The standard method of teaching color theory is cumbersome at best. Computer graphics can solve problems of time and tedium and cover much more material as well.

BUCOLIC:

A Program for Teaching Color Theory to Art Students

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Traditional methods for learning color theory are time-consuming and labor-intensive. Much time is spent on exercises that involve mixing pigments and painting various geometric designs. It is difficult to see the effects of using particular colors in an exercise until it is completely painted. Since the painting process is tedious, students are unlikely to improve any part of an exercise once they have finished it—in fact, a typical course covers only a few exercises, because each is repeated several times. Mixing pigments in set proportions and making evenly spaced color scales is also difficult, since pigments are made in different strengths. While this exercise may be worthwhile to a painter, learning color theory should not depend on these skills. Some of the problems arising through the use of pigment can be eliminated by using colored paper in-

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stead; however, paper is available in only a small number of colors. In addition, because both pigment and paper are examples of reflected color, courses tend to emphasize this aspect of color theory, while devoting only a small amount of time to emitted color. Even when emitted color is discussed, students rarely have an opportunity to work with it extensively.

Previous work

Computer graphics has been used to alleviate some of the problems inherent in learning color theory the traditional way. Color spaces and notations have been discussed, and various programs have been written to explain them. These include works by Joblove and Greenberg,[1] Smith,[2] and Meyer and Greenberg.[3] Color theory has been studied from the psychological and physiological points of view by Goetz, Beatty, and Rasquinha,[4] and various phenomena have been explained by Truckenbrod to help designers and programmers choose colors for graphics programs.[5] Most of the software associated with this work has taken the form of demonstrations for researchers. Although some institutions are using small personal computers for basic color theory exercises as exemplified by Mones,[6] the limited color palette and low spatial resolution of most small computer color displays makes some color theory exercises difficult or impossible to implement.

BUCOLIC

BUCOLIC, or the Brown University COLor InstruCtor, is a program for teaching color theory to art students. Unlike most previous color theory work in computer graphics, BUCOLIC is directed toward art students who have no experience with computers. The idea of writing BUCOLIC was suggested by Roger Mayer of Brown's Art Department, who was inspired by the work of Brown's computer graphics group. At that time the group had written a few demonstration programs for illustrating color principles to computer graphics students. Mayer saw the potential of using computer graphics to implement exercises in his traditional color theory course. He described the pigment and colored-paper exercises, and we discussed ways to adapt and expand them for use in a computer graphics system.

We taught the color theory course in the fall of 1983, using BUCOLIC in addition to the pigment exercises. Twenty students attended four hours of lecture and discussion and one hour of supervised work—in groups of four—with BUCOLIC each week. They were able to work with the BUCOLIC exercises and the final project independently outside of class for a limited time (because the equipment was shared with the graphics group). The BUCOLIC exercises roughly followed the sequence of the course material; thus, each exercise was performed both with pigment or colored paper and with BUCOLIC. BUCOLIC added a new dimension to the course, because students worked extensively with emitted color instead of having one or two isolated demonstrations.

Exercises

BUCOLIC consists of six exercises and a large final project, which share a common user interface. The menu of exercises that the student sees when entering BUCOLIC is shown in Figure 1.

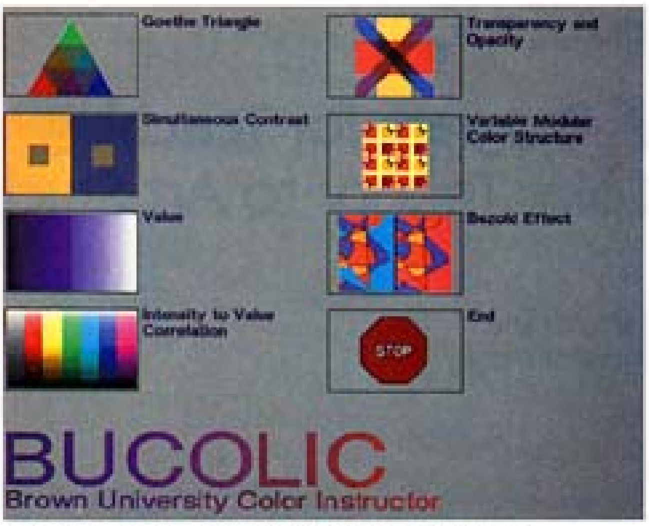


Figure 1. BUCOLIC menu of color theory exercises.

