating this effect. With Transpositional combination, a set is combined with one or more transpositions of it into a superset, which can then be divided into transpositionally related subsets.

Other visual means can be employed to emphasize the process or grouping and dividing. For example, luminance or spatial affinity can help make a subset more identifiable.

3.2.5. Set in Linear Development

The use of sets in linear development and overall organization in atonal music is presented through the set-based contour design and the two different models of voice leading. These approaches can be applied to temporal visual composition as well.

Contour refers to the general shape of music, going up and down, higher and lower. It is the aspect of music easier for the listeners to attend to. Our impression of a contour segment is only related to the relative vertical positions of notes in it. As long as the relative height of notes in a segment is kept, no matter at which pitch it starts from and no matter what interval value will be between its component notes, the contour of the segment is considered the same. Because of this property, a set theory approach can be employed in contour analysis and design. The relative height of notes in a segment can be represented by a set. Segments formed based on the inversion, retrograde and retrograde-inversion of this set will evoke the impression of the same contour being played inversionally or reversely. By working with contour in this way, our attention can be focused on the essential property of a contour; rich variations can also be created on top of a unified structure. Since we might be more sensitive to the order in luminance than to the order in hue, this set-based approach for contour design would be more readily applied to luminance-based color classes.

Set can play its role in linear organization either through association or through transformation. Under the associational model, set members spread across the composition are associated by a variety of means and form a coherent linear structure. In music, those means include register, timbre, metrical placement, dynamics, and articulation. For color composition, those means could be luminance, texture, graphical pattern, temporal rhythm, and color articulation (to be introduced in Chapter 4).

In the transpositional model, notes across multiple voices form a set in the way similar to a chord in tonal music. This set is then transposed or inverted creating a pitch-class counterpoint which guides the progression of the composition.

Besides being the element to be transformed, sets can also be used to control the interval of the transposition. When the transposition intervals are the same as the interval-class content of the set being transposed, the transposition is said to be along a motivic path. This adds another dimension for the presenting the compositional idea encoded in the set.

In compositions organized by these two models, the multi-threading characteristic of set theory-based composition is presented in different manners. With the association model, the linear structure formed out of set members separated in time or space is similar to a net with various parts being revealed and hidden dynamically. In contrast, the set transpositions in the transpositional model form a much more systematic structure, in which the path of each set member could be considered as one thread. Of course, this structure controlled by the transpositional logic only functions as the backbone for a much richer scene of composition in the foreground.

3.3. Color-Class Set

Color-class set is the most essential material for set theory-based composition. In this section, analysis and experiments carried out on the content and composition of color-class set are presented.

3.3.1. Color-Class Set Content

Color-Class Set Table[6]

In the early stage of the development of this set theory-based approach, a color-class set table is constructed for collecting and analyzing existing color schemes and color studies from the point of view of organizing set materials. The aim is that after having such a list, different color combinations can be used in the composition purposefully at different points when different effects, such as contrast or harmony, or different types of transitions, such as increase, soften, or slowing down, are needed. This list could be expanded to include color studies at different levels. Besides context-independent color relationship, color and the size of the application area, color

[6] Many of the set properties and examples in the table are from Johannes Itten, *The Art of Color* (New York: Van Nostrand Reinhold, 1973), Lisa Sawahata, *Color Harmony Workbook* (Gloucester, MA: Rockport publishers, Inc., 2001), and Leslie Cabarga, *The Designer's Guide to Color Combinations* (Iconoclassics Publishing Co., 2002).

and simultaneous contrast, and color study in time could also be included.

The table is designed to have sets or compositions in one column, their property (active, inactive, contrast, harmony, etc.) in the next column, and some examples in another one. Because of the nature of the table as a working place for consolidating color-class set related materials, both the categories and the contents do not mean to be complete. They are listed here as a work in progress to show the directions I explored or planned to explore. Both of them can be expanded along with the continuation of research.

Color Combination or Composition	**Property**	**Examples**
Color Scheme		
Analogous (012)	Harmonious, pleasing.	
Complementary (06) (Dyads)	Colors enhance one another, producing an almost vibratory visual sensation when seen side by side.	
Clash (05) or (07)	Brash, surprising.	
Split Complementary (057)	More pleasing than a true complementary set.	
Triadic (048)		
Tetradic (0268)		
0369		
0246810hexads		
Tetrads+w+b		
Neutral		
Monochromatic		
Achromatic		
Primary	The elementary nature of this color scheme makes it a favorite for children's books, toys, and bedrooms. The purity of the primary scheme has made it an important palette for such artists as Piet Mondrian and Roy Lichtenstein.	

Secondary	It has a fresh, uplifting quality and can be made quite subtle by using tints and shades of the secondary hues.	
Tertiary Triad		
Quantitative Proportion		
Goethe: y:r:b=3:6:8 is based on equal luminance*size which could be calculated explicitly during the composition.		
Degree of Purity and Brilliance		
Same composition, change the luminance and saturation level.		
Contrast		
Hue		
Light-Dark (luminance)		
Cold-Warm		
Saturation		
Extension		
Simultaneous Contrast		
Successive Contrast		
Composition		
Color Expression		
1. Color Set		*Color Harmony Workbook* (Sawahata)
Around Blue	Cold	
Around Red	Hot	
Around Violet	Cool	
Around Orange	Warm	
High Luminance	Light	
Low Luminance	Dark	
Low Saturation	Pale	
High Saturation	Bright	
	Powerful	
	Rich	
	Romantic	

	Vital	
	Earthy	
	Friendly	
	Soft	
	Welcoming	
	Moving	
	Elegant	
	Fresh	
	Traditional	
	Refreshing	
	Tropical	
	Classic	
	Dependable	
	Calm	
	Regal	
	Magical	
	Energetic	
	Subdued	
	Professional	
	Victorian	
	Deco	
	Atomic	
	Far-out Sixties	
	Current	
	Earth	
	Rave	
2. Color Timbre		*The Art of Color (Itten)* P130-131
Spring	Youthful, light, radiant.	
Summer	Warm, saturated, active colors at their peak being contrasted and amplified by their complements.	
Autumn	The green of vegetation dies out, to be broken down and decomposed into dull brown and violet.	
Winter	Withdrawal, cold and centripetal radiance, transparency, rarefaction.	
3. Color in Context		*The Art of Color (Itten)* P133-135
Yellow on White	Yellow looks dark and rayless; the white thrusts it into a subordinate position.	
Yellow on Light Pink	Simultaneous effect shifts it towards	

	greenish yellow, and its radiant power is subdued.	
Yellow on Orange	Acts like a purer, lighter orange. The two colors together are like strong morning sun on ripening wheat fields.	
Yellow on Green	Radiates outward, outshining the green.	
Yellow on Red-Violet	Has an extreme and characteristic power, hard and inexorable.	
Yellow on Medium Blue	Radiant but alien and repellent in effect. Sentimental blue will not readily tolerate the bright wit of yellow.	
Yellow on Red	A loud joyful noise, like trumpets on Easter Morn. Its splendor sends forth a mighty knowledge and affirmation.	
Yellow on Black	Radiantly cheerful. It is in its brightest and most aggressive luminosity. It is vigorous and sharp, uncompromising and abstract.	
Red on Lemon Yellow	Shows a dark, subdued force. It is dominated by the force of yellow.	
Red on Dark Pink	Acts with quiet, extinguishing heat.	
Red on Green-Blue	Like a blazing fire.	
Red on Lilac	A subdued glow which drives the lilac to active resistance.	
Red on Yellow-Green	An impudent, rash intruder, loud and common.	
Red on Orange	Smoldering, dark and lifeless, as if parched.	
Red on Dark Brown	Red fire flares with a dry heat	
Red-Orange on Black	Demonic, sinister	
Blue on Yellow	Very dark, devoid of radiance.	
Blue on Black	Gleams in bright, pure strength.	

Blue on Lilac	Withdrawn, inane. and impotent.	
Blue on Dark Brown	Blue is excited into a strong vibrant tremor; brown simultaneously awakens into live color. The brown that was dead is resurrected by the power of blue.	
Blue on Red-Orange	Retains its dark figure, yet becomes luminous, asserting and maintaining its strange unreality.	
Blue on Quiet Green	Markedly displaces towards red. Only by this "evasion" can it escape from the paralyzing saturation of the green and return to active life.	
Global Colors		*The Designer's Guide to Color Combinations CD-Rom* (Cabarga)
China		
Japan		
Korea		
Vietnam		
Tibet		
India		
Native American		
American		
Spain		
France		
Italy		
Germany		
Austria		
Holland		
Scotland		
Mexico		
Peru		
Guatemala		
Brazil		
Argentina		
Ethiopia		
Egypt		
Guinee Mali		
Senegal		
Ghana		
Finland		
Sweden		

Norway Denmark		
Rumania		
Hungary		
Czech Republic		
Russia		
Bali		
Bali Java		
Hawaii		
Cuba Bahamas		
Tahiti		
Iran		
Palestine		
Armenia		

Figure 37. Table for studying color set properties.

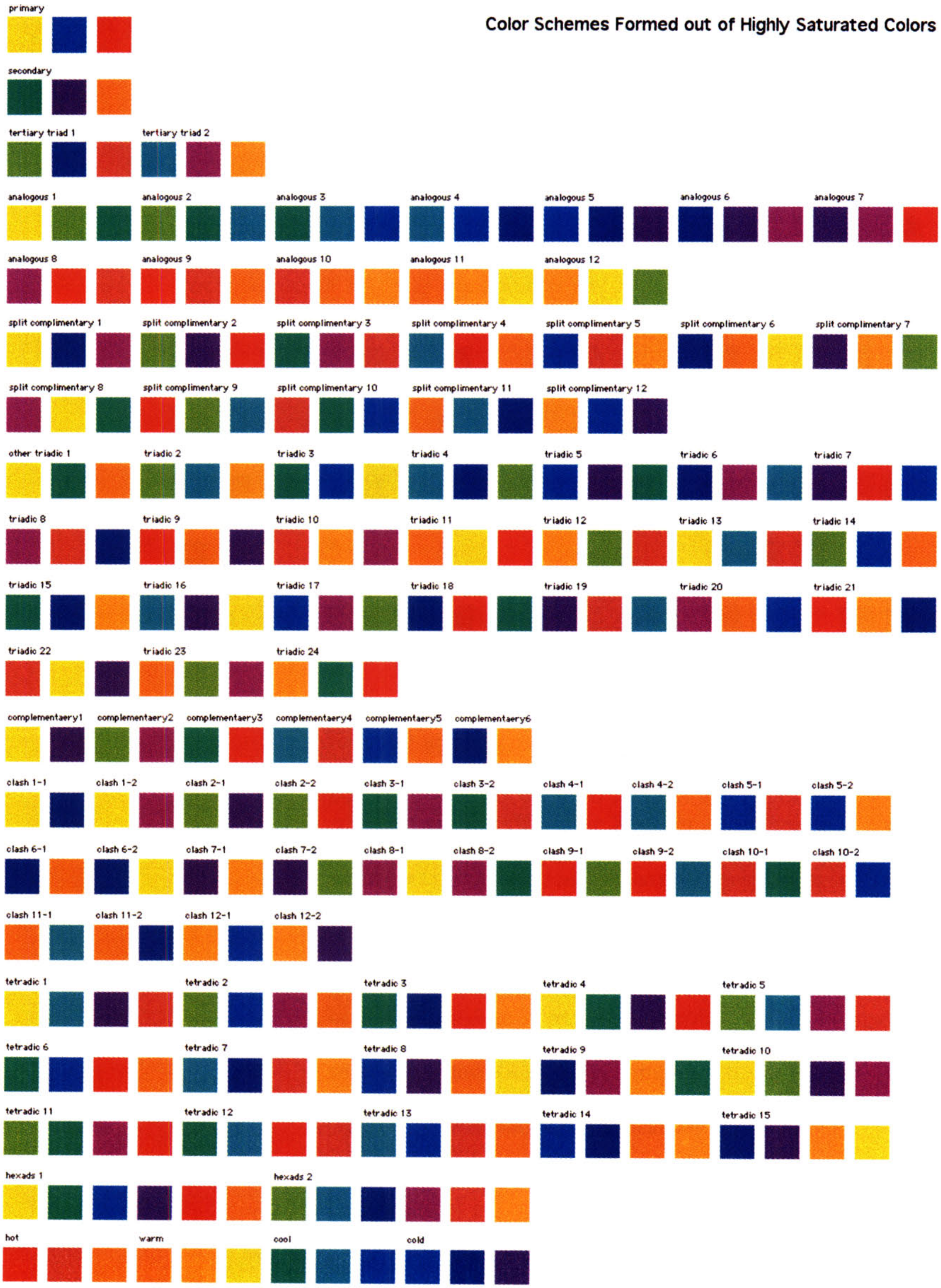
Analysis of Color-Class Sets Based on Compositional Meaning

In order to get familiar with the set material and have a concrete sense of their properties visually, I started the process of plotting all the characteristic color schemes.[7] Fig. 38 displays the resulted image. However, different from my expectation, after went through this process, I didn't get the sense of control over the set materials. It is not easy for me to see obvious characteristics of different schemes; it is even more difficult to find from them properties meaningful for set theory-based composition.

After running into these problems, I changed to a different approach of exploration. Instead of using color schemes rooted in traditional visual art as the starting point, I begin to explore properties of the color-class set by positioning myself in an imagined process of set theory-based composition. The analysis is then guided by questions I would ask and aspects I would concern during the process of composition. For example, when choosing the set for a composition, questions one might ask are: how many colors I would like to have in the set; which colors, or in other words colors with what kind of intervals, I would like to use, etc. Under this line of thinking, I categorized the color-class sets by the number of set members, and analyzed them on the color wheel in order to better detect meaningful interval relationships.

[7] The RGB values for colors in the schemes are converted from the CMYK values of colors on the color wheel from Lisa Sawahata, *Color Harmony Workbook* (Gloucester, MA: Rockport publishers, Inc., 2001).

Color Schemes Formed out of Highly Saturated Colors



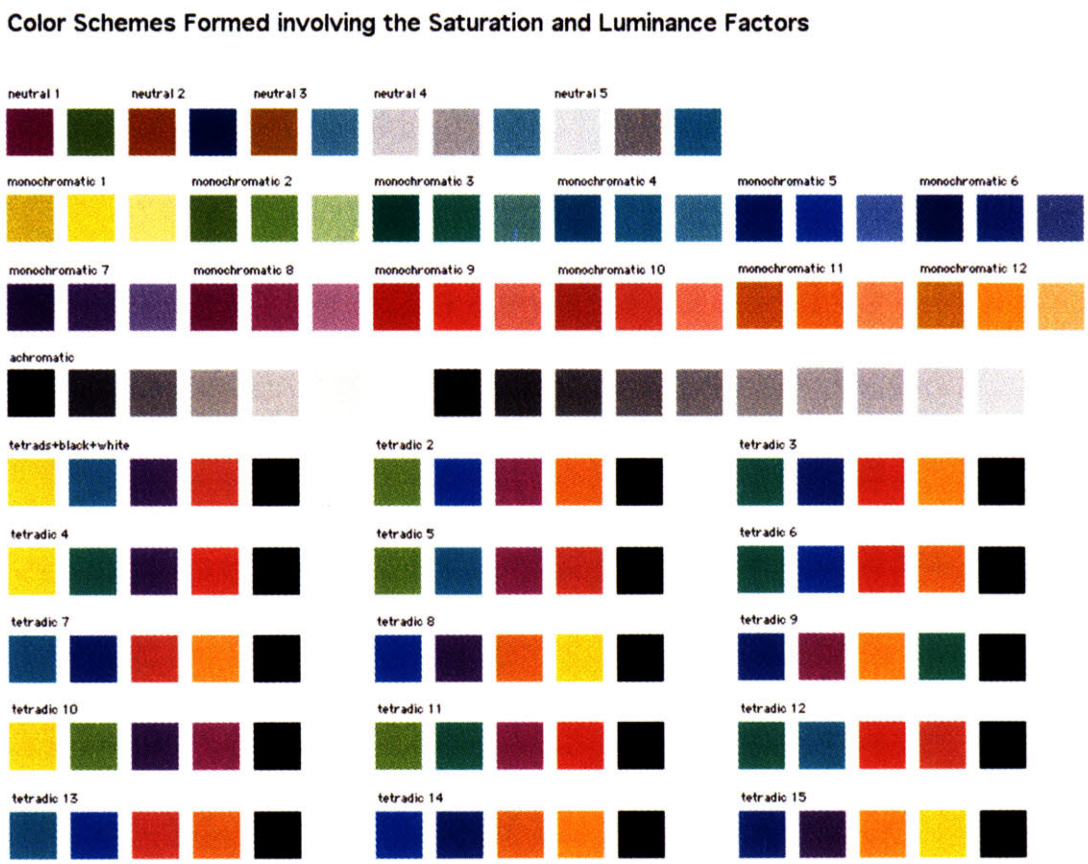


Figure 38. Color schemes.

During the analysis, I found that there are different trends of interval changes across sets with the same number of set members. Even though it is not common in set theory-based music composition to use sets with different interval-class content, a well-designed change of set-classes based on interval change along discernable directions might bring to the composition set design on another level.

My analysis of set with 2-6 members is presented below. For each category, the sets are further categorized into the interval change trend they belong to. In the high level design of interval change, those sets belonging to multiple trends can play a special role of mediating the interval change from one trend to another. Across the different trend groups, there are also gradual changes of certain aspects of the trend.

The sets are listed following the following formatting rules:

1) Sets having common member(s) at the beginning are written as: common member(s) + distinctive member(s).

2) When two sets are at the same level along the direction of change, the number from the set not in normal form will be written in braces and placed next to the number from the one in normal form. 0 + 1 (11) is an example. If the normal form is not the normal form of the set in braces, the number will be enclosed in quotation marks, and the normal form of this set will be written next to it. 0 1 3 + 5("10" 0 2 3 5) is an example.

3) Sets that have already been included under another trend are enclosed in braces as well.

4) To maintain visual clarity, sets are written by numbers as they are on the color circle. If this is not the normal form of the set and it has its unique position in the process of change, the number(s) will be enclosed by quotation marks and followed by its normal form. "9" 0 2 3 4 7 in
0 1 2 4 + 6("10"), 7("9"), 8, "9" 0 2 3 4 7 is an example.

Two-Member Set Classes (6)

There are 6 two-member set classes and one trend of interval change across them. The six classes of sets are:

0 + 1(11), 2(10), 3(9), 4(8), 5(7), 6

As displayed in Fig. 39, along with the increasing of the second number, the two colors in color-class sets of these set classes are getting less and less similar and having stronger and stronger contrast.

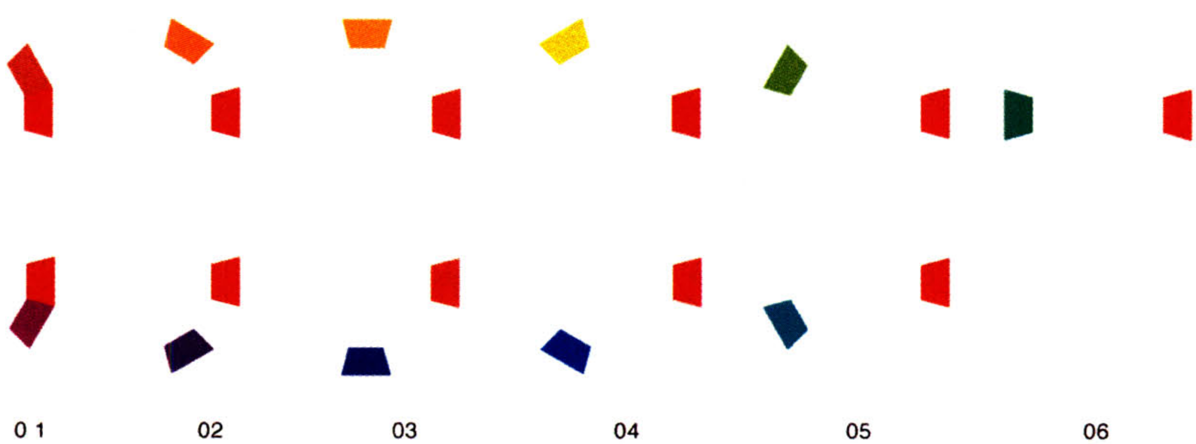


Figure 39. Two-member sets.

Three-Member Set Classes (12)

There are 12 three-member set classes. Five visually meaningful trends of interval change across them are presented here. The set classes are listed under the groups they belong to following the formatting rules introduced above.

1. 01+ 2(11), 3(10), 4(9), 5(8), 6(7)

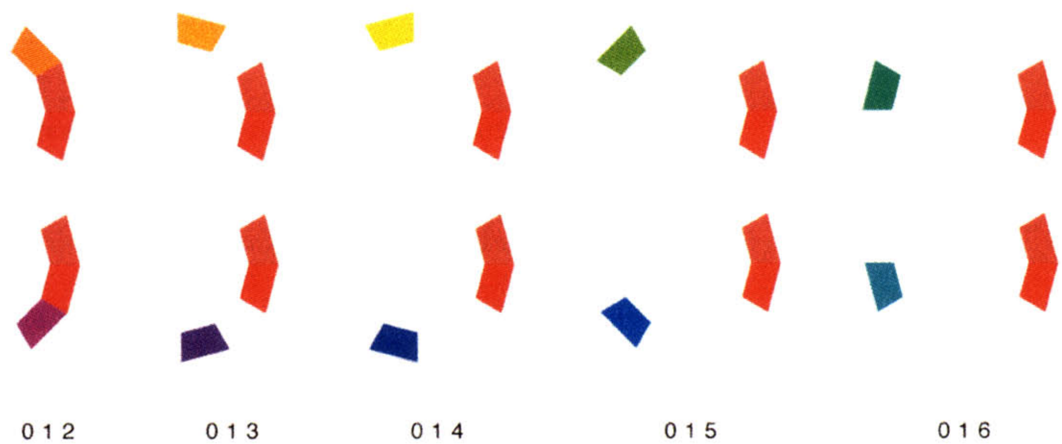


Figure 40. Three-member sets group 1.

0 and 1 are two colors with the lowest contrast, when they combine with a third color, with the number increase from 2 to 6 or decrease from 11 to 7, the third color forms a stronger and stronger contrast with the 01 pair. More variations could be introduced when these three colors playing different roles in the scene. For example, one design scenario could be using one color from the 01 pair as an accompaniment to the other and forming a contrast together with the third color. Another scenario could be having 0 or 1 contrasting with the third color, with the other one from the 01 pair playing a role of harmonizing the two colors in contrast.

Along this line of thinking, even though from the musical set theory point of view the color-class sets in the 5 set classes listed above has no similarity and close relationship as color-class sets in a single set class or color-class sets satisfying additional relationships, they share the same compositional idea. Only that the degree of contrast between the third color and the first two colors are different.

2. 0 2 + 4(10), 5(9), 6(8), 7

Color-class sets in this group of set classes have properties similar to group 1. They also have a close pair and a third one contrasting with this pair. Compared with the color-class sets in group1, the pair formed out of the first two colors in this group is less tight, and the "one in contrast with two" effect is not as strong as with the first group.

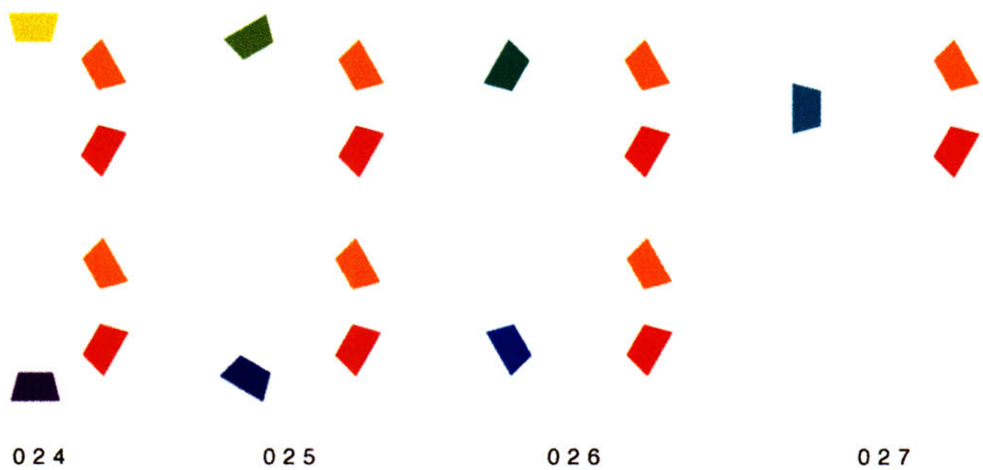


Figure 41. Three-member sets group 2.

3. 0 3 + 6(9), 7(8)

With class sets in this group, the effect similar to group 1 and 2 can still be seen in the 0 3 7(8) sets, but is already very weak.

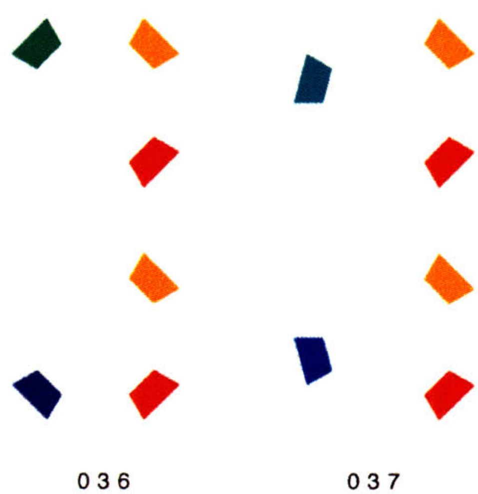


Figure 42. Three-member sets group 3.

4. 0 4 8

To complete the line of change across the above three groups, set class 0 4 8 is listed here by itself as a group. The 1 color in contrast to 2 colors effect is totally lost in this group. The three colors in sets of this set class are at equal distance along the color wheel.

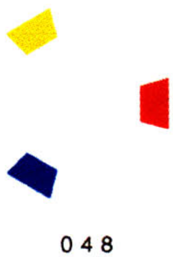


Figure 43. Set 0 4 8.

However, when placed along the lines of two other trends displayed below, this set class acquires very different interpretations.

5. (0 1 2), (0 2 4), (0 3 6), (0 4 8)

Set classes in this group have all been included in other groups and discussed under different contexts. They form a new group here representing the changing relationship among three colors. From left to right as displayed in the figure below, the distances between the three colors are getting bigger and bigger equally. The visual effect would be that the tight relationship between the three colors is becoming looser and looser.

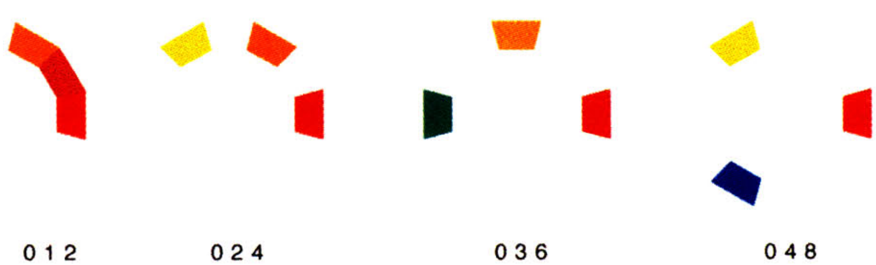


Figure 44. Three-member sets group 4.

6. (0 2 7), (0 4 8), (0 3 6), (0 2 4), (0 1 2)

   As displayed in the figure below, from left to right, the trend in this group is that two colors in contrast with one color are approaching to that color at equal pace. Their relationship with that color changes from high contrast to analogous. In other words, the relationships between the one color and those other two changes from the loosest to the tightest.

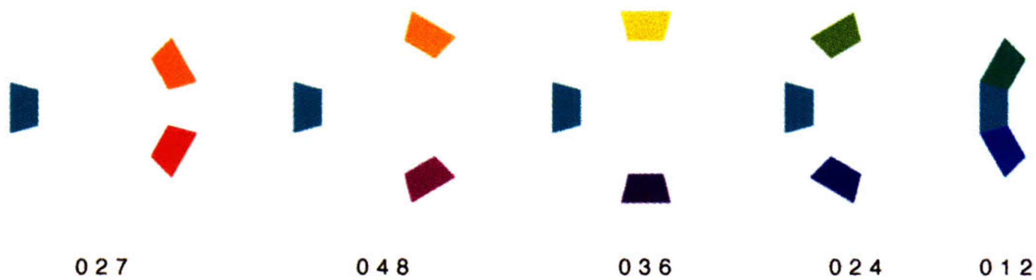


Figure 45. Three-member sets group 5.

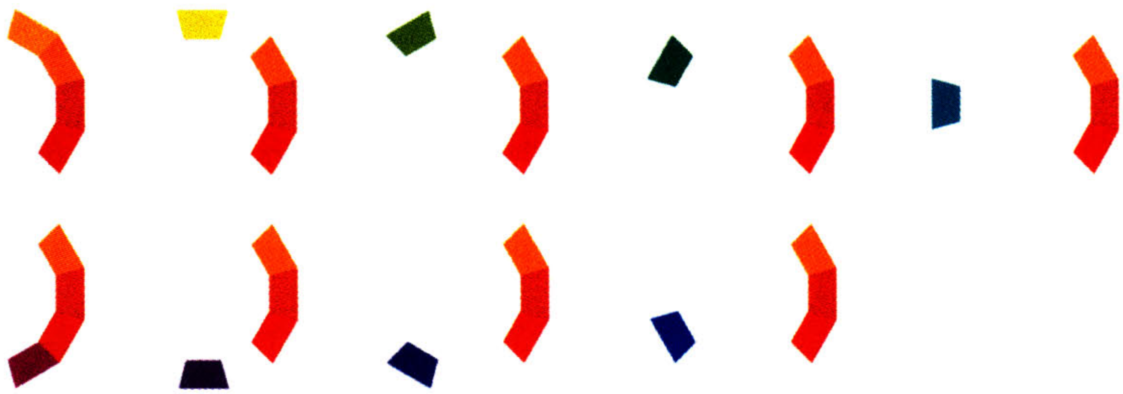
Four-Member Set Classes (29)

13 groups are formed out of the 29 four-member set classes. Those one-member groups at the end of the list are set classes that cannot be grouped into any meaningful trend.

1. 0 1 2 + 3(11), 4(10), 5(9), 6(8), 7
2. 0 1 + (2 3(10 11)), 3 4(9 10), 4 5(8 9), 5 6(7 8), 6 7
3. 0 1 3 + 5(“10” 0 2 3 5), 6(“9” 0 2 3 6), 7(8)
4. 0 1 + (3 5(8 10)), 4 6(7 9), 5 7(6 8)
5. 0 2 + 5 7(7 9), 6 8
6. 0 2 3 + (5(“10” 0 1 3 5)), 6(“9” 0 1 3 6), 7(“8” 0 1 3 7)
7. 0 2 4 + 7(9), 8
8. (“0 1 2 11” 0 1 2 3), “0 1 3 10” 0 2 3 5, “0 1 4 9” 0 3 4 7, 0 1 5 8, (0 1 6 7)
9. 0 2 4 6, 0 3 5 8, (“0 4 6 10” 0 2 6 8)
10. (0 1 2 3), (0 2 4 6), 0 3 6 9
11. 0 2 5 8 (0 3 6 8)
12. 0 1 4 7
13. 0 1 4 8

Images and brief description of the first 10 groups are included below.

