Smart Lighting:
LED Implementation and Ambient Communication Applications

by

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Introduction

This project builds upon the Smart Lighting project in Dr. Alice Agogino's Berkeley Expert Systems Technology (B.E.S.T.) research lab.

In an effort to make the laboratory more energy efficient, an efficient lighting system using sensing and actuation (controlled by wireless motes) was installed. With this control, the system experienced a 13% reduction in energy usage[i]. The B.E.S.T. laboratory implements the current smart lighting system in which users can customize their own light settings so as to increase user satisfaction and simultaneously reduce energy usage. In order to provide as much control as possible, users can specify which specific luminaires are activated and at what brightness—therefore, not all lights need be on at one time. Currently the system uses T8 fluorescent light bulbs (which reduce energy usage compared to incandescent bulbs). LEDs possess more sustainable qualities—long life, lack of mercury, high-efficiency—when compared to fluorescents; to what extent can the implementation of LEDs make the smart lighting system more sustainable?

Further, because the conclusions found by Yao-Jung Wen show that the user control of lighting preferences also contributes to a reduction in energy usage (Agogino, Granderson, Wen p. 30)[i], improvements to the control of the lighting system—the user interface—are explored.

While lighting represents a tremendous opportunity for increasing user satisfaction, its capabilities extend beyond simple workspace illumination: the opportunities for lighting in ambient communication applications represent a new opportunity for Smart Lighting. Using both color and light actuation strategies, lighting can be used as an actor in communication in human computer interactions.

LED Implementation

Retrofitting the smart lighting setup with LED luminaires aims to continue with the goal of energy reduction (and overall sustainability). In order for the LED system to be implemented in the existing Smart Lighting system, the LED luminaires must be capable of being wirelessly controlled, dimmable, and provide the same possible maximum output (that produces satisfactory workspace illuminance levels by IES recommendations[ii]).

LEDs were selected as the lighting of choice because they currently represent the next progression in energy efficient lighting. LED lighting fixtures, while currently used mostly for task lighting, can consume less energy than other fixtures like fluorescents or incandescents depending on application.

Current Energy Usage

Per data collected by Wen, in the current lighting setup the fluorescent powered system[i], the energy drawn is 3567.2 Kwh/year. This benchmark establishes that the lamps are on for 14 hours per day for 260 days per year (the amount of work days per year). This energy benchmark defines all lights to be controlled using one switch—namely either all lights are on or off (this represents maximum energy usage); it can be assumed energy savings due to the user-defined control system (where each lamp can be individually controlled) will be the same for the existing fluorescent system and the retrofitted LED system.

LED Energy Usage

Choice of luminaires

Replacement LED luminaires are constrained to commercial LED fixtures to make the results of the retrofit study implementable. The LED luminaire replacement option selected for testing is the Cree LR6. At the time of selection, the Cree LR6 was the flagship LED lighting solution for Cree, a recognized manufacturer of solid-state lighting (whose products are recommended in such programs as LEDCity or LEDUniversity).

Figure 1: CREE LR6 LED Luminaire[iii]

The luminaire selection is intended for installation using current lighting infrastructure: The luminaires wire into the 110V alternating current found in conventional US electrical lighting wiring standards. The luminaire is also capable of being dimmed using select conventional lighting dimmers.

Metrics for study

In order to study the efficacy of the LED luminaire, metrics for study must be established. These metrics are based on photometric principles. The energy that is emitted by a luminaire covers radiated energy in both the invisible and visible (380nm to 830nm) spectrum. Photometry describes only that radiated energy that is visible to the human eye; the photometric equations relate the radiometric energy (total radiated energy) to photometric energy (visible light energy) as flux:

$$\Phi_{photometric} = K_m \int_{380nm}^{830nm} \Phi_{radiometric} V(\lambda) d\lambda$$

where Φ is the flux of the light source, K_m is the constant that relates the spectral efficacy, V relates the sensitivity of the eye to certain wavelengths, and λ is the wavelength of energy. The units of $\Phi_{photometric}$ are *lumens*, which are the photometric equivalent of *watts*, the unit of measurement for $\Phi_{radiometric}$.[iv]

While photometric flux can be used as a metric for comparison of the light sources, it is not the ideal measurement factor because it does not take into account the actual amount of light that reaches work surfaces (essentially, the light that can be used). Different factors can affect the amount of light from the luminaire that actually reaches a workplane, e.g. lighting environment or luminaire direction. For the purposes of this LED retrofit, the current Smart Lighting setup (fluorescent) is a control group; however, because of the nature of LED luminaires and the current fluorescent luminaires, the angle of photometric flux is substantially different (fluorescent tubes radiate in all directions and rely on reflection for light to reach the workplane, while LED luminaires direct all produced light in one direction). Therefore, directly comparing photometric flux values (which are usually provided by lighting manufacturers) will not be a satisfactory method of comparing newer LED systems to the current fluorescent setup.

Illuminance removes these uncertainties because it quantifies the amount of photometric radiation that actually reaches a given surface. It is a measure of flux over a given area; illuminance is measured in *lux* (where 1 lux = 1 lumen per square meter). Using the measure of illuminance, the effectiveness of these two different types of luminaires (old and retrofitted) can be compared.

In order for the retrofitted system to compare with the current fluorescent system, the lighting levels should satisfy IES levels for normal office work (500 lux)[ii] as a maximum benchmark.

Control System

As the light source is only a portion of the Smart Lighting system, the ability of the LED luminaires to be controlled wirelessly with microcontrollers must also be tested. In the current setup, one mote (wireless microcontroller) is wired to every lighting fixture to control the luminaires to represent user preferences. The motes individually control the lighting levels of each fixture based on commands sent wirelessly from a central server. The two main tasks that must be accomplished by the motes are to (1) turn the lights either on or off and (2) adjust the brightness of the luminaire.

Testing of the actuation of the LED luminaires is done using the Arduino microcontroller[v]. While implementation of the controllers would be accomplished using wireless motes (as in the current system Wen's research), the actuation capabilities of the Arduino are similar and can be used as a test platform for quicker prototyping.

Arduino Overview

Hardware actuation testing was conducted on the Arduino Duemilanove microcontroller.

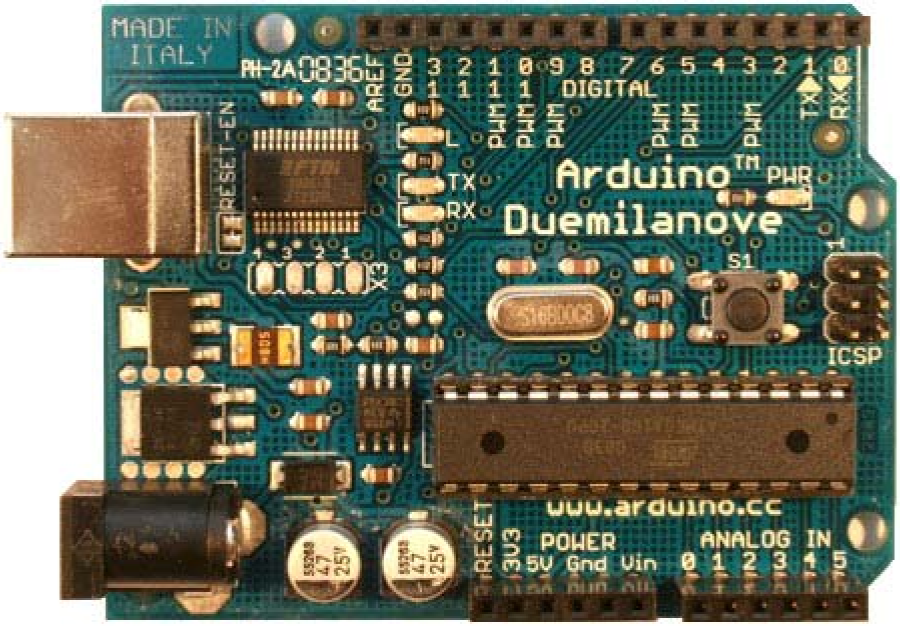


Figure 2: Arduino Duemilanove[vi]

This microcontroller provides 14 digital input/output pins and 6 discrete analog input pins (built in 10-bit A/D converters). Six of the 14 digital pins can also be reassigned for PWM output using the Arduino's internal PWM function. The coding environment is based off of the Processing language, which can be viewed as a simplified version of C. All of these pins on the

Duemilanove are easily accessible without requiring soldering which makes it an appropriate microcontroller for prototype testing.