In the Goethe Triangle exercise, based on Goethe's color triangle,[7] students work with different systems of color primaries and several color-mixing schemes. A student begins the Goethe Triangle exercise by selecting its icon from the exercise menu, causing the screen to appear as in Figure 2(a). Within the large triangle, the three small triangles at the vertices are the primary colors. Initially these are red, green, and blue, the primary colors of light. The triangles in between the primaries are the secondary colors made by mixing the primaries on either side. The remaining three triangles are the tertiary colors made by mixing the adjacent primary and opposite secondary colors. In this exercise, students change the color of the primary triangles; BUCOLIC automatically changes the secondary and tertiary colors when a primary is changed.

The primary colors may be modified in either the RGB (red, green, blue) color space or the HSV (hue, saturation, value) color space. We included the RGB space because we wanted students to become familiar with properties of emitted color by mixing the light primaries. The HSV color

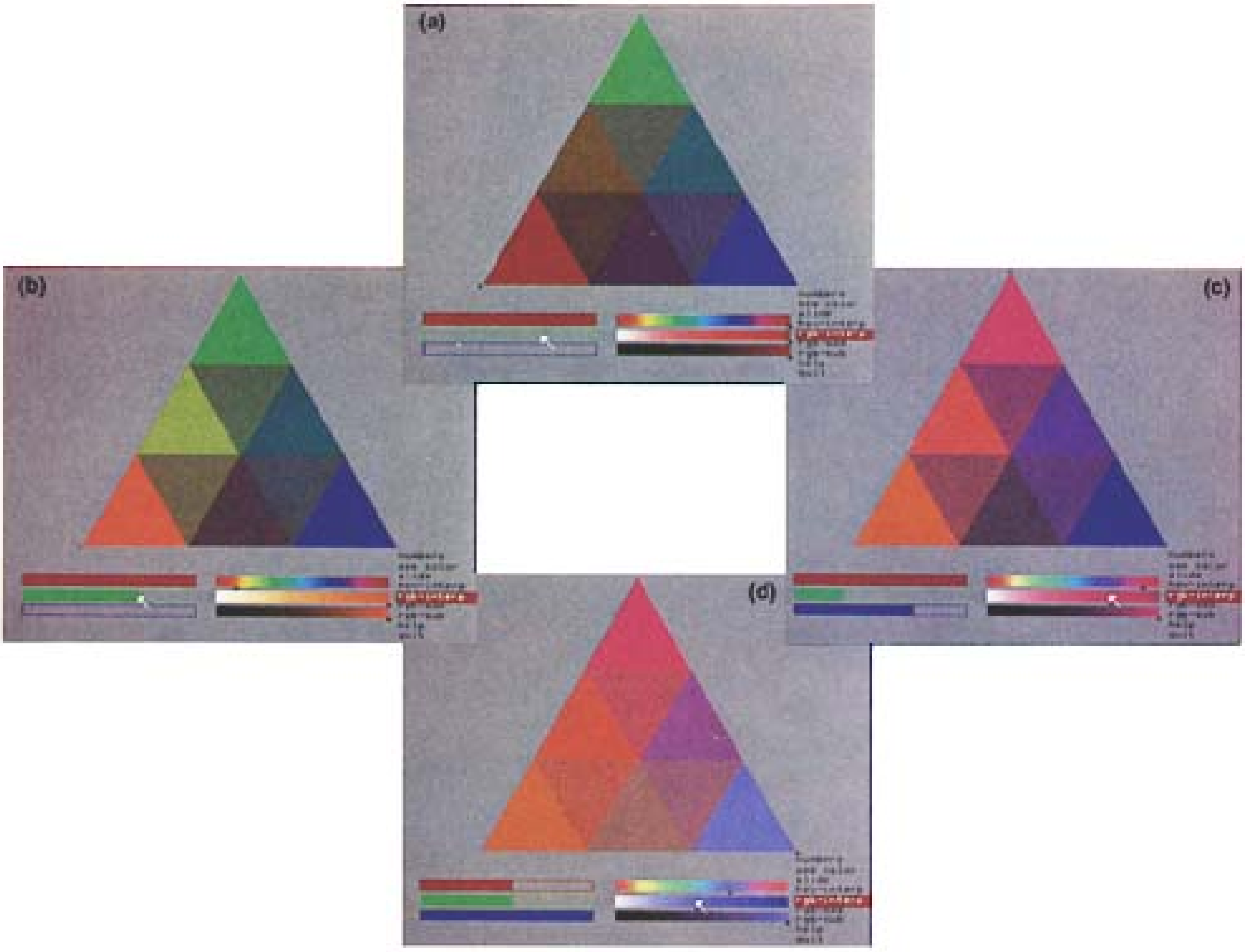


Figure 2. The Goethe Triangle exercises: The triangles at the vertices are initially the light primaries: red, green, and blue (a). The bottom left triangle has been made yellow by adding green (b). The hue and saturation of the top triangle has been changed (c). The saturation of the bottom right triangle has been lowered (d).