Group 1*:* 0 1 2 + 3(11), 4(10), 5(9), 6(8), 7

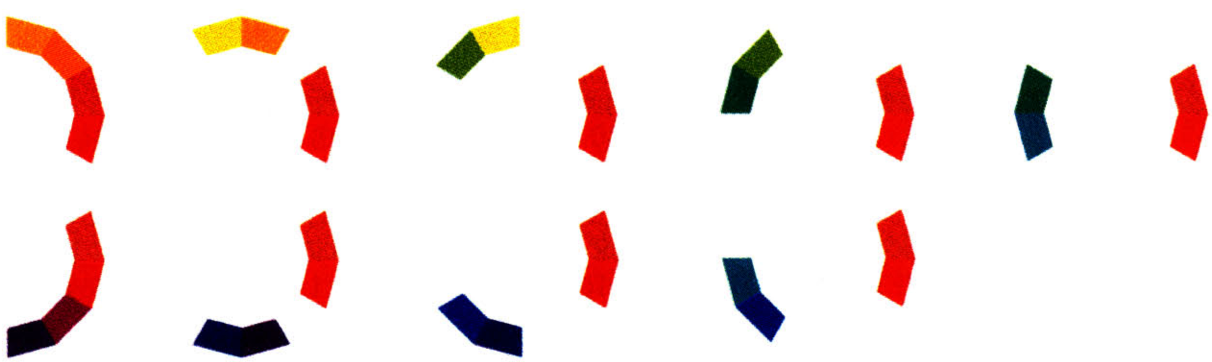


0 1 2 3 0 1 2 4 0 1 2 5 0 1 2 6 0 1 2 7

Figure 46. Four-member sets group 1.

0 1 2 are considered as a group. From left to right, the fourth color forms a stronger and stronger contrast with this group.

Group 2*:* 0 1 + (2 3(10 11)), 3 4(9 10), 4 5(8 9), 5 6(7 8), 6 7



0 1 2 3 0 1 3 4 0 1 4 5 0 1 5 6 0 1 6 7

Figure 47. Four-member sets group 2.

0 1 are considered as a group, the other two colors form another group. From left to right, the contrast between these two groups is getting stronger and stronger.

***Group 3**:* 0 1 3 + 5(“10” 0 2 3 5), 6(“9” 0 2 3 6), 7(8)

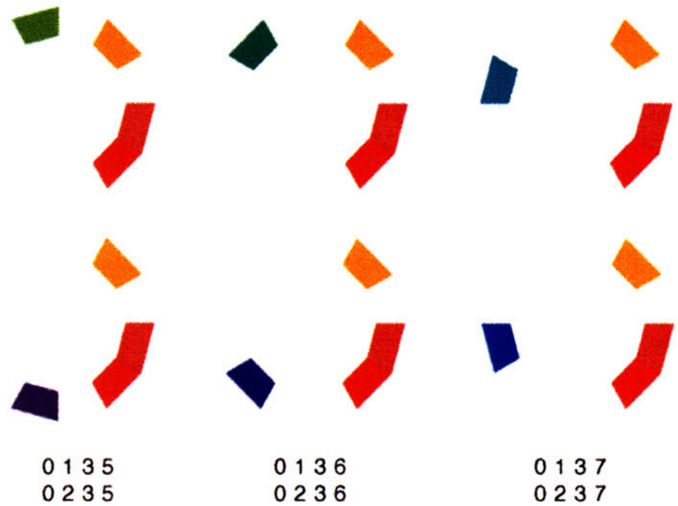


Figure 48. Four-member sets group 3.

0 1 3 are considered as a group. From left to right, the fourth color forms a stronger and stronger contrast with this group.

***Group 4**:* 0 1 + (3 5(8 10)), 4 6(7 9), 5 7(6 8)

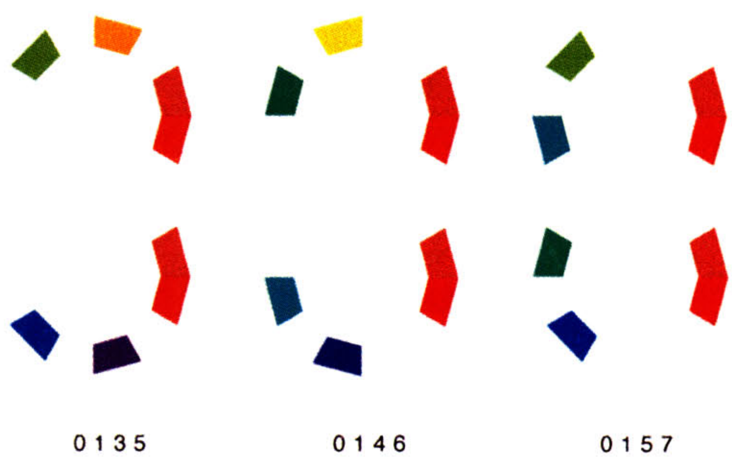


Figure 49. Four-member sets group 4.

0 1 are considered as a group, the other two colors form another group. From left to right, the contrast between these two groups is getting stronger and stronger.

***Group 5**:* 0 2 + 5 7(7 9), 6 8

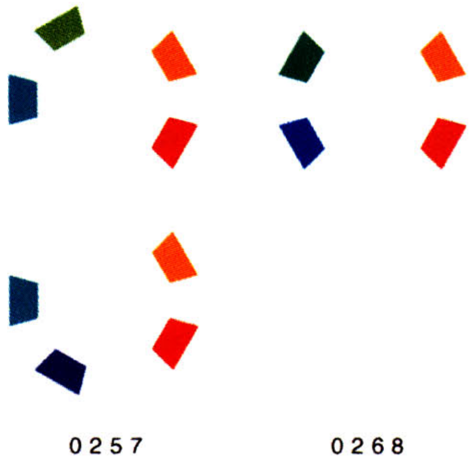


Figure 50. Four-member sets group 5.

0 2 are considered as a group, the other two colors form another group. From left to right, the contrast between these two groups is getting stronger and stronger.

***Group 6**:* 0 2 3 + (5("10" 0 1 3 5)), 6("9" 0 1 3 6), 7("8" 0 1 3 7)

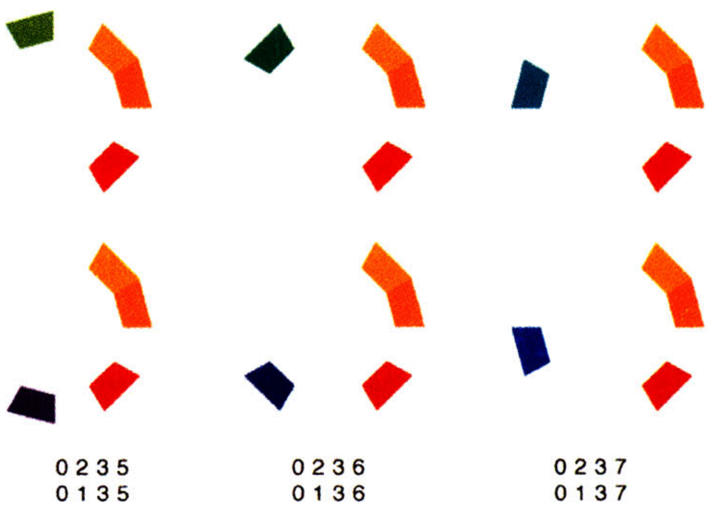


Figure 51. Four-member sets group 6.

0 2 3 are considered as a group. From left to right, the fourth color forms a stronger and stronger contrast with this group.

Group 7: 0 2 4 + 7(9), 8

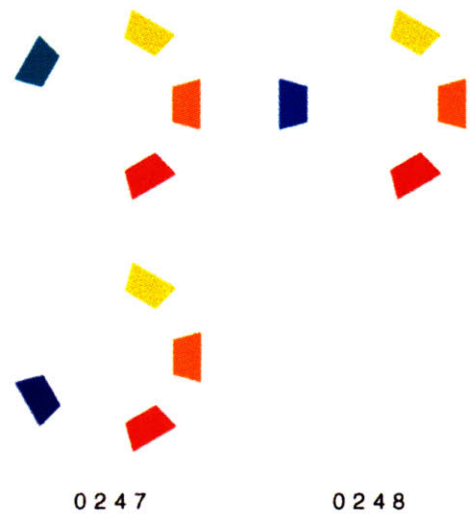


Figure 52. Four-member sets group 7.

0 2 4 are considered as a group. From left to right, the fourth color forms a stronger and stronger contrast with this group.

Group 8: ("0 1 2 11" 0 1 2 3), "0 1 3 10" 0 2 3 5, "0 1 4 9" 0 3 4 7, 0 1 5 8, (0 1 6 7)

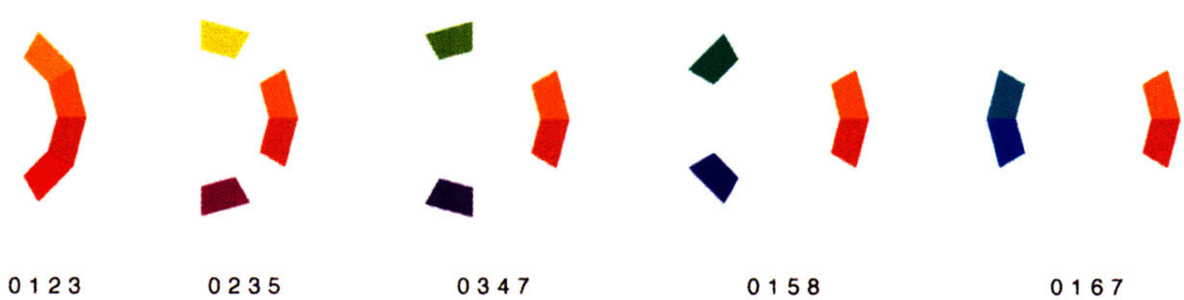


Figure 53. Four-member sets group 8.

0 1 are considered as a group. From left to right, the other two colors getting farther and farther away from this group at equal pace.

***Group 9**:* 0 2 4 6, “11 2 4 7” 0 3 5 8, (“10 2 4 8” 0 2 6 8)

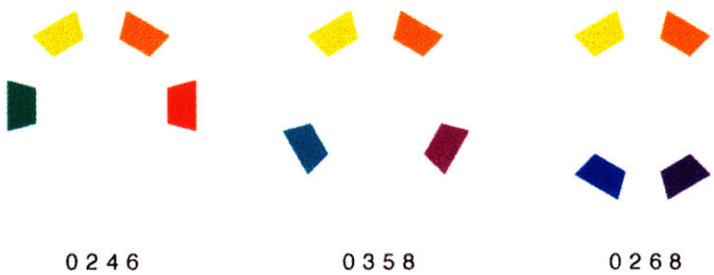


Figure 54. Four-member sets group 9.

2 4 are considered as a group. From left to right, the other two colors are getting farther and farther away from this group at equal pace.

***Group 10**:* (0 1 2 3), (0 2 4 6), 0 3 6 9

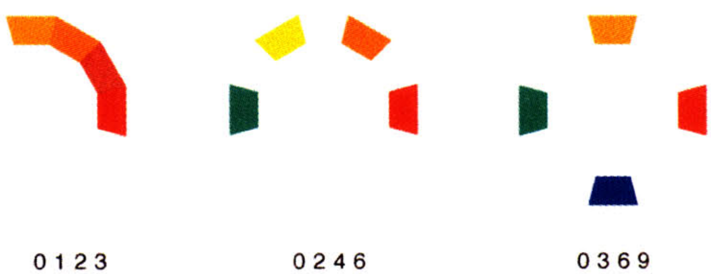


Figure 55. Four-member sets group 10.

From left to right, the distances between the four colors are getting bigger and bigger equally. The visual effect would be that the tight relationship between the four colors is getting looser and looser.

Five-Member Set Classes (38)

1. 0 1 2 3 4
2. 0 1 2 3 + 5(10), 6(9), 7(8)
3. 0 1 2 + 4 5(9 10), 5 6(8 9), 6 7(7 8)
4. 0 1 2 4 + 6("10"), 7("9"), 8, ("9") 0 2 3 4 7, ("10" 0 2 3 4 6)
5. 0 1 2 + 5 7(7 9), 6 8
6. 0 1 3 4 + 6(10), 7(9), 8
7. 0 1 3 + 5 6("9 10" 0 1 3 4 6), 6 7("8 9"), ("7 8" 0 1 5 6 8), ("8 9") 0 1 4 5 7
8. 0 1 4 5 8 (9)
9. (0 1 3 5 6), 0 1 4 7 8, ("0 1 5 9 10" 0 1 3 4 8)
10. (0 1 2 6 8), (0 1 2 5 9) 0 3 4 5 8, (0 1 2 4 10) 0 2 3 4 6
11. 0 1 5 6 8(10), ("0 1 5 6 9" 0 1 4 7 8)
12. 0 2 3 5 7(10), 0 2 3 5 8(9)
13. ("0 2 4 6 7") 0 1 3 5 7 ("0 1 6 8 10"), ("0 2 4 7 8") 0 1 4 6 8 ("0 1 5 7 9")
14. (0 2 4 6 8 (8 10), 0 2 4 7 9
15. 0 2 4 6 8(10), 0 2 4 6 9
16. 0 1 2 5 8
17. 0 1 3 5 8
18. 0 1 3 6 8
19. 0 1 3 6 9
20. 0 1 4 6 9
21. 0 2 3 6 8
22. 0 2 4 5 8

Six-Member Set Classes (50)

1. 0 1 2 3 4 5
2. 0 1 2 3 4 + 6(10), 7(9), 8
3. 0 1 2 3 + 5 6(9 10), 6 7(8 9), 7 8
4. 0 1 2 3 + 5 7(8 10), 6 8(7 9)
5. 0 1 2 3 + (7 8), 6 9, ("5 10") 0 2 3 4 5 7
6. 0 1 2 + 4 5 6(8 9 10), 5 6 7(7 8 9), 6 7 8
7. 0 1 2 4 + 6 7(9 10), 7 8(8 9)
8. 0 1 3 4 + 6 7(9 10), 7 8(8 9)
9. (0 1 3 4 6 7), 0 1 4 5 8 9, (0 1 2 3 7 8)
10. 0 1 2 4 5 7, 0 1 3 4 5 7
11. (0 2 3 4 5 7), ("0 3 4 5 6 9"0 1 2 3 6 9), ("0 4 5 6 7 11" 0 1 2 3 7 8)
12. 0 2 3 5 6 8, ("0 3 4 6 7 10")0 1 3 4 7 9
13. 0 2 3 4 6 9
14. 0 2 4 6 8 10

15. 0 1 2 4 5 8(9)
16. 0 1 2 3 5 8(9)
17. 0 1 2 4 6 8
18. 0 1 2 4 6 9
19. 0 1 2 4 7 9
20. 0 1 2 5 6 8
21. 0 1 2 5 6 9
22. 0 1 2 5 7 8
23. 0 1 2 5 7 9
24. 0 1 3 4 5 8
25. 0 1 3 4 6 8
26. 0 1 3 4 6 9
27. 0 1 3 5 6 8
28. 0 1 3 5 6 9
29. 0 1 3 5 7 8
30. 0 1 3 5 7 9
31. 0 1 3 6 7 9
32. 0 1 4 5 6 8
33. 0 1 4 5 7 9
34. 0 1 4 6 7 9
35. 0 2 3 6 7 9
36. 0 2 3 4 5 8
37. 0 2 3 4 6 8
38. 0 2 3 5 7 9
39. 0 2 4 5 7 9

Similarly, the five-member set classes and six-member set classes are analyzed. As displayed in the result, the ratio of visually meaningful groupings is getting smaller and smaller. The more the members are in the set, the more the set classes that cannot form any trend with others.

3.3.2. Color-Class Set in Composition

At the same time of developing the theoretical framework and analyzing the set material, I also carried out a line of thinking and experimentation on the fundamental aspects of using color-class set in temporal visual composition. Similar to my approach in color-class set analysis, I positioned myself in front of the most basic decisions I need to make during the process of creation and studied the compositional issues through thinking over each specific situation.

Changes on Different Levels

After deciding the set material based on the compositional idea and the property of the set, one might immediately think what are the possible changes we can make to the set we chose, or even more practical, to the initial colors we chose which conform to the set relationships. From small to big, here are a list of changes one could consider:

1. Change the order of the colors spatially or temporally.
2. Change the luminance or saturation of individual or all colors, or in other words, change a color to another color in the same color class.
3. Transpose or inverse the current set, or in other words, change the current set of colors to another set within the same set class.
4. Change the current set to its Z-related set, complementary set, subset or superset.
5. Change the current set to other sets in the trend group it belongs to following the trend of that group.
6. Continue the change in 5 and change to other trend groups at the intersection set.

Use in Temporal Visual Creation

How would we use a set of colors and their changes in the temporal visual creation? To make this question more approachable, I started from the simplest situation and moved to the more complex ones step by step.

1D

Itten's experiments on color harmony and variations in *The Art of Color* are good examples of using color-class set in 1D composition. In Itten's book, the concept and use of harmony is very similar to color-class set or set class in this study. "By color harmony I mean the craft of developing themes from systematic color relationships capable of serving as a basis for composition. Since it would be impossible to catalogue all combinations here, let us confine ourselves to developing some of the harmonic relationships." (Itten) He further analyzed the properties of a series of harmonic relationships equal to the color-class set (05), (048), (027), (0268), (0369), (02468), etc. and pointed out that the choice of a chord (set) and its modulation (change of the set) are the basis of a composition and cannot be arbitrary. In the examples displayed in Fig. 56, he experimented with different composition variations of a set formed out of red, yellow and blue (primary color scheme).

Starting from this concrete visual example, I analyzed issues related to using color-class set in 1D composition by going through important aspects involved during the creation.

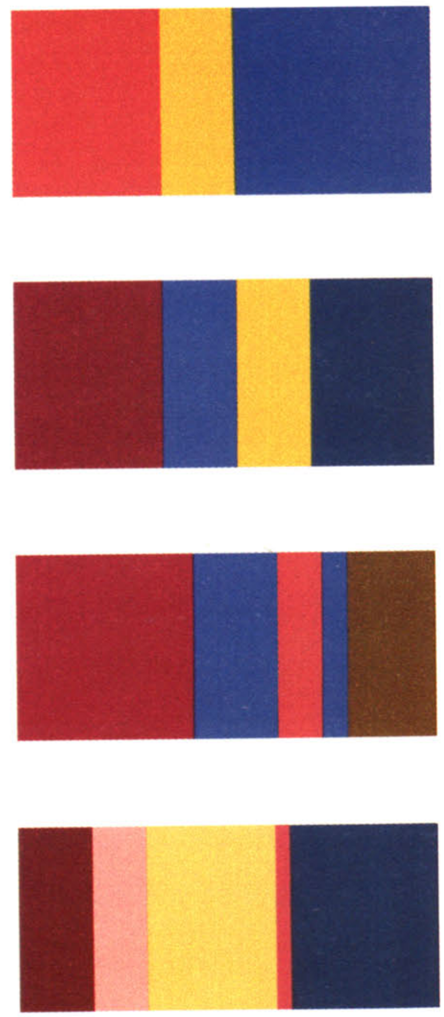


Figure 56. Color harmony variations (from Itten, *The Art of Color*, P119).

1. Composition elements

   From the most general point of view, composing in 1D includes deciding the color content (set and change), the position or order of each color in a sequence, the extension or width of each color area, and considering about the interaction between the colors.

2. Spatial composition variations

   The order and width of the color bars can be categorized under one aspect: elements involved in creating spatial composition variations.

3. Types of color interaction or context

   For 1D composition the interaction between colors or a color and its context which need to be considered include the contrast of hue, luminance, saturation, and extension.

4. Types of set composition

   Set composition based on luminance scale (treat different luminance levels as scale in music and compose on top of this underlying framework) is characteristic to 1D creation. Many of Klee's creations experimenting with tonality using the wet-on-dry wash technique are of this type. (More analysis and discussions see *Tonal Scale* under the section *Five Studies on Themes of Paul Klee* in Chapter 4, *Experiments*)

2D

In 2D composition, the important aspects discussed above have different characteristics.

1. Composition elements

   In 2D composition, instead of deciding the position of a color in a sequence, one needs to think where in a two dimensional grid to position the colors. The number of colors affecting our perception of one color or being affected by that color also changes from 2 to 8.

2. Spatial composition variations

   In 2D, there are more types of spatial composition variations and there are also more elements involved.

   One is a grid relationship. Elements to be considered in this case include:

   1) The 2d position of a color, or in other words, the relative positions of all the colors.

	0			
	1			
0	4	1	0	4
	1			
	0			

Figure 57. Spatial relation.

   2) The amount of spots in a grid using a color. Changing the amount would be an indirect way to change the extension, or in other words, the quantitative proportion of a color in the composition.

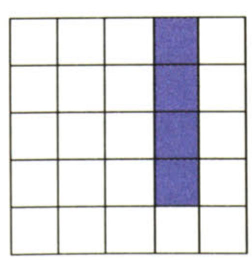


Figure 58. Quantitative proportion.

3) The growing or expansion of the cells using a color. This is a dynamic way to change the extension of a color.

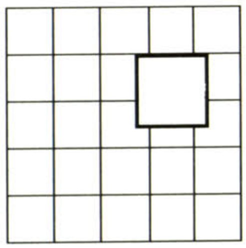


Figure 59. Dynamic expansion.

4) The sizes of the intervals across both directions of the grid. Changing the size of the intervals is a way to change the extension of colors structurally.

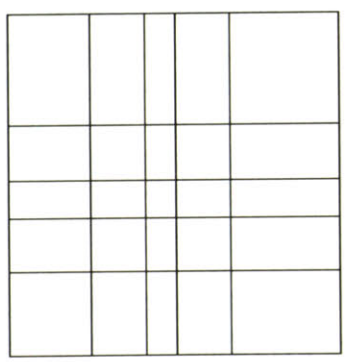


Figure 60. Structural deformation.

Another type is the enclosed relationship. For example, one color square is being inside another color square like in Fig. 61. The illustrated relationship could be repeated by positioning the current enclosing color inside another color which occupies a bigger area. This relationship could also be interpreted as one color on top of another. As displayed in Fig. 62, the size of the inner color plays an important role in changing the interpretation.

There can also be irregular spatial compositions guided essentially by the set relationship. The following two graphical scenarios are examples of this type of spatial composition.

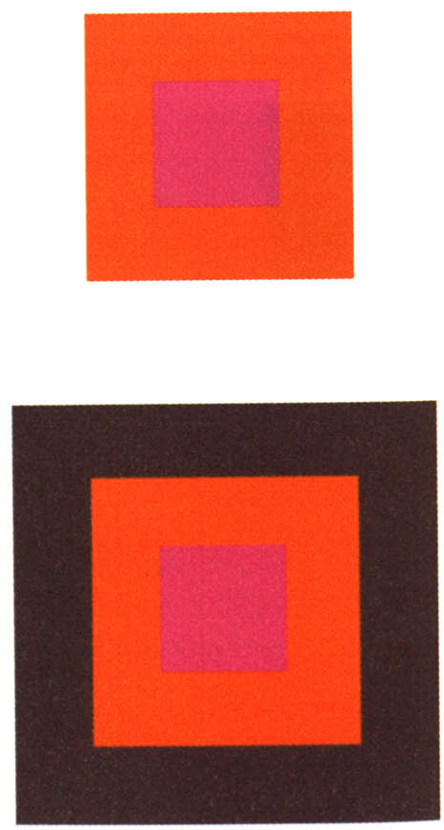


Figure 61. Enclosed relationship.

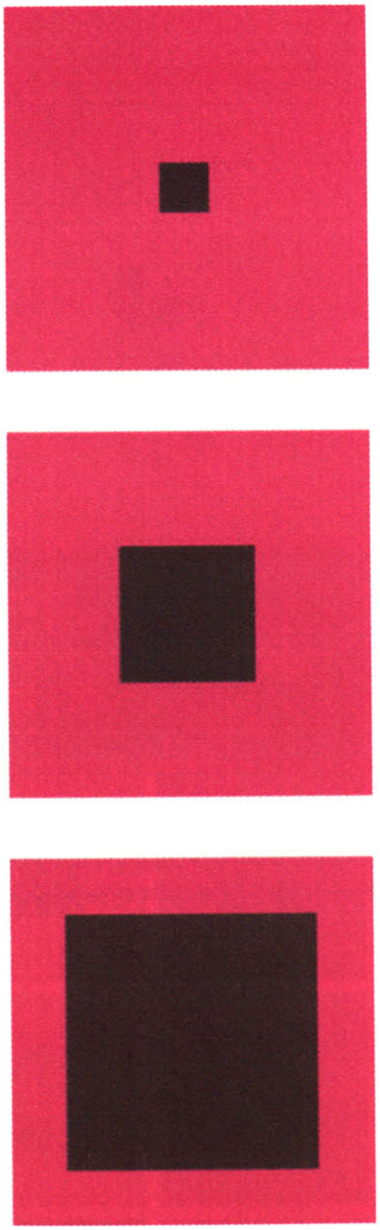


Figure 62. On top of vs. enclosed.

1) Stripes with varying width are moving around the scene. Colors along the stripes are changing randomly. When colors at pixels where stripes overlap satisfy the relationship of certain set, they will mix into a single color, otherwise those overlapping parts will be painted as transparent layers.

2) Dense flows of color pixels are moving around the scene. When the color of some pixels form certain set relationship with their neighbors, they will stop independent movement, form a shape, move and distort as a unit from then on.

3. Types of color interaction or context

Besides the contrast of hue, luminance, saturation, and extension, the surrounding relationship (both in grid and in enclosed relationship) in 2D composition makes simultaneous contras another prominent figure in forming the enriched effect out of color interdependency.

4. Type of set composition

Some visually meaningful 2D set compositions are:

1) In many of Klee's grid based compositions, there are systematic designs of the luminance of colors throughout the grid. These designs are either used to achieve interesting tonal patterns or to suggest certain direction or path of movement based on systematic tonal relationship. Both cases are similar to composition of luminance-based color-class set.

2) In a series of experiments, Klee applied set operations to colors in a grid spatially. Fig. 63 displays the operation of reflection and complementary reversal.

3) In *Computer Graphics: Color-Based Color*, Edward Zajec introduced a more systematic

application of set operation in spatial context. A series of four colors (ordered set) is first chosen to be the basic vocabulary and serves as the organizing principle. Seven more series are then derived from the original series through permutation. Following different design of spatial movement of the principle series, 4 by 4 matrices are formed along time out of the eight color series variations.

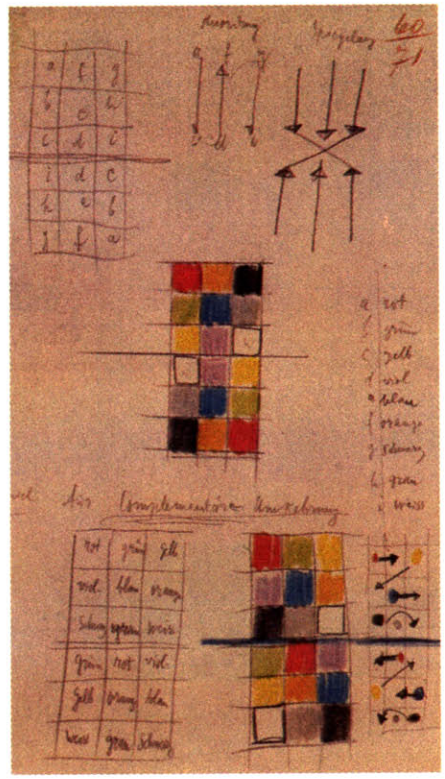


Figure 63. Reflection and complementary reversal (sketch by Klee from *The Nature of Nature*, P146).

3D

By 3D I do refer to 2D plus the dimension perpendicular to the screen. However, the third dimension I am addressing here is not the third dimension represented through perspective but the depth suggested by luminance and other color-related visual hints.

As discussed throughout this study, colors on the color circle have varying values of luminance and thus suggest different depth effects. To decide the exact relative depth between colors, color of the background to be taken into account (context again!). On black or dark background, the higher the luminance, the closer a color looks. Whereas on white or bright background, light colors seem to be held to the plane of the background and dark colors advance forward.

The accurate control of color dimensions on the computer and the concept of luminance-based color class and color-class set provide the basis for composing the depth relationship systematically. Besides designing depth patterns across individual colors, the tonal plane concept introduced before presents the depth composition along a different line of thinking. By organizing colors into planes with different luminance and suggested depth the theme of the set is revealed along the third dimension.

Itten wrote in The Art of Color: “Forces acting in the direction of depth are present in the color itself.” Besides luminance, other aspects of color and color application also affect our depth perception. For example, warm color advance, cold color retreat, pure color advance relative to a duller one. These factors can all be considered in the composition of the depth dimension.

4D(3D + time)

Temporal visual composition is by nature spatial-temporal. Its realization is relying on both dimensions. Any component in the temporal composition has to present itself visually in a spatial format. There is no temporal melody, temporal context, or temporal development that can be discussed totally independent of the spatial properties. On the other hand, time is already part of many of the spatial composition ideas described above, such as the grid cell expansion and the two 2D graphical scenarios.

This intertwined relationship between spatial and temporal design is further revealed in the following experiments.

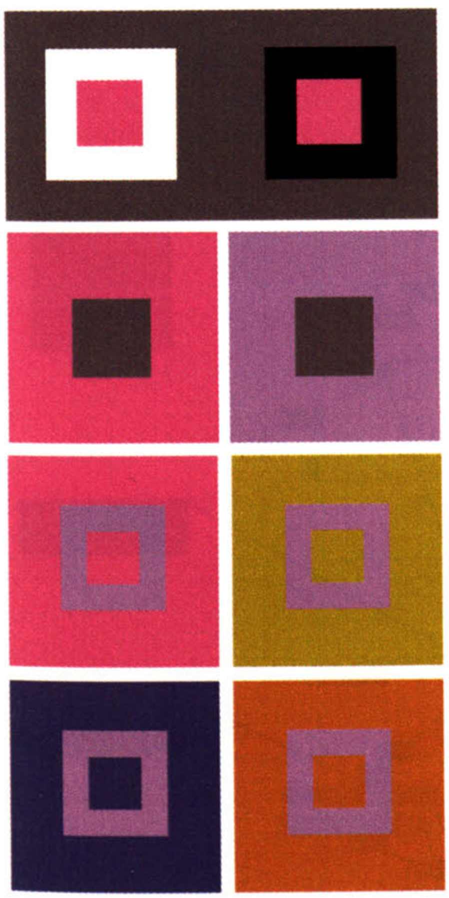


Figure 64. Color interaction studied through color change along time.

Colors changing along time must reside in certain spatial organizations, whether they are as regular as the color grid or as irregular as random strokes of colors. When designing the temporal color development, it is important to consider at the same time how the color perception would be affected by spatial context. A series of experiments was carried out to look at this issue from different point of views.

1. Spatial relationship at points in time vs. spatial context of a changing color

   As displayed in Fig. 64, the experiment uses some of the layouts in Itten's study about the relative nature of color perception, simultaneous contrast, and color expression in relate to other colors. Different from Itten's study though, the focus here is how the surrounding colors would affect a changing color. Instead of analyzing a whole sequence of static spatial relationships at different points in time, it is more akin to the current study to look at how the changing color as an entity is being affected.

2. Spatial context from temporal changes

   The nature of the experiment is further changed when the surrounding colors are also under change. It could either be thought of as experiment about how a color or its temporal change would be affected by other temporally changing entities around it, or be thought of as an experiment on how the temporal change of a color's context would affect the perception of this color or of this color's temporal change.

3. Perception of temporal change affected by spatial relationships

   Fig. 65 illustrates the idea for another line of experiment: how the perception of the same group of temporally changing entities would be affected by their spatial composition. In the simple test captured in Fig.65, a set theory-based music composition is used to trigger the color change. The three voices in the music are mapped to three color blocks. The dynamically changing color blocks are then laid out in three different ways to show how the spatial composition would affect colors with the same temporal change.