Mote Overview

The 2 motes developed for testing are the MICA2 motes developed by Crossbow and the TMoteSky by MoteIV.

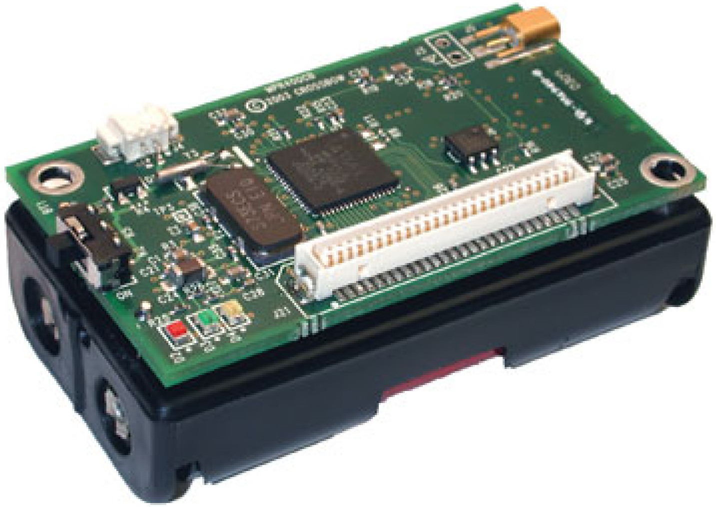


Figure 3: MICA2 Mote[vii]

The motes run TinyOS which is based off of the NesC programming language. The motes possess both sensing and actuation capabilities on the smaller architecture using digital outputs.

On/Off Switch Diagram

To actuate the LED luminaires either on or off, the power line of the test luminaire is wired through a 5V relay which is actuated using an N-Channel mosfet that is controlled using a digital output from the microcontroller. Figure 4 depicts the circuit diagram for the on/off control of the luminaire.

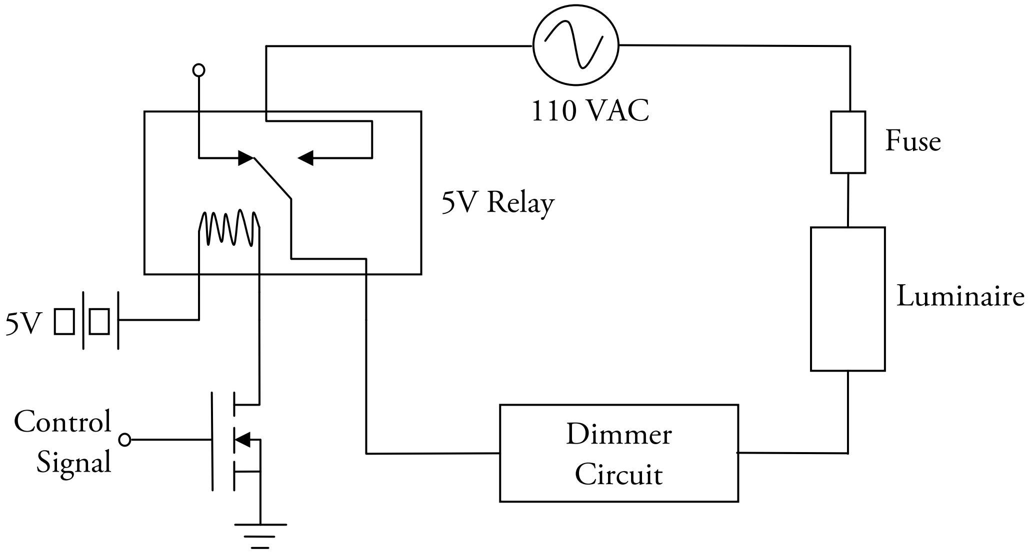


Figure 4: Circuit Diagram for Computer-Controlled On/Off Switch

The mosfet and relay are used to protect the microcontroller from the high voltage and current in the Alternating Current (AC) circuit that powers the luminaire. The microcontroller is further protected by using a voltage follower that mimics the control signal. When the controller outputs a high voltage, the relay closes and the light turns off (and vice-versa). The dimmer circuit will be discussed further, later. Testing reveals that the on/off control circuit operates effectively.

Dimming

The current fluorescent system takes advantage of dimmable ballasts that rely on a voltage input to dim the fixtures. Currently, no such driver exists for LED luminaires. Ideally, dimming the LED luminaires would be accomplished by driving the LEDs with a pulse width modulation (PWM) signal. However, the commercial LED luminaires do not provide such PWM drivers, but do allow for dimming using select conventional lighting dimmers. These dimmers rely on a concept similar to PWM: Using a triac (a two-way semi-conductor gate) and capacitors, these lighting dimmers alter the period of time in which the 60Hz 110V alternating current (power from the wall) is high. The dimmers effectively shorten the duty cycle of the sinusoidal power wave that powers the luminaire. In order to modify the length of the duty cycle of the dimmers, a potentiometer is physically manipulated by the user.

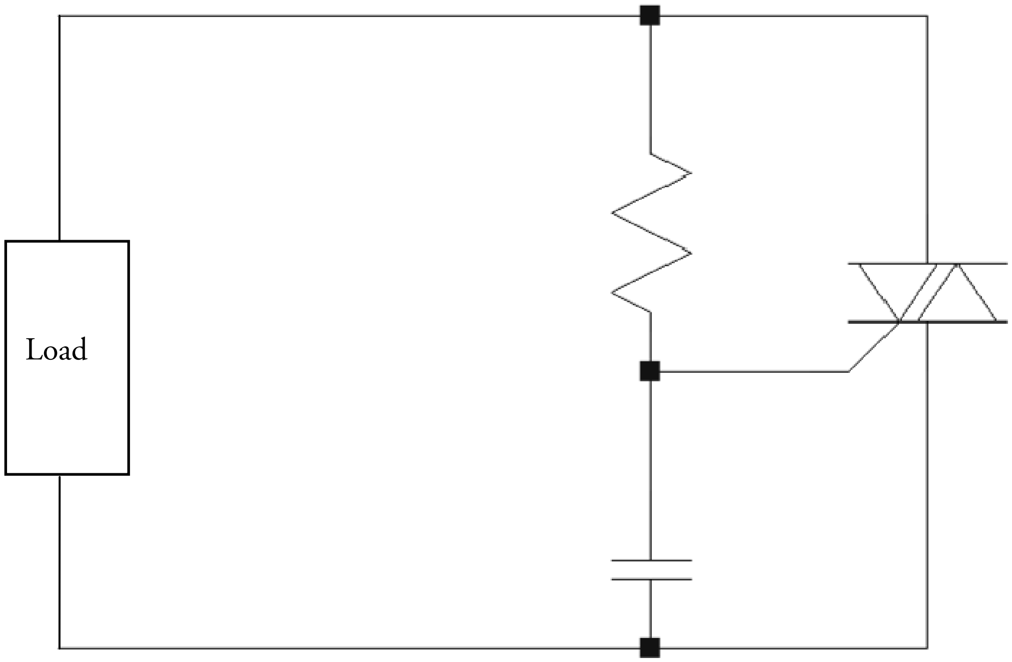


Figure 5: Circuit Diagram for Typical Dimmer[viii]

The most effective way to dim the luminaires at this current stage of technology is by controlling such a dimmer with a microcontroller. There are currently no obvious choices for a digitally controlled potentiometer to replace the manual potentiometer in the dimmer that can withstand the high voltages of the alternating current. However, the microcontroller can be used to digitally control the timing of the triac which allows for voltage to conduct (and thus control the duty cycle).