space is provided in addition, since it is considered more natural for artists.[2] The red, green, and blue bars at the bottom left of the screen are used for the RGB color space, and they show how much red, green, and blue the current triangle contains. For example, in Figure 2(a) the red triangle is the current triangle, since it is highlighted by the small black pointer to its left. The RGB bars show that this triangle contains full red, and no green or blue. The red triangle can be changed by selecting a location on one of the RGB bars. In Figure 2(b) a point on the green bar has been selected, the red has changed to gold, and the secondary and tertiary colors have changed appropriately.

The HSV bars on the right side of the screen are used in the same way. The three bars represent the hue, saturation (purity or whiteness), and value (intensity or blackness) indicated by the black pointers underneath the bars for the current triangle. In Figure 2(c), the top primary triangle has been changed to pink by lowering the saturation and changing the hue. In Figure 2(d), the saturation has been lowered on the blue primary triangle on the right. The RGB and HSV bars always represent the current color.

The color-mixing scheme used in this example is RGB interpolation. Several others, including RGB additive and subtractive and HSV interpolation, may also be explored. The user interface for changing colors is consistent throughout the BUCOLIC exercises and final project.

The Simultaneous Contrast exercise introduces the work of Josef Albers.[3] One of the phenomena that Albers explored is the relationships of colors when presented in various contexts. For example, one color may be made to look like two very different colors or two different colors can be made to look like the same color when they are placed in different contexts. (Various Albers exercises have been implemented previously.[4-6]) This exercise has a