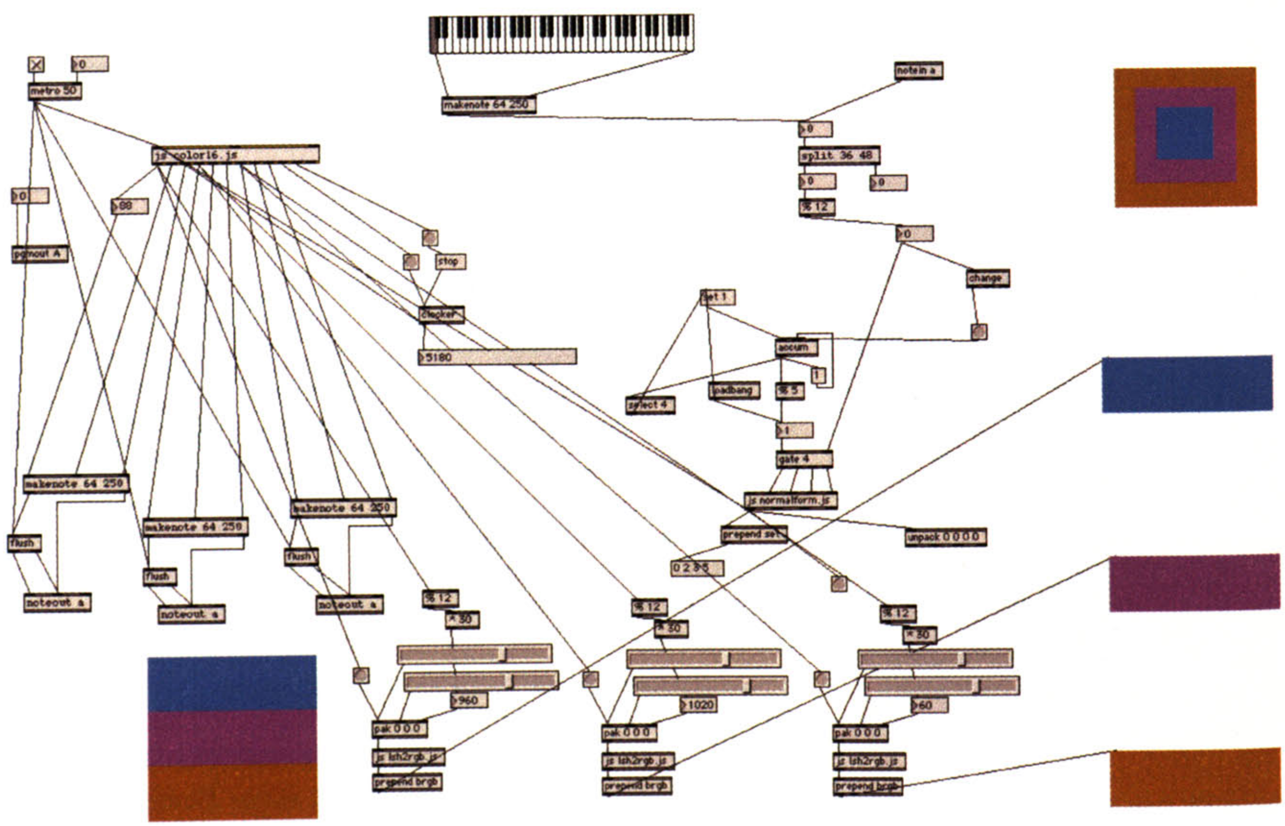


Figure 65. Temporal color change triggered by set theory-based music in different spatial layouts.

The supportive relationship between the spatial and temporal composition is also presented through experiments of using spatial rhythmic pattern or progression to enhance the perception of temporal rhythm or melody.

Limited by the long tradition of using static medium for visual creations, we normally don't have a clear picture of what a temporal rhythmic pattern "looks like". Some visual experiments are carried out to help gain a concrete sense of temporal pattern presented through visual instead of aural media. In some of the experiments, temporal rhythmic patterns similar to those in music are used to directly trigger the display of colors or forms. However, without any visual trace left in the graphics, it is hard to form the perception of the temporal pattern simply by connecting the memory of the moments when the colors are being displayed. In further experiments, the temporal pattern is integrated into the spatial composition through various means. And the perception of the temporal rhythmic pattern is strongly enhanced by its graphical "presence".

Figure 66. Spatial rhythm.

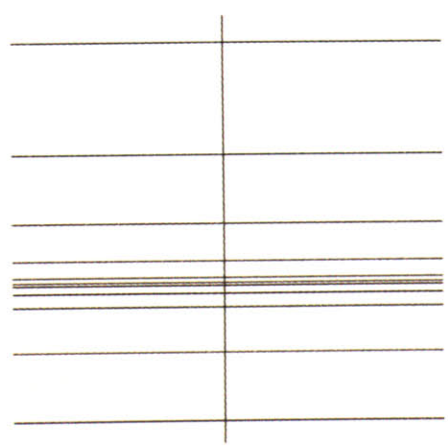


Figure 67. Spatial progression.

Two examples of the spatial integration are: 1) reflecting temporal rhythm in spatial rhythmic pattern sharing similar intervallic properties; and 2) employing temporal rhythm to control the temporal revelation of the spatial progression of lines or other graphical elements.

Scales of the Abstract Compositions

The abstract spatial temporal set compositions explored above can be graphically realized at different scales. On one end, the color grid and other combinations could form the whole scene; on the other end, they could also be used as patterns in a bigger composition with each color cell in the grid as a pixel.

Similar to Klee's concept of dividual and individual, the application of certain combination at different scales can also be interchangeable and can be used as an articulation of the structure at another level.

Set and Spatial Temporal Patterns

In music, the thematic characteristic of a set can be enhanced through using rhythmic patterns typical to that style. Color-class sets also forms themes with unique characteristics either from the design point of view, from visual perceptual and psychological point of view, or from cultural consideration. Spatial and temporal patterns working well with different color-class sets could be explored and employed during the composition to strengthen the overall coherence initiated by the set.

Chapter 4. Experiments

The set theory-based approach is experimented in a series of graphical studies and digital art creations. This chapter describes in detail the experiments at these two levels and discusses some perceptual and compositional issues about temporal visual composition studied along with the experiments.

4.1. Five Studies on Themes of Paul Klee

"Ingres is said to have created an artistic order out of rest; I should like to create an order from feeling and, going still further, from motion." (Klee) This sentence at the beginning of Paul Klee's *The Thinking Eye* expresses his interest in looking at visual art from the process point of view, both in terms of the artists' process of creation and in terms of the beholders' process of appreciation. Consequently, he experimented in many of his creations various graphical means to introduce the temporal dimension to visual art and the order and design involved for this procedural aesthetics.

Klee has also looked intensively into musical composition for principles essential to art in general and employed them in his pictorial compositions. This idea is clearly stated in his writing on polyphony: "There is polyphony in music. In itself the attempt to transpose it into art would offer no special interest. But to gather insights into music through the special character of polyphonic works, to penetrate deep into this cosmic sphere, to issue forth a transformed beholder of art, and then to lurk in waiting for these things in the picture, that is something more. For the simultaneity of several independent themes is something that is possible not only in music; typical things in general do not belong just in one place but have their roots and organic anchor everywhere and anywhere" The thematic development of shapes and the rhythmic articulation and tonal movement of colors are some of such examples.

Because of the common interest for the temporal aspect of visual creation and the similar approach of looking into music for inspiration, when brainstorming graphical content for my experiments, the idea of using some themes in Klee's painting as the starting point came to my mind. With the underlying temporal and compositional thinking, the graphical elements in those paintings already share a common language with the experiments undertaken.

Through a thorough analysis, five themes are identified out of Klee's paintings to be as graphical ideas to start from: Color Timbre, Cardinal Progression, Tonal Scale, Fugue, and Polyphony. The titles are given based on their graphical characteristics or their potential use in temporal visual composition. Studies along the following directions are carried out for each theme:

1) Analyzing the graphical vocabulary, temporal implications, and compositional characteristics of the theme.

2) Designing algorithms reflecting the above properties.

3) Developing interfaces for generating and playing with the graphical and compositional vocabularies in each theme.

4) Expanding the temporal and compositional thinking already existed in the static graphics, creating temporal composition employing the set theory-based approach.

5) Studying temporal perception and composition issues introduced during the experimentation over each theme.

The musical sense in Klee's paintings has also attracted Gunther Schuller to translate the paintings into music. Thus came his most famous musical work, *Seven Studies on Themes of Paul Klee*. The title for this section, *Five Studies on Themes of Paul Klee,* is created as a reminiscence of this composition for the common connection to Klee's work and artistic thinking.

In the following part of this section, the characteristics of each theme and the interface, algorithm and compositional experiments developed under them are first introduced. Some perceptual and compositional issues unique to temporal visual composition introduced during the experimentation are then discussed together.

4.1.1. Graphical Experiments

Color Timbre

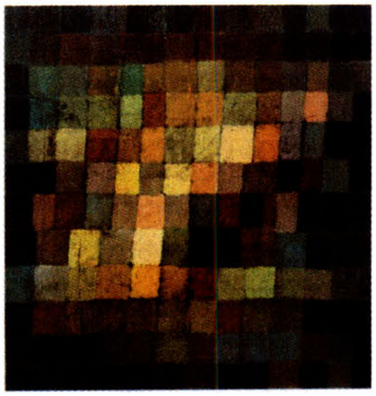


Figure 68. Alter Klang, 1927.

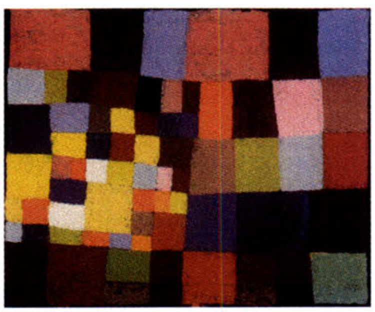


Figure 69. Garden in Bloom, 1930.

Figure 70. Blue-Orange Harmony, 1923.

The following works and experiments by Paul Klee are categorized under this theme.

Color Table (On Major Grey), 1930, pastel combined with black paste on paper mounted on cardboard, Kunstmuseum, Berne.
New Harmony, 1936, oil on canvas, The Solomon R. Guggenheim Museum, New York.
Blossoming, 1934, oil on canvas, Kunstmuseum, Winterthur.
Rhythmical, 1930, oil on canvas with original frame, Center Georges Pompidou, Paris.
Rhythmical, More Rigorous and Freer, 1930, watercolor paste on paper mounted on cardboard.
Harmony of Rectangles in Red, Yellow, Blue, White and Black, 1923, oil on cardboard, Kunstmuseum, Berne.
Blue-Orange Harmony, 1923, oil on paper, private collection.
Pictorial Architecture, Red, Yellow, Blue, 1923, oil on board, original frame, Kunstmuseum, Berne.
Alter Klang, 1927, oil on cardboard, Offentliche Kunstsammlung, Basle.
Garden in Bloom, 1930, paint and pastel with paste on a black ground on paper, private collection, Switzerland.
Color Plate Qu1, 1930, pastel with colored paste.
Abstract in Relation to a Flowering Tree, 1925, oil on cardboard.
Static-Dynamic Gradation
Flora on the Sand
Architecture, 1923, oil on board, Staatliches Museum, Berlin
Harmony of the Northern Flora, 1927, oil on chalk-primed cardboard, private collection, Switzerland.
Fire at Full Moon, 1933, watercolor, wax coated, on canvas, Folkwang Museum, Essen.
Garden by the Stream, watercolor on paper, private collection, Switzerland.
Glass Façade, 1940, wax crayon on burlap, Kunstmuseum, Berne.

Graphical characteristics

1) Paintings in this category all have the similar appearance of a chessboard-like grid filled up with rich variations of colors.

2) Most of them also share the property of having relatively darker colors in the surrounding area, and brighter ones towards the center.

3) Some have the tendency of splitting the grid into smaller ones towards the center. The bigger & darker outside and smaller & brighter inside design might follow Klee's idea of achieving visual harmony through the balance between dimension and energy.

4) Many of them suggest different levels of movement through distortion, or using Klee's words, "irregular projection with highly mobile (perhaps fluid) base." In some of them, the colors work together with the distortion in creating the suggested movement. For example, in *New Harmony* (Fig. 71), colors close in luminance and saturation on the slightly distorted grid creates "a gentle rocking and swinging effect radiating a sense of playful effortlessness" (Düchting). In *Blossoming* (Fig. 72), colors in high contrast of both hue and luminance work well with the more intensive distortion and size change of the grid in suggesting a wave-like motion. In *Rhythmical* (Fig. 73) and *Rhythmical, More Rigorous and Freer*, the repetitive and abrupt color contrast along with the distortion of the grid into horizontal bars suggests a strong rhythmical to and fro movement.

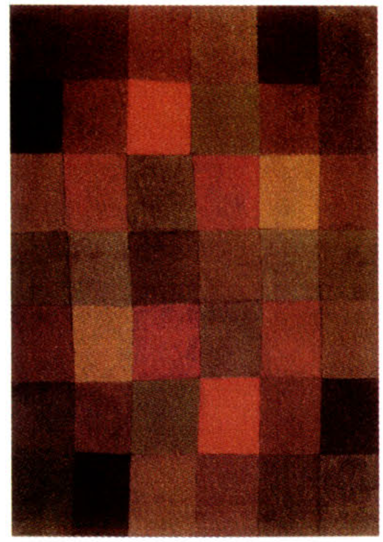


Figure 71. New Harmony, 1936.

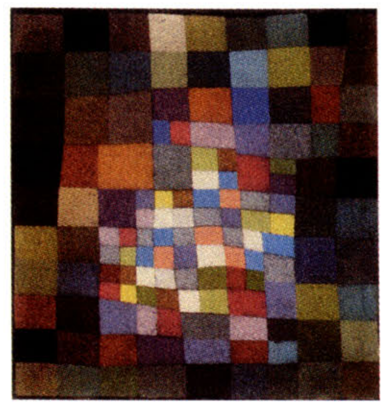


Figure 72. Blossoming, 1934.

Figure 73. Rhymical, 1930.

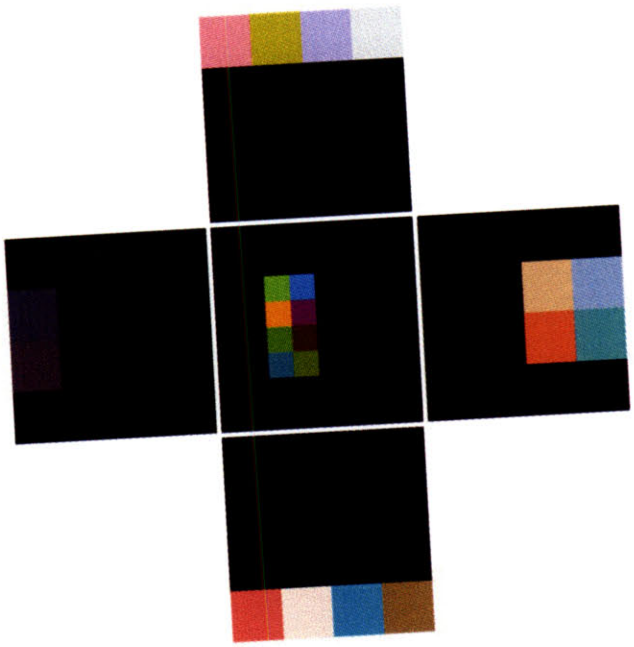
Interface Design

When doing experiments under each theme, an intuitive environment for playing with key features of the theme would be very important for generating new composition ideas. Even though the final composition might be created algorithmically through programming, I believe that a direct interaction with the graphical components provides an opportunity for the artists to experience the essential property of the design and could help bring up creative ideas which are impossible otherwise. John Whitney's writing about color use addressed similar topic on the importance of intuitive exploration, "Color for the painter is normally an intuitive experience of direct one-to-one interaction between three components – pigment, hand and eye. These intimate hands-on interactions call upon a part of the creative mind other than the reasoning channels…"

Interfaces for the theme experiments are all connected to the main interface, taking advantage of the intuitive color selection through color keyboard and the systematic time control through the absolute timeline. The structure and main features of the main interface are introduced in detail in

Chapter 5, *Consolidation of Technology available for Temporal Visual Composition.*

The matrix-based graphics data organization in Jitter works well with the color grid graphical property of this theme. The high-level design features could be achieved by directly controlling the low-level native components in Jitter graphics computation and rendering. This offers great convenience in both the interface and the algorithm development.



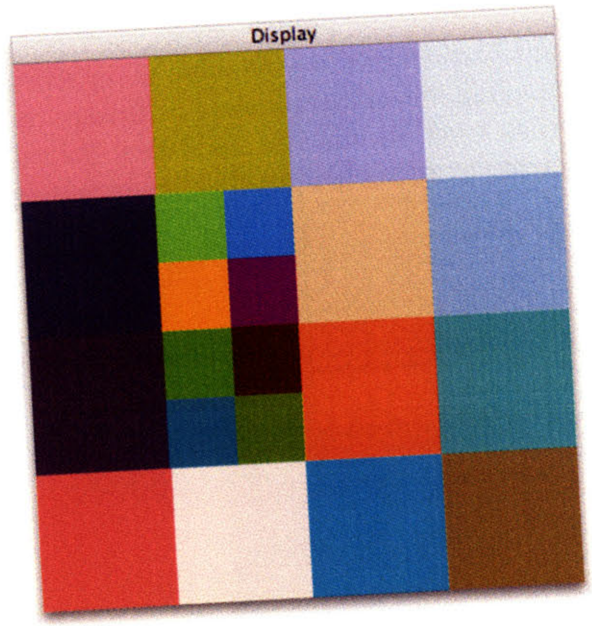


Figure 74. Matrix-based interface for color timbre (working matrix and final graphics).

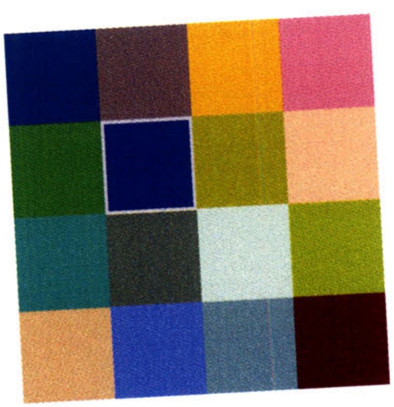


Figure 75. Change colors in the matrix manually.

As displayed in the Fig. 74, the user can choose any part in the main matrix and embed new matrix to the selected area. Colors in the grid are simply RGB values stored at the matrix cells and can be defined and updated easily. With this feature, both the grid splitting and the color design could be experimented at will.

The color in the matrix cells could be defined through programming. They could also be defined or edited manually by assigning color selected from the color keyboard to the selected cell (Fig. 75). With the tight connection to the color keyboard, one could also move the mouse around the palettes in the color keyboard and observe the color change of the matrix cell, finalizing a color when it looks good within the spatial context in the matrix.

In order to create the movement effect, a nurb surface is created in Jitter. The matrix graphics generated through the above process is mapped to the nurb surface as texture. By adjusting parameters controlling the movement of the nurb surface, movement with different intensity could be generated. Fig. 77 displays some examples. The movement of the nurb surface could be generated by defining the behavior of the surface algorithmically in the code. It could also created manually by adjusting the x, y, z values of the control point matrix of the nurb surface (see Fig. 76). The cellblock object in Jitter provides a matrix layout for changing the values with spatial mapping to the image. The process of editing the values corresponding to a point in the space is similar to sculpting the surface, pulling it forward or pushing backward. When working with the timeline at the same time, one could sculpt the matrix both spatially and temporally.

Figure 77. Color timbre suggesting movement of different intensity.

-0.9000	-0.5000	0.0000	0.5000	1.0000
-1.0000	-0.5000	0.0000	0.2000	1.0000
-1.0000	-0.2000	0.0000	0.5000	1.0000
-1.0000	-0.5000	0.0000	0.5000	1.0000
-1.0000	-0.5000	0.0000	0.5000	1.0000

-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
-0.5000	-0.5000	-0.5000	-0.5000	-0.5000
0.0000	0.0000	0.0000	0.0000	0.0000
0.5000	0.5000	0.5000	0.5000	0.5000
1.0000	1.0000	1.0000	1.0000	1.0000

0.0000	0.000
0.0000	0.000
0.0000	0.000
0.0000	-0.50
0.0000	0.000

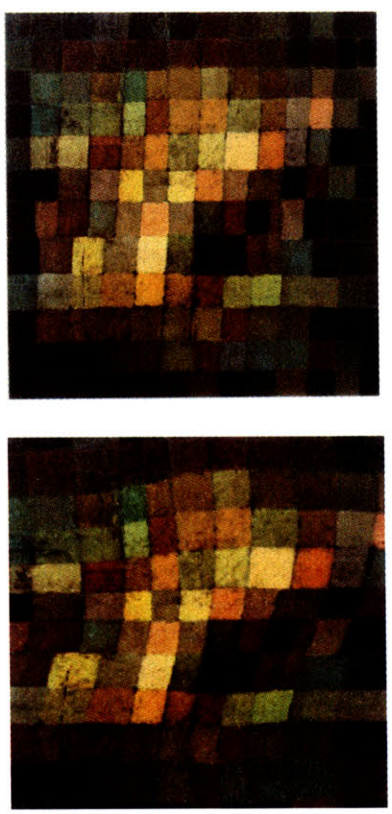


Figure 76. Manual sculpting.

The above figures displays the cellblock object and one example of the editing of Klee's painting *Alter Klang*.

Algorithm Design

In order to employ the compositional vocabularies in each theme into large-scale compositions, algorithms are designed for generating characteristic graphical and compositional features through programming.

For this theme, an algorithm is designed to split the matrix cells when moving from the surroundings towards the center, and change the luminance and saturation of colors applied to each cell at the same time. The principle for the color change is that the smaller the dimension of the cell, the higher the luminance and saturation of the color.

Compositional Thinking

1) Color orchestration vs. color timbre

In his analysis of paintings under this theme in *Painting Music,* Düchting writes: "The different shades of color combine like musical chords into a harmonic whole, in which the mood communicated by the colors is analogous to that of major or minor keys. The rich orchestration of color tones appears as a unified whole, even though the eye can still detect individual melodic phrases and differentiated structural rhythm."

Here Düchting looks at the paintings as orchestrations, as compositional pieces. However, in temporal visual creations, the time assigned to each static scene is far from enough for the viewer to discern these rich compositional contents. I would propose to metaphorically think of these spatial compositions as color timbre, which could be further designed and employed in the temporal composition.

Klee himself had actually once described his color design using terms for musical timbre metaphorically. He looks at the hue of colors as one dimension, and sees the space out of color distance. "A wide span from pole to pole lends space to breathe in and out deeply, which can even turn into a wheezing struggle for air. A lesser span muffles the breath into a sotto voice. Around about the grey area, it is only possible to whisper. Either you raise yourself above this position to the violins or sink below it to the violoncellos."

Guided by the set theory-based approach, the color timbre could be formed out of color members in a set and their transformations along time. Subset or individual set member could be emphasized as the key color similar to the fundamental frequency in a musical timbre.

The orchestration view would still be valid if we look at the scene area spatially and think of things that happen within this area across time as the visual content. Similarly, during the temporal visual composition, spatial wise, one should consider the coexistence of the overall orchestration and the rich individual melodies and rhythms.

2) Multi-threading

Graphics under this theme is closest to the impression a tapestry could give to people. On top of the basic graphical layout, multiple lines of color development could be presented temporally through color change of individual cells, presented spatially by making the graphics as woven out of multiple threads of colors, or presented spatial-temporally by making colors across those threads changing along time, or from another point of view, making colors moving along those threads across time.

Issues introduced in the experiments under this theme which merit further discussion include:

1) Temporal change within spatial context: how the temporal change of one color cell would affect and be affected by its surrounding colors and the overall spatial composition. "Psychologically, it is neither color nor sound, absolute, isolated, which touch and influence us, but the alternating series of color and sounds. Thanks to its principle of mobility, the art of colored rhythm increases this alternation which exists already in ordinary painting, but only as a group of colors simultaneously fixed on an immobile surface and without changing relationships" (Survage). Temporal visual compositions starting from graphics under the current theme would fit the best what is being described in Survage's writing. Here, the color alteration or change along both the spatial and temporal dimension are rich and vivid. How could we

integrate these two lines of alternation organically and how to take advantage of the contributions from both the spatial and the temporal aspects in creating an engaging visual experience are the issues requiring further study.

2) Temporal change of spatial composition: how the temporal evolvement of the overall spatial composition could preserve certain identity over time and won't be lost in the changes of individual cells.

3) Designed eye movement: in many paintings under this theme Klee experimented the idea of creating certain path based on luminance or color change to guide the beholders' viewing process and consequently the appreciation of the work. What would then be the means to create such paths in temporal visual creations? The luminance or hue gradation across grid cells would be too subtle for the viewer to catch during the rapid change of the visual content. Emphasizing points along a path across time could be one alternative.

Cardinal Progression

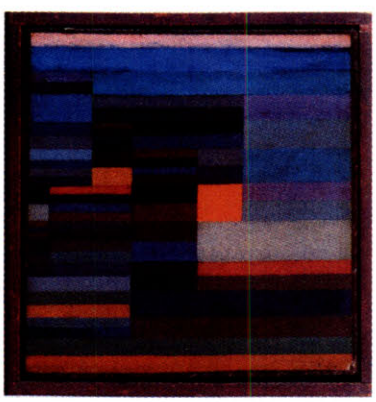


Figure 78. Fire in the Evening, 1929.

Following is a list paintings under this theme.

Fire in the Evening, 1929, oil on board, The Museum of Modern Art, New York.
Monument in Fertile Country, 1929, watercolor and pencil on paper mounted on cardboard, Kunstmuseum, Berne.
Highways and Byways, 1929, oil with a plaster ground on canvas, Museum Ludwig, Cologne.
Moving Rapids, 1929, watercolor.
Castle of a Chivalric Order, 1929, pen-and-ink.
Young Trees on Cleared Ground, 1929, India ink and pen-and-ink.
Colored-Woman, 1929, pen-and-ink and watercolor
Little Ensign at the Foot of the Mountain, 1929, pencil.
In the Current of Six Crescendos, 1929, oil.
Old man reckoning
Movement in Locks, 1929, pen drawing on paper, private collection, Switzerland.

Graphical Characteristics

1) Paintings under this theme share the same form of visual articulation Klee called ‘cardinal progression’. In this structure, horizontal fields are dissected in many places by vertical or slanting lines. At the point of dissecting, the horizontal field is split on one side into halves of the other side. “The logic of this is reminiscent of musical notation in which a semi-breve has the same value as two minums, four crotchets, eight quavers and sixteen semi-quavers.” (Düchting)

2) The complex and systematic linear structure described above is similar to a framework for rhythmic design in music. With the existence of such a framework, colors could be employed vividly and expressively without loosing the coherent order important for visual construction.

3) The linear composition and the color composition in these paintings form an inseparable whole. On the one hand, the articulation of one of them relies on the other; on the other, the color and linear composition come to the beholder one after another, competing for the attention in an unsettling way. To go back to the analogous in 2) above, this inseparable relationship might be similar to the relationship between melody and rhythmic patterns in music.

Figure 79. Monument in Fertile Country, 1929.

Figure 80. Highways and Byways, 1929.

Interface Design

The interactive matrix editing interface described in the previous theme is applicable for the experiments under this theme as well.

Algorithmic Design

An algorithm is designed to place vertical or slanting lines to a grid made up of parallel horizontal lines. On one side across the length of each vertical or slanting line, the intervals between the intersecting horizontal lines will be split in halves by adding another horizontal line starting from that intersecting place. By adjusting the position and length of the

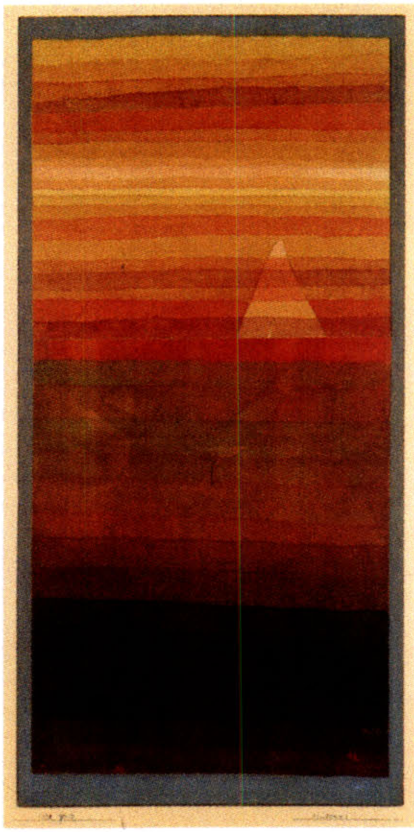


Figure 81. Lonely, 1928.

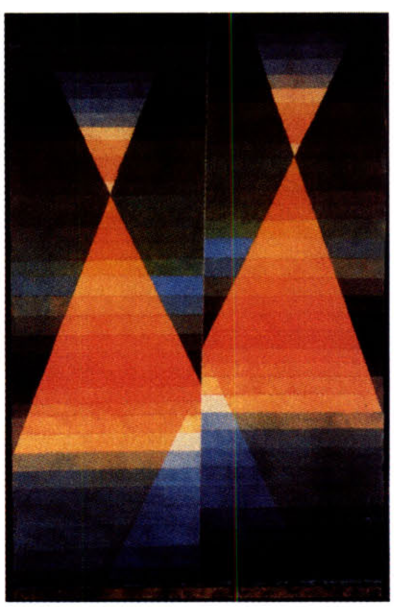


Figure 82. Double Tent, 1923.

vertical or slanting lines, different designs of the cardinal progression type of linear constructions generated automatically. Two modes could also be chosen from to decide whether the pattern generated will follow certain schematic design or not. For example, one schematic design could be developed by only splitting the intervals on the side closer to the edge.

Compositional Thinking

1) The tight connection between the linear construction and the color composition make it possible to use the spatial pattern to enhance the color design. For example the linear pattern could be divided and shaped in certain way to emphasize the visual property of the color applied to that area.

2) The rich variations of intervals out of the systematic cardinal progression relationship renders this type graphics a good test field for experimenting with the grouping of set members or the use of subsets in generating subtle but powerful color transitions.

Issues Introduced

Paintings under this theme are vivid examples displaying the importance of systematic spatial structure in color composition. They point out the direction of studying and developing graphical systems similar to rhythmic structure in music.

Tonal Scale

The following experiments and works by Klee are categorized under this theme:

Lonely, 1928, watercolor on paper, private collection, USA.
The Herald of Autumn, 1922, watercolor.
Separation in the Evening, 1927, watercolor on paper, mounted on board, private collection, Switzerland.
Contrast at Night, 1924, watercolor and gouache.
Just before the Lightning Flash, 1923, watercolor
Scene of Calamity, 1922, watercolor, pen drawing with Indian ink on pencil, paper mounted on board, Kunstmuseum, Berne.
Eros, 1923, watercolor on paper, mounted on board, Angela Rosengart Collection, Lucerne.

Double Tent, 1923, watercolor on paper, Angela Rosengart Collection, Lucerne.
Group Linked by Stars
Articulated Movement on a Black Base with Differential Movement in the Tonal Area, an example from one of Klee's lessons.
Articulated Movement with Movement Differential in the Tonal Region, figuration example from Klee's lectures.
Unambihuous Movement and Countermovement (in a plane)
Battle Scene from the Comic Opera "The Seafarer", 1923, watercolor, Kunstmuseum, Basle.

Graphical Characteristics

1) Works under this theme all have the graphical component of transparent color band. These bands are normally designed to gradate from one color to its complementary, from light to dark of one color, or from white to black. Many of them are only composed of horizontal bands, some have bands going both horizontally and vertically, such as *Just Before the Lightening Flash* (Fig. 84), some are overlaid with diagonally dissected areas, such as *Unambiguous Movement and Countermovement* (Fig. 85) and *Double Tent* (Fig. 82). When these works are originally created, Klee used a wet-on-dry wash technique applying watercolors layer for layer onto grids made up of parallel lines.

2) The works all displays a strong sense of rhythm through the clear luminance or hue difference across the bands.

3) Some of them show transition from one pole to another either in terns of hue or in terms of luminance. Some suggest different type of movement through different value change across the bands. For example in *Articulated Movement with Movement Differential in the Tonal Region* (Fig. 83), horizontal bands with different luminance change patterns are used to express the movement of standing, gliding, striding, and leaping.