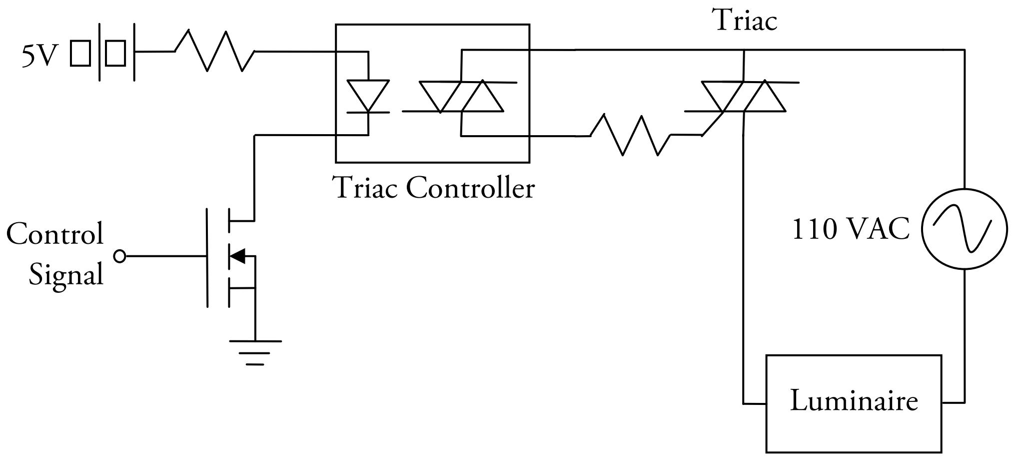


Figure 6: Circuit Diagram for Computer-Controlled LED Dimmer

The triac is driven using a triac-driver (MOC3051) which is controlled by the control voltage from the microcontroller; the circuit diagram in Figure 6 is adapted from the MOC3051 application note[ix]. Testing reveals that the proposed circuit in Figure 6 does not function to dim the LED circuit. The error lays in the dimming circuit in Figure 6, for manually dimming the luminaire, a Leviton 705-W Push Dimmer functions to dim the luminaire.

How many luminaires would be needed to illuminate the lab?

The illuminance of the LED luminaires is calculated then used to predict the amount of luminaires needed to replace the current setup.

The Lumen Method

The Lumen method[x] calculates the luminaires needed to produce an illumination level in a given room[i] as in a test situation using the following assumptions:

1. The office dimensions are 15m x 10m and features a typical ceiling/wall/floor reflectance of 80/50/20%. The fixture mounting height is defined at 1.65m.
2. Each fixture is one LED luminaire that inputs 12W power.
3. The lamps have a color temperature of 2700K.
4. The office is designed for work surface illuminance of 500 lux to meet the IES recommendations for visual tasks of medium contrast or small size[xi].
5. The lights are on for 14 hours (from 7am to 9pm) per day, 260 days per year.

The coefficient of utilization (CU) for this LED luminaire is 0.77 as provided by the CREE lighting designers[xii]; as the CU is a basic measurement of how much light reaches the workplane, the CU is higher at 0.77 for LEDS (as compared to 0.7 for fluorescents) because LEDs direct their entire light output downwards. The lumen method accounts for the number of luminaires required to light a given space:

$$\text{Number of Luminaires} = \frac{\text{Illuminance} \times (\text{Room Area})}{(\text{Lumens Per Luminaire}) \times \text{CU}}$$

$$= \frac{500 \times (15 \times 10)}{650 \times 0.77} = 149.86 \approx 150 \text{ luminaires}$$

Experimental Measurement

This number of LED luminaires needed is also approximated using an experimental approach where the illuminance levels for the test LED luminaire are measured.

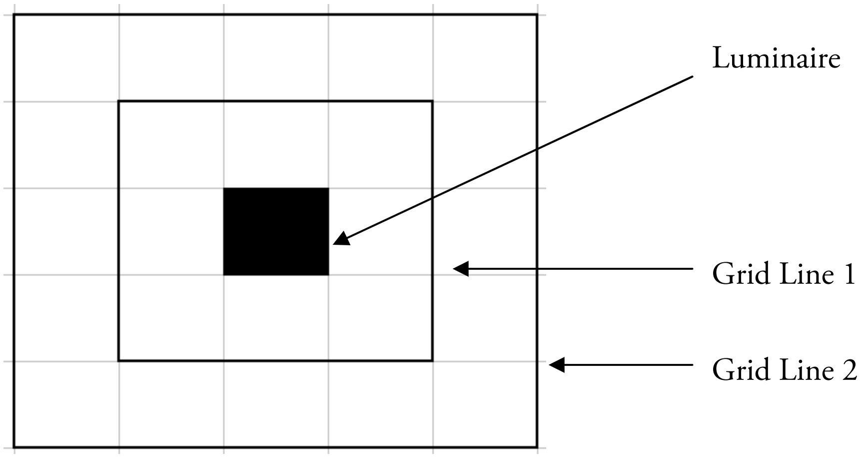


Figure 7: Experimental Luminaire Illuminance Test Grid

The luminaire is placed at the correct distance above the workplane and all surrounding light is removed; the illuminance level on the workplane is then measured (~75 lux). Then, the luminaire is moved to varying locations above the workplane to simulate the 0.9m x 0.9m grid of luminaires (which would provide ~150 luminaires) and the illuminance levels are measured. Because the illuminance levels are additive, the levels are added up for the relevant luminaire illuminance values (as indicated in Figure 7: Experimental Luminaire Illuminance Test Grid). This value provides an approximate illuminance value for any given location underneath the luminaire grid (where illuminance levels beyond 3 grid lines provide diminishing illuminances).

$$\begin{aligned}\text{Illuminance } &= 70(\text{direct illumination}) + (4\times 50)(\text{one grid line removed}) + (4\times 25)(\text{2 grid lines} \\ &\quad \text{removed}) + (4\times 12)(\text{3 grid lines removed}) \\ &= 418\,lux\end{aligned}$$

With a 0.9m x 0.9m grid (~150 luminaires), at least 418 lux is provided; therefore, the 150 luminaire calculation is experimentally approximated as accurate.

Annual Energy Consumption

Annual energy consumption with luminaire on/off control (comparison setup with fluorescent system):

$$
\begin{aligned}
\text{Annual Energy Consumption} &= (\text{Number of Luminaires}) \times (\text{Power}) \times (\text{Daily Operating Hours}) \\
&\quad \times (\text{Operating Days per Year}) \\
&= 150 \times 12\,watts \times 14\,\frac{hours}{day} \times 260\,\frac{days}{year} \\
&= 6552\, {}^{Kwh}\!/_{year}
\end{aligned}
$$

Comparison

The energy consumption for the fluorescent system is calculated as $3567.2\,KWh/year$. The LED fixture tested would represent an energy consumption increase of 183%. At its current technological state, LED fixtures are not capable of providing enough light to reach the IES 500 lux level when used as the sole lighting source. Table 1[xiii] shoes energy comparisons for similar LED lighting fixtures in the same test room.

Luminaire	Lumens	Required Luminaires	Energy Usage (Watts)	Energy Used per Year (kwh)
CREE: LR6	650	150	12	6,545
Philips Color Kinetics: eW Downlight Powercore	414	235	15	12,846
BEGA: L8785	1800	54	26	5,121
Enlux: DL Downlight	700	139	14	7,090
Juno Lighting: IC22LED	600	162	14	8,272

Table 1: LED Luminaire Energy Comparisons

To test the difference between the LED luminaires and fluorescent luminaires in light attenuation, the illuminance (*lux*) from the lamps is measured at varying heights. Figure 8 illustrates the test setup and Figure 9 and Figure 10 illustrate the results of the test.