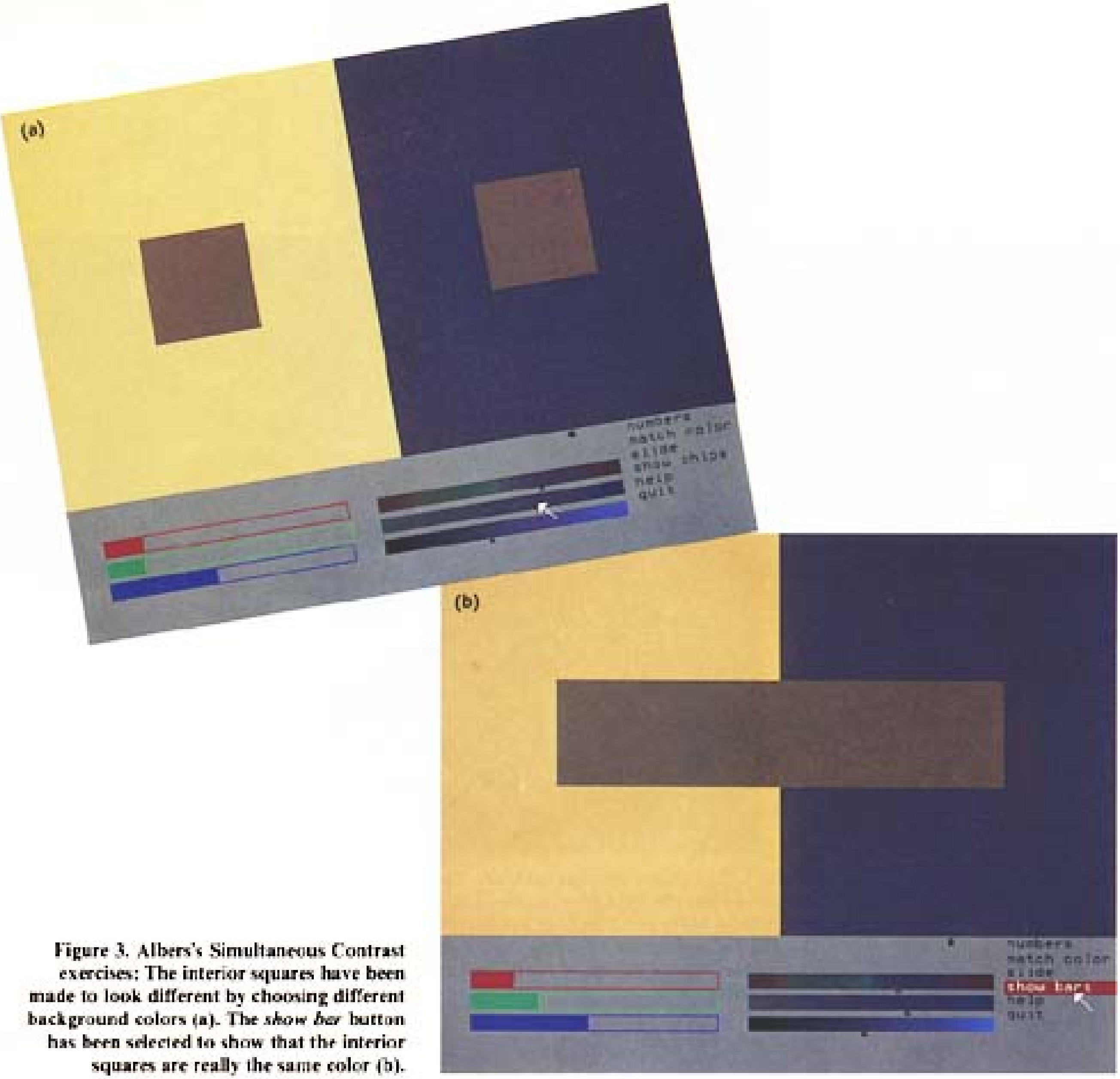


Figure 3. Albers's Simultaneous Contrast exercises: The interior squares have been made to look different by choosing different background colors (a). The *show bar* button has been selected to show that the interior squares are really the same color (b).

feature that allows students to toggle between two modes. As shown in Figure 3, one mode displays the small squares isolated on the background rectangles (Figure 3[a]), and the other mode displays bars of the small squares spanning across both background rectangles to show the relationships between the squares and between the squares and their opposite backgrounds (Figure 3[b]).

The next two exercises demonstrate value and intensity or brightness. The Value exercise presents a scale of color from black to a particular color to white. The color of the scale is chosen with the RGB and HSV bars, and the student may toggle between a linear scale and a gamma-corrected scale. The Intensity to Value Correlation exercise presents a problem posed by Itten.[9] The primary and secondary color scales are presented in columns along with one column devoted to a gray scale. Students adjust the saturation and value of each of the rectangles, keeping the same hue, so that when each row is viewed by itself, the perceived brightness of each rectangle in the row is the same. The icons for these exercises may be seen in Figure 1.

The Transparency exercise models four strips of an acetate-like material on a lightboard (Figure 4). The color and opacity of each strip can be changed. BUCOLIC determines the "transparent" colors where the strips overlap. The opacity ranges from completely opaque to translucent, where the strips behave like color filters. The strips may be perceptually stacked, using the *put on top* menu button.

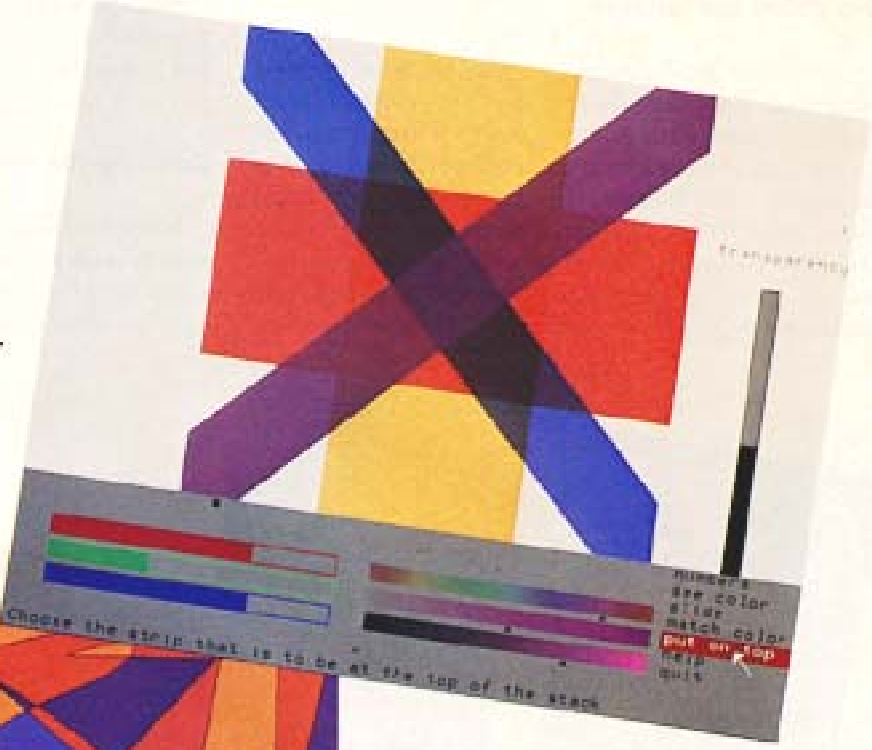


Figure 4. The Transparency exercise: Students may choose the color and transparency of four colored strips.