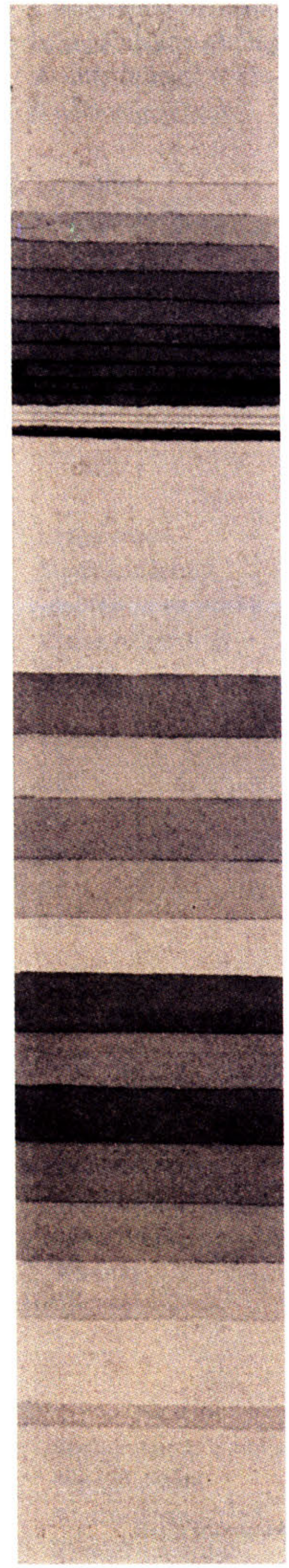


Figure 83. Articulated Movement with Movement Differentials in the Tonal Region, 1929.

Interface Design

A 1D matrix is used to provide easy control of the number of stripes generated and their values. The figure on the right

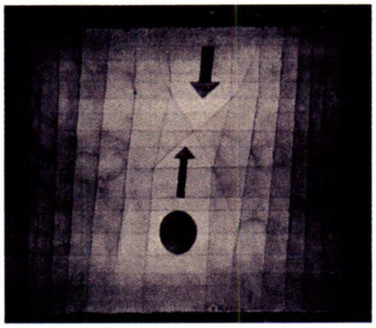


Figure 84. Just before the Lightening Flash, 1923.

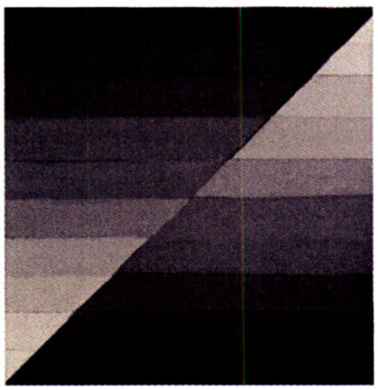


Figure 85. Unambiguous Movement and Countermovement.

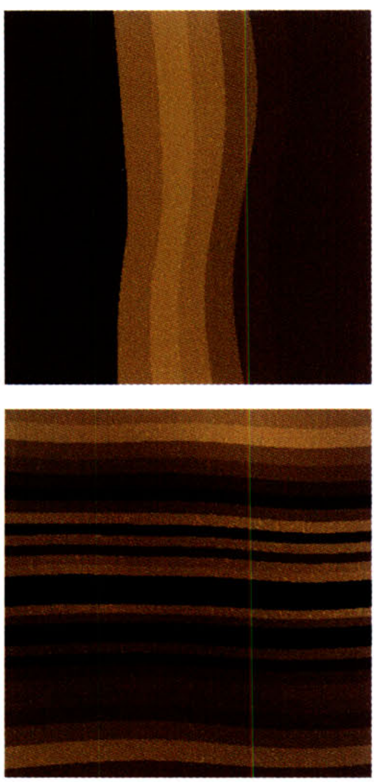


Figure 86. Example creations of vertical and horizontal stripes.

displays two experiment graphics generated from controlled and random 1D matrix. (Fig. 86)

Algorithmic Design

Instead of controlling the generation of spatial patterns, the algorithm developed for this theme focuses on value change, hue or luminance, across the stripes spatially and their change temporally.

Compositional Thinking

1) Many of the works under this theme are from Klee's study about tonal scales. He plotted the equal interval progression from black to white and return using the wet-on-dry technique, and called this the tonal scale. He studied order, tension, and movement created out of the scale framework. With the easy control of luminance in digital color, it is now possible to expand the exploration along this direction, build and use scales out of luminance in a way similar to scales in music. Rich compositions could be created on top of the scale framework both spatially and temporally.

2) The luminance-based set proposed in this study is a concrete example of the above general idea about music like scale. The set members define members in the scale similar to defining the members in the major or minor scales in music. Because of the easy control of luminance across colors in digital media, the application of the luminance set or scale is not restricted to black and white or achromatic colors. Tonal planes or progressions could also be generated across chromatic colors.

Issues Introduced

1) The strong sense of rhythm in most works under this theme suggests an analysis of the factors leading to this effect or the visual element needed for the generation of rhythm graphically.

2) How to take advantage of the luminance-based scale in creating rich and coherent effect, what is the role of rules or systematic frameworks in the creative process? Similar to the role of the graphical rhythmic system in

the previous theme in supporting color composition, the visual scales could prevent the rich variations of color from becoming random by providing necessary confinements. Abraham Moles addressed this topic in his book *Information Theory and Esthetic Perceptions*: "There is no art without constraint. To say that music is an art is to say that it obeys rules. Pure chance represents total liberty, and the word construct means precisely to revolt against chance. An art is exactly defined by the set of rules it follows." Rules or systematic frameworks have never played as crucial a role in visual creations as in music. How rules are valued and employed in musical composition is worth looking into and borrowing from analogously.

Figure 87. Growth of Night-Blooming Plants, 1922.

Fugue

The following are works in this category:

Fugue in Red, 1921, watercolor on paper, private collection, Switzerland.
Growth of Night-Blooming Plants, 1922, oil on cardboard
Crystal Gradation, 1921, watercolor
Dream City, 1921, watercolor on paper mounted on board, Staatliche Museen, Berlin.
Nocturne for Horn, 1921, watercolor, private collection, USA
Growth, 1921, oil on cardboard, Musee National d'Art Moderne, Paris.
Spirits (Figures from a Ballet), 1922, watercolor and pencil on paper, Kunstmuseum, Berne.
Cool Dry Garden, 1921, watercolor edged in tinfoil
Red Nuances, 1921, watercolor
Dying Plants

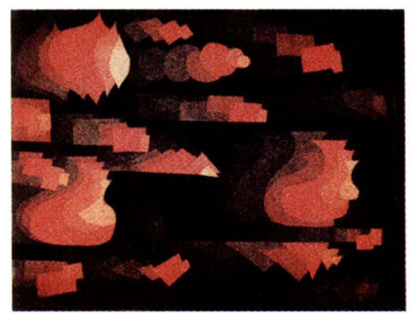


Figure 88. Fugue in Red, 1921.

Graphical Characteristics

Paintings under this theme all have the following two features:

1) Multiple themes represented by different forms.
2) Multiple layers of the same form with slight distortion, varying size, and luminance changing from dark to light.

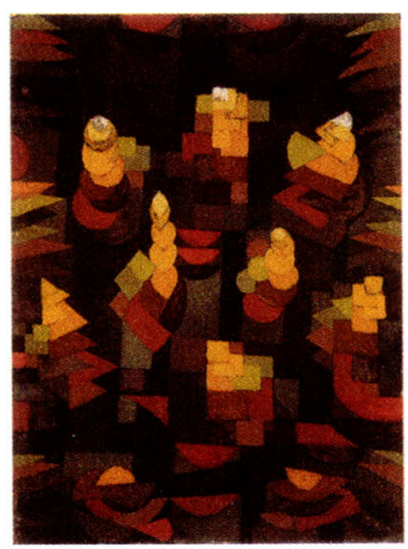


Figure 89. Growth, 1921.

The unfolding of the themes either take up the lead in the painting alternatively, as in *Fugue in Red* (Fig. 88), or penetrate and overlap each other, as in *Growth* (Fig. 89).

Interface Design

To make it easy to play with these features, an interface with the following functions is designed and developed.

1) Artists can draw the outline of the shape for a theme by creating and adjusting control points in a sketching place. The outline curve is then sent to another part of the interface where it will be filled up and made as a mask for texturing planes in the scene. (Fig. 90)

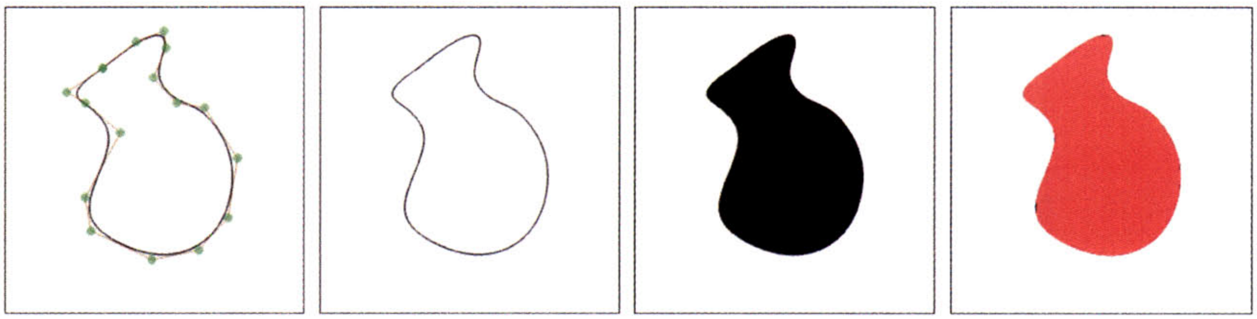
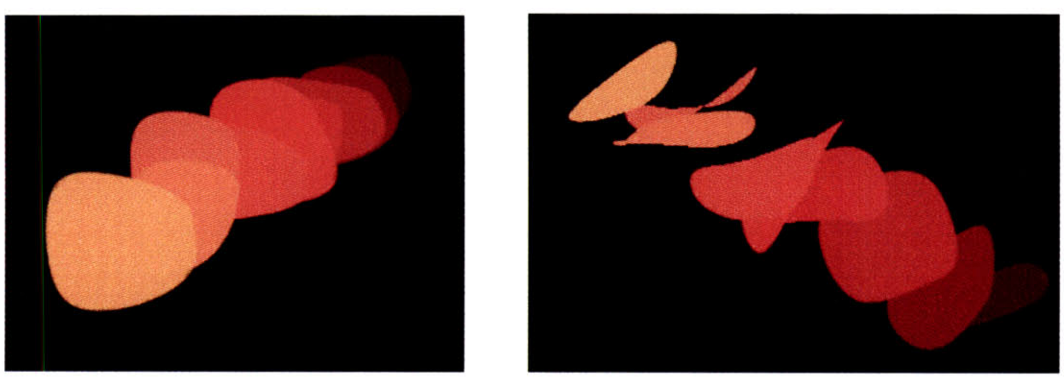


Figure 90. Creating theme shape using the sketching interface.

2) An interactive 3d scene is provided, in which the artist can insert different themes, adjust their positions, scales, and number of layers. The interactive 3d nature of the scene space also enables a 3d navigation of the picture space and the possibility of looking at the same graphical construction from different points of view. The following images are screen captures of some theme experiments.



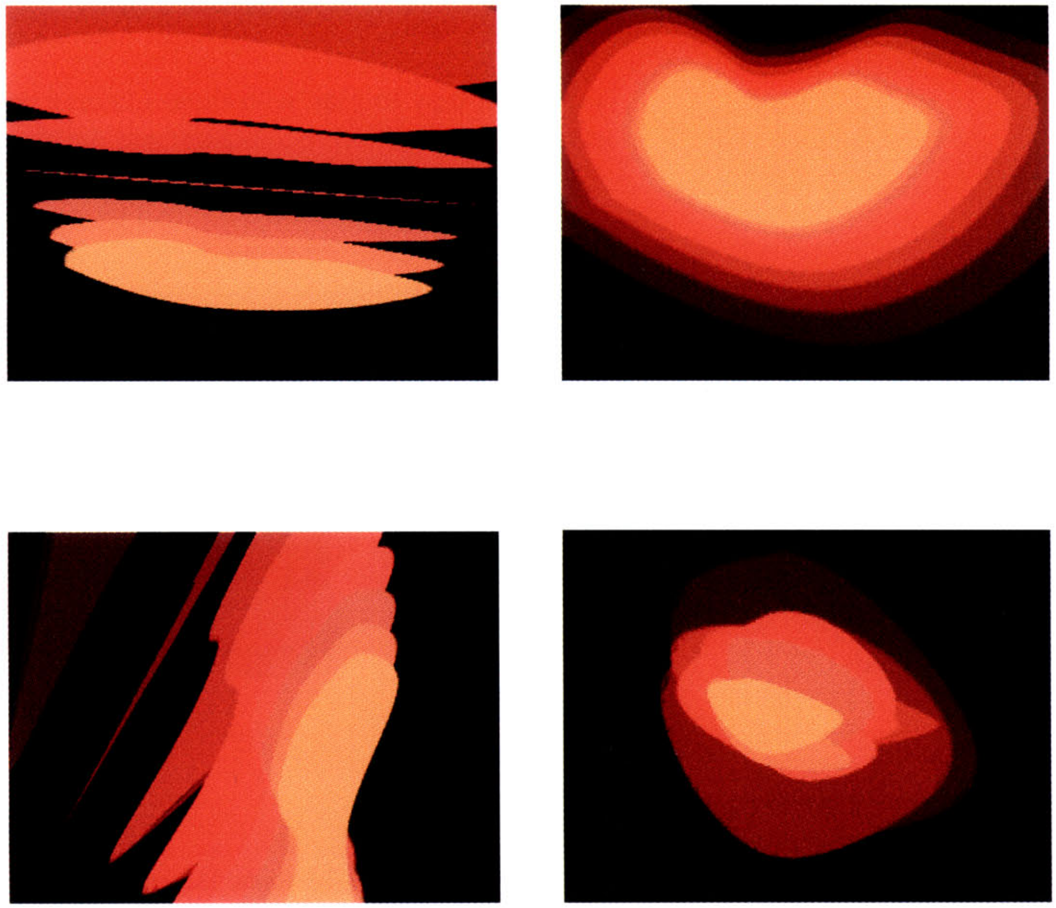


Figure 91. Experiments of theme shapes.

3) The distance between each layers of a theme and the size of each layer could be adjusted through an interface, in which points represent layers, the vertical position of the points represent the size of the corresponding layer, the horizontal distance between the points represent the distance between the layers along the dimension of progression.

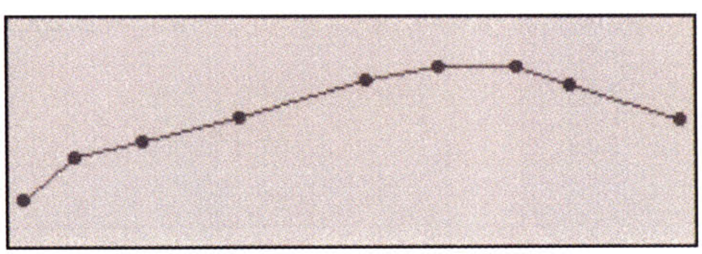


Figure 92. Interface for adjusting relative size and distance among theme layers.

4) A color palette connected to the color keyboard in the main interface is provided, with which the artists can prepare colors for each of the layers of a theme (Fig. 93). To edit or change a color in the palette, click the color block to select it. The color from the color keyboard will instantly update the selected color block and the color of the corresponding layer in the scene.

Figure 93. Color palette of the interface.

Algorithmic Design

An algorithm is designed to control the color change across the component layers of one theme (shape). The time and temporal rhythm parameters are employed to work together with the luminance and spatial parameters in composing a complex temporal color development across the theme layers.

Compositional Thinking

Will Grohmana interpreted the fugue structure in painting *Fugue in Red*: "The four main forms (jug, kidney, circle and square) can be interpreted as the theme, response, theme in the third and response in the fourth part. The alternating key signature is represented by the changing shape of the forms and the development of the theme is indicated in the color progression (yellow-pink-pink-violet)." In temporal visual composition, these fugue materials could be played with by many new means. For example, one could change the shape and spatial composition of the theme forms along time, designing a dynamic spatial relationship among the four parts of the fugue based on the overall compositional development. One could also change the size, distortion, and color of individual layers in a theme along time. Using the above described algorithm to design a theme development much richer than the one time luminance change from dark to light.

Issues Introduced

"The temporal element is clearly indicated by the way the mass of forms looms out of the dark background becoming increasingly more brilliant until finally achieving the brightness of colors" (Düchting). As displayed in this example, *Fugue in Red*, the graphical means could help express sense of time even in a static painting. How could they be wisely used to aid the temporal articulation in temporal visual creations? Besides the general sense of time, those floating progressions of colors and forms in *Fugue in Red* and other paintings under this theme also suggest a strong sense of rhythm. How then could these graphical resources be employed to present or enhance the temporal rhythmic pattern in a temporal visual composition? How could our precise spatial visual perception be of help for our relatively low-resolution temporal visual perception in constructing an accurate temporal framework? The general issue of exploring graphical resources aiding the temporal design and articulation is what is introduced by this theme.

Polyphony

The following works by Klee are under this theme:

Polyphonic Setting for White, 1930, watercolor with pen and ink on paper mounted on cardboard, Kunstmuseum, Berne.
Architecture of the Plane
House Interior and Exterior, 1930, watercolor.
Shifted Center of Gravity
Outside and Inside
Polyphony, 1932, oil on canvas, Offentliche Kunstsammlung, Basle.
Light and Sharpness, 1935, pencil and watercolor on paper mounted on cardboard, Kunstmuseum, Berne.
Ad Parnassm, 1932, oil on canvas, Kunstmuseum, Berne.
Three Subjects, Polyphonic, 1931, color.
Polyphonic-Abstract, 1930, watercolor.
Hill and Air, Synthesis, 1930, watercolor.
Unraveling Ball of Wool, 1932, black-and-white watercolor.
Ventriloquist and Crier in the Moor, 1923, watercolor and ink on paper mounted on board, The Metropolitan Museum of Art, New York.
Evening in the Valley, 1932, oil on board, private collection, Switzerland.
Palace Garden, 1931, oil on canvas, The Museum of Modern Art, New York.

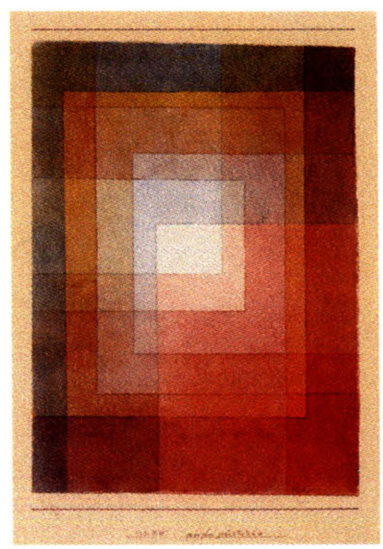


Figure 94. Polyphonic Setting for White, 1930.

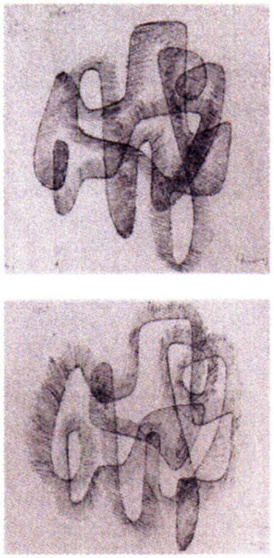


Figure 95. Swing, Polyphonic, 1931.

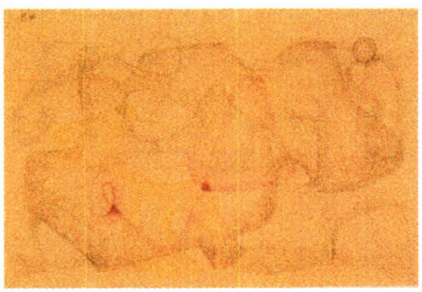


Figure 96. Dynamic-Polyphonic Group, 1931.

Figure 97. Light and Sharpness, 1935.

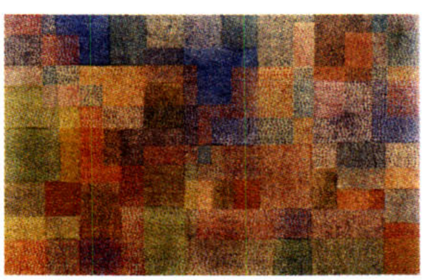


Figure 98. Polyphony, 1932.

Dynamic-Polyphonic Group, 1931, colored chalk on paper, private collection, Switzerland.
Swinging, Polyphonic (and a Complementary Repeat), 1931, pen and blue ink on two pieces of scratch paper mounted on cardboard, Kunstmuseum, Berne
Spring Picture

Graphical Characteristics

The common characteristics of paintings under this theme are that there are multiple structured areas resonating simultaneously like parallel voices in music. In these paintings, different graphical means are employed to construct these "voices":

1) Multiple parts are delineated by a single stoke crossing itself couple of times before forming a loop or by multiple strokes each enclose its own area. Color or graphical structures like cross-hatching are employed to mark each part. The intertwining of the parts and the permeation of the colors form the simultaneity of the voices. *Swinging, Polyphonic (And a Complementary Repeat)* (Fig. 95) and *Dynamic-Polyphonic Group* (Fig. 96) are examples of this type.

2) Transparent, overlapping color planes are used as the multiple voices. For example, in *Polyphonic Setting for White* (Fig. 94), eight color planes are composed spatially to achieve the designed path of movement through the interpenetration of colors across these transparent layers.

3) A layer of background color is first applied either in a cloud pattern or following specific design. Another layer with a different pattern formed out of dense dots is overlaid on top of the background. In the layer with dense dots, the pattern is formed by arranging dots of the same color into clearly defined areas. The way those dots is applied is similar to the pointillism technique. Multiple voices come out of the designed mis-mapping between these two graphical systems. The different perceptual process involved for interpreting the pattern on each layer makes the competition among those voices even more restless. *Light and sharpness* (Fig. 97) and *Polyphony* (Fig. 98) are examples belonging to this type.

Interface Design

An interface for playing with the multiple voices using the second type of graphical means is created. It has an interactive scene space, in which the artist can add color planes, scale them, move them around, and set their colors and transparency. The Detonate object in Max/MSP/Jitter is connected to the scene space to provide an easy input for temporal color change on each plane. As displayed in the Fig.99, the Detonate object provides temporal information input for multiple tracks. Even though it is designed for note event input and edition, the Detonate object is indeed dealing with a collection of general temporal events that could have very different meanings. Those music specific parameters could be redefined accordingly. For example, the parameter for note velocity could be redefined as the luminance of color.

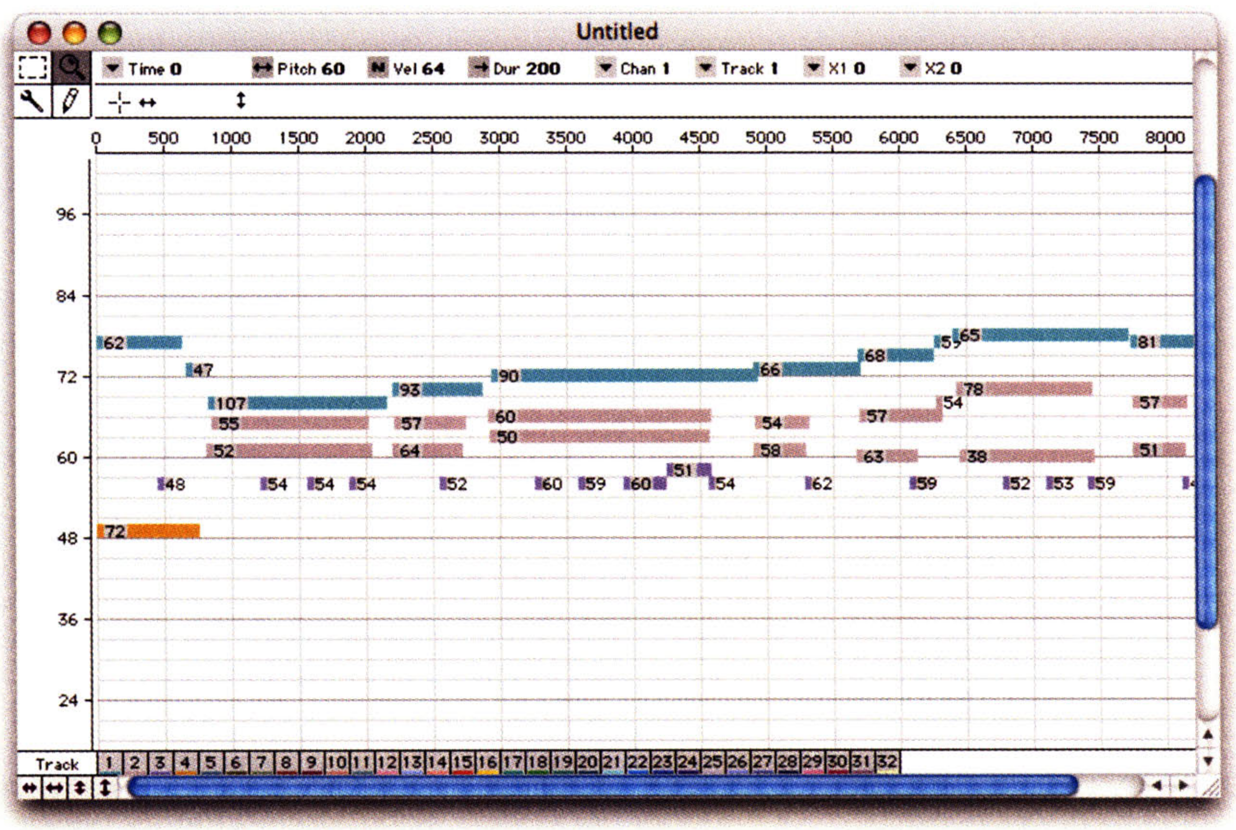


Figure 99. Detonate object in Max/MSP/Jitter.

When composing color as temporal events, how an individual color would appear and disappear comes up as an issue one has to decide before going further. Borrowing the term in music, this could be designated as color articulation. A color can appear or disappear immediately; it can fade in or fade out following certain designed curves like the attack and decay of musical notes; it can also cross-fade directly from or into another color, which is similar to modulation in music. Either one of these types of articulation has to be chosen in order to use a color in a temporal creation. During composition, different color articulations could be used purposely based on their unique visual effects and the composition idea.

To support the exploration of this temporal visual element, an interactive line interface is provided, with which the artist can draw or edit the curves for "Attack" (fade in) and "Decay" (fade out) or the curve for cross-fade between two colors. (See Fig.100)

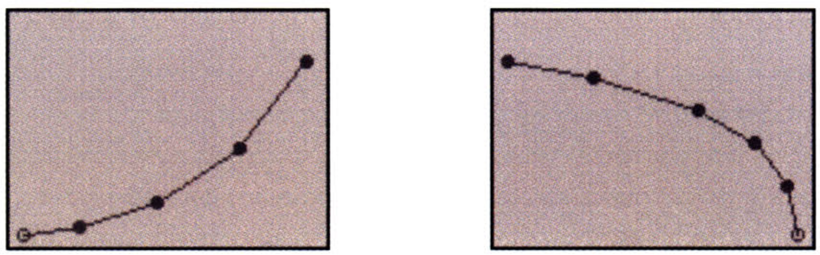


Figure 100. Editable "Attack" and "Decay" curves.

To display the different visual effects of different color articulations, multiple test windows are placed next to each other each showing the temporal development using one of the articulation means (Fig. 101). This test window also provides a place to display the editing result of the "Attack-Decay" curves. The artists can create a desired articulation using these two interface elements combinatorially.

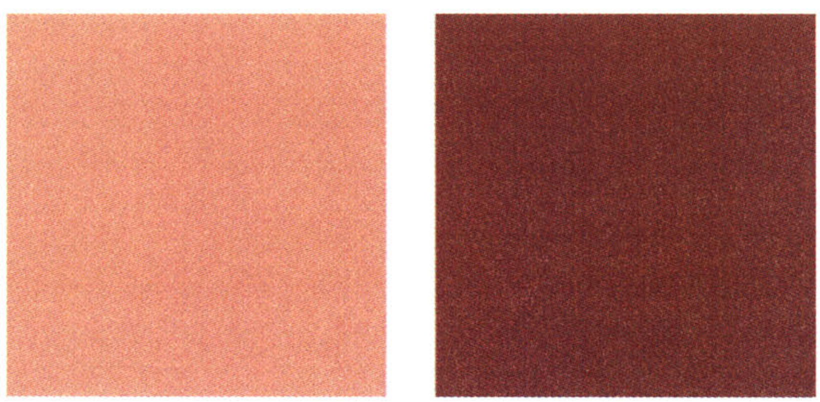
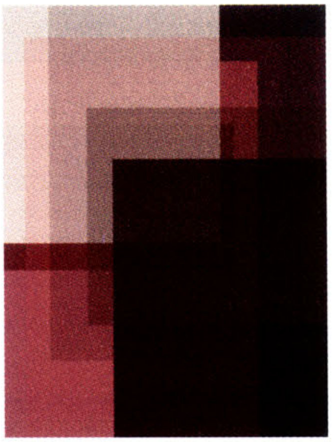
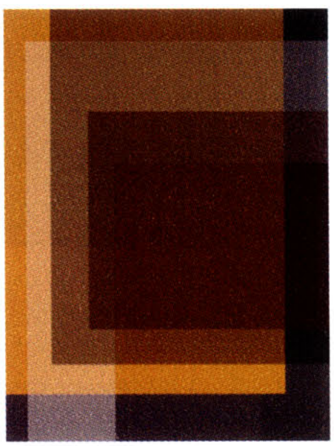
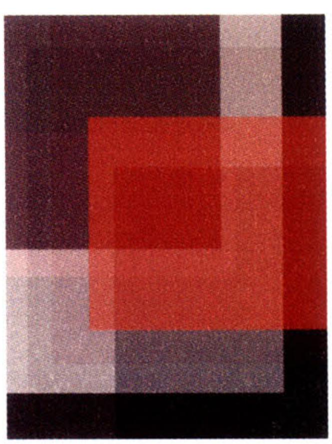
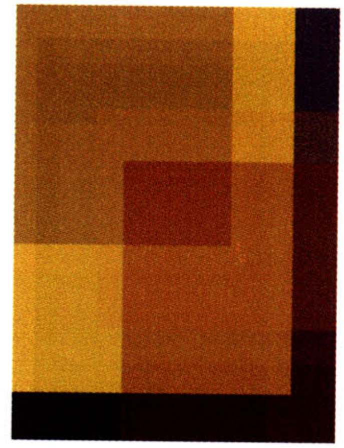


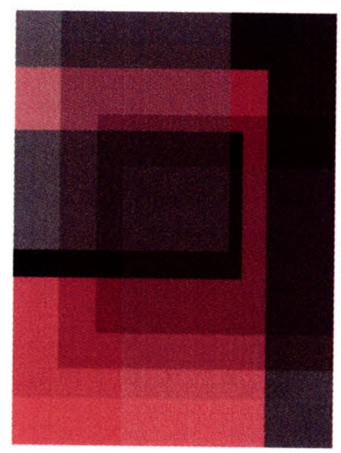
Figure 101. Immediate and fade in articulation.

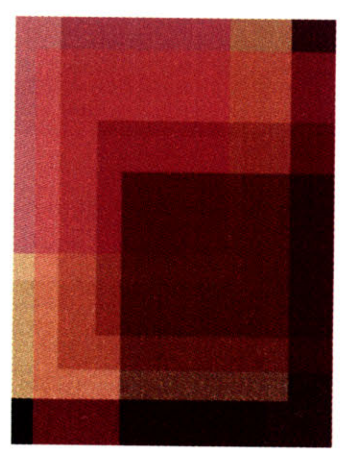












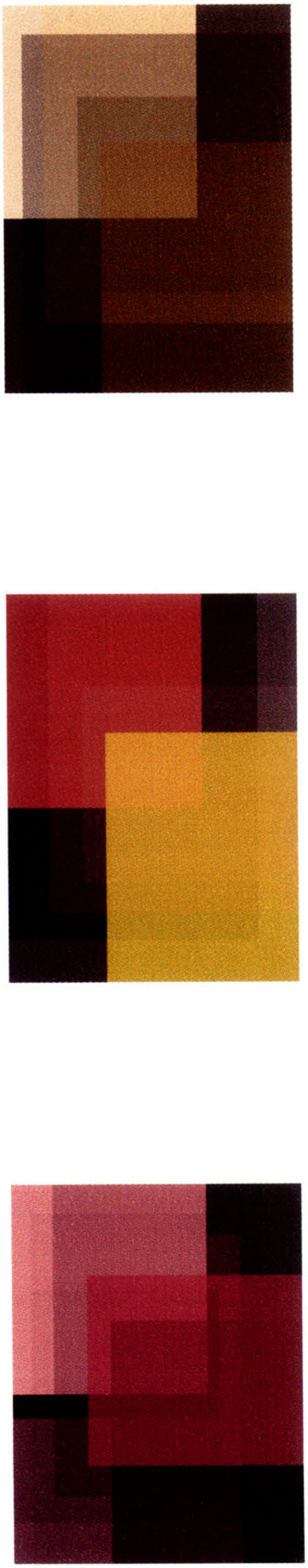


Figure 102. Temporal Polyphony.