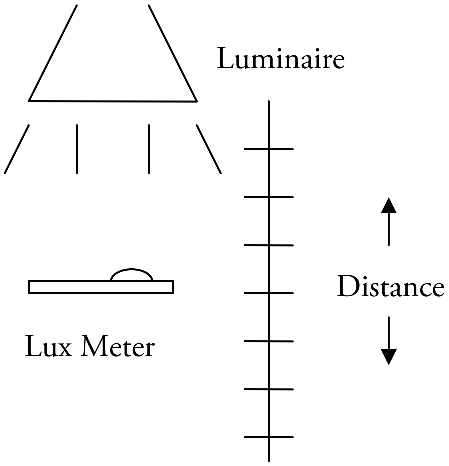


Figure 8: Illuminance Attenuation Test Setup

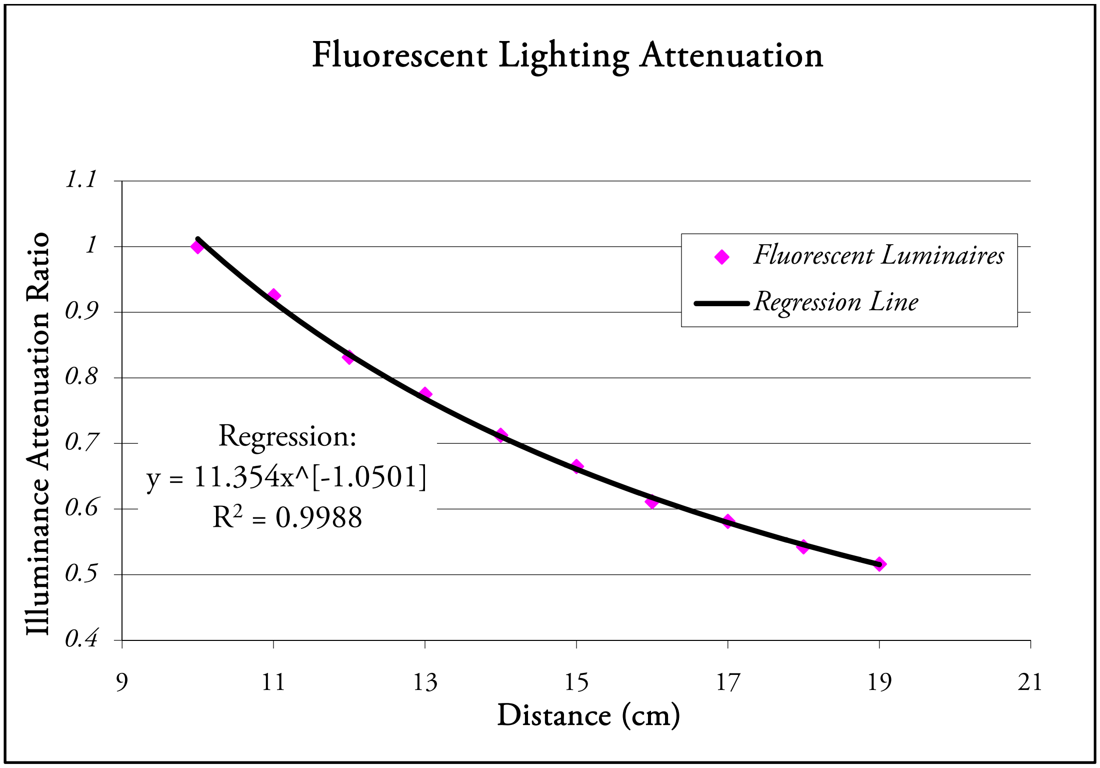


Figure 9: Fluorescent Lighting Attenuation

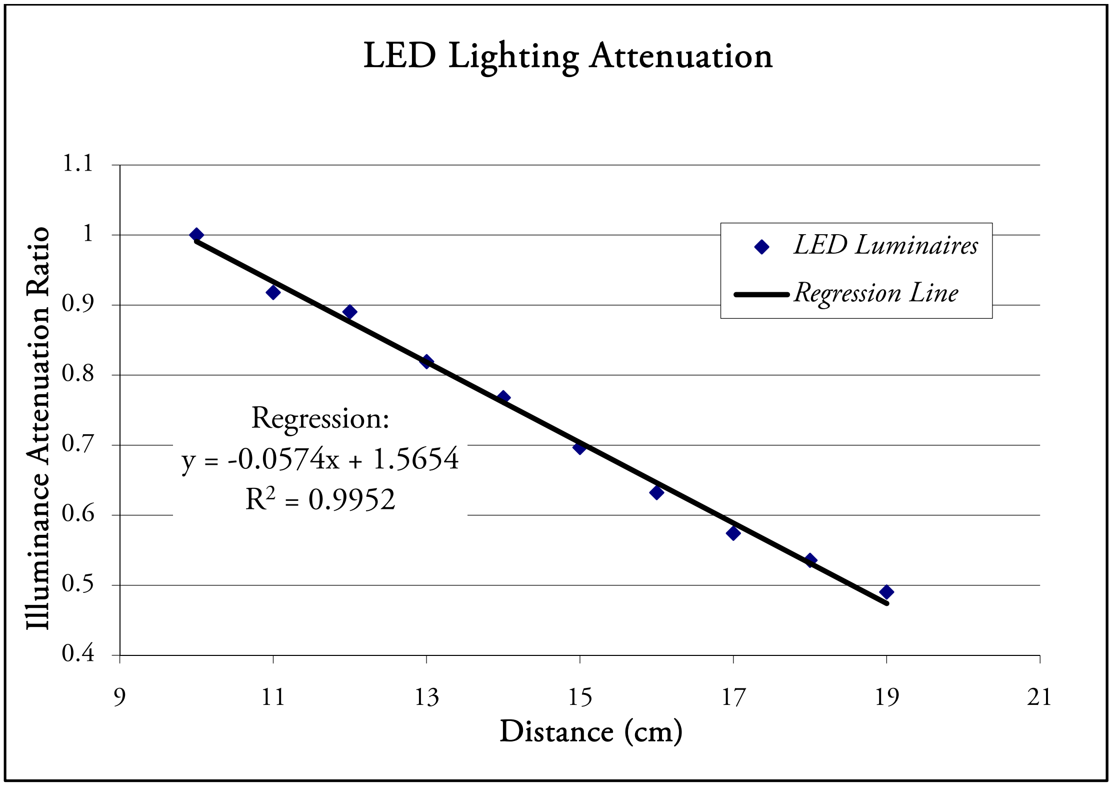


Figure 10: LED Lighting Attenuation

Though these tests are conducted using higher output lamps than would be used for higher output lamps than would be used for desk lamps, they represent general attenuation behavior of illuminance. The tests show that LED lamps lose illuminance linearly as distance increases while fluorescent lamps display exponential behavior and level off. Therefore at close distances (task lighting), LEDs would be a suitable choice and possible source of energy reduction.

User Interface[xiv]

Introduction

To further contribute to the goals of user satisfaction, an improved control interface for the lighting system (based on user interface metrics and principles) is designed collaboratively with James Bonnell and Andrew Favor. The goal of this interface is to provide a novel way to control lights in a shared office space. This interface strives to provide user customizable lighting preferences in their work area to conserve energy, as well as improve user experience in their place of work. No system will be effective unless used; the final project for the Graduate class Information 213 (User Interface Design taken with James Bonnell and Andrew Favor) presents recommendations for an improved user control of the Smart Lighting system in the laboratory.

Problem Statement

Computer interfaces will allow users to define their preferred lighting conditions as well as quickly toggle them on and off based on the users location/mode of work.

Design Process

The lighting control prototype is developed through a process of multiple iterations and evaluations using test subjects. Tasks are focused around the primary focus being office and research lab users. These tasks are developed using contextual inquiry from which user needs and ultimately three primary tasks are developed:

Task 1: Allowing a user to quickly turn the lights on and off with minimal technical knowledge

Task 2: Allow a user to quickly define lighting preferences

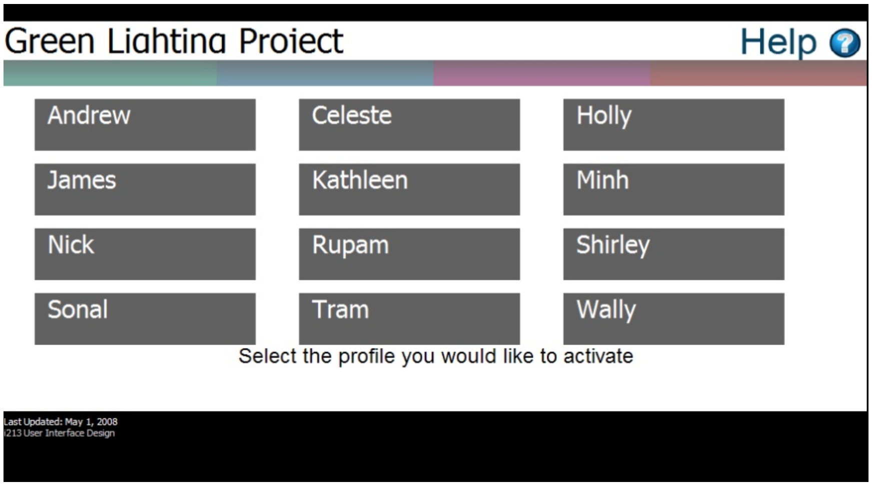
Task 3: Allow a user to quickly change lighting according to their usage context

From these tasks, a first prototype is developed which is tested among target users.

Initial design feedback is based off of heuristic evaluation according to Nielsen's heuristics[xv] as well as a team developed heuristic. These two sets of evaluations are numerically combined to yield a matrix of recognized problems and their severity, along with the estimated difficulty in remedying these problems.

The most widely recognized necessary improvements are designing help menus, and providing more textual representation and user feedback from the interface.