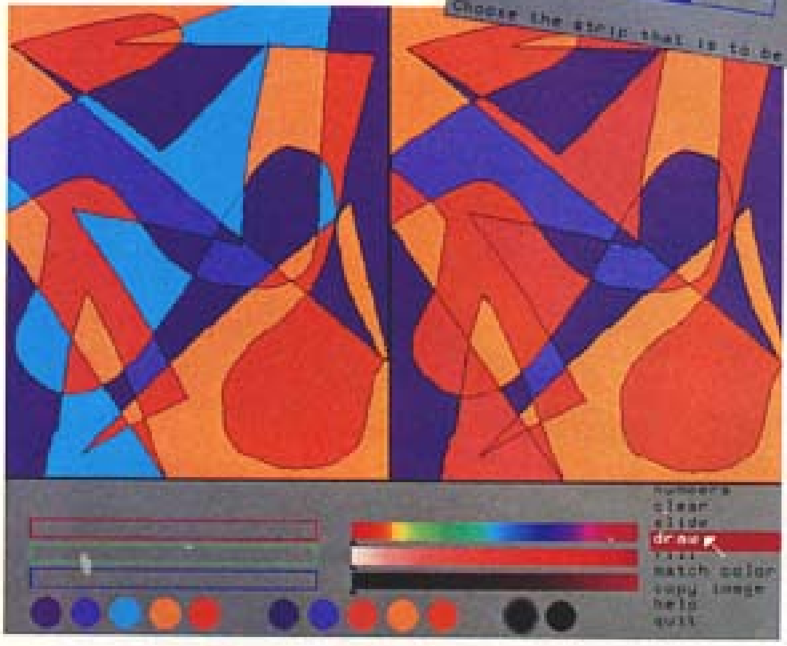


Figure 5. The Bezold Effect exercise: Students change one color in two identical compositions to make them look different.

The last exercise is the Bezold Effect, originally discovered by M.E. Chevreul but named for Wilhelm von Bezold, a rugmaker who wanted to make a few rug designs in a small number of colors look like many. Bezold found that if he used the same rug design, but changed one or two colors only, the design looked different.[9,11] In this exercise students create a composition on the left half of the screen by drawing outlines and filling them in from the five paint pots underneath (Figure 5). The colors in the paint pots may be changed. When the composition is finished, BUCOLIC will copy the image onto the right side of the screen. At this point, the student changes the color in one of the five paint pots underneath the copied composition to create the Bezold effect.

Final project

The final project of the color theory course, which was designed by Roger Mayer and was previously done in pigment, ties together all of the exercises. Finished examples of the modular project are shown in Figure 6. The purpose of the project was primarily to integrate the exercises but also to create an aesthetic work. The design is made of a 12-by-12 grid of repeated modules or quiltlike squares. Each module is colored differently to achieve various effects, such as the ones described in the exercises. There are two steps in creating a modular project: first, designing the module, and second, coloring the modules in the grid.

Designing the module

The module is designed using a pixel editor, as shown in Figure 6(a). An actual size version of the module is shown on the left side of the screen. Colors for the module are chosen from 16 paint pots at the bottom of the screen. As in the Bezold Effect exercise, the student chooses the colors for the paint pots. Since the module is a prototype for each of the 144 modules in the finished work, the paint pots serve only as a coding mechanism; the actual colors do not matter, but the pixels colored from each paint pot designate a (perhaps noncontinuous) region of the module. Figure 6(b) shows a later stage in designing the module and Figure 6(c) shows the finished module.

Coloring the grid

When the module is completed, it is saved and the user returns to the grid menu. BUCOLIC automatically repeats a module in the grid as shown in Figure 6(d); then coloring operations are performed. The simplest operation is