Algorithmic Design

Algorithms are also designed for creating multiple voices using transparent color planes. They are written regarding two aspects of the composition. One is for controlling the spatial composition of the planes along time. For example, it can change the size, shape, and position of individual plane, add new planes or remove existing ones. The other is for controlling the temporal color development of each plane. A set theory-based color composition is programmed, which considers the color progression on each plane and the color relationship across all the planes at the same time. Factors to consider in controlling the color relationships include the luminance contrast, and the hue, saturation, and transparency difference. For example, some scenes could be designed as different luminance and saturation variations of the same color; while others are composed of complementary or high contrast colors. Some scenes have strong depth effect resulting from the high luminance difference; some on the other hand have a 2d graphical appearance because of the close luminance and saturation value across the planes. Fig. 102 includes screen-captures of an experiment using only the algorithm for temporal color development. As displayed in the images, planes with fixed spatial relationship can result in very different compositions due to the temporal change of color and transparency.

Compositional Thinking

1) Polyphony is originally a term used to describe music containing multiple voices of equal significance which are played simultaneously. Klee thinks of polyphony as a compositional method that flattens the temporal dimension to some extend, makes "yesterday and today as simultaneity", and thus creates complex and interesting patterns of movement. For this purpose of juxtaposing temporal events, Klee thinks that painting is superior to music because the spatial quality of painting provides an enriched form that could enhance the sense of simultaneity. If the multi-voice static painting is already a counterpart of the polyphonic music with enriched quality, the temporal development on top of such a multi-voice system would bring us much further along the search for rich and complex visual experiences.

2) The temporal color and shape development of those graphical constructions forming the polyphonic voices are inherently part of a multi-threading composition. Compared with the multi-threading under the color timbre theme, the spatial competition among the threads is more along the Z dimension, the dimension perpendicular to the 2d graphical plane. The larger area of the threads under this theme enables them to have a strong effect on the overall composition through their shape and color change along time. Because of this fact, the multi-threading under the current theme can be employed in temporal visual composition at a level higher than that in the color timbre theme.

3) As partially described in the algorithm design, the temporal visual composition along the direction of this theme is similar to polyphonic music composition. The set theory-based compositional thinking will both be applied to the temporal color progression for each voice, and to the design of the combinatory effect across them at key moments. The color development along time is similar to melody; the color relationship across layers is similar to chord.

Issues Introduced

1) As presented in the interface design, the issue of color articulation is introduced naturally when experimenting the color progression on those color planes which form the voices in the polyphonic composition. Its property and role in composition will be further discussed in the following section on compositional issues.

2) If the effect from the spatial context on the temporal color change of a cell in the color timbre theme is subtle and perceptual, the effect of spatial context on a voice in this theme is impossible to be neglected and is a visual fact forced onto the viewers. The study of how spatial context affect the temporal development of one voice becomes very necessary and important in this case.

3) Designed eye movement is another issue worth to revisiting. In the paintings under the color timbre theme, this path is formed directly from the changes in tonal or chromatic values across the color cells. Designing such a path of eye movement is also the aim of many paintings under this theme. However, the process involved to achieve this result is more complicated. The designed tonal or chromatic difference across the space is achieved through the interpenetration of colors on multiple transparent layers. For painting *Polyphonic Setting for White*, Klee also made a diagram showing the spatial layout of the steps along the movement path. No matter whether this diagram came before or after the final painting, a delicate composition of the planes with different color and transparency must have been evolved to realize the design in the diagram through their combinatorial result. Fortunately, the existence of those planes where the contributors to the final colors come from keeps this process of creation visible and being able to be appreciated. This clearly exposed process of color formation also gives the final color an unstable property. At the moment when a contributor is linked to the plane it is from, its contribution to the final color seems to be in a fleeting status. The combinatory color at each point is always in a dynamic process of finalizing, breaking into parts, and moving back and forth. Properties like these that are already suggested from Klee's static painting can certainly be enhanced or taken further along the direction of simultaneous interpretation through subtle temporal designs.

4.1.2. Compositional Issues

In this section, some fundamental issues about composition at different scales are pulled together for further discussion. To a certain extent, some of them have already been introduced in individual theme studies, while others applicable to all the themes will be introduced here for the first time. In both cases, the issues will be discussed from the point of view of the role they play in temporal visual - especially color - composition in general.

Color Articulation

For most of us who have become used to thinking of color as part of a static image it might be hard to imagine the fact that in temporal visual creations, time is a fundamental element for the perception of color. In the context of temporal composition, how a color appears and disappears is an inseparable part of the color event. It is in some sense similar to the stroke or texture of how a color is applied in static visual creations. Eggeling expressed in his writing a similar understanding about temporal visual experience: "Becoming and duration are not in any way a diminution of unchanging eternity; they are its expression.... Being and becoming are one.... What would be grasped and given form are things in flux".

In music, the articulation of the tone greatly affects its perceived timbre. For acoustic music, this is decided by the property of the instrument and the method of performance. In computer music, it is achieved through the design of the attack decay envelope. Both the shape and the duration of the attack and decay segments have great influences on timbre. For example, a very short attack is characteristic of percussive sounds, pipe organ and other hand has longer attacks. Similarly, there are also characteristic temporal articulations from physical visual events such as the flashing of stroboscopic light and the extreme slow fading of sunset. However, for temporal visual composition, whether a color articulation has its corresponding natural phenomenon is not important. Designing color articulations with different visual effects and employing them in appropriate compositional scenarios are more essential. For example, a hard juxtaposition from abrupt color occurrences could be employed purposely to achieve a high contrast effect needed at certain point of a composition.

John Whitney wrote in his book *Digital Harmony* that "Upon a second look at video phosphors we seem to have landed upon a new continent of exotic perceptions. There is no hint how these colors will be perceived... like any new world, this region of color experience in temporal flux has been an object of the imagination... On a continent where color presents itself as "from before to now to later," the **transiency** of color lies open to exploration." As the description of how a color appears and disappears, color articulation is a major aspect of the transiency of color. Almost thirty years has past, the control we have over temporal color generation has improved tremendously compared with the video phosphors, but the visual properties of color transiency and how this understanding could contribute to temporal composition are still almost unexplored.

Color Melody

"A note – A,B,C,D, and so on – has no meaning in itself; it is just a note. It is the combination of the notes which can create music" (Claude Levi-Strauss). Similarly, to make meaningful temporal composition out of color events, forming recognizable temporal sequence of color is a necessary first step. As shapes or patterns are fundamental elements for graphical composition, visual sequences or melodies, using the musical term, are fundamental elements for temporal visual composition.

Many pioneers in temporal visual creation had a clear understanding about the role of visual melody in composition and employed different means to create it.

In Eggeling and Richter's early stage of creation for scroll painting, which were made into film later on, they made a large number of drawings as transformations of one form element or another. They called these temporal visual sequences their "themes" or "instruments" and "orchestrate" them through different stages during the composition.

John Whitney used motion function to advance the graphical elements in time and form the visual melodies. To form meaningful patterns, values provided to the function are carefully selected so that each element would obey a rule of direction and rate and not drift aimlessly or randomly. These individual melodies can in turn dynamically form and reform the pattern configuration of harmonic resonance.

In his attempt to orchestrate "color action pattern", Edward Zajec used a series of four colors with unique sequence as the basic melody. He then employed his dimensional upgrade method to expand "this four-color series into successively larger units while preserving its structural identity"(Zajec).

Visual Exposition, Conflict, Climax, and Resolution

In order to engage the viewers throughout the composition, it is important to understand the rules for sculpting the audience's emotional response along the unfolding of the work. This topic in music composition has been thoroughly discussed by Leonard Meyer in his book *Emotion and Meaning in Music*. John Whitney wrote in *Digital Harmony* that temporal visual composition is also centered around this same idea of audience engagement. He emphasized at several places in the book that: "only **structured** motion begets emotion".

A well designed structure that could arouse, suppress, and satisfy the viewers' expectation would be very helpful in engaging the viewers into a temporal visual intercourse with the artist. In *The Visual Story: Seeing the Structure of Film, TV, and New Media*, Bruce Block borrowed the terms from story structure and explicitly defined the three basic parts for visual structure: visual exposition, visual conflict and climax, and visual resolution. Even though his analysis about visual structure has a focus on film, many of the principles are also applicable or suggestive to temporal visual composition. Some relevant ideas from his writing are briefly quoted here.

Visual exposition is the place to introduce the main visual components used in the creation and lay down the rules for all the basic visual components, space, line, shape, tone, color, movement, and rhythm. The visual rules will become guidelines for later creation and provide the creation the visual unity, style, and in turn the visual structure.

Visual conflict describes the process during which the intensity slowly builds until it reaches its most intense moment or climax. The increase and decrease of the intensity is realized through controlling the contrast and affinity of each visual component.

Visual resolution is where the conflict is over and the visual intensity decreases by way of the affinity increasing among the visual components.

There is one point I would like to add on with regard to the visual exposition. Besides defining rules about the behavior of each visual component, this could also be a place to introduce some compositional rules or in other words rules about the temporal development of the visual components. Then in later composition these rules could be purposely violated or conformed to, creating or releasing intensity.

Rhythm

Rhythm is defined in different ways when it is being discussed in different context. Even under the same subject of temporal visual creation, different scopes or points of view also lead to different understandings about rhythm. For example, in her thesis *Dynamic Visual Formation: Theory and Practice*, Isabel Meirelles looked at rhythm as a standalone object which serves as a building block for dynamic visual content generation. She analyzed it as a compound of rhythmic cycle and interval and studied how its components define the starting point, amount of time, and recurrence of certain dynamic visual material. Bruce Block looks at rhythm as a characteristic visual phenomenon which could be described as repetitive alternation at a certain rate or tempo. From his cinematic concern he further studied the formation of this visual pattern as a result of the object or camera movement in relation to the film frame.

The topic of rhythm is brought up here for the purpose of calling attention to the construction of a temporal framework for visual composition. I prefer to see rhythm of part of a metric structure from a compositional point of view. As defined by Gary Wittlich in *Aspects of Twentieth-century Music*, metric structure includes meter, tempo, and all rhythmic aspects which produce temporal regularity or structure, against which the foreground details or durational patterns are projected. For temporal visual composition, an underling temporal grid like the metric structure would be of no less importance than it is for music composition. Especially in the current situation when temporal visual composition is not yet a well-established concept, the existence of a metric structure could help keep the artists' attention for a systematic design along the temporal dimension. It will also regulate individual rhythmic patterns and integrate them along with other pace changes into a unified framework. The rhythmic patterns themselves are also temporal frameworks at a higher level for the foreground visual progression. Together with the overall metric structure, they provide the temporal grid for complex visual ideas to develop on top of, and help prevent the fluid visual change from becoming temporally shapeless.

Temporal Context

Temporal context affects the composition at micro scale through the phenomenon that other colors appear before and after one color would affect the appearance of that color. Temporal context also plays an essential role at the structural level of composition in a way similar to the role of temporal context in harmonic progression in music. Since it is such an important issue for temporal visual composition and would merit a whole other thesis on it, I am not going to further expand the discussion here.

4.1.3. Perceptual Issues

Besides the compositional issues listed above, some perceptual issues are also pertinent to temporal visual creation and are worth being mentioned here.

Spatially Adept vs. Temporally Adept, Parallel vs. Serial

Music as a well-developed temporal art form has been taken as the source for inspiration for many temporal visual composition explorations including the current study. Even though the analogy from music to temporal visual creation is not intended to be literal, it would still be helpful to look into some differences between visual and aural perception that might have influence on appreciation of the temporal composition in these two different media.

In *Audio-Vision*, Michel Chion wrote about the difference in speed between visual and aural perception. The ear analyzes, processes, and synthesizes faster than the eye. "Take a rapid movement – a hand gesture – and compare it to an abrupt sound trajectory of the same duration. The fast visual movement will not form a distinct figure, its trajectory will not enter the memory in a precise picture. In the same length of time the sound trajectory will succeed in outlining a clear and definite form, individuated, recognizable, distinguishable from others… This is not a matter of attention. We might watch the shot of visual movement ten times attentively, and still not able to discern its line clearly. Listen ten times to the rapid sound sequence, and your perception of it will be confirmed with more and more precision."

Because “the ear’s temporal resolving power is incomparably finer than that of the eye”, while we can already see visual continuity from moving picture at a rate of twenty-four frames per second, to hear continuous sound, the ear demands a much higher rate of sampling.

Chion further pointed out that: “Overall, in a first contact with an audiovisual message, the eye is more spatially adept, and the ear more temporally adept.” Zajec on the other hand quoted in his writing findings by Bela Julesz that the visual processe manifests itself in both a parallel (spatial) and a serial (temporal) fashion. “When conditions require tat a large number of vsual stimuli be simultaneously perceived, the spatial aspects will dominate, and we can think of the process as being parallel. When the conditions require a linear, sequential perception of the stimuli, the temporal aspects will become prominent, and we can consider the process as being serial.”

Visual perception, especially temporal visual perception is a very complex process. Its nature and mechanisms is far from being clearly revealed. However, some of the visual and aural perceptual phenomena like those mentioned above are still worth to be considered and experimented during the process of composition.

Visual Memory

Visual memory plays an important role at different levels in the appreciation of temporal visual composition. At the micro level, it is the existence of visual memory that makes it possible to see the apparent motion through connecting the visual impressions from successive images. At the structural level, the audience is engaged in a composition through their integration of the present seeing, the memory of past progression of the work, and the expectation of the content in the future.

Gombrich claimed that the process of painting appreciation also involves such a process of temporal integration. He described a magnification of the process of looking at a picture: “We build it up in time and hold the bits and pieces we scan in readiness till they fall into place as an imaginable object or event, and it is this totality we perceive and check against the picture in front of us. Both in hearing a melody and in seeing a representation, what Bartlett called the 'effort after meaning' leads to a scanning backward and forward in time and in space…."

Not to mention the incredibly small temporal scale of these picture appreciation actions and the fact that they might all happen subconsciously, it is obvious that a picture is always there for the beholder to check against back and forth. While on the contrary, the visual material in temporal visual creation is ephemeral and transient. There is nothing one can get a hold of physically. The time span needed to hold those bits and pieces seen across time is also much larger. Instead of being a possible element involved in the processing of seeing as in the case of picture appreciation, visual memory plays an indispensable role in appreciating temporal visual composition.

Brian O'Doherty also wrote about this property of temporal visual creation which is fundamentally different from traditional visual art. He compared the process of seeing in Richter's *Rhythm 21* with its already very close counterpart, the scroll painting. He pointed out the involuntary nature of the viewing process and described the experience of seeing as being "collaged" by the rapid succession of images and maintaining them in "an ambiguous sea of remembering and forgetting".

During the process of composing, it would be helpful to be conscious of this fact that visual memory is a requisite element in appreciating a work, and be aware of that memories of the successive images could only last over a limited time span. Given these understandings, repetition could be employed when a visual melody is to be formed as an identifiable component in the composition. One could also purposely play with the temporal threshold of the visual memory to generate intended effects at both the level of apparent motion formation and the level of compositional idea development. More importantly, the fact that the visual content existing in the memory is not as long lasting and comprehensive as that in the static visual art works shows the importance of presenting to the viewer clearly the rules employed in the composition. Only after being supplied with the view of a consistent framework can the viewers efficiently organize the visual materials in their memory, form expectations based on what has happen, and be satisfied or surprised following the logic in the rules. What makes the situation more complicated is that these rules themselves have to be introduced through the mediation of visual memory and are introduced at the same time as the work is unfolding. It is then the artists' task to wisely utilize the temporal visual materials. At the same time of employing them as contents of the composition, he or she can exhibit the compositional rules to the viewers through the characteristic and consistent manner with which these materials are being utilized.

Rhythm Forced onto the Viewer

Different from the fact that the beholders can brows a painting at any pace they prefer and go back to certain features as many times as they want, the process of viewing a temporal visual creation is not totally under the control of the viewer. Even though they can still choose to focus on different parts of the scene or different features, they cannot decide what they are going to see the next, and are not able to go back and forth at will for features they are interested in. The temporal visual creation unfolds or presents itself to the viewer. The compositional design by the artist plays a much more important role in forming the viewing process. The pace or rhythm of seeing is in some sense forced onto the viewer. This factor has to be included in consideration when designing visual content. Subtle features the appreciation of which need the traditional viewing process for static images might not create the intended effect. While composing the work, the role of the composition as both creating the visual content and defining the viewing process or the visual experience needs to be clear in the artists' mind.

Path for the Eye to Follow along Time

Since temporal visual composition plays a dual role of creating visual content and defining to a great extent the way in which the audience will view the content, designing paths for the audience's eye to follow acquires a more important position in temporal visual composition than in the creation of static visual art works. It becomes an innate part of the composition other than a potential design idea.

The different nature between the temporal and static visual media also renders that different design method need to be explored for creating the guiding path in temporal creations.

Many of the visual hints employed in static visual creations, such as hue or tonal difference, need to be made more explicit in order to keep them identifiable from the flux of temporal graphics. For example, highlighting in sequence different parts along the path could be a way to vividly attract the viewers' attention. There could also be methods unique to temporal composition. For example, in scenes with 3D properties, the change of point of views or camera positions and transformations could be employed in guiding the audience's point of attention.

Temporal Color Timbre

In the compositional thinking under the Color Timbre theme, the chromatic combination formed out of colors in the chessboard pattern is called as color timbre metaphorically. This name is chosen for two reasons: first, the overall chromatic impression comes from the composing color cells in a way similar to the timbre of a tone coming from its partials; second, this chromatic combination could be further employed in the temporal composition.

During my experimentation with the color sets, I found that, when randomly choosing color from color sets and displaying them in sequence, the sequences formed out of different sets present obviously different chromatic impressions. Using a similar metaphor as that for the color timbre, I would like to call these different chromatic impressions formed out of temporal combination of their member colors temporal color timbres.

In *Paul Klee*, Will Grohmann described the color and form relationship in Klee's painting *Fugue in Red* that "The range of colors unfolds in an ordered arrangement of connected forms." For an unfamiliar visual material like temporal color timbre, a group of connected forms like those in paintings under the Fugue theme might be a helpful graphical means to enhance the unification of member colors.

4.2. Digital Art Creations

Throughout the design and development of the set theory-based composition approach, three digital art works employing this approach have been conceived and worked on. In order to show the general applicability of this approach, I purposely designed three works of different genres and with different compositional characteristics: one abstract animation, one interactive dance performance, and one interactive multimedia installation.

In the abstract animation, both the graphical content and the temporal evolvement could be nailed down to a very delicate level. The interactive dance performance has an overall structure with strong sense of opening, climax, and tension release. Under this framework, the movement of the dancer affects the graphics and the music; the music and the graphics interact with each other. In the interactive multimedia installation, it is the action of the participants that guides the composition. Important parameters for both the graphics and music are unpredictable. Because of this nature, the work has an open structure without a predefined opening and ending.

All three works are still under development or need further improvement at this moment. However, the thoughts and efforts in implementing this compositional approach to real large-scale works have already provided very helpful contexts for the development of the theory and fostered a positive dynamics between the research and the creative process.

4.2.1. Color Progression I – Abstract Animation

The abstract animation is designed to exhibit important concepts in this approach, such as color timbre, color scheme, set transformation, and multithreading.

In his book *Audio-vision* about the mutual influence of sound and image with a focus on cinema, Michel Chion wrote that there doesn't exist an audiovisual counterpoint under similar conditions as musical counterpoint. This is because the sound track of a film cannot form an internally coherent entity with its own individuality. The vertical relationship between the audio element and the narrative image is more dominant than the horizontal relationship formed among the audio elements. This is however not the case for abstract animation. The sound or music in abstract animation is freed from supporting the narrative content in the image; it could by itself be an individual composition. In this study about temporal visual composition, not only the mutual influence of sound and image at micro scale but also the relationship between the musical and visual composition will be considered. Such a relationship could be designed in many different ways, for example, 1) the two parts developed as individual compositions running parallel to each other loosely, 2) the two individual compositions interact with each other enhance or counteract the other one at different places, 3) the two compositions share same organizing principle or same means of material generation without having direct correspondence.

In order to make the role of compositional thinking in temporal visual creation more salient, this animation uses a more extreme design. Instead of creating two individual compositions interacting with each other, graphical and musical materials are used as equal components in the composition of a combinatory work. Fugue form is utilized to provide a clear and strong sense of temporal structure.

Even though the idea of the design is to apply this temporal visual composition method to the temporal progression of color, shape, context, speed and rhythm are inseparable components to make this composition visually realized. Visual experiments and studies in the previous chapter will be important source for visual ideas.

4.2.2. Color Progression II – Interactive Dance Performance

Overall Design

In this project, the set theory-based color composition is used in the real-time-generated graphics for an interactive Dance Performance. The main idea of the work is to consider the performance of the dancer, the dancer's shadow and the digital graphics all as components for an overall visual composition. For example, in the beginning section, two stripes are animated in imitation of dialogue with the movement of the water sleeves of the dancer. In the second section, graphics like smoke and waves are designed to express the essence of the dance in an abstract way. It is the pose of the dancer and intensity of her movement that decides the generation and the form of the smoke and wave graphics. In the last section, the dancer "controls" her shadow to "dance" together with video captured from her dance and her shadow.

Technically, this project is created in a graphical programming environment Max/MSP/Jitter. Motion tracking and color tracking based on video captured from the dance in real time are used to generate the interaction between the physical and the virtual. For example, the amount of movement and the position of the dancer provide parameters for animating those two stripes in the graphics that echo the movement of the water sleeves of the dancer. Voice and real-time drawing on a Wacom tablet also contribute to the graphical content and effects.

These non-traditional means of graphics generation renders the unique characteristics of the temporal visual composition for this type of works. The composition in this case defines only the overall structure of development. Each time the work is performed, the action of the dancer and the artist, who controls the voice and the drawing, could trigger the generation of audiovisual content very different from those generated at other times.

Color Design

This work is designed to show the styles, patterns, and sounds that are characteristic of the Tang Dynasty (A.D. 618-907) of China. Accordingly, colors characteristic of the Tang Dynasty are chosen to form color sets in this composition. I looked into variety of sources for colors to form the color sets. The first one is the Dunhuang cave paintings[8]. The second one is the Tang Tri-color glazed pottery (Tang San Cai). I also looked at colors in the paintings, attires, and architectures of the Tang Dynasty.

Colors in Dunhuang murals from Tang Dynasty are rich in color types, application degrees and color mixtures. Colors used include azurite, mineral green, cinnabar, vermilion, earth

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[8] Descriptions about coloring in the Dunhuang Art in Tang Dynasty is based on Wen-chieh Tuan, *Dunhuang Art: through the eyes of Duan Wenjie* (New Delhi: Indira Gandhi National Centre for the Arts : Abhinav Publications, 1994).

red, gamboge, indigo blue, gold, black ink, etc. The highly developed skill in color creation and coloring made paintings of the first half of Tang the most magnificent ones in Mogao paintings. The following figure displays some typical colors in Dunhuang cave painting during the Tang Dynasty. [9]

Figure 103. Typical colors in Dunhuang cave painting during the Tang Dynasty (Image published with permission from Jiaoying Shi).

Different color schemes are used in paintings in different period of time to show their unique mood and style. The background color plays an important role in affecting the overall appearance. In early Tang period, earth-red was used to achieve a sense of density and candor. The earthen color of the wall was also used as background to create an effect of harmony. In High Tang period, some masters used the white-washed walls of earlier period as background to achieve a vivid and bright color tone which became the artistic style of this period. Colors of attire in the paintings of different period of time also have different characteristics. For example, in the early Tang period, the colors tend to be soft and harmonious, whereas the mid-Tang favors bright, high-saturated colors. This factor of color scheme change is considered in composing the temporal color development in my work.

[9] The colors are from Jiaoying Shi, *A Case Study of Virtual Museum - Reconstruction and Restoration of Dunhuang Caves in China.*

The colors of Tang Tri-color pottery include yellow, green, brown, blue, black, and white with the first three as the major colors. Besides the color itself, another aspect I take from Tang Tri-color pottery art is the texture of colors permeating into each other, which was generated by its special process of production.

This attention to the texture is not only with the Tang Tri-color art. It is an integral part in my searching for colors of the Tang Dynasty. This is consistent with my study of color sets in spatial composition. In some analyses of art works, colors from the paintings are analyzed by quantity (what percentage of the scene is covered by one color). I believe that color by itself could only tell a limited story about the work under study. The spatial composition and how the colors are applied have to be considered at the same time. Back to the coloring in Dunhuang murals of Tang Dynasty, two techniques are used to create different graphical effects. The first one is adding technique with which different tones of the same color are added layer by layer to create tonal complexity and three-dimensional effects. Figures thus painted have tonal richness, thickness and a lustrous effect. The second one is contour-control technique. It is mostly used to show the three-dimensional effect of the deity figures. This technique in Tang Dynasty is a synthesis of one such technique from the West and another invented in China. It has various accents. For example, "One of them was the traditional Chinese contour-control technique with Tang innovations such as adding red on the cheeks referred to as "red face", "lotus face", "peach blossom make-up" and the "twilight make-up" in the Dunhuang Songs ... Another technique is the slight application of light on a white background to create shining smooth jade faces, ... There was yet another modified technique as presented by the Buddhas and Bodhisattvas in Cave Nos. 321 and 220 who have a white line on the bridge of their noses, faithful to its Indian influence." (Tuan, 1994)

These graphical characteristics of the color application provide design ideas for spatial-temporal composition in various ways. JColor system could be employed to generate the permeating texture at micro level. The adding and contour-controlling techniques imply both similar effects as in the mural paintings at the normal scale and abstract applications of the same graphical idea at macro scale or along time.

Setup of the Performance

1) Floor Plan

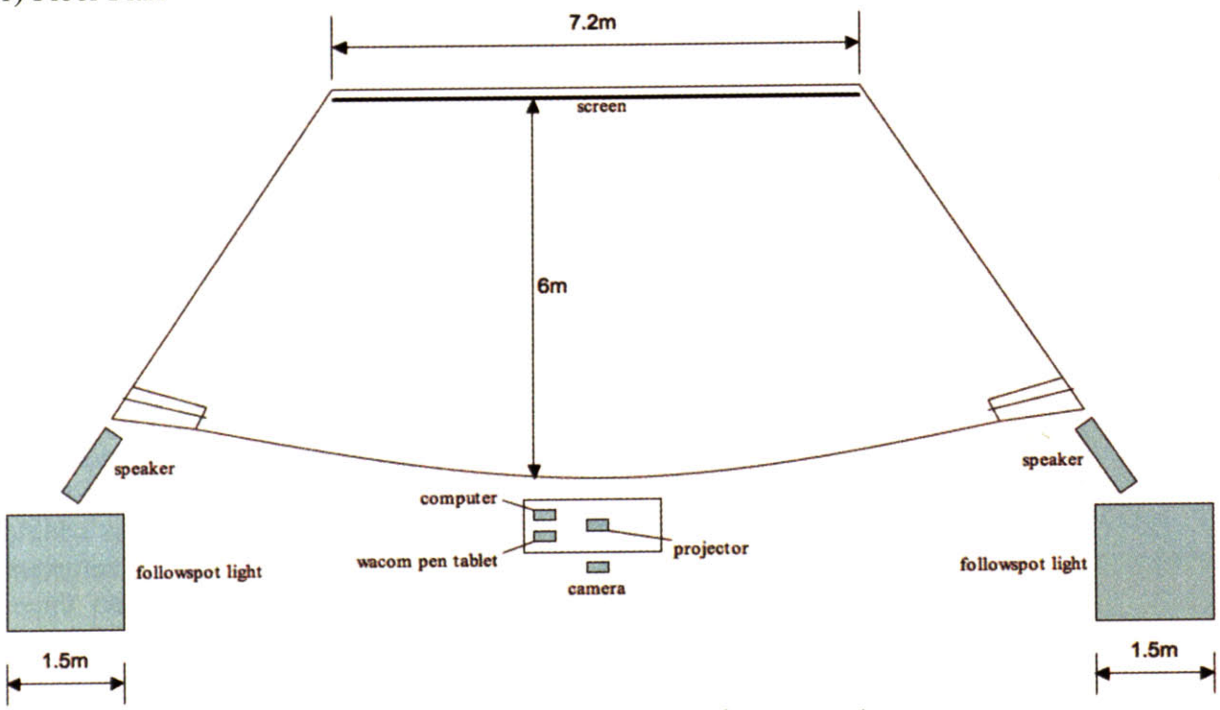

Figure 104. Floor plan of the dance performance setup.

2) Specifics

- Two followspot lights are used to provide good lighting for the dancer and keep the screen relatively dark at the same time.
- Max/MSP/Jitter running on a MacBook Pro Laptop is used to control the graphics and music in real time.
- Wacom Intuos3 9x12 Pen Tablet is used to control the generation and movement of the 3D graphics in real time.
- A DV camera is used to capture the scene and provide information for real time video processing and graphics generation.
- A projector is used to project the real time generated graphics on the screen.
- Two sets of speakers are used for the music and sound effects.

4.2.3. Color Progression III – Interactive Multimedia Installation

Overall Design

In this project, I applied the set theory approach of temporal visual composition to interactive installation. This is a format of digital art that normally lacks a structure over time and consequently has problems with engaging participants for longer period of time. For two purposes, I designed this installation as an interface with which the participants can compose both the music and the graphics based on the set theory approach. The first purpose is to call attention to disciplined composition in temporal visual creation and to introduce this set theory-based composition approach. The second purpose is to experiment whether such a participation in the temporal composition could extend participants' time of involvement with interactive installation works.

The main parameters for controlling the development of the work at structural level are defined. Different options for controlling those parameters are also provided so that the participants can choose the level of involvement they prefer.

When there is no participant, the music and color have their own default set theory-based composition correspondingly. These two lines of composition evolve together along time, sometimes run in parallel without tight relationship, and sometimes interact with each other to trigger new directions for the work to follow.

One option for the participant to involve is to adjust the values of certain parameters and watch out the change over time. These parameters could be the value of individual color or pitch, the set member to emphasize, the range of transposition, etc. They could also be parameters that are more temporally oriented, such as the time cycle of a changing process. This option is similar to improvisational performance in music. What the participants add on to the basic framework is the expression of the work in their own ways.

Another option is closer to the composition interface idea. The participants' involvement in this option is also more intensive. With this option, the participants can choose the set for the composition, conduct different operations with the set, and decide the change from one stage to another. They are basically guiding the composition of the work in real time with immediate audiovisual feedback. How their choice will form the content and where their design will lead the work going to might be what attracts them to keep playing with the interface. For the potential audience, the participant's process of playing brings to them an audiovisual composition developed in real time.

Similar to the performance project, the interface for interactive music and graphics composition and generation is also created in the graphical programming environment Max/MSP/Jitter. In one of the interaction options, motion tracking is used to enable the participants to change certain parameters for the composition with physical movement. Details about the two interaction mechanisms will be introduced in the later part of this section.

Color

To support my hypothesis that involvement in the composition process might expand the time span for participants' interest, the main idea of color design is to have the participants' actions not only generate immediate visual content but also affect the overall temporal development. This is exemplified in the motif development, in the progression to the climax, and in many other processes. A memory system is built to support this design in various ways. It records the actions of the participants, prepares them as materials in later parts of the composition, or analyzes them and triggers automatic processes based on the analysis result.