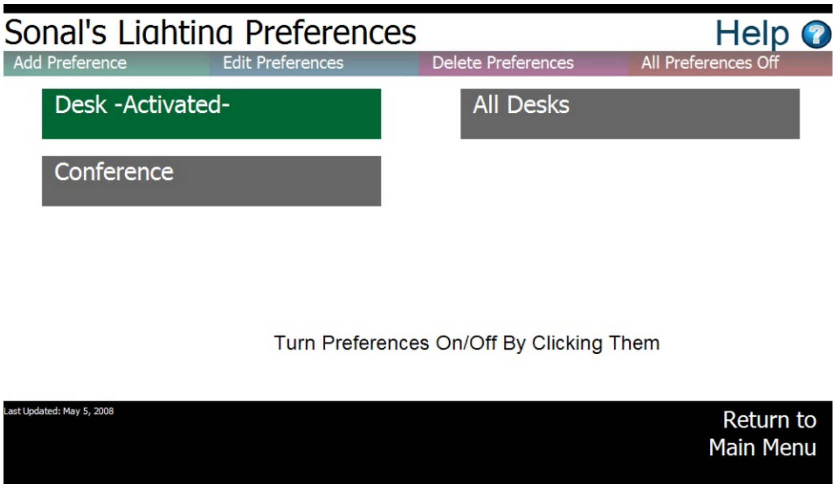
The design for the main pages of the interface navigation is based on a common drop down menu across the top of the screen which delineates the title and available options from the main functions. A contextual help menu was located in the upper right labeled "Help" as seen in Figure 11. This help menu and all of the other links throughout the project are designed to be specific to the current page to provide automatic context. From this main menu, users can activate their personal profile.



Select the profile you would like to activate

Figure 11: Main menu screen

The personal user space follows the same layout and functionality, but with added menu items across the top navigation bar. From this screen users are able to add, delete, activate and modify their saved preferences as seen in Figure 12.



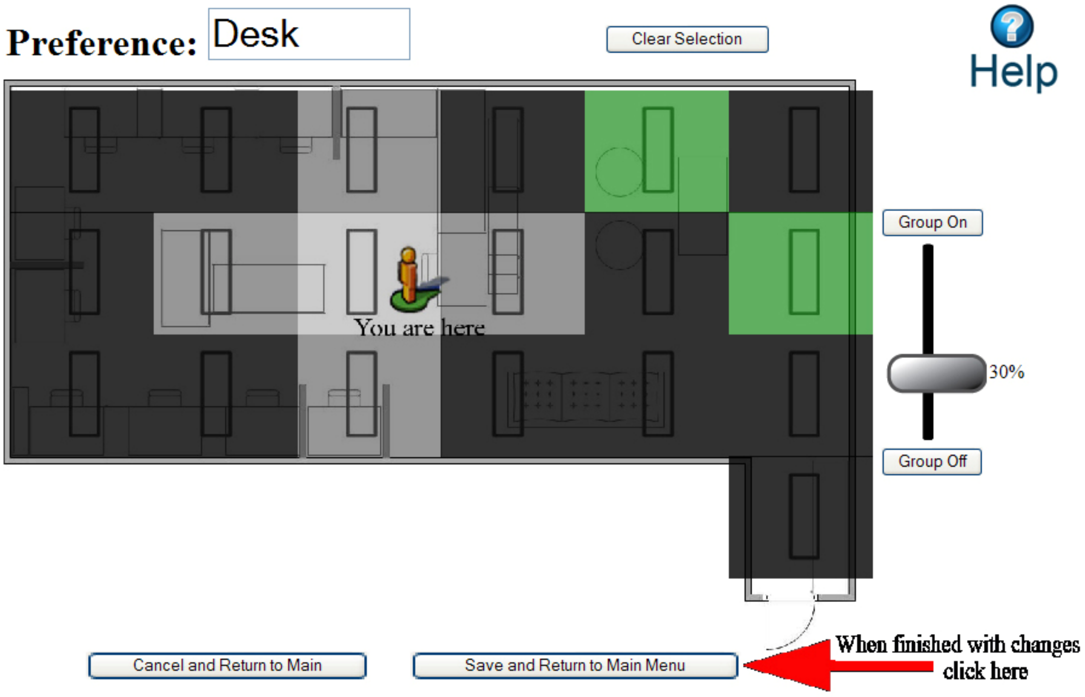
Turn Preferences On/Off By Clicking Them

Figure 12: User page.

Immediate feedback is provided to the user when a preference is activated by coloring that preference green and adding the text "-Activated-" next to the preference. The names of each of these buttons is based on the name the user associated with the setting in the editing screen for preferences, minimizing memory load as described by Donald Norman[xvi].

The editing screen which users use to modify lighting preferences (as in Figure 13) is designed to be very dynamic to provide immediate visual feedback to the user for the lights that were selected, as well as their current values. A person shaped icon was used to represent the user's location in order to orient the user within the graphical space.

If any of the lamps are selected, as indicated by the associated section of the room being colored green, the slider on the right appears from behind the floor plan to allow the user to alter selected lights. A numerical display next to the slider provides light level feedback to the user during any adjustments.



Preference: Desk

Figure 13: Preference editing screen.

As soon as any alteration to the setup is made, a fly-in arrow appeared in the lower right of the screen indicating to the user the next step available to them when they are finished with their updates. All light value updates are also shown to the user by altering the darkness of the color corresponding to each of the lights.

Design Testing

With this prototype, the system is evaluated using target users. To evaluate the system, 8 total testers are selected. They selected to be representative of the personas around which the system is designed—college students and educators. Testing population is divided into two groups, with each group testing either the control condition or the new interface first. To further the equity in testing and minimize learning effects, anyone who has experience with the old interface tests that interface first and similarly for those who had experience with the new interface. Table 2 shows the testers in their groups and their demographic information.

User #	Age	Sex	Major	Degree
A1	24	Male	ME	Masters
A2	21	Male	ME/MSE	Bachelors
B1	31	Female	Business	Bachelors
B2	23	Male	CS/Japanese	Bachelors
B3	33	Male	CS	PhD
B4	26	Female	Information	Masters
A3	21	Male	English	Bachelors
A4	28	Female	Education	PhD

Table 2: Test subject demographic information

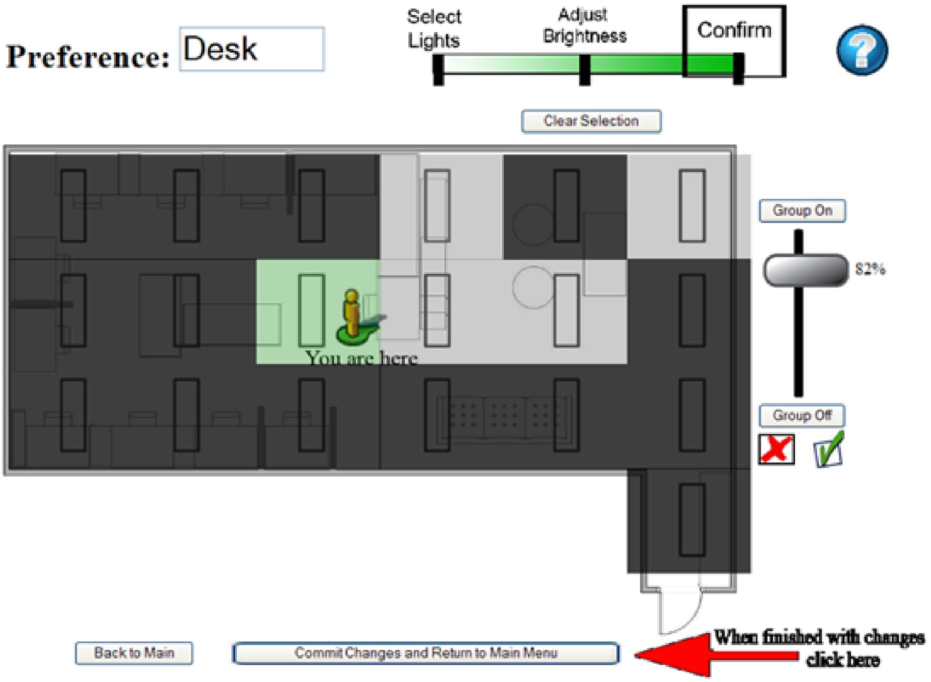
For quantitative evaluation of the interfaces, a set of tasks is developed for the users to complete on both the old and new interfaces and rated them on a set of metrics for comparison. For qualitative evaluation, we allow the testers to explore the system before completing the tasks in a think-aloud mode so as to garner users' intuitions about the system.