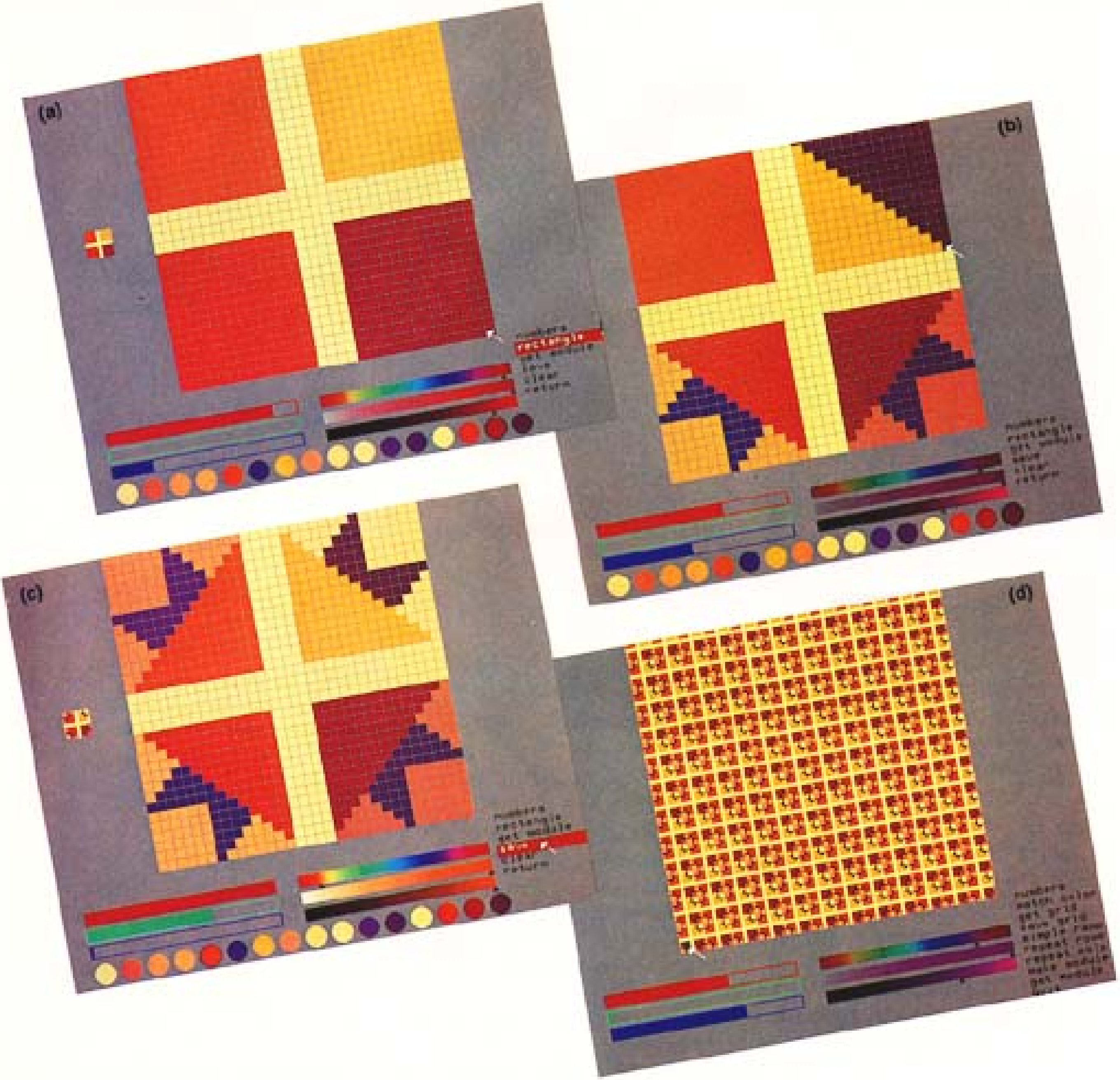
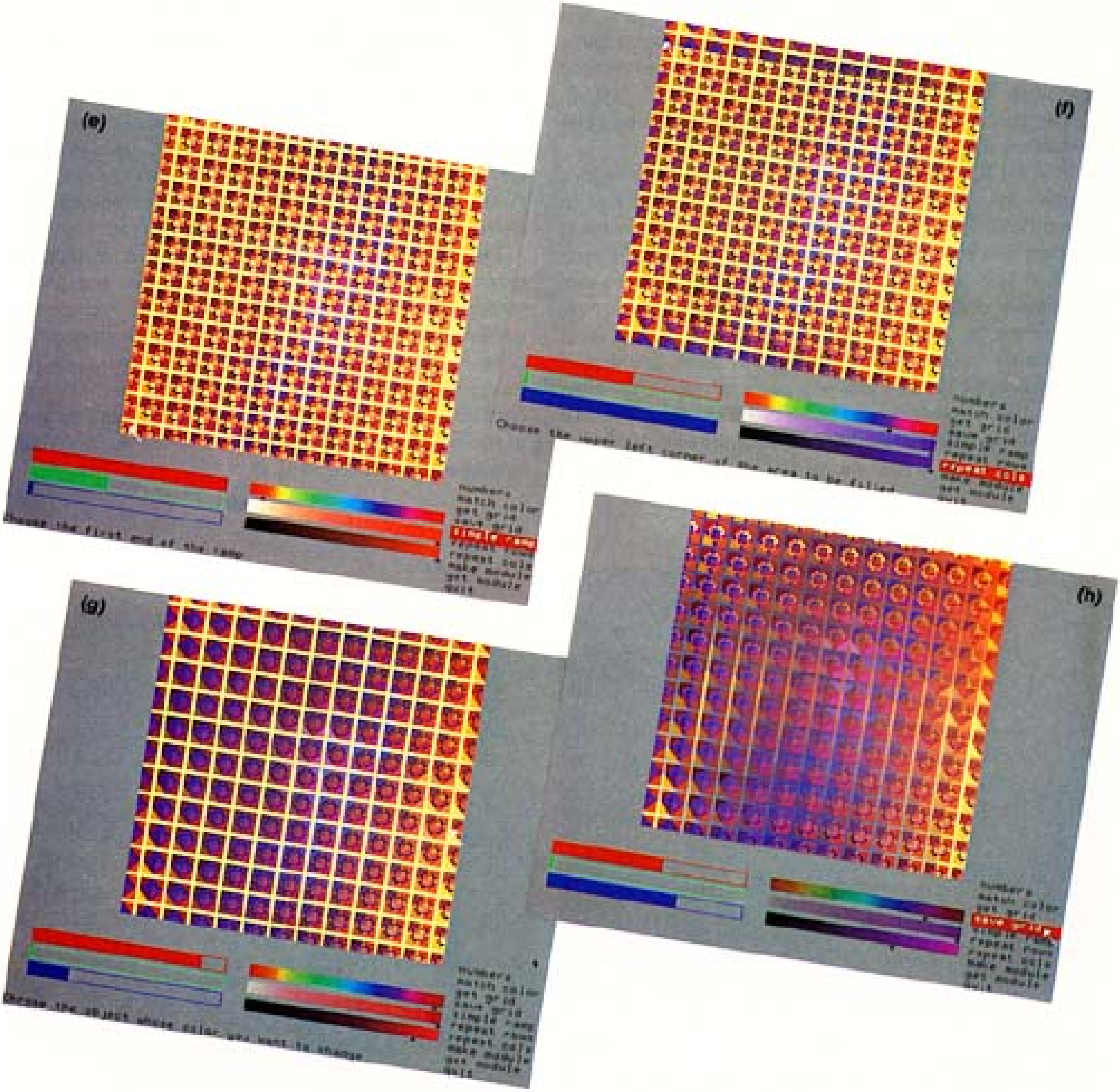