For the motif development, the transformational voice leading in musical set theory is used as the basic form. The participants can flexibly work on two different structural levels. On one level they can transform or combine a set and form the motif; on the other, they can transform the motif as a unit and create different variations. During this process, the memory system analyzes these color sequences with respect to their length, the amount of times they are used, and other factors. This information is interpreted as the participants' compositional intention. Certain sequences are then identified as color motif and will be further developed by the system automatically. Others are remembered as characteristic vocabularies of the participant and will be employed in later compositions (with or without modification) to help form his/her unique style. At the same time when the computer is developing and presenting a motif, the participant can keep generating new motifs to counteract to or replace the current one.

On top of the rules set up by the motif and its variations, the participants can create tension by doing unexpected transformations to components in the motif through control at the individual set level. To create tension out of complex patterns, the participants can compose multiple versions of the same motif by transforming them at very different intervals. With help from the memory system, it is also possible to compose multiple motifs, or juxtapose multiple motifs and transpose them as a group.

Besides motif development, the participants' action can also affect the happening and the length of the climax. The memory system can interpret high frequency transformations in a short period of time as the intention of the participants to approach to a climax, and trigger highly intense climax style visual sequences. The intensity of the climax and how long it will last are decided by properties of the triggering actions. For example, if the transformations involve only one set or rhythmic pattern, the climax will have low intensity. Whereas if there are multiple patterns with high contrast involved, the climax will be more intense and longer. Regular transformations trigger less intense climaxes, irregular transformations trigger climaxes with higher intensity. While the climax sequence is being displayed, the participants can keep performing to add onto it and extend its duration.

Through these approaches, the participants can purposefully guide the development of the work through their compositional actions. It is my hope that the long-term effect that their action at one moment may have on the overall development can engage the participants and allow them to become familiar with the concept of temporal visual composition.

Music [10]

Music in this work is algorithmically generated in real time either automatically or in response to the participants'

[10] The music composition is a collaborative work with composer Ping Jin, who provides the information about the characteristic rhythmic patterns in Chinese traditional music and the dynamics, velocity, position and frequency of use for each pattern in a work.

interaction. The main compositional idea is to use rhythmic pattern to strengthen the musical image of the chosen set class.

Three distinctive sessions with different set content and rhythmic patterns are designed. These three sessions are not intended to be played (generated in this case) one after another. In the automatic mode, the progression among these sessions are either triggered by certain conditions in the musical parameters or by the interaction from the graphics. In the participant interaction mode, the participant can explicitly choose one of the sessions to be the current session.

In each session, a musically meaningful framework of set class and rhythmic patterns working with that set are defined. For example, in one session, the set class is an abstraction of the Chinese five-tone scale. And rhythmic patterns typical for Chinese music are defined corresponding to this set class. The dynamics, velocity, and where and how much (rough aspect ratio) each rhythmic pattern will be used in the session are also defined based on the characteristics of Chinese music. The following table displays such a framework.

	Slow1 30%	Middle 25%	Fast 30%	Slow2 15%
rPattern00	80%	30%	0%	20%
rPattern01	60%	20%	25%	40%
rPattern02	80%	20%	0%	40%
rPattern03	40%	20%	20%	60%
rPattern04	80%	20%	20%	30%
rPattern05	70%	40%	20%	50%
rPattern06	30%	80%	80%	30%
rPattern07	40%	80%	60%	20%
rPattern08	50%	50%	80%	30%
rPattern09	0%	10%	20%	0%
rPattern10	80%	60%	0%	50%
rPattern11	60%	60%	25%	40%
rPattern12	40%	40%	10%	40%
rPattern13	25%	50%	50%	50%
rPattern14	10%	30%	30%	20%
rPattern15	0%	15%	30%	10%
rPattern16	0%	20%	90%	0%

Figure 105. Rhythm and velocity framework of a session.

The top row of the table defines the linear change of velocity in the session through the order and temporal percentage of each velocity type. The lower rows define the relative percentage for the frequency of use for each rhythmic pattern in each velocity section.

On top of the general description for the use of each rhythmic pattern, there are also detailed algorithms tailored for specific patterns. For example, the combination of certain rhythmic and dynamic patterns will trigger another rhythmic pattern.

Notes are generated from different variations of the set class and are articulated following the dynamic, velocity and rhythm framework. In the note generation and set transformation, there are specific rules defined based on the musical characteristics of the set class. Some examples are: 1) certain intervals need to be avoided in the transposition, to give an example, for set 02579, during transposition and inversion avoid forming 1 or 6 interval between two notes immediately next to each other; 2) to add variation, repeat when a pitch-class goes to its immediate next pitch-class; and 3) during the transposition, there is a general octave range restriction for each set, for example, 0247 small octave range, 0135 big octave range, 1245 and 135 small to medium octave range.

There are also rules considering of the use of both the rhythmic pattern and the set content. For example; 1) within on rhythmic pattern, only choose notes from different octave in the corresponding pitch-class but do not to transposition; 2) keep the number of different sets as an inverse of the level of complexity of the rhythmic pattern; and 3) use dynamics and rhythm to control the repetition of notes

In each session, following the same design rules, three voices are created with only slightly different specifications at the opening part.

The rhythmic patterns in one of the sessions are written to be applicable for different set classes and would be more appropriate for the participant interaction mode, in which the participants might choose the set class in real time. The other two session designs can also be used in the participant interaction mode. By adjusting set content and operations, certain novel effects might be created.

Interactive Progression

1) Interactive progression resulted from the interaction between color and music

When there is no participant playing with the installation, the music and graphics will move on by themselves. They both follow their own set theory-based composition and will interact and change each other when the parameters in both of them meet certain requirements. Even though both the music and the graphics are composed using the same set, they are not designed as direct mapping of each other. Based on the esthetics of each of them, the compositions follow different paths as two separate lines. These two lines would intersect at certain points and affect the status of the others based on their current information. In this way, the music and the graphics could evolve to be endless variations on top of the same set coherence. Besides set change within a set class, set class change could also happen. When certain circumstances are met, the current set class will transit to another one which is ideal for the new condition.

2) Interactive progression triggered by user interaction

When there is interaction from the participants, the set and operation used in the default music and graphics will be replaced by the input from the participants. From then on, the interaction between music and graphics goes to the second place. The participants' action takes over the control in the evolution of the work.

Two versions of interaction mechanisms have been designed to provide the set and operation information.

i. One is through the MIDI keyboard. The participants can select set members by pressing corresponding keys in the lower octaves; choose starting note in middle octaves; and change the value of individual notes in the higher octaves. To change the value, pairs of black and white keys are used for raising or lowering down the value of each members in the set. Different wheels and controller on the keyboard can be used to control the set operations (See Fig. 106). This design is closer to the serious composition process. Changing set and adjusting operations while listening to the resulted music and looking at the resulting graphics is a composing process with immediate audiovisual feedback.

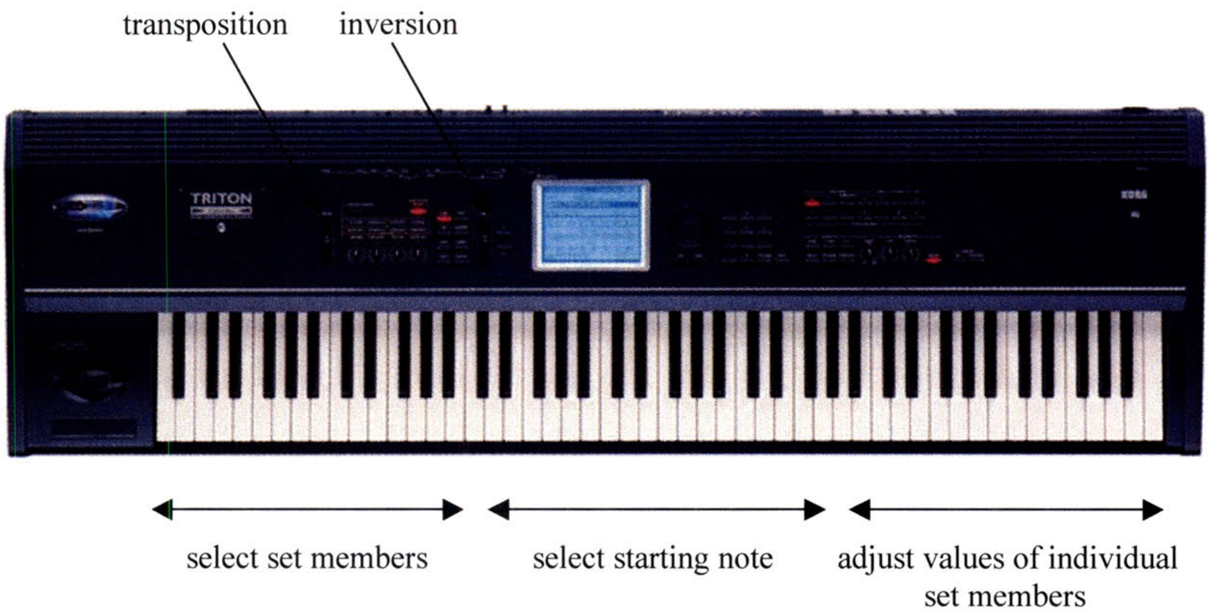

Figure 106. Illustration of the interactions using MIDI keyboard.

ii. The other one is through motion capture of the movement of the participants on top of the graphics. The position of the participants, the direction and speed of his/her movement will be used to decide the set members and operations. With this interaction mechanism, the participants could have a strong sense of physically involving with the composition. The change of the music and graphics will stimulate the new move in composition even more directly.

Setup of the Installation

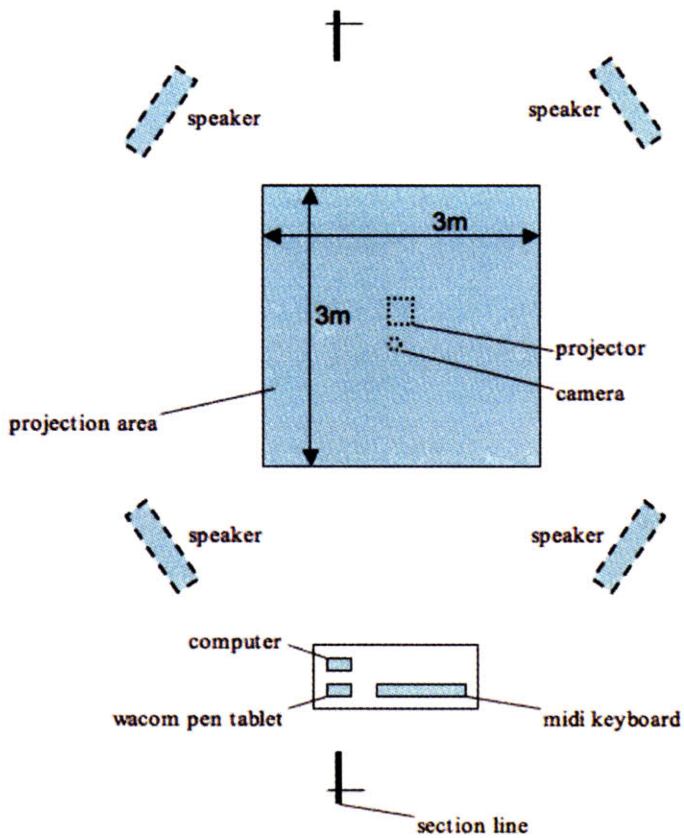

Figure 107. Floor plan of the installation setup.

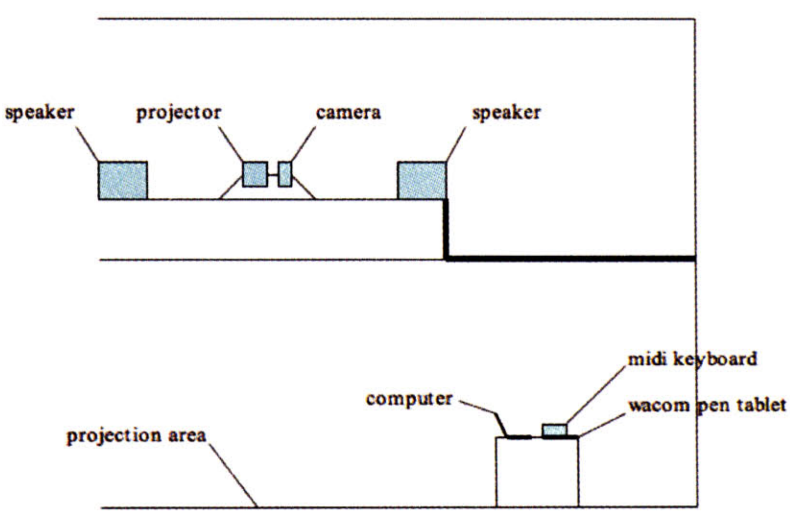

Figure 108. Section of the installation setup.

Chapter 5. Interface and System Developed for Temporal Visual Composition

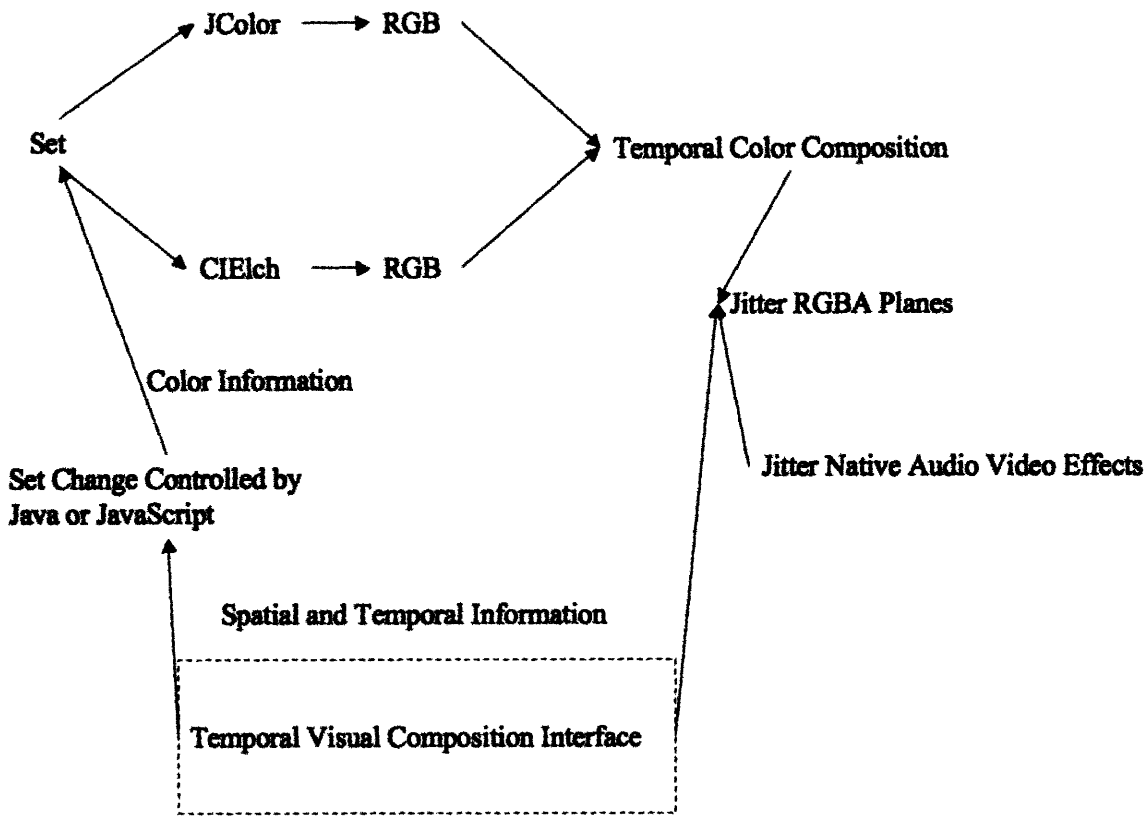

Figure 109. Diagram of the interface and information flow in the experiments.

The above diagram displays the data and interaction flow in experiments carried out in this study. It is composed of three main parts, a temporal visual composition interface, a color calculation system, and a rendering environment. With the interface, the artists can both compose spatially on the interactive canvas and compose temporally on the timeline. They can also select or define color information with the color keyboard in the interface. The color information such as set members or operations are then transferred to the color calculation system that either applies this information to colors on the color wheel or uses it in the generation of color timbre at the spectral level. Before getting into the color calculation system, algorithm could be written to generate complex temporal progression based on the set, operation and temporal information. The RGB values of colors reflecting the temporal color composition are then integrated with the spatial temporal information from the composition interface in the rendering environment to form the final temporal visual creation.

In the following sections, the temporal visual composition interface and the JColor system will be introduced in detail.

5.1. Temporal Visual Composition Interface

The temporal Visual Composition interface consists of a color keyboard, an interactive canvas, and an absolute timeline. This design came naturally from tasks encountered during the visual experiment and composition: color set selection, graphical information quantification, and absolute time organization.

Color Keyboard

During the creative process, keeping the felt impulses from being interrupted is very important. "One day I must be able to improvise freely on the keyboard of colors: the row of water colors in my paintbox." In this declaration Klee made in 1910, besides the metaphor for mastering color as a pictorial means, he may also have expressed the desire to work with color with the same interactivity as working with sound.

While composing set theory-based music, it is often helpful to find the favorite set by listening to it played out on the piano and try with the keyboard different combinations of the set members both vertically and horizontally. An interface like the music keyboard which provides intuitive color access and direct visual feedback would also be helpful for color composition. With such a tool one can easily select and look at the combinatory result of multiple colors to find the preferable color set through rounds of visual testing. One can also experiment with spatial and temporal combinations by choosing different variations of the set members. The color keyboard component of this interface is designed and developed for this purpose. The final design is the result from a series of problem-solving process. In the following writing, I will list these problems I faced during the interface development and explain how the current design came as an appropriate solution.

1. How to connect to color use in the history?

   Based on the color studies in Chapter 2, I choose to use CIELAB color space for a perceptually meaningful control of color on the computer. However, for a color keyboard for art creation it would be better to let the artists easily connect back to color use in visual art tradition. Itten's 12-hue color circle in which "each hue has its unmistakable place" is a good summary of color wheels in the history. It clearly represents the relationship between the primary, secondary and tertiary colors.

Figure 110. Itten color circle.

The color wheel in the Color Harmony Workbook by Lesa Sawahata is the numerically defined color wheel I found most close to Itten's color circle. The CMYK values of the 96 colors on the wheel and 10 grayscale colors could be easily converted into RGB and other color representations.

Figure 111. Color wheel in the Color Harmony Workbook.

I then had the idea of using the values of 12 colors on this color wheel with the medium saturation and luminance for the index colors of my color keyboard. A color wheel is created based on the same order as Ittens color circle with each color representing one of the 12 colors classes for set theory-based composition. (Fig. 112)

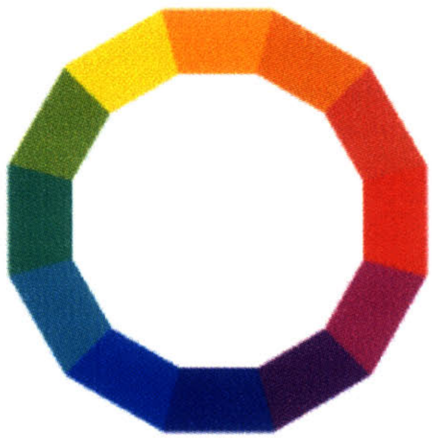

Figure 112. Index color wheel.

Compared with colors in any slice of the CIELAB color space (Fig. 113), these representative colors are closer to the impression of a color (color class in the set theory context) in our mind and would provide a vivid hint during the color selection process.

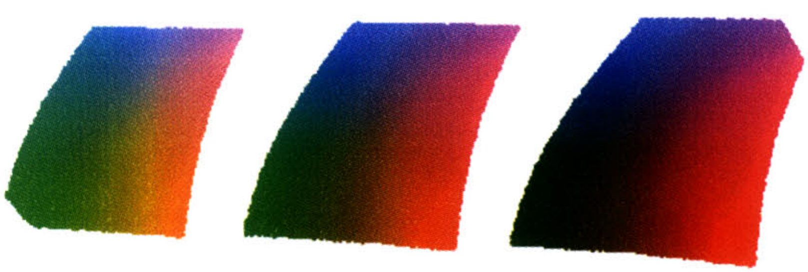

Figure 113. CIELAB color space at luminance 80, 70, and 60.

2. How to provide both an overview and the easy access to individual colors?

   1) Early experiment of a 3d CIELCH color space cylinder

In my first experiment I created an interactive color cylinder of the CIELCH color space (Fig. 114). It has 12 slices corresponding to 12 colors equally spread along the hue circle at colors close to the 12 colors in traditional color wheel. On each rectangle slice color samples are laid out on a grid equally divided the vertical luminance dimension into 10 and the horizontal saturation dimension into 8. The user can rotate and scale the cylinder to select colors. Those selected colors will be listed in the testing area as color boxes with the number of the slice (hue) the color belongs to, its saturation and luminance position labeled under the boxes. Users can drag those color boxes around, resize them, or overlap them to see different spatial compositions. Users can also choose to display color of the overlap areas as color of the color box on the top, as transparent layers, or as color mixed from all layers.

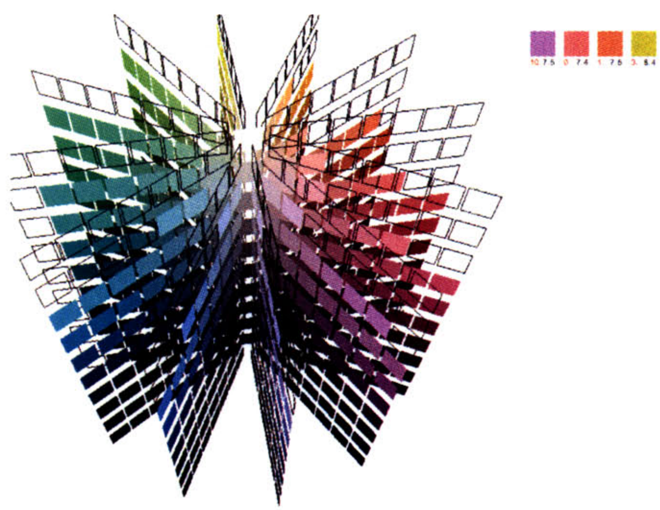

Figure 114. 3D CIELAB cylinder color selection system.

This interface has two problems. First, only limited number of colors can be displayed, slider or other means is needed to access other colors in between those displayed along all three dimensions. Thus the artist cannot have a direct view of all the colors available before focusing on a specific one. Second, with the 3d interface it is hard to display all the color samples equally, and the rotation and zooming involved also hindered the creative process. The disorientation and other problems common to all 3d interfaces also exist here.

2) Analysis of existing color selection system

After experimenting with the 3D option, I turned to look at the 2D color selection interfaces in existing software, such as the Apple Color Picker, the swatch object in Jitter, and the Adobe Color Picker.

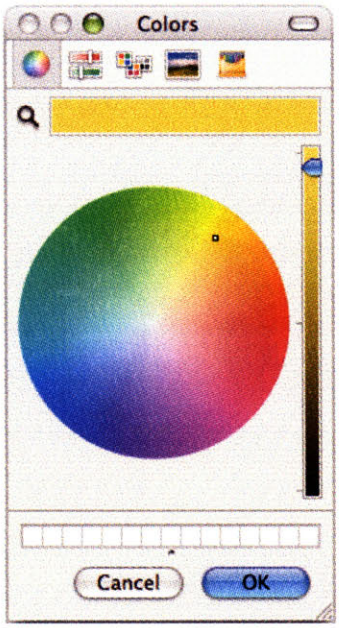

Figure 115. Apple color picker.

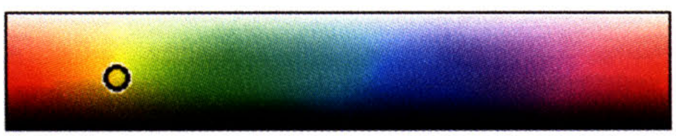

Figure 116. Jitter swatch object.

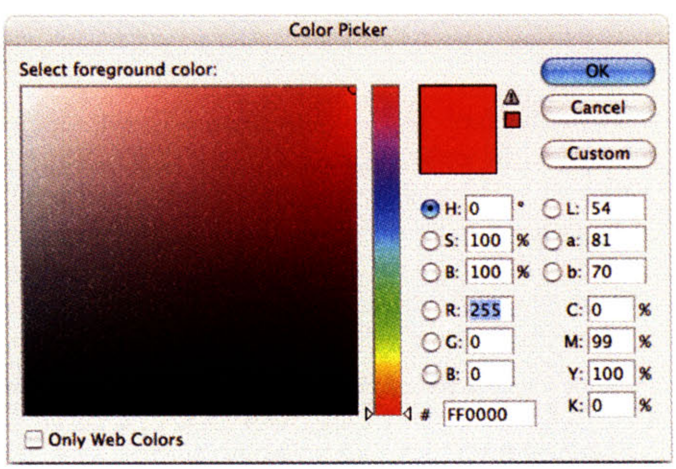

Figure 117. Adobe color picker.

With these interfaces, the user can select and change between different colors every smoothly on a 2D interface. This would be the kind of quality I am looking for an interface for art creation.

However, there would be problems with using either one of these in my study.

First, the color in all these interfaces is rendered based on HSL color space instead of CIELCH. This makes them incompatible with the CIE-based overall framework. Even though one can convert between HSL and CIELCH, the perceptual correspondence is lost then.

With the Adobe Color Picker or its Lab color sliders one can define CIELAB values of a color, but the overall color context is lost. Also neither the slider nor the numerical input is an intuitive way to choose color. Furthermore, the colors thus generated are sometimes deceiving. For CIELAB colors which cannot be displayed in RBG space, the system predicts a close color for it. This might make the numerical relationship unpredictable.

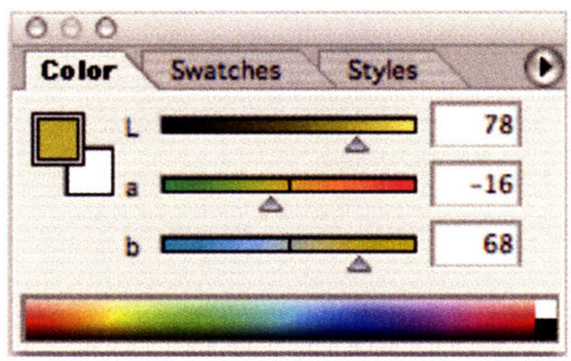

Figure 118. Photoshop Lab sliders.

Second, the Jitter Swatch Object and the Apple Color Picker are not organized along the color dimension important to this study. As displayed in the following figure, with the Jitter Swatch Object, in order to get all the colors, one needs to use a slider to go through different saturations of the spectrum image.

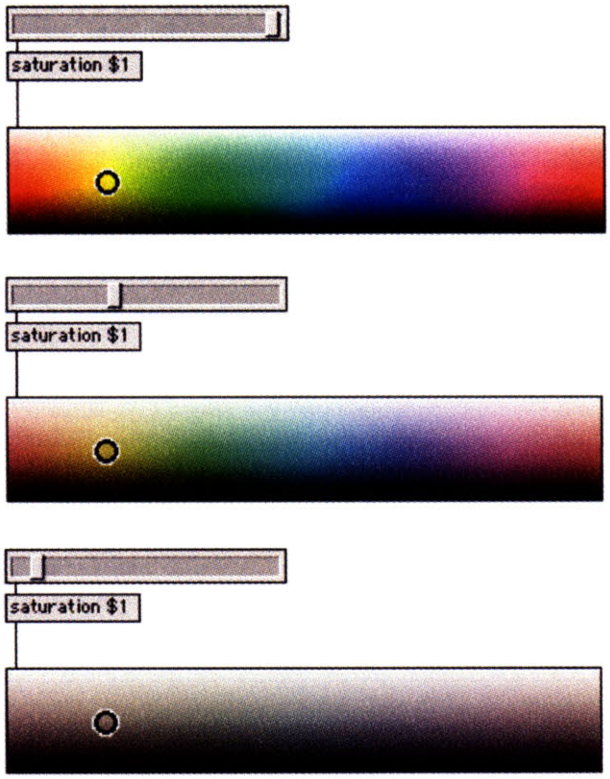

Figure 119. Organization along the saturation dimension.

With the Apple Color Picker, one needs to change the luminance of the color wheel image to display all the colors (Fig. 120). Even though for the luminance-based set this way of organization would work, for the first step, an interface focus on hue-based sets is more important for the study.

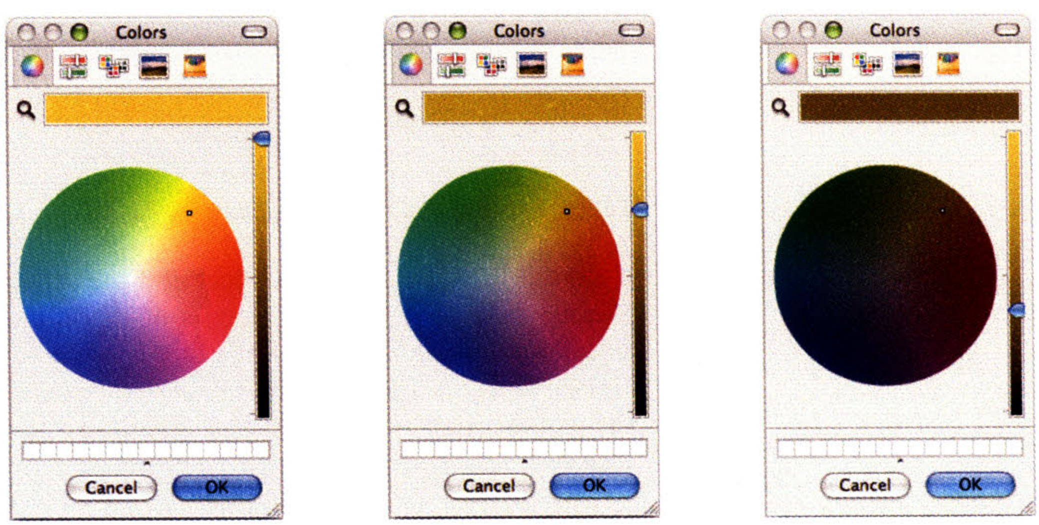

Figure 120. Organization along luminance dimension.

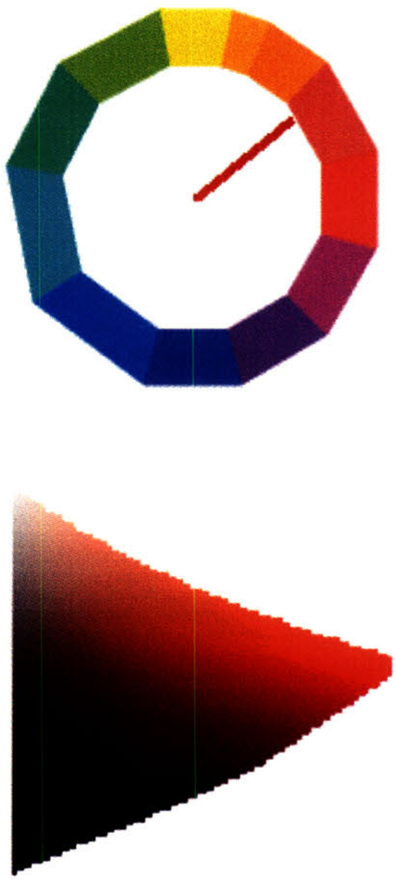

Figure 121. Dialable color wheel and dynamically changing palette.

3) Dynamically changing palette driven by color wheel

Based on the idea of connecting to visual art tradition and the experience learned from the previous experiment and analysis, I designed a color selection interface intuitive for the creative process. It is composed of two parts a dialable color wheel with color and order as discussed under the first problem, and a dynamically changing color palette (See Fig. 121).

When the user dial around the color wheel, a slice of the CIELAB color space at the corresponding hue angle is displayed. This slice should have all colors of this hue with different luminance and saturation. But only part of this rectangle slice could be displayed using in RGB system. I purposely choose not to proximate colors out of RGB space to avoid mixing colors with different hue into one slice. As another aspect of the fact, what one can use on the computer are exactly those displayable by the RGB system. Following the convention in painting, such a slice with all the luminance and saturation of a hue is called a palette from now on in this study. Because the RGB displayable colors are different at different hue slice, the palette displayed is dynamically changing along with the dialing. The user can conveniently pick colors from a palette in the same manner as with the Jitter Swatch or the other color pickers.