The average time of completion of the existing interface is 7 minutes 9 seconds, while for the redesigned user interface is 5 minutes 2 seconds. On average, the completion time of designated common tasks is reduced by 2 minutes.

While completion time is a good preliminary indicator, we also developed a quantitative test scoring system in which a numerical score for a test was derived depending on factors such as execution time, positive comments, negative comments, errors made in task completion, and frequency of accessing help. The score becomes more negative as the tester's evaluation of the system becomes "worse" ("worse" is defined by longer execution time, frequent accessing of help, errors, and negative comments).

The average score for the old interface is -9.1, while the average score for the new interface is -7.2; the difference shows that the new interface scores more positively by 2.0 (21%).

The last form of quantitative evaluation is the post-test user satisfaction survey. This survey allows testers to relay whether or not they felt that using the interface is "easy" or "difficult" based on a numeric scale where 1 is the "easiest" and 5 is the most "difficult". The average satisfaction rating for the old interface is 1.98 while the new interface rates at 1.61. This is a 19% improvement in satisfaction from the old interface to the new interface.



Preference: Desk

Figure 14: First iteration preference screen with problematic elements.

Qualitative observation during testing reveals two major design issues. The first major issue is the progress bar at the top of the preference definition screen (Figure 14) which was intended to be a simple status bar to direct the user as to what task was next, but users naturally assumed that it is active and controls actions within the screen.

The second major issue is the use of green "check mark" and the red "x-mark" underneath the actual light slider (Figure 14). The point of those buttons was to have users click on the check mark when they had determined the light intensity for the group of lights they had selected; once that group was set with the check mark, the user could then select another group of lights to set at a different setting before committing and saving the lighting preference. Testers struggled with the interface before finally consulting the help screen or clicking on the check mark because it was the only button left to press.

The redesign of the user interface control of the Smart Lighting system will be more usable based upon these recommendations. Utilizing user needs assessments and user testing methods, a more intuitive system is developed. Being more usable will ultimately lead result in higher user satisfaction and energy reductions.

Ambient Communication

Lighting possesses applications beyond utilitarian illumination: Through careful application in such aspects as placement, shadows, or color spectrum, lighting can communicate to users. It is for these reasons that lighting has many artistic applications; it has a power to elicit emotions and communicate deeper meanings to its viewers. As Jean Rosenthal describes in lightings use in performance, "Dancers live in light as fish live in water". With these capabilities, lighting can speak to viewers and users without the need for explicit translation into words: Lighting is able to communicate on the periphery of one's attention.

It is at this intersection between utilitarian lighting and art that lighting exists as a form of *ambient communication*.

As Gilles Privat[xvii] outlines, ambient communication can be described through its handling of the users' time, space, and attentive availability. Ambient communication looks to work with the growing lack of time for users; in addressing space, communication is situated in "the familiar natural environment of users, not an artificial one" (Privat); and ambient communication should not encroach on the cognitive availabilities of the users except where necessary.

Lighting becomes especially relevant as a form of ambient communication through its use of space and requirement of user attentiveness (or lake thereof). Because of its ability to be projected on any surface, lighting inherently provides an ability to communicate in a familiar context, and because it can change this context, lighting can redefine this context in an appropriate manner. Depending on its use (brightness, color, actuation, etc.) lighting need not draw a user's primary focus unless such an effect is desired.

The user's attention to light is affected by many factors: physiological, psychological, and cultural. Of special note is the user's reaction to color, for colors have the potential for specific or personal associations.

As important as the actuation of communication through light, ambient sensing describes the inputs that define the two-way street of ambient communication.

Related Research

Much research is being conducted in the field of ambient intelligence and communication at many universities and research labs as it relates to human-computer interaction. At Philips Research et al., Nevenka Dimitrova defines ambient intelligence as a multimedia perspective[xviii].

At the MIT Media Lab, Pattie Maes and her Fluid Interfaces research group study ambient communications and the “human-machine interaction”[xix]. With more related experiments using light, Angela Chang et al. present the LumiTouch which uses light as “an ambient representation and active data transmission” that notifies users of the context of their communication with the other users using the LumiTouch[xx].

In the area of human psychology in relation to color, work has been done to link colors and emotions (both in medical and artistic areas of study).

Color as a form of communication

As the human reaction to color is important in ambient communication applications, the science behind color is reviewed.

Science behind Color

In reacting to electromagnetic radiation, the human eye can only visualize a certain portion of the range of wavelengths in the spectrum (380nm to 830nm)[iv]. It is the eye’s reaction to discrete radiation wavelengths that is registered as color—light at 475nm is observed as blue, 675 nm is observed as red, etc. However, light is not usually comprised of single wavelengths, but is actually a combination of energies of different wavelengths that produce different colors; the combination of all wavelengths in the visible spectrum produces white light.

The light receptors in the human eye diverge as either rods or cones: cones are responsible for the sensing of color, while rods sense black and white. When illuminance levels are low, human vision becomes scotopic where the rods become primarily responsible for vision (and the cones no longer sense light) and colors are more difficult to register. Conversely, when illuminance levels are high, human vision becomes photopic and the cones become the primary sensors. The anatomy of the eye reveals that the sensing area in the eye directly behind the iris—the fovea (what one sees when focusing forward)—is comprised of only cones, which is why when viewing in the dark (scotopic vision), it may be easier to see using peripheral vision (due to the lack of rods in the fovea).

Using tristimulus principles, any perceived light can be broken down into three color components of red, green, or blue basis. In its basic investigations, the International Commission on Illumination defined these red, green, and blue component colors at 700, 546.1, and 435.8 nm, respectively.

Knowing that light can be analyzed into three components of red, green, or blue (RGB), any can color can also be recreated using three RGB light sources; this mixture of light is described as *additive* color mixing. (Conversely, *subtractive* color mixing is the mixture of physical pigments—as opposed to colored light. In *subtractive* color mixing, the primary colors are red, *yellow*, and blue.)

Color Theory

Color can also be notated using methods that describe a relationship among the colors with such tools as color wheels. The factors in a color go beyond its *hue* (the property that is defined by a color's red, blue, and green values). The Munsell system defines colors based on their *hue*, *chroma* (saturation), and *value* (lightness). A color's *chroma* describes its "purity" with lower chroma values appearing more washed out (as in pastels)[xxi]. The brightness or darkness of a color is defined by its *value* with low values representing nearly black and high values approaching white.[xxii]

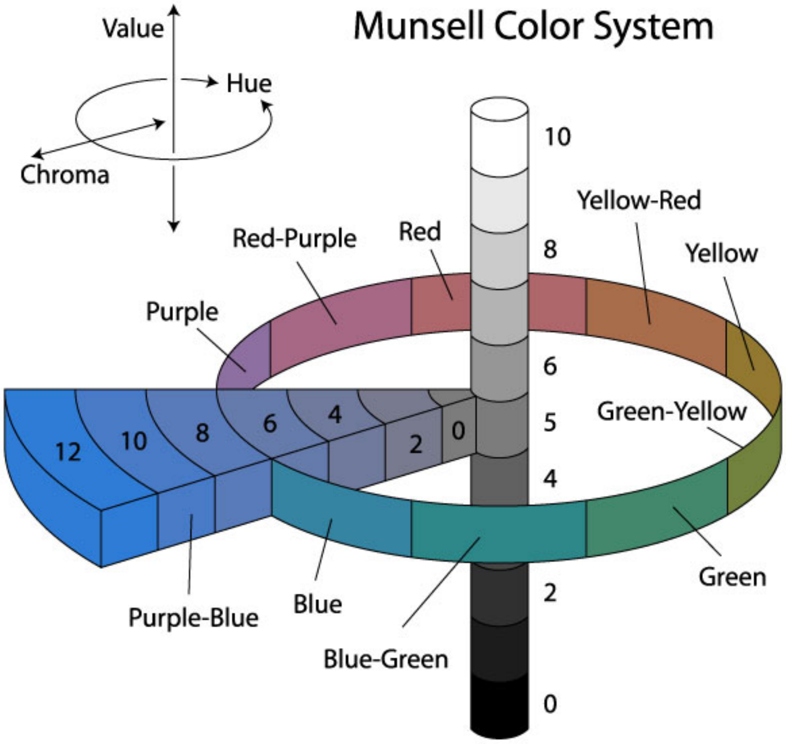


Figure 15: Munsell Color System[xxiii]

Using Color technically

Knowing the different ways in which color can be characterized, the interactions of color with each other can be used a toolbox for color utilization.