Figure 6. The BUCOLIC final project: The module is designed with a pixel editor. The module is shown in its actual size on the left of the screen (a) through (c). The finished module is

coloring an individual region of a module by selecting it with the cursor and choosing a new color using the RGB and HSV bars. In addition, BUCOLIC automatically interpolates the color of a region across the modules in part of a row or column. Only similar regions can be interpolated; this is the reason for having color-coded regions in the prototype module. To interpolate across part or all of a row, first the *simple ramp* menu button is selected. Next, the region at one end of the row is selected, and then the region at the other end of the row is selected. BUCOLIC changes the color of the regions of the intervening modules to display a smooth interpolation between the colors of the selected modules.

This feature can be carried further to interpolate many rows or columns in one operation. The result is many simple ramps performed over a rectangular area, either by row or by column. To do this, the *repeat rows* or *repeat cols* (columns) button is selected. The upper left and lower right corners of a rectangular area are chosen. Clearly these operations can save the large amount of time necessary to color each region individually.

A grid is colored using these primitives. Figures 6(e) to



repeated in a 12-by-12 grid (d). Regions in the grid are colored individually and in groups using the *amp* and *repeat* buttons (e) through (g). The finished project (h).

6(g) show several stages in coloring a grid, and the finished project is shown in Figure 6(h). Two more projects are shown in Figure 7.

Student reactions

Students reacted very favorably to working with BUCOLIC. They especially liked the speed with which they could complete many repetitions of an exercise. The ability to sketch ideas in a short time was particularly useful during the final project. The students were allowed to execute the final project using either pigment or BUCOLIC. Initially, half of the students chose to work in pigment, but they all used BUCOLIC for planning their designs. Some of those who originally chose to work in pigment decided not to do so after sketching their ideas with BUCOLIC, stating that they would not learn anything more by painting what they had already created.