During the process of dialing the color wheel for a whole round, the changing palettes displays and provides access to all the colors available. Such a dialing process also gives the user a good overall sense of the color they are selecting. From the iconic color wheel, they know what color in the traditional or everyday sense they are working with (selecting different flavors of this color).

4) Range adjusted color wheel

You might have noticed that the color wheel in figure 27 has those 12 iconic colors spread out unequally. This is an adjustment to make the color wheel both connecting to tradition and driving the perceptually meaningful color generation. In my further analysis, I found that colors around CIELAB hue circle are not aligned with colors on the traditional color wheels. Some colors occupy ranges bigger than the equally assigned range in traditional color wheel; some occupy ranges that are smaller. Accordingly, the locations of those colors are also different, even though the order is the same. In order to keep the visual hint consistent with the underlying CIELAB hue circle, I adjusted the size of each iconic color and position them by aligning the center of the color area with the closest hue on the CIELAB hue circle.

3. How to make the keyboard more convenient for set theory-based composition?

   Based on the discussion in Chapter 3, *Development of the Approach*, a color class is a collection of colors with hue value in certain range and with all the different saturations and luminance. Similar to selecting pitches at different octave in a pitch class during the set theory-based music composition, selecting and comparing colors in a color class would be a very frequent action in set theory-based color composition. To make an interface reflect and support this feature, the dialable color wheel and dynamically changing palette combination is expanded into the following design:

Figure 122. Color Keyboard interface – blank display spaces reserved for 12 colors.

12 display spaces are created for the 12 color classes corresponding to the 12 colors in Itten's color wheel and other typical ones in the history (Fig. 122). When dialing around the color wheel, the dynamically changing palette

will be displayed in one of the 12 display spaces when the hue is within the range of the color that space is reserved for (Fig. 123).

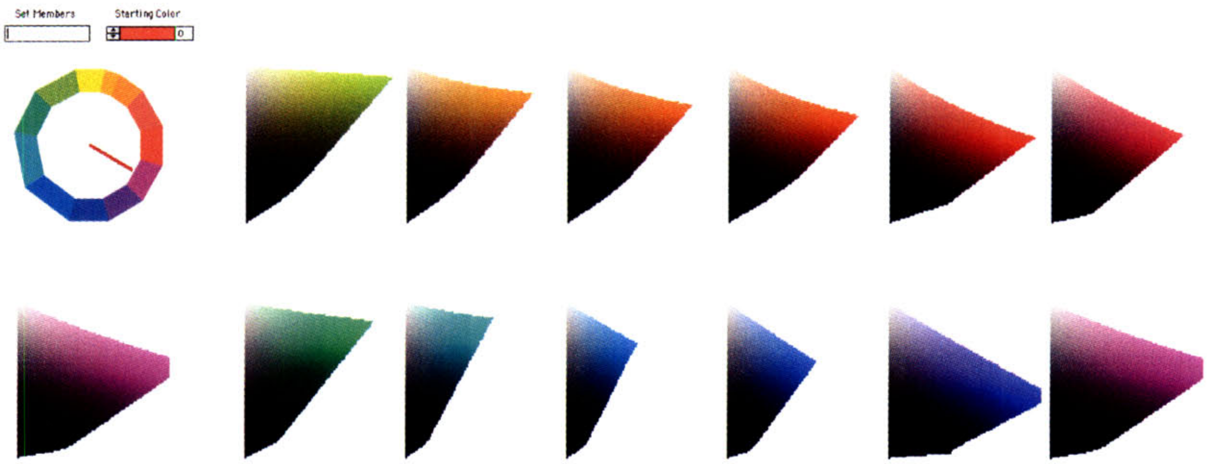

Figure 123. Color Keyboard interface – palettes for all of the 12 colors.

The palette in each display space has the same interactive function as the main palette. The user can move mouse around smoothly in the palette to look for the favorite color.

On top of this structure, when the user types a set in the text field above the color wheel, colors in the set will be highlighted on the color wheel. At the same time, a slice of the hue at the center of each set member's color range will be displayed in the corresponding display space (Fig. 124).

Figure 124. Color Keyboard interface – set 0 1 4 with red as the starting point.

Now when the user dials the color wheel, the action won't evoke palettes for all of the 12 colors. Only when the pointer is within a set member's range will the dialing action change the palette of that member. The user can slightly dial the color wheel within one set member's range to experiment with different hue variations of that color class and then pick the favorite color from the palette of the selected hue.

In this interface, for set notation red is defined as 0, red orange as 1, orange as 2, yellow orange as 3, yellow as 4, and so on following the order on the color wheel. This assignment is only to provide a reference for numerical set manipulation. With the existence of the transposition operation which number is assigned to which color is actually not important.

If the user drags the number on the right of the box labeled "starting color", a new starting color will be displayed in that box as hint (Fig. 125). All the set members will be transposed to new positions with that color as 0 relatively. Both the highlight on the color wheel and the palettes in the display spaces will be updated accordingly.

Figure 125. Color Keyboard interface – set 0 1 4 transposed, with yellow-green as the starting point.

Besides transposing a set by changing the starting point, functions specially designed for set operations and special relationships are also part of the interface. Users can simply input important values for an operation or select the intended relationship; the result will be displayed in the testing area automatically.

Interactive Canvas

When designing the interactive canvas, two different creative processes are in my mind. One is to compose the spatial and temporal composition directly using the canvas and the timeline. The other is to generate the composition through programming.

In the first type of process, users can create and transform shapes or change their colors on the canvas interactively. Together with the timeline, the canvas provides the environment to define the visual information at all the key points along time. The computer can then interpolate in between following the designed interpolation curve. The function of the canvas in this process is similar to the canvas in other animation software such as Flash.

For the process of using programming to generate the temporal visual creation, the canvas serves as a sketching and notation space that opens a visual window looking into and talking to the code. When creating temporal visual creations that have clear storyboard or definite design ideas, two distinctive sub-processes are involved. One is the sketching of the visual ideas on paper; the other is the realization of this design through programming. It is very counterintuitive and difficult to make these two sub-processes work together. From one side, in order to use the sketch to guide the programming, one has to quantify those visual ideas into numbers. The process of measuring the position and size of visual components in the sketch and label the numbers on the paper is both tedious and counterintuitive. When sketches are done on papers of varied sizes, those measured values need to be further scaled following a standard paper size. From the other side, to adjust the code to represent the visual idea, many trial and error rounds have to be carried out before the desired result can be achieved. In existing interfaces for graphics creation by programming, the canvas is only used to display the result of the creation but has no direct support to the creation process. The missing of a digital bridge between the visual idea and logical thinking makes the programming a helpless process of fumbling and guessing.

The interactive canvas in this interface has different functions to help keeping the creative process less disturbed by the above-mentioned problems. On the canvas, the user can redraw from the sketch graphical features useful for programming. In this way, critical numerical information is recorded into the system in a graphical manner. The resulting drawing could be further scaled or edited to fit the desired visual effect in a way much direct than guessing numbers in the code. This note style information is then working together with the temporal information provide values for parameters in the programming to adapt to at different points of time or at different stages.

Absolute Timeline

In temporal visual composition, the timeline plays an extremely important role. It could both work together with the interactive canvas providing an environment for creating temporal visual content at micro scale and provide a display of the overall compositional form of the work. This second function is very important for working on temporal visual creation from a compositional point of view. In *The Visual Story: Seeing the Structure of Film, TV and New Media*, Bruce Block uses graph to diagram the visual structure, the development of visual exposition, confliction, and resolution over time. With timeline in my interface, this structural overview is directly connected to the visual creation. The temporal development of any aspect of any visual component could be plotted under request. The plotted graph is also editable and the modification on the graph will change the visual component directly.

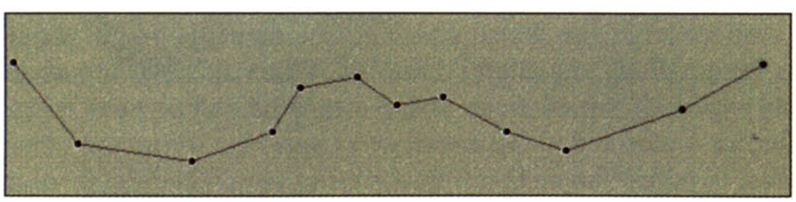

Figure 126. Example timeline overview of one visual component.

Multiple layers could be used for graphics or colors that have different temporal compositions. Their relationship relative to each other and to the overall development provides a platform at a higher level for the artist to further work on the composition. For the second type of creation processing through programming mentioned in last section, temporal graphs could also be displayed on the timeline to provide visual ideas of the temporal composition hidden in the code. Similar to the interactive canvas, this timeline is editable and can feed values back to the programming to avoid unnecessary trial and error.

The timeline in Flash, Adobe Premiere and many other animation or film editing software uses the frame as the basic unit, normally 20-30 frames per second. This is designed following the convention in filmmaking but possesses many problems for temporal visual composition in which accurate control of time is very important. When I was once working on an abstract animation using Adobe Primer, since there are limited amount of frames within a second, even a simple temporal interpolation task becomes very difficult and could only be approximated within those frames, not to mention complex temporal compositions which are based on price temporal relationships. To better support the temporal composition at both the micro and the macro scale, the timeline in this interface is designed to be organized by absolute time instead of frame. Key frames in other animation software turn out to be the combination of certain visual information in the canvas and points on the timeline corresponding to them. This idea of having a price temporal system is not unfamiliar. The composition of music is strictly embedded in a well-defined framework of time. It is the compliance with this framework which renders the rich variations in the composition meaningful and aesthetically pleasant.

The absolute timeline and the precise control of time in this interface also naturally open up the connection with music composition at different levels. Since both are based on accurate time, compositions with both visual and musical components could be designed under the same framework. The variety of ways used in music to organize time systematically could also be borrowed and experimented in the visual domain. Even some interfaces for music time input could be shared. For example, in Masx/MSP/Jitter there is an interface object called Detonate. With this object the user can play out a rhythmic pattern on a midi keyboard, the temporal information about the start time, pitch, velocity, duration of each note are recorded on a editable chart. Multiple tracks could be recorded and organized on the chart. The information from the chart could then be used later composition. When we are now considering temporal visual creation as composition and giving more concerns to the temporal pattern of visual components, it is not too novel to use midi keyboard along with the Detonate object to provide temporal information for visual creation following the temporal sense transmitted through our body.

This above interface design could be realized in different graphics and interface programming environments, such as Java, C++, Processing and Max/MSP/Jitter. Max/MSP/Jitter was chosen over the others for the following reasons:

1) As a graphical programming environment, graphical and interactive thinking is innate to Max/MSP/Jitter. This makes it a good environment for building graphical user interface.

2) Since Max/MSP/Jitter was originally designed to control MIDI events in computer music composition, there are already objects useful for temporal composition. Objects in Max/MSP/Jitter could be controlled by algorithms written in Javascript for complex or automatic compositions. New external objects can also be easily developed in Java or C. This makes it convenient to connect stand-alone systems, such as JColor, into this environment.

3) Since the graphical part of this environment, Jitter, shares a common language with the computer music composition (Max) and audio process (MSP) parts, it is very good for compositions integrating the visual and musical components.

4) Jitter's support for interactive 2D and 3D graphics makes it possible to build the interactive canvas interface and create composition directly with the interface. Jitter's support for low-level drawing with OpenGL commands makes it possible to create complex graphical evolutions through programming. The matrix-based structure optimizes Jitter's real-time image processing capability and makes it possible to create graphical contents and take live input in real time. This opens up the new direction of performing a visual art work in a way similar to performing a music piece and also makes it ready for a new type of composition in which the contents are prepared or defined in advance, prior to being performed in real time. Besides supporting real-time graphics creation and manipulation, Max/MSP/Jitter also has objects of the "pattr family" which enable the user to save values

of all the named parameters across time and come back at anytime to render high-resolution images if they want.

5) Its high performance real-time video processing and the thus enabled capability of motion tracking, its easy communication with sensory information, and its support for multiple live video input all make Jitter a good platform for developing large-scale digital art works. Consequently, abstract graphical experiments carried out in Jitter can be easily incorporated into large-scale creations; temporal visual composition interfaces and approaches developed in Jitter can also be directly utilized in the creation of large-scale digital art works.

5.2. JColor System

Functions

As introduced in Chapter 2, JColor is a color generation and manipulation system developed during my in-depth study of color perception and measurement. The basic idea of this system is to create spectral representation of color either through design or through simulation and then generate or manipulate color based on this information. It has following major functions:

1) Color generation based on artificially designed spectral pattern or based on the spectral reflectance curve of pigments.

2) Color mixing calculated based on spectral reflectance curves.

3) Color manipulation using signal processing techniques such as filtering, AM, FM, wave-shaping, and granular.

4) Visual effect simulation through physical modeling of color spectra.

5) Design and creation of temporal color.

This control of color at the spectral level provides more perceptually meaningful parameters to work with in composing complex temporal color patterns. Even though the metranism property of visual perception renders many colors with different wave contents look the same, the systematic underlying composition could still be revealed through time.

The low-level color generation and manipulation in this system is connected to the high-level color selection in the CIELAB space through the CIE chromatic diagram. This enables flexible transformation between numerical color controls at composition, color, and spectral levels. For example, the high level set structure could have a direct control over color generation and manipulation at the spectral level. A characteristic set could be used to create component frequencies for a new color; it could also be used to define a series of center frequencies for filtering an existing one.

Interface

An interactive graphical user interface is developed to support some of the above functions (Fig. 127).

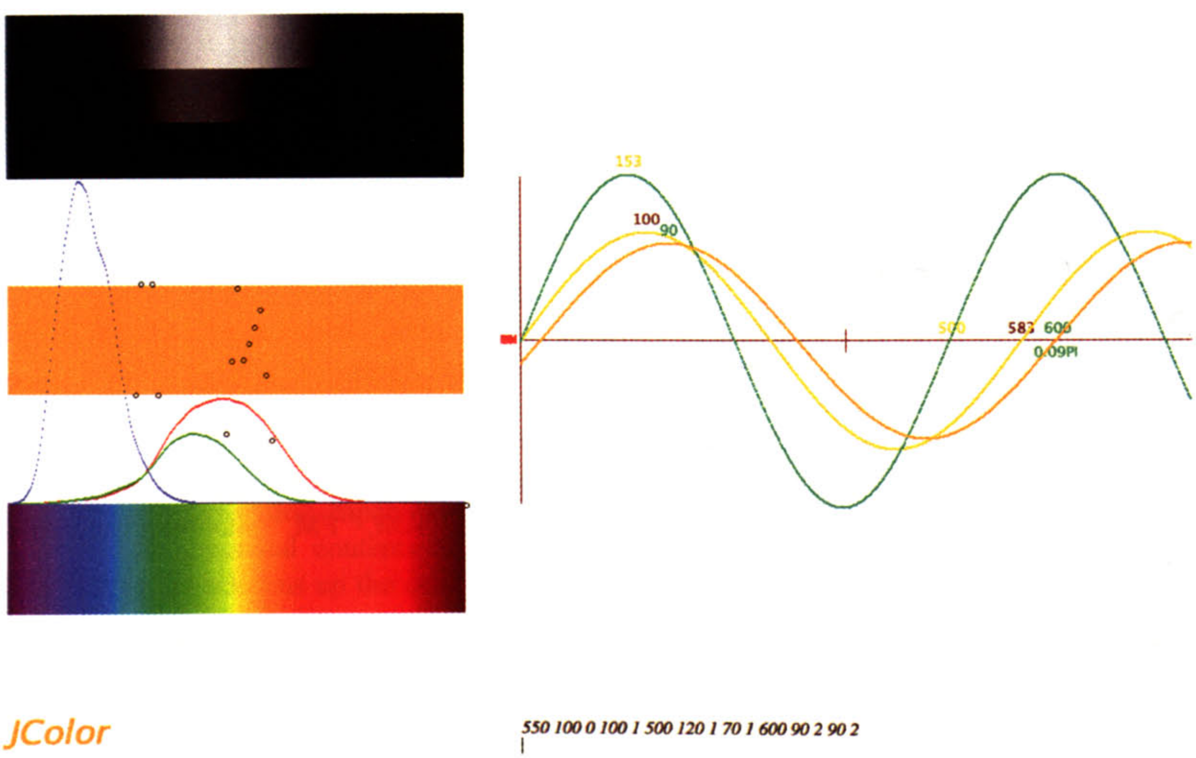

Figure 127. JColor interface.

As displayed in Fig. 127, the interface provides two ways to generate color. With the left part of the interface, the user can create a color by drawing its spectral profile. With the right part of the interface, a color could be created by explicitly defining its wave components.

On the left part of the interface, the user can draw or modify with the mouse the spectral profile of a color. The color stripe in the center displays the resulting color. Fundamental factors from light physics and color vision are presented as visual hints to help with the process of spectral profile creation. At the bottom, colors across the visible range are plotted to give the user a sense where along the spectrum they are drawing. The three curves in the center are the sensitivity curve of the three types of cones. The three stripes on the top plot the relative contribution by each type of cone to the final luminance perception. These grayscale images came from multiplying the cones' sensitivity to frequencies across the visible range by their quantity (The average person has only one blue cone for every 20 green and every 40 red cones). By displaying these important factors next to the drawing area, the users can have a general idea about the hue and the luminance of the color they are creating.

The right part of the interface has two sub-areas. In the one on the top, there is a red light gun like button. The user can click that button to generate a curve representing a light wave. The amplitude, frequency, and phase of that wave could be further adjusted after generation. More waves could be added to form a chromatic color. This method of creation gives the user a direct control over the component waves. After using the interface and getting familiar with the hue and luminance effect of adding spectral component at different range, the user can use programming to control the generation of colors with different wave components and assign temporal changes to those components to form temporal colors. In the sub-area at the bottom of the right part of the interface, users can type in numerical representations of wave components and their temporal change. Corresponding waves will be generated and animated in the sub-area on the top. The resulted color profile and color will also be displayed in the left part of the interface. This function serves as an intermediate step between using the interface and pure programming. When using programming to generate color and control its temporal behavior, all the algorithms and objects in this system are in support in the back. The user only needs to focus on programming the wave content and the temporal pattern.

Temporal Color

With the access to wave components of a color, it is possible to define the temporal change of each component, for example, the speed and range of change for each aspect, the amplitude, wavelength, and phase, of a component wave. This leads to the generation of a new type of color which has the temporal pattern of its wave components as part of its properties. To identify this dynamic visual content as a new type of color, temporal color, is not for the sake of inventing a new term. It provides the locale for further studying and working with the new function of color as a temporal flux instead of as a static pigment.

In *Digital Harmony*, John Whitney pointed out the fact that "most studied and recorded differences between color and tone are related to the perception of static color versus the transient nature of tone". He called for exploration of the transiency of color "on a continent where color presents itself as 'form before to now to later'". He also imagined the future when "full control of the profound experience of color in dynamic transformations will become a visual tensional force and an instrumentality of art.... color, less a subject of static contemplation as in painting today, will be more a force of dynamic expressive power."

The computational speed nowadays makes it possible to generate color in real time through calculation based on its spectral components. The signal processing techniques provides various means to manipulate the spectral representation of a color. Identifying temporal color as a new visual component, developing systematic ways to compose this visual instrument, and employing it into higher-level composition, push Whitney's idea about dynamic expressive power even further into the domain of temporal visual composition.

Temporal color in some sense is similar to the instrument design in Csound and could be used in higher-level temporal composition in the same way as the Csound instruments being used in its score design. Files corresponding to the intrument file and score file in Csound could be created and called color file (component waves and their changing along time) and composition file (temporal composition of colors defined in the color file). These color file deals with color composition at a micro level, the composition file composes these temporal ingredients into a meaningful piece. These two levels of composition are highly interactive. When composing the colors defined by the color files, changes of individual light waves are still accessible and could be adjusted according to the overall design.

The system provides predefined temporal colors. Artists could also design and built their own from scratch. The predefined temporal colors are either template temporal color designs for the user to start with or simulations of natural color or color change through physical modeling.

Difference between JColor and CSound or other Audio Synthesis System

Even though the JColor system was originally inspired by CSound, there is a fundamental difference between JColor and CSound or music synthesis systems in general. The musical systems create complex sound by generating its component waves. JColor on the other hand only uses information of a color's spectral components and generates color based on this *frequency domain representation*, if we use the same term as in computer music.

This fundamental difference shows that some signal processing techniques are more ready and convenient to be used in JColor than in musical synthesis systems. It also suggests a potential representation of temporal color similar to sonograph in music.

In computer music, in order to directly manipulate the spectrum of a sound, one has to first translate audio data from the time domain into the frequency domain and then re-synthesize a time domain audio signal based on the modified frequency domain information. The Fast Fourier Transform is normally used in this process. Its underlying theory is the Fourier theorem that any periodic wave can be expressed as the sum of a series of harmonically related sinusoids, each with its own amplitude and phase. The ideal situation is to apply the Fourier transform on exactly one cycle of the wave being analyzed. For real world sound, which are mostly not strictly periodic, the Fourier transform has to be performed on consecutive time slices in order to get a sense of how the spectrum of that sound change over time, which generates the sonograph representation. However, such a transformation has an innate inaccuracy and trade-off between frequency resolution and time resolution. This is because when applying the transformation to one slice of a signal, any time resolution that occurs within that duration is lost. The audio data within this slice of time is considered to be one cycle of a wave that does not change across this period of time.

For temporal color, even though one can create it through composing its component waves and their temporal change, the color is always generated based on its spectrum. A frequency domain representation is always there ready for application of signal processing techniques such as filtering or frequency tracking. There is no need to window the time domain signal, generate inaccurate frequency domain representation and then use the modified frequency domain representation to rebuilt the time domain wave inaccurately again.

Combining this representation along time following similar conventions like the sonograph could form a graphical representation of the temporal color as well. A temporal color or color composition could be reconstructed or performed based such a graphical representation. Since there is no transformation involved, it is a direct recreation of a temporal color based on its temporal notation, similar to performing a piece of music based on its score.

If a mapping between graphics and music is needed, mapping this graphical representation of temporal color to the sonograph would have more meaning than mapping an arbitrary image that has certain temporal origin, such as an image resulted from sectioning an animation using a plane parallel to the time dimension, to the sonograph. This mapping of two graphical representation of frequency domain information stacked along time might suggest many creative possibilities. For example, one could map the temporal color representation into one octave in the sonograph, create content in other octaves in relation to this octave, and then re-synthesize this "multi-octave color" into music.

Chapter 6. Conclusion

In summary, this thesis introduces interests and explorations in history about the temporal aspect of visual art; proposes a set theory-based approach for temporal visual composition; develops and experiments with this approach in various types of compositions; discusses perceptual and compositional issues unique to temporal art; and develops a series of interfaces supporting the composition process.

This chapter summarizes the contributions of this research, lists my next steps continuing the current study, and points out issues suggestive for the temporal visual composition research.

6.1. Contributions

The contributions of this thesis are presented at different levels:

1. It introduces the concept of disciplined composition along the temporal dimension and presents an example for this unfamiliar concept through the design of a set theory-based composition approach and the creation of art works that conform to (or violate) rules defined in this approach.

2. The composition approach and interfaces provide an environment for artists to begin to develop and control works of temporal art in a disciplined way.

3. The interactive development process of the composition approach, the composition interface and the art works provides a model for artists to refine the provided environment or develop their own when there are needs for new means of expression and control, along with the maturing of temporal art as a discipline.

4. Beyond the contributions stated above, this thesis initiates and invites more research on the theory of temporal visual composition.

6.2. Next Steps

1. One ongoing work is to continue the development of the three digital art projects introduced in the second section of Chapter 4, *Experiments*. This will help acquire more concrete senses about the role of disciplined composition in temporal art creation and help further refine the compositional approach proposed in this study.

2. Another continuation is to keep studying and analyzing perceptual phenomena and fundamental issues in temporal visual composition. Topics such as identity and duration will be added to the list of study. Latest research in visual perception, especially motion perception, will also be utilized in the analysis.

3. Designing and developing more interfaces supporting temporal visual composition is also a long-term task in the same spirit as this thesis.

4. As introduced at the beginning, the study in this thesis came from a bigger framework of research about the temporal dimension of visual art. Returning to the bigger framework, exploring more approaches or methods for temporal visual composition, and looking into more aspects influencing or induced from the temporal visual creation will thus be the next step in the long run. Besides color, the temporal composition of other important elements such as shape, texture and movement will be studied. Influences from other art forms will be also experimented with.

6.3. Suggestive Issues

Based on my experience in this study, some issues are sensed to be important for temporal visual composition research. They are provided here as suggestions for future researchers in this field.

1. In this study, there is an inseparable relationship between the experiments and projects carried out and the composition approach developed. The composition approach is highly grounded in the visual creation process and will be applied back to it as well. Similar

to graphical study by Klee, color study by Itten, and Bartok's approach to musical composition, a theory is only meaningful when it comes from and goes back to the process of artistic creation.

2. Another topic concerns the role of technology in temporal visual composition. As introduced earlier in the history section, it is the invention of the optical toys and the film technology that brought to life temporal dimension in visual art. The ease of the composition process and the type of composition that could be achieved are also a function of the technology available at each period of time. It is also clearly exhibited in this study that technology is both supportive and provocative to the development of temporal art. Furthermore, when thinking about the role of technology (computer-based in this case), we should not be limited by its current format of representation but should also think of its power to control other means of display and foresee its potential in the future. For example, the gamut available to a typical computer monitor (the RGB triangle on the CIE chromatic diagram) only covers around one third of the entire space of possible chromatics. This posits a huge limitation to the functioning of the spectral color system. However, the same color generation and manipulation algorithms could be employed to control laser projections, which have a much larger gamut. The gamut of some types of laser projectors even covers almost the whole chromatic space. Foreseeing the future of computer display, a spectral information-based system might replace the RGB system and becomes a more versatile alternative bringing to us a tremendous amount of colors we have never seen so far on the computer.

3. In this research, the study of temporal visual composition as a discipline, the creation of art works, and the technology and medium mobilized to serve these purposes form a vigorous triangle. This brings up the topic about where artists should position themselves and the computer in temporal art. Using the terms from Klee's book *The Thinking Eye*, is the computer just an eye rendering and displaying the artist's composition or it could also become a thinking eye contributing to the creative process? In this study,

the interfaces developed by considering important aspects in the composition process provide an environment to best keep the creative impulses from being interrupted. The functions that have set theory logic encoded effectively utilize the strength of the computer in supporting the generation of aesthetic payoffs through numerical manipulations. The algorithms written to control the temporal development of the graphical materials are by themselves the products of composition. The spectral color system brings new visual material -- temporal color as well as new compositional potentials. Along with the development of digital art, the computer could take more active roles in the creative process. Another question under this topic is: Is the artists' use of computer operative or creative? As presented in this study, far beyond executing specific functions, artists can utilize the computer in the same way as other creative materials in presenting design ideas, structuring temporal developments, and engaging audiences with their works.

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A Brief Introduction to Pitch-Class Set Analysis (http://www.mta.ca/faculty/arts-letters/music/pc-set_project/pc-set_new/pages/introduction/toc.html)

Appendix A. Color Conversion

A table with the xy-coordinates of the most used primaries and whitepoints. The gamma-correction is usually defined as 1/0.45 = 2.2222, so use for very critical work this value instead of the 2.2 from the table. Gamma-correction is not dealt with in this tutorial at the moment.

Primaries	White Point	Gamma	RGB (x,y) coordinates
PAL, SECAM, EBU/ITU	D65	2.2	r: (0.64,0.33) g: (0.29,0.60) b: (0.15,0.06)
NTSC (1953)	CIE C	2.2	r: (0.67,0.33) g: (0.21,0.71) b: (0.14,0.08)
NTSC (modern)	D65	2.2	r: (0.630,0.340) g: (0.310,0.595) b: (0.155,0.070)
SMPTE-C, CCIR 601-1	D65	2.2	r: (0.630,0.340) g: (0.310,0.595) b: (0.155,0.070)
Apple RGB, Trinitron	D65	1.8	r: (0.625,0.34) g: (0.28,0.595) b: (0.155,0.07)
sRGB, HDTV, CCIR 709	D65	2.2	r: (0.64,0.33) g: (0.30,0.60) b: (0.15,0.06)
CIE RGB	CIE E	2.2	r: (0.735,0.265) g: (0.274,0.717) b: (0.167, 0.009)
Adobe RGB (1998)	D65	2.2	r: (0.64,0.33) g: (0.21,0.71) b: (0.15,0.06)

The CIE white points are defined for some standard illuminants. The D-series are supposed to represent black body radiators with a temperature of 100 times the given number, in Kelvin.

White point	CIE xy-coordinates
CIE A (tungsten lamp)	(0.4476,0.4074)
CIE B (direct sunlight)	(0.3484,0.3516)
CIE C (average daylight with sun)	(0.310063,0.316158)
CIE E (standard reference)	(1/3,1/3)
D50	(0.3457,0.3585)
D55 (photography, cloudy daylight)	(0.3324,0.3474)
D65 (standard daylight)	(0.312713,0.329016)
D75	(0.299,0.3149)
D93 (old CRT monitors)	(0.2848,0.2932)

D65 The native while point for Apple Cinema Display

Given the chromaticity coordinates of an RGB system (x_r, y_r), (x_g, y_g) and (x_b, y_b) and its reference white (X_W, Y_W, Z_W), here is the method to compute the 3 × 3 matrix for converting RGB to XYZ:

$$[X \quad Y \quad Z] = [R \quad G \quad B][M]$$

where

$$[M] = \begin{bmatrix} S_r X_r & S_r Y_r & S_r Z_r \\ S_g X_g & S_g Y_g & S_g Z_g \\ S_b X_b & S_b Y_b & S_b Z_b \end{bmatrix}$$

$$X_r = x_r / y_r$$
$$Y_r = 1$$
$$Z_r = (1 - x_r - y_r) / y_r$$

$$X_g = x_g / y_g$$
$$Y_g = 1$$
$$Z_g = (1 - x_g - y_g) / y_g$$

$$X_b = x_b / y_b$$
$$Y_b = 1$$
$$Z_b = (1 - x_b - y_b) / y_b$$

$$\begin{bmatrix} S_r & S_g & S_b \end{bmatrix} = \begin{bmatrix} X_W & Y_W & Z_W \end{bmatrix} \begin{bmatrix} X_r & Y_r & Z_r \\ X_g & Y_g & Z_g \\ X_b & Y_b & Z_b \end{bmatrix}^{-1}$$

The inverse matrix (i.e. the matrix converting XYZ to RGB) is computed by inverting matrix [M] above.

With the algorithms given above, it is possible to convert a set of XYZ-coordinates to another white point or another set of primaries. First convert with the current coefficients matrix XYZtoRGB1 back to RGB, then calculate a new coefficients matrix RGBtoXYZ2 for the conversion from RGB to XYZ with the new white point and-or the new RGB primaries and do the conversion back to X'Y'Z'. Conversion of RGB coordinates to another set is also possible. Convert with the current matrix RGBtoXYZ1 to XYZ and convert back with a new matrix XYZtoRGB2 to RGB.