Josef Alber's *Interaction of Color*[xxiv] describes the various phenomena that govern the way color is perceived and interacts with each other. In his study of color, Alber's explores the methods in which color effects can be produced by utilizing colors' interactions; such effects include making different colors appear alike. Alber's highlights the "interdependence of color" through form, amount of colors, hue of the colors, and separation of colors.

The color wheel can also be used to further describe colors in their relationship to others: Primary hues are those that cannot be made by mixing other colors (red, green, blue); secondary hues are those made by mixing two primary hues; tertiary hues are made by mixing a primary with a secondary; and complementary hues are those that are opposite each other on the color wheel (and when mixed with a *subtractive* method, they will create a neutral).[xxv]

Color and Emotional Responses

Using color as a form of ambient communication relies on color's ability to communicate a message to users. One such method of communication is the elicitation of a reaction from those viewing the light.

In *Health and Light*[xxvi] John Ott explores the effects of different types of light on his health. Though his experiments do not provide a correlation between the types of light and the types of health effects, Ott shows a correlation between light and health effects.

In *Color Harmony*, Lesa Sawahata and Kiki Eldridge associate the types of colors with emotions and reactions: fully saturated red physically stimulates the body; cold blues tend to slow the mind and body; cool colors of base blue (but blended with yellows and reds, subtractively mixed) soothe, calm, and relax; etc.

A preliminary test of these hypotheses was conducted on the E10 students in Dr. Agogino's class: Six colors are displayed on the projector one-by-one in a dark classroom; as each color was displayed on the screen, the students are asked to select the adjective which best describes the emotion they feel is elicited. Results show a strong correlation between three colors and associated emotions:

- Pale Blue: "Calm" or "Relaxed"
- Orange: "Energetic" or "Cheerful"
- Red: "Focused," "Excited," or (OTHER – written-in response)

Red is the only color that draws a substantial number of written-in responses; while the 8 listed adjectives have positive connotations, all of the written-in responses were negative. This correlation between red and *both* positive and negative emotions is of note. (See Appendix for a copy of the test colors, survey and results).

Despite these associations that exist between certain colors and emotions, color psychology is viewed with skepticism with preliminary conclusions that no consistent mapping exists[xxvii], for while some colors may hold associations in some cultures, in other cultures the associations may be completely different. The bodily response to these colors may vary based on mental conditioning. Nevertheless, though, ambient color displays have the ability to alter a setting, and much like an audience at a sports game, the setting has the ability to influence the actors within the setting.

Actuation

In order to test the capabilities of light in ambient communication, a prototype must be developed. The test system must be able to cycle through the range of colors on the color wheel in order to view the effectiveness of different colors in communicating to users. For the initial iteration of the lighting display, the lights will produce a color gradient within a lamp shade; the colors can then be viewed from outside the lamp shade as they change.

Figure 16: Ambient Communication Prototype

Lighting Hardware Options

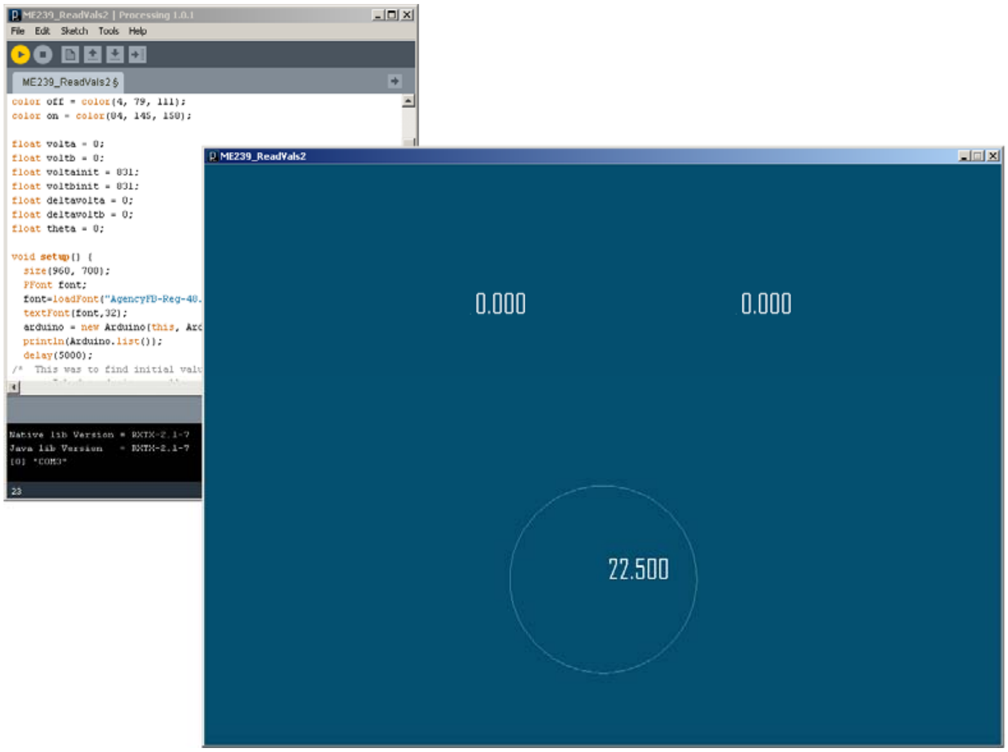
The options for producing color lighting vary across all lighting options; however, in keeping with the low energy ethos of the Smart Lighting project, the options are narrowed to LEDs and fluorescent bulbs. In terms of producing color, both LEDs and fluorescents can only produce one color at a time, but LEDs can be more directly controlled using a microcontroller. Further, the principles of additive color mixing can be utilized with LEDs in order to effectively create an entire spectrum of colors. Therefore, the prototype will be created from an array of red, green, and blue LEDs.

Arduino/Processing

The microcontroller used for the ambient color display is the Arduino Duemilanove microcontroller (as is used in prototyping the LED luminaire retrofit). This microcontroller provides 14 digital input/output pins and 6 discrete analog input pins (built in 10-bit A/D converters). Six of the 14 digital pins can also be reassigned for PWM output using the Arduino's internal PWM function. The coding environment is based off of the Processing language, which can be viewed as a simplified version of C. All of these pins on the Duemilanove are easily accessible without requiring soldering which makes it a good microcontroller for prototype testing. The sensing and on-board processing capabilities of the Duemilanove are limited by its memory; however, the board possesses a serial interface, which allows it to communicate with a computer.

By coupling the Arduino Duemilanove microcontroller with the Processing[xxviii] program environment (that runs on a computer), the sensing capabilities are substantially expanded.

Processing is a form of object-oriented programming based off of Java. It possesses capabilities as video and audio processing which can then be converted into actuation controls for the Arduino board.



```
color off = color(4, 79, 111);
color on = color(84, 145, 158);

float volta = 0;
float voltb = 0;
float voltainit = 831;
float voltbinit = 831;
float deltavolta = 0;
float deltavoltb = 0;
float theta = 0;

void setup() {
  size(960, 700);
  PFont font;
  font=loadFont("AgencyFB-Reg-48.
  textFont(font,32);
  arduino = new Arduino(this, Arc
  println(Arduino.list());
  delay(5000);
/*  This was to find initial valu
```

```
Native lib Version = RXTX-2.1-7
Java lib Version   = RXTX-2.1-7
[0] "COM3"
```

```
23
```

Figure 17: Sample Processing Programming Window and Output

The current prototype is not wireless; however, control of the ambient system can also be conducted using wireless motes (which can also communicate with Processing using serial communication). As the prototype develops, wireless motes will become useful for integration as they make the ambient communication setup more mobile and versatile.

Lighting Capabilities

Using RGB LEDs, the test system is able to replicate most of the visible color spectrum using color mixing capabilities. In order to change the relative strengths of the RGB channels, each color LED is dimmed depending on the desired color. To dim the LEDs, pulse width modulation (PWM) is employed. PWM provides a much more effective method of dimming the LEDs as opposed to decreasing voltage provided to the diodes. The PWM method also has the added benefit of saving energy used, for instead of the circuit wasting energy in the form of resistance to decrease applied voltage, when the LEDs are dimmed, they are simply turned off—expending no energy.