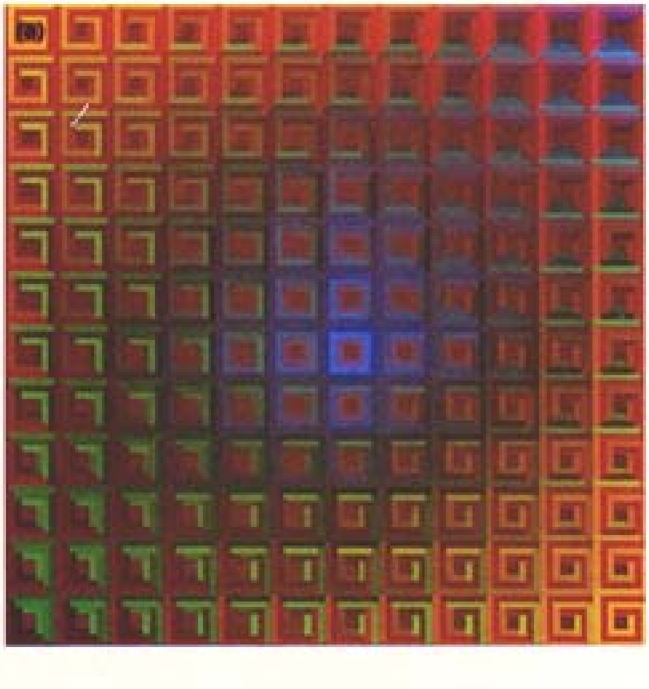
BUCOLIC allowed students to create more complex designs than they would have made if they had had to complete their projects in pigment. Traditionally, students worked with grids of 24-by-24 or 30-by-30 modules. If each module had had 16 parts, they would have had to mix thousands of different colors. With BUCOLIC they could experiment by using the same modules but coloring them differently in each of several grids. They could also experiment by saving a grid at a particular point and then trying different branches to finish it. By spending less time tediously painting the modular projects, students were able to learn more by trying many ideas.

In the exercises traditionally performed with colored paper, students enjoyed being able to adjust colors subtly instead of being limited to a small number of options. Since BUCOLIC was being written only a few steps ahead of the students' work, their feedback was invaluable in helping us provide enough functionally and a good user interface. Likewise, they enjoyed seeing their ideas materialize from week to week.

Future work

From experience in teaching the course, we felt that some of the exercises should be reworked to force solutions to depend more actively on student input. Some exercises, for instance, could have a "manual" and an "automatic" mode. In the manual mode the students would have to find solutions to the exercises, while the automatic mode would offer BUCOLIC's solution. As BUCOLIC replaces some of the pigment exercises, or at least reduces the number of times that each pigment exercise is performed, more exercises could be introduced into the course.

For BUCOLIC to work to its best advantage, computer graphics equipment should be much more accessible to students than is usually possible at present. We hope that this problem will be alleviated with the decreasing price of color frame buffers designed for small, affordable computers. In the interim, we would like to rely more heavily on hard copy in the form of slides, but reproducing the colors of the monitor on film is difficult, because many variables cannot easily be controlled. ■



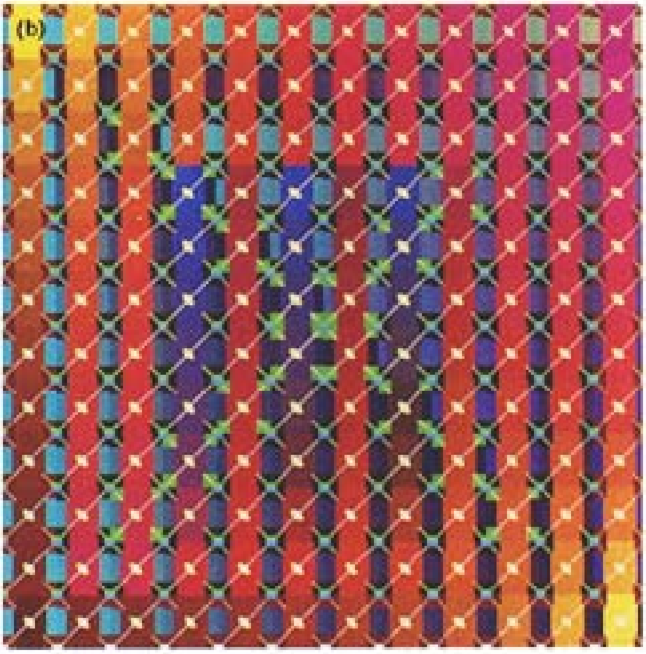


Figure 7. Two modular projects: Ann Fischer and Erica Ilton (a) and Diana Rathborne (b).

Implementation

BUCOLIC is written in C under Berkeley Unix 4.2 on a DEC VAX 11/780 and a Lexidata 3400 graphics system. The pictures were imaged on a Matrix Instruments QCR D-4/2 film recorder.

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