RGB Working Space	Reference White	RGB to XYZ [M]	XYZ to RGB $[M]^{-1}$
Adobe RGB (1998)	D65	0.576700 0.297361 0.0270328 0.185556 0.627355 0.0706879 0.188212 0.0752847 0.991248	2.04148 -0.969258 0.0134455 -0.564977 1.87599 -0.118373 -0.344713 0.0415557 1.01527
Apple RGB	D65	0.449695 0.244634 0.0251829 0.316251 0.672034 0.141184 0.18452 0.0833318 0.922602	2.95176 -1.0851 0.0854804 -1.28951 1.99084 -0.269456 -0.47388 0.0372023 1.09113
BestRGB	D50	0.632670 0.228457 0.000000 0.204556 0.737352 0.00951424 0.126995 0.0341908 0.815696	1.75526 -0.544134 0.00634681 -0.483679 1.50688 -0.0175762 -0.253000 0.0215528 1.22570
Beta RGB	D50	0.671254 0.303273 0.000000 0.174583 0.663786 0.040701 0.118383 0.0329413 0.784509	1.68323 -0.771023 0.0400012 -0.428236 1.70656 -0.0885376 -0.236018 0.0446899 1.27236
BruceRGB	D65	0.467384 0.240995 0.0219086 0.294454 0.683554 0.0736135 0.188629 0.0754517 0.993447	2.74566 -0.969257 0.0112707 -1.13589 1.87599 -0.113959 -0.435057 0.0415557 1.01311
CIE	E	0.488718 0.176204 0.000000 0.310680 0.812985 0.0102048 0.200602 0.0108109 0.989795	2.37067 -0.513885 0.00529818 -0.900040 1.42530 -0.0146949 -0.470634 0.0885814 1.00940
ColorMatch	D50	0.509344 0.274884 0.0242545 0.320907 0.658132 0.108782 0.133969 0.0669845 0.692174	2.64229 -1.11198 0.0821698 -1.22343 2.05902 -0.280725 -0.393014 0.0159614 1.45599
DonRGB4	D50	0.645771 0.278350 0.00371134 0.193351 0.687970 0.0179862 0.125098 0.0336802 0.803513	1.76039 -0.712629 0.00782072 -0.488120 1.65274 -0.0347411 -0.253613 0.0416715 1.24477
ECI	D50	0.650204 0.320250 0.000000 0.178077 0.602071 0.0678390 0.135938 0.0776791 0.757371	1.78276 -0.959362 0.0859318 -0.496985 1.94780 -0.174467 -0.269010 -0.0275807 1.32283
Ekta Space PS5	D50	0.593891 0.260629 0.000000 0.272980 0.734946 0.0419970 0.0973486 0.00442493 0.783213	2.00438 -0.711029 0.0381263 -0.730484 1.62021 -0.0868780 -0.245005 0.0792227 1.27254
NTSC	C	0.606734 0.298839 0.000000 0.173564 0.586811 0.0661196 0.200112 0.114350 1.11491	1.91049 -0.984310 0.0583744 -0.532592 1.99845 -0.118518 -0.288284 -0.0282980 0.898611
PAL / SECAM	D65	0.430587 0.222021 0.0201837 0.341545 0.706645 0.129551 0.178336 0.0713342 0.939234	3.06313 -0.969258 0.0678674 -1.39328 1.87599 -0.228821 -0.475788 0.0415557 1.06919
ProPhoto	D50	0.797675 0.288040 0.000000 0.135192 0.711874 0.000000 0.0313534 0.000086 0.825210	1.34594 -0.544599 0.000000 -0.255608 1.50817 0.000000 -0.0511118 0.0205351 1.21181
SMPTE-C	D65	0.393555 0.212395 0.0187407 0.365253 0.701049 0.111932 0.191659 0.0865558 0.958297	3.50570 -1.06906 0.0563117 -1.73964 1.97781 -0.196994 -0.544011 0.0351720 1.05005
sRGB	D65	0.412424 0.212656 0.0193324 0.357579 0.715158 0.119193 0.180464 0.0721856 0.950444	3.24071 -0.969258 0.0556352 -1.53726 1.87599 -0.203996 -0.498571 0.0415557 1.05707
WideGamut	D50	0.716105 0.258187 0.000000 0.100930 0.724938 0.0517813 0.147186 0.0168748 0.773429	1.46281 -0.521793 0.0349342 -0.184062 1.44724 -0.0968931 -0.274361 0.0677228 1.28841

Appendix B. Technical Documentation

1) Javascript code for the default set theory-based music composition

```
// inlets and outlets
inlets = 3;
outlets = 12;
var tpo=2000;

function AutoSet()
{
  var setContent=new Array();
  var setDuration=0;
  var setSecD=new Array();
  var setSecS=new Array();
  var setSecR=new Array();
  var rPatternS=new Array();
  var rPatternD=new Array();
  var rPatternP=new Array();
  var octRange=0;
}

// define global variables and set defaults
var autoSet=new Array();
autoSet[0]=new AutoSet();
autoSet[0].setContent=new Array(0,2,4,7);
autoSet[0].setDuration=30;
autoSet[0].setSecD=new Array(.30,.30,.30,.10);
autoSet[0].setSecS=new Array(38, 75, 160, 40);
autoSet[0].setSecR=new Array(4);
autoSet[0].setSecR[0]=new Array();
autoSet[0].setSecR[1]=new Array();
autoSet[0].setSecR[2]=new Array();
autoSet[0].setSecR[3]=new Array();
autoSet[0].rPatternS=new Array(17);
autoSet[0].rPatternD=new Array(17);
autoSet[0].rPatternP=new Array(17);
autoSet[0].octRange=2;

autoSet[0].rPatternS[0]=new Array(0.,  .125, .25,  .375, .5,  .625, .75 , .875, 1.,  5.5, 6., 6.5,
7., 7.37, 7.70,  8., 8.17, 8.337,  8.5, 8.663, 8.83, 9., 9.3, 9.63, 10);
autoSet[0].rPatternD[0]=new Array(.125, .125, .125, .125, .125, .125, .125, .125, 4.5,  .5, .5,
.5, .37, .33,  .3, .17, .167,  .163, .163,  .167,  .17, .3, .33, .37, 2);
autoSet[0].rPatternP[0]=new Array(8,4,0,5);

autoSet[0].rPatternS[1]=new Array(0.,  .125, .25,  .375, .5,  .625, .75 , .875, 1.,  5., 5.125,
5.75, 6., 6.5);
autoSet[0].rPatternD[1]=new Array(.125, .125, .125, .125, .125, .125, .125, .125, 4., .125,
.625,  .25, .5,  .5);
autoSet[0].rPatternP[1]=new Array(6,3,3,5);

autoSet[0].rPatternS[2]=new Array(0.,  .125, .25,  .375, .5,  .625, .75 , .875, 1.,  5., 5.125,
6.5, 6.625,  8., 8.125, .95, 10., 10.5, 11., 11.3, 11.63, 12., 12.5, 13.5);
autoSet[0].rPatternD[2]=new Array(.125, .125, .125, .125, .125, .125, .125, .125, 4., .125,
1.375, .125, 1.375, .125, 1.375,  .5,  .5,  .5, .3,  .33,  .37, .5,  1.,  .5);
autoSet[0].rPatternP[2]=new Array(8,4,0,4);

autoSet[0].rPatternS[3]=new Array(0.,  .125, .25,  .375, .5,  .625, .75 , .875, 1.,  5., 5.125,
5.25, 5.375);
autoSet[0].rPatternD[3]=new Array(.125, .125, .125, .125, .125, .125, .125, .125, 4., .125,
.125, .125, 1.625);
autoSet[0].rPatternP[3]=new Array(4,4,3,6);

autoSet[0].rPatternS[4]=new Array(0.,  .1250);
autoSet[0].rPatternD[4]=new Array(.125, 3.875);
autoSet[0].rPatternP[4]=new Array(8,2,2,3);
```

```
autoSet[0].rPatternS[5]=new Array(0., 1.5, 2., 3., 4., 4.125);
autoSet[0].rPatternD[5]=new Array(1.5, .5, 1., 1., .125, 3.875);
autoSet[0].rPatternP[5]=new Array(7,5,4,6);

autoSet[0].rPatternS[6]=new Array(0., .75, 1., 1.5, 2., 2.5, 2.75, 3., 3.5, 4.);
autoSet[0].rPatternD[6]=new Array(.75, .25, .5, .5, .5, .25, .25, .5, .5, 2.);
autoSet[0].rPatternP[6]=new Array(4,7,7,4);

autoSet[0].rPatternS[7]=new Array(0., .5, 1., 3., 3.5, 4., 5.);
autoSet[0].rPatternD[7]=new Array(.5, .5, 2., .5, .5, 1., 2.);
autoSet[0].rPatternP[7]=new Array(4,8,6,2);

autoSet[0].rPatternS[8]=new Array(0., .75, 1.);
autoSet[0].rPatternD[8]=new Array(.75, .25, 1.);
autoSet[0].rPatternP[8]=new Array(5,5,8,3);

autoSet[0].rPatternS[9]=new Array(0., .125, .25, .375, 1.5, 2., 2.5, 3., 3.5, 4., 4.5, 5., 6.5, 7.,
7.5, 8., 8.5, 9.);
autoSet[0].rPatternD[9]=new Array(.125, .125, .125, 1.125, .5, .5, .5, .5, .5, .5, .5, 1.5, .5,
.5, .5, .5, .5, 2.);
autoSet[0].rPatternP[9]=new Array(0,1,2,0);

autoSet[0].rPatternS[10]=new Array();
autoSet[0].rPatternD[10]=new Array();
autoSet[0].rPatternS[10][0]=0.;
autoSet[0].rPatternD[10][0]=8.;
autoSet[0].rPatternP[10]=new Array(8,6,0,5);

autoSet[0].rPatternS[11]=new Array();
autoSet[0].rPatternD[11]=new Array();
autoSet[0].rPatternS[11][0]=0.;
autoSet[0].rPatternD[11][0]=4.;
autoSet[0].rPatternP[11]=new Array(6,6,3,4);

autoSet[0].rPatternS[12]=new Array();
autoSet[0].rPatternD[12]=new Array();
autoSet[0].rPatternS[12][0]=0.;
autoSet[0].rPatternD[12][0]=2.;
autoSet[0].rPatternP[12]=new Array(4,4,1,4);

autoSet[0].rPatternS[13]=new Array();
autoSet[0].rPatternD[13]=new Array();
autoSet[0].rPatternS[13][0]=0.;
autoSet[0].rPatternD[13][0]=1.5;
autoSet[0].rPatternP[13]=new Array(3,5,5,5);

autoSet[0].rPatternS[14]=new Array();
autoSet[0].rPatternD[14]=new Array();
autoSet[0].rPatternS[14][0]=0.;
autoSet[0].rPatternD[14][0]=1.;
autoSet[0].rPatternP[14]=new Array(1,3,3,2);

autoSet[0].rPatternS[15]=new Array();
autoSet[0].rPatternD[15]=new Array();
autoSet[0].rPatternS[15][0]=0.;
autoSet[0].rPatternD[15][0]=.5;
autoSet[0].rPatternP[15]=new Array(0,2,3,1);

autoSet[0].rPatternS[16]=new Array(0., .25, .5, .75, 1., 1.25, 1.5, 1.75);
autoSet[0].rPatternD[16]=new Array(.25, .25, .25, .25,.25, .25, .25, .25);
autoSet[0].rPatternP[16]=new Array(2,4,9,3);

for(var j=0;j<17;j++)
{
for(var k=0;k<4;k++)
{
 var c=autoSet[0].rPatternP[j][k];
 for(var p=0;p<c;p++)
 autoSet[0].setSecR[k].push(j);
```

```
}
}

autoSet[1]=new AutoSet();
autoSet[1].setContent=[0,2,4,6];
autoSet[1].setDuration=30;
autoSet[1].setSecD=new Array();
autoSet[1].setSecD[0]=1.;
autoSet[1].setSecS=new Array();
autoSet[1].setSecS[0]=40;
autoSet[1].rPatternD=new Array(16);
autoSet[1].rPatternS=new Array(16);
autoSet[1].octRange=3;

autoSet[1].rPatternS[0]=new Array(0., .5, 1., 1.5, 2., 2.5, 3., 3.5);
autoSet[1].rPatternD[0]=new Array(.5, .5, .5, .5, .5, .5, .5, .5);

autoSet[1].rPatternS[1]=new Array(0., 1., 3.);
autoSet[1].rPatternD[1]=new Array(1., 2., 3.);

autoSet[1].rPatternS[2]=new Array(0., .25, .5, .75, 1., 1.166, 1.332, 1.499, 1.666, 1.833, 2.,
4.)
autoSet[1].rPatternD[2]=new Array(.25,.25, .25,.25, .166, .166, .167, .167, .167, .167, 2.,
4.);

autoSet[1].rPatternS[3]=new Array(0., .5, 1., 3.);
autoSet[1].rPatternD[3]=new Array(.5, .5, 2., 4.);

autoSet[1].rPatternS[4]=new Array(0., .5);
autoSet[1].rPatternD[4]=new Array(.5, 2.5);

autoSet[1].rPatternS[5]=new Array(0., .333, .666, 1.);
autoSet[1].rPatternD[5]=new Array(.333,.333, .334, 2.);

autoSet[1].rPatternS[6]=new Array(0., 2.5);
autoSet[1].rPatternD[6]=new Array(.5, .5);

autoSet[1].rPatternS[7]=new Array(0., .5, 1., 1.5);
autoSet[1].rPatternD[7]=new Array(.25,.25,.25, .25);

autoSet[1].rPatternS[8]=new Array(0., 0.166, 0.332, 0.499, 0.666, 0.833, 2., 2.166,
2.332, 2.499, 2.666, 2.833);
autoSet[1].rPatternD[8]=new Array(.166, .166, .167, .167, .167, .167, .166, .166, .167,
.167, .167, .167);

autoSet[1].rPatternS[9]=new Array(0., .25, .5, .75);
autoSet[1].rPatternD[9]=new Array(.125, .125, .125, .125);

autoSet[1].rPatternS[10]=new Array();
autoSet[1].rPatternD[10]=new Array();
autoSet[1].rPatternS[10][0]=0.;
autoSet[1].rPatternD[10][0]=8.;

autoSet[1].rPatternS[11]=new Array();
autoSet[1].rPatternD[11]=new Array();
autoSet[1].rPatternS[11][0]=0.;
autoSet[1].rPatternD[11][0]=4.;

autoSet[1].rPatternS[12]=new Array();
autoSet[1].rPatternD[12]=new Array();
autoSet[1].rPatternS[12][0]=0.;
autoSet[1].rPatternD[12][0]=2.;

autoSet[1].rPatternS[13]=new Array();
autoSet[1].rPatternD[13]=new Array();
autoSet[1].rPatternS[13][0]=0.;
autoSet[1].rPatternD[13][0]=1.5;

autoSet[1].rPatternS[14]=new Array();
autoSet[1].rPatternD[14]=new Array();
```

```
autoSet[1].rPatternS[14][0]=0.;
autoSet[1].rPatternD[14][0]=1.;

autoSet[1].rPatternS[15]=new Array();
autoSet[1].rPatternD[15]=new Array();
autoSet[1].rPatternS[15][0]=0.;
autoSet[1].rPatternD[15][0]=.5;


autoSet[2]=new AutoSet();
autoSet[2].setContent=[0,1,3,4];
autoSet[2].setDuration=30;
autoSet[2].setSecD=new Array();
autoSet[2].setSecD[0]=1.;
autoSet[2].setSecS=new Array();
autoSet[2].setSecS[0]=40;
autoSet[2].rPatternD=new Array(15);
autoSet[2].rPatternS=new Array(15);
autoSet[2].octRange=5;

autoSet[2].rPatternS[0]=new Array();
autoSet[2].rPatternD[0]=new Array();
autoSet[2].rPatternS[0]=0.;
autoSet[2].rPatternD[0]=6.;

autoSet[2].rPatternS[1]=new Array(0.,  .125);
autoSet[2].rPatternD[1]=new Array(.125, 2.875);

autoSet[2].rPatternS[2]=new Array(0., .25,  .5, .75, 1.666, 3.5);
autoSet[2].rPatternD[2]=new Array(.25,.25, .25, .25, .334, .5);

autoSet[2].rPatternS[3]=new Array(0.,  2.5, 3.5);
autoSet[2].rPatternD[3]=new Array(.25, .25, .25);

autoSet[2].rPatternS[4]=new Array(0., .25,  3.5,  3.75);
autoSet[2].rPatternD[4]=new Array(.25,.25, .25,  .25);

autoSet[2].rPatternS[5]=new Array(0.,  .66, 1.32, 2.5,  5.);
autoSet[2].rPatternD[5]=new Array(.66, .66, .68, .5,  .5);

autoSet[2].rPatternS[6]=new Array(0., 2.);
autoSet[2].rPatternD[6]=new Array(2., 3.);

autoSet[2].rPatternS[7]=new Array(0., .25, .5,  .75,  1.,  1.25, 1.5,  1.75,  2.,  2.25,  2.5,  2.75);
autoSet[2].rPatternD[7]=new Array(.25,.25, .25, .25, .25, .25,   .25, .25,   .25,  .25,   .25,  .25);

autoSet[2].rPatternS[8]=new Array(0., 3.,  3.25,  3.5, 3.75,  4., 4.25, 4.5,  4.75);
autoSet[2].rPatternD[8]=new Array(3., .25, .25,   .25,  .25,  .25, .25,  .25,  .25);

autoSet[2].rPatternS[9]=new Array();
autoSet[2].rPatternD[9]=new Array();
autoSet[2].rPatternS[9][0]=0.;
autoSet[2].rPatternD[9][0]=8.;

autoSet[2].rPatternS[10]=new Array();
autoSet[2].rPatternD[10]=new Array();
autoSet[2].rPatternS[10][0]=0.;
autoSet[2].rPatternD[10][0]=4.;

autoSet[2].rPatternS[11]=new Array();
autoSet[2].rPatternD[11]=new Array();
autoSet[2].rPatternS[11][0]=0.;
autoSet[2].rPatternD[11][0]=2.;

autoSet[2].rPatternS[12]=new Array();
autoSet[2].rPatternD[12]=new Array();
autoSet[2].rPatternS[12][0]=0.;
autoSet[2].rPatternD[12][0]=1.5;

autoSet[2].rPatternS[13]=new Array();
```

```
autoSet[2].rPatternD[13]=new Array();
autoSet[2].rPatternS[13][0]=0.;
autoSet[2].rPatternD[13][0]=1.;

autoSet[2].rPatternS[14]=new Array();
autoSet[2].rPatternD[14]=new Array();
autoSet[2].rPatternS[14][0]=0.;
autoSet[2].rPatternD[14][0]=.5;


function msg_int(a)
{
 if(inlet==0)
   ctime=a;
}

function list(a)
{
 if(inlet==0)
 {
   autoSet[2].setContent[0]=arguments[0];
   autoSet[2].setContent[1]=arguments[1];
   autoSet[2].setContent[2]=arguments[2];
   autoSet[2].setContent[3]=arguments[3];
 }
}

var ctime=0;
var scount=0;
var dur=0;//autoSet[0].setDuration*1000;
var rindex=new Array(3);
rindex[0]=0;
rindex[1]=0;
rindex[2]=0;
var rlength=new Array(3);
rlength[0]=0;
rlength[1]=0;
rlength[2]=0;
var stime=new Array(3);
stime[0]=0;
stime[1]=0;
stime[2]=0;
var curtime=new Array(3);
curtime[0]=0;
curtime[1]=0;
curtime[2]=0;
var count=new Array(3);
count[0]=0;
count[1]=0;
count[2]=0;
var stops=new Array(3);
stops[0]=0;
stops[1]=0;
stops[2]=0;
var stopc=new Array(3);
stopc[0]=0;
stopc[1]=0;
stopc[2]=0;
var stopd=new Array(3);
stopd[0]=0;
stopd[1]=0;
stopd[2]=0;
var stopf=new Array(3);
stopf[0]=0;
stopf[1]=0;
stopf[2]=0;
var firstTime=new Array(3);
firstTime[0]=0;
firstTime[1]=0;
firstTime[2]=0;
```

```
var trackNum=1;
var secNum=0;
var setNum=0;

function bang()
{
if(scount==0)
{
  dur=autoSet[setNum].setDuration*1000;
  outlet(9,bang);
  scount=1;
}
else
{
 if(setNum==0)
 {
  if(ctime<autoSet[0].setSecD[0]*dur)
  {
   tpo=60./autoSet[0].setSecS[0]*1000;
   secNum=0;
  }
  else if(ctime<(autoSet[0].setSecD[1]+autoSet[0].setSecD[0])*dur)
  {
   tpo=60./autoSet[0].setSecS[1]*1000;
   secNum=1;
  }
  else if(ctime<(autoSet[0].setSecD[2]+autoSet[0].setSecD[1]+autoSet[0].setSecD[0])*dur)
  {
   tpo=60./autoSet[0].setSecS[2]*1000;
   secNum=2;
  }
  else if(ctime<dur)
  {
   tpo=60./autoSet[0].setSecS[3]*1000;
   secNum=3;
  }
  else
  {
  outlet(10, bang);
  init();
  ctime=0;
  //setNum=(setNum+1)%3;
   setNum=1;
  scount=0;

  }
 }
 else
 {
   if(ctime<dur)
     tpo=60./autoSet[setNum].setSecS[0]*1000;
   else
   {
     outlet(10, bang);
     init();
     ctime=0;

     setNum=2;
     scount=0;
   }
}
if(setNum==0)
{
 if(ctime<4*tpo)
  trackNum=1;
 else if(ctime<8*tpo)
  trackNum=2;
 else
  trackNum=3;
```

```
}
else
 trackNum=3;

for(var i=0;i<trackNum;i++)
{
if(count[i]==0)
{
 if(firstTime[i]==0)
 {
   stime[i]=ctime;
   if(setNum==0)
   {
       var len=autoSet[0].setSecR[secNum].length;
       rindex[i]=autoSet[0].setSecR[secNum][Math.floor(Math.random()*len)];
   }
   else
       rindex[i]=Math.floor(Math.random()*autoSet[setNum].rPatternS.length);
   rlength[i]=autoSet[setNum].rPatternS[rindex[i]].length;
   pjNoteGen(0,i);
 }
 else
 {
  if(stopf[i]==0)
  {
   var gam=Math.floor(Math.random()*10);
   var ratio=0;
   if(i==2)
     ratio=6;
   else
     ratio=2;
   if(gam<ratio)
   {
    stops[i]=ctime;
    stopf[i]=1;
    stopd[i]=4+Math.floor(Math.random()*2);
   }
   else
   {
    stime[i]=ctime;
    if(setNum==0)
    {
       var len=autoSet[0].setSecR[secNum].length;
       rindex[i]=autoSet[0].setSecR[secNum][Math.floor(Math.random()*len)];
    }
    else
       rindex[i]=Math.floor(Math.random()*autoSet[setNum].rPatternS.length);
    rlength[i]=autoSet[setNum].rPatternS[rindex[i]].length;
    pjNoteGen(0,i);
    }
   }
   else
   {
    if(ctime-stops[i]>stopd[i]*tpo)
      stopf[i]=0;
   }
 }
}
else
{
  curtime[i]=ctime-stime[i];
  if(count[i]<rlength[i])
  {
     if(curtime[i]>autoSet[setNum].rPatternS[rindex[i]][count[i]]*tpo)
          pjNoteGen(count[i],i);
  }
  else
     count[i]=0;
}
}
```

```
}
}

var nindex=new Array(3);
nindex[0]=4;
nindex[1]=4;
nindex[2]=4;
var narray=new Array(3);
narray[0]=new Array(4);
narray[1]=new Array(4);
narray[2]=new Array(4);
var lnote=new Array(3);
lnote[0]=0;
lnote[1]=0;
lnote[2]=0;
var snote=new Array(3);
snote[0]=0;
snote[1]=0;
snote[2]=0;
var note=new Array(3);
note[0]=0;
note[1]=0;
note[2]=0;
var vel=new Array(3);
vel[0]=0;
vel[1]=0;
vel[2]=0;
var rnote=new Array(3);
rnote[0]=new Array(2);
rnote[1]=new Array(2);
rnote[2]=new Array(2);
var rtimes=new Array(3);
rtimes[0]=0;
rtimes[1]=0;
rtimes[2]=0;
var notep=new Array(3);
notep[0]=0;
notep[1]=0;
notep[2]=0;
var repeatindex=new Array(3);
repeatindex[0]=0;
repeatindex[1]=0;
repeatindex[2]=0;

function narrayGen(i)
{
 snote[i]=Math.floor(Math.random()*12);
 if(snote[i]==(lnote[i]+1)%12||snote[i]==(12+lnote[i]-1)%12||snote[i]==(lnote[i]+6)%12)
  snote[i]=(snote[i]+1)%12;
 narray[i][0]=(snote[i]+autoSet[setNum].setContent[0])%12+(3-
 Math.floor(Math.random()*5))*12+48;
 narray[i][1]=(snote[i]+autoSet[setNum].setContent[1])%12+(3-
 Math.floor(Math.random()*5))*12+48;
 narray[i][2]=(snote[i]+autoSet[setNum].setContent[2])%12+(3-
 Math.floor(Math.random()*5))*12+48;
 narray[i][3]=(snote[i]+autoSet[setNum].setContent[3])%12+(3-
 Math.floor(Math.random()*5))*12+48;
 lnote[i]=(snote[i]+autoSet[setNum].setContent[3])%12;
}


//generate notes
function pjNoteGen(index,r)
{
  if(nindex[r]==4)
  {
    narrayGen(r);
    nindex[r]=0;
  }
  else
```

```
{
        if(setNum==0)
        {
        if(rtimes[r]>0)
        {
         note[r]=rnote[repeatindex[r]];
         rtimes[r]-=1;
                repeatindex[r]=(repeatindex[r]+1)%2;
        }
        else
         note[r]=narray[r][nindex[r]];
        }
        else
         note[r]=narray[r][nindex[r]];


        if(setNum==0)
        {
         if(secNum==0)
          vel[r]=30+Math.floor(Math.random()*20);
         else if(secNum==1)
          vel[r]=40+Math.floor(Math.random()*30);
         else if(secNum==2)
          vel[r]=50+Math.floor(Math.random()*50);
         else if(secNum==3)
          vel[r]=40+Math.floor(Math.random()*20);
        }
        else if(setNum==1)
          vel[r]=50+Math.floor(Math.random()*30);
        else if(setNum==2)
          vel[r]=40+Math.floor(Math.random()*70);

        count[r]++;

        if(setNum==0)
        {
        if(rindex[r]==0&&index==8)
        {
         rtimes[r]=9;
         rnote[r][0]=notep[r];
         rnote[r][1]=note[r];
        }
        else if(rindex[r]==1&&index==8)
        {
         rtimes[r]=3;
         rnote[r][0]=notep[r];
         rnote[r][1]=note[r];
        }
        else if(rindex[r]==2&&index==8)
        {
         rtimes[r]=8;
         rnote[r][0]=notep[r];
         rnote[r][1]=note[r];
        }
        else if(rindex[r]==3&&index==8)
        {
         rtimes[r]=2;
         rnote[r][0]=notep[r];
         rnote[r][1]=note[r];
        }
        else if(rindex[r]==5&&index==1)
        {
         rtimes[r]=1;
         rnote[r][0]=notep[r];
         rnote[r][1]=note[r];
        }
        else if(rindex[r]==6&&index==1)
        {
         rtimes[r]=1;
         rnote[r][0]=notep[r];
```

```
        rnote[r][1]=note[r];
        }
        else
        {
         nindex[r]++;
         notep[r]=note[r];
        }
        }
        else
        {
         nindex[r]++;
         notep[r]=note[r];
        }
        outlet(2+3*r, autoSet[setNum].rPatternD[rindex[r]][index]*tpo);
        outlet(1+3*r, vel[r]);
        outlet(0+3*r, note[r]);
        }
}

function init()
{
rindex[0]=0;
rindex[1]=0;
rindex[2]=0;
rlength[0]=0;
rlength[1]=0;
rlength[2]=0;
stime[0]=0;
stime[1]=0;
stime[2]=0;
curtime[0]=0;
curtime[1]=0;
curtime[2]=0;
count[0]=0;
count[1]=0;
count[2]=0;
stops[0]=0;
stops[1]=0;
stops[2]=0;
stopc[0]=0;
stopc[1]=0;
stopc[2]=0;
stopd[0]=0;
stopd[1]=0;
stopd[2]=0;
stopf[0]=0;
stopf[1]=0;
stopf[2]=0;
firstTime[0]=0;
firstTime[1]=0;
firstTime[2]=0;

nindex[0]=4;
nindex[1]=4;
nindex[2]=4;

narray[0]=new Array(4);
narray[1]=new Array(4);
narray[2]=new Array(4);

lnote[0]=0;
lnote[1]=0;
lnote[2]=0;

snote[0]=0;
snote[1]=0;
snote[2]=0;

note[0]=0;
note[1]=0;
```

```
note[2]=0;

vel[0]=0;
vel[1]=0;
vel[2]=0;

rnote[0]=new Array(2);
rnote[1]=new Array(2);
rnote[2]=new Array(2);

rtimes[0]=0;
rtimes[1]=0;
rtimes[2]=0;

notep[0]=0;
notep[1]=0;
notep[2]=0;

repeatindex[0]=0;
repeatindex[1]=0;
repeatindex[2]=0;
}
```

2) Javascript code for calculating the normal form of a four-member set

```
// inlets and outlets
inlets =5 ;
outlets = 4;

var note=new Array(4);
var noteArray=new Array(4);
var findex=0;

function list()
{
 for(var i=0; i<arguments.length;i++)
    note[i]=arguments[i];
 calcnorm();
}

function sortNumber(a, b)
{
   return a - b
}

function calcnorm()
{
  for(var i=0;i<4;i++)
   {
     noteArray[i]=new Array();
     noteArray[i][0]=note[i];
     noteArray[i][1]=0;
     noteArray[i][2]=0;
     noteArray[i][3]=0;

     var temparray=new Array();
     for(var k=0;k<4;k++)
     {
        if(k!=i)
           temparray.push(note[k]);
     }
     for(var n=0;n<3;n++)
     {
        if(temparray[n]<note[i])
             temparray[n]+=12;
     }
     temparray.sort(sortNumber);
```

```
  noteArray[i][0]=note[i];
  noteArray[i][1]=temparray[0]%12;
  noteArray[i][2]=temparray[1]%12;
  noteArray[i][3]=temparray[2]%12;

  for(var h=1;h<4;h++)
  {
    if(noteArray[i][h]<note[i])
       noteArray[i][h]+=12;
  }
}

var dist1=noteArray[0][3]-noteArray[0][0];
for(var i=1;i<4;i++)
{
 if(noteArray[i][3]-noteArray[i][0]<dist1)
 {
    dist1=noteArray[i][3]-noteArray[i][0];
 }
}

var narray1=new Array();
for(var m=0;m<4;m++)
{
  if(noteArray[m][3]-noteArray[m][0]==dist1)
    narray1.push(m);
}

if(narray1.length==1)
   findex=narray1[0];
else
{
   var dist2=noteArray[narray1[0]][2]-noteArray[narray1[0]][0];
   for(var i=1;i<narray1.length;i++)
   {
       if(noteArray[narray1[i]][2]-noteArray[narray1[i]][0]<dist2)
           {
            dist2=noteArray[narray1[i]][2]-noteArray[narray1[i]][0];
           }
   }
   var narray2=new Array();
   for(var m=0;m<narray1.length;m++)
   {
      if(noteArray[narray1[m]][2]-noteArray[narray1[m]][0]==dist2)
            narray2.push(narray1[m]);
   }
   if(narray2.length==1)
           findex=narray2[0];
   else
   {
     var dist3=noteArray[narray2[0]][1]-noteArray[narray2[0]][0];
     for(var i=1;i<narray2.length;i++)
     {
       if(noteArray[narray2[i]][1]-noteArray[narray2[i]][0]<dist3)
       {
          dist3=noteArray[narray2[i]][1]-noteArray[narray2[i]][0];
       }
     }
     var narray3=new Array();
     for(var m=0;m<narray2.length;m++)
     {
       if(noteArray[narray2[m]][1]-noteArray[narray2[m]][0]==dist3)
          narray3.push(narray2[m]);
     }
     if(narray3.length==1)
      findex=narray3[0];
     else
     {
      var tf=noteArray[narray3[0]][0];
      var tfindex=0;
```

```
        for(var i=1;i<narray3.length;i++)
        {
            if(noteArray[narray3[i]][0]<tf)
            {
                tf=noteArray[narray3[i]][0];
                tfindex=i;
            }
        }
        findex=narray3[tfindex];
    }
  }
  }
  var sn=noteArray[findex][0];
  for(var j=0;j<4;j++)
  {
    if(noteArray[findex][j]<sn)
        noteArray[findex][j]+=12;
    noteArray[findex][j]-=sn;
  }
  outlet(0,noteArray[findex]);
}
```