Prototype Design

To control the LEDs, each separate color LED array is connected directly to a voltage source; each color array circuit is controlled using an N-Channel mosfet whose gate channel controlled using the PWM capabilities of the Arduino Duemilanove. Figure 18 depicts the circuit diagram for one branch of the ambient color display; a total of 9 LEDs are used (3 for each color: red, blue, and green). The ambient display contains 3 total branches, which mix their colors together to form all possible colors; the respective brightness of each branch (and thus color) is controlled using PWM: The PWM signal controls a mosfet gate which regulates the voltage that flows through the circuit from a 5V power source. Table 3 depicts the LEDs used and the corresponding resistor for each color wash branch. Together, all 3 branches form the ambient color display prototype capable of mixing all colors.

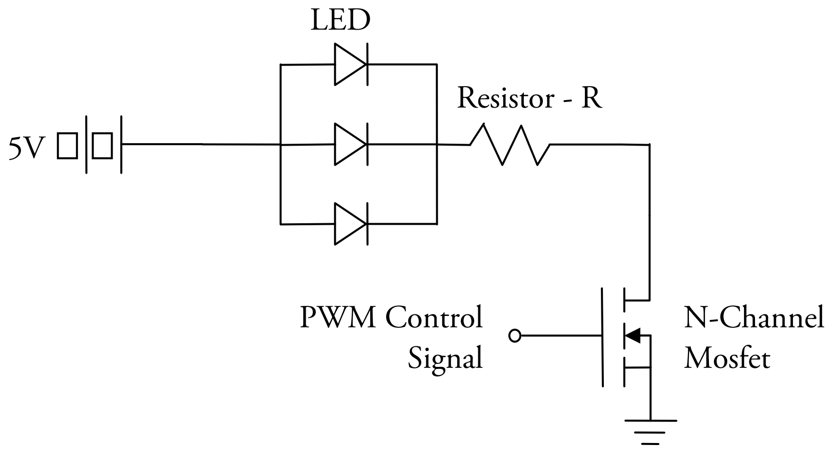


Figure 18: Circuit Diagram for Ambient Communication Color Wash

LED Color	LED Voltage	LED Current	Output	Resistor – R Value
Red	1.9 – 2.15 V	20 mA	18 cd	150 Ω
Green	3.2 – 3.4 V	20 mA	10 cd	85 Ω
Blue	3.2 – 3.4 V	20 mA	35 cd	85 Ω

Table 3: LED and Resistor Selection

The PWM controls whether or not the mosfet is allowing current to flow to the LEDs; using the mosfet allows for multiple LED control while powering using specific voltage and not over-drawing current from the microcontroller.

Algorithm for Response

As colors are used primarily as a major tool in the ambient communication display, the relationships of colors to each other is crucial, for a color is interpreted not in isolation, but in relation to other colors (Albers). Using Josef Alber's exploration of color interaction, the ambient display system will make most effective use of color.

Two main modes of communication exist for the ambient display: *reflective* and *proactive*. The reflective modality of the display will simply provide viewers with information that the system has gathered and analyzed; the aim of the proactive modality is to use the light display to elicit responses from the user (such as promoting creativity—see classPace below).

The reflective mode of communication can be used by the system to communicate different types of information as it fits within the framework of ambient communication previously described. Possible applications include relaying information about weather forecasts, colleague or peer availabilities, social settings, etc.

The proactive modality requires more exploration in its claim to influence the user through light. In order to elicit such reactions, the proactive mode relies on color associations as explored in color experiments.

In both modalities, it can be important for the ambient color display to interact with the color of the surrounding environment. With this application, it is beneficial to examine the complementary colors to explore the most appropriate color matchings.

Sensory Inputs

Different sensors can exist throughout space; however, to what the actuation system responds can vary depending on desired outcome.

When combined with the analyzing power of the Processing environment, the sensing capabilities expand with the use of cameras and microphones.

ClassPace[xxix]

The classPace project was initiated by Sohyeong Kim and Nate Gandomi for the Tangible User Interface Class in the School of Information at UC Berkeley. Despite the conclusion of the class, their work continues on the project with the contributions of this research. ClassPace is an ideal case study of the applications of ambient communication using the developed prototype.

Introduction to *ClassPace*

The *ClassPace* system is a classroom response system that aims to improve classroom interaction using three approaches: assessing student engagement or understanding, reflecting these factors to both students and instructor in lecture settings, and proactive fostering of student creativity and involvement in discussion and teamwork settings. *ClassPace* will provide a suitable test for the ambient display system in both reflective and proactive modalities.

The system will serve to further open the three lines of communication that exist within an educational setting: instructor-to-students, students-to-instructor, and students-to-students. Aggregate data gathered on student engagement (through explicit user input and implicit student behavior) can be used to analyze pedagogical patterns to improve instructor effectiveness. By visualizing student engagement and understanding, *ClassPace* will allow students to diagnose their own progress and understanding. Additionally, instructors will be able to identify which topics require further time and attention. *ClassPace* will provide a way for students to share and view non-verbal, non-textual feedback within the context of a classroom.

Development of System

Input Device

Students will relate their engagement to the *ClassPace* system using an input device that translates a spectrum of input values ranging from not engaged to highly engaged. Currently the sensor is a foot pedal that is discrete and has natural affordances to fast and slow (which relate to the pace of the class).

This data will inform the ambient lighting display as to how to communicate to the class. Instructors in small class settings often gauge student interest by observing factors such as body language. Ideally, future *ClassPace* iterations will be able to mimic such observations with sophisticated input sensors.

Ambient Output Display

Data from *ClassPace* inputs will be transformed into a visualization using the ambient output display.

Instead of using a display which provides and presents each individual user as an icon, the sensory input will be aggregated and communicated by lighting a wall (or other surface) with a color gradient. To communicate the overall class interest, the color gradient will shift depending on the input. The design change of moving to a color gradient is to situate the communication in a more familiar environment to the users (teachers and students)[xvii] : The goal for mapping colors to class pace opinion is to present the data to users using associations between the two.

Further, the design aims to account for the *cognitive* availability of the users. A display featuring individually displayed icons requires users to personally process the data and form their own conclusions. By aggregating the data for the user and displaying in an unobtrusive manner using only colors, the system will remove the tax on user attention allowing the user to center their attention on the primary focus of class—learning or teaching. Because we can observe and respond to color without much conscious thought, ambient lighting provides a viable method of reflecting user input.

The color gradient display can also be used to test the *proactive* behavior of *ClassPace*. Again, color will be a primary driver in communicating with the users, but instead of being merely reflective of an aggregate opinion, it will attempt to foster creativity as an additional actor in the design space. *ClassPace* provides a unique framework in order to conduct more research on possible mappings between lighting behavior and human response.

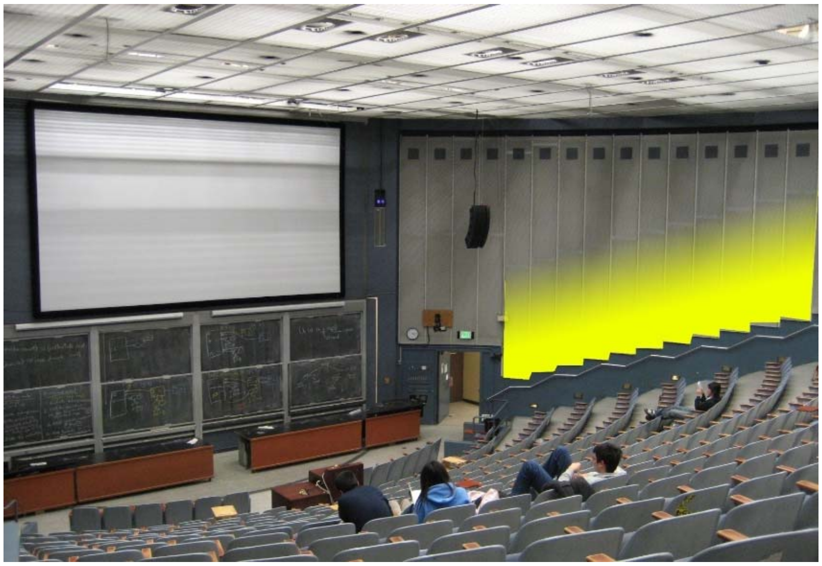


Figure 19: Ambient Display Mock-Up

Large classrooms often cause a feeling of disconnectedness in students. Students do not interact with each other, while the instructor delivers information to them. An ideal classroom creates an interactive experience where students engage with each other, the instructor and the material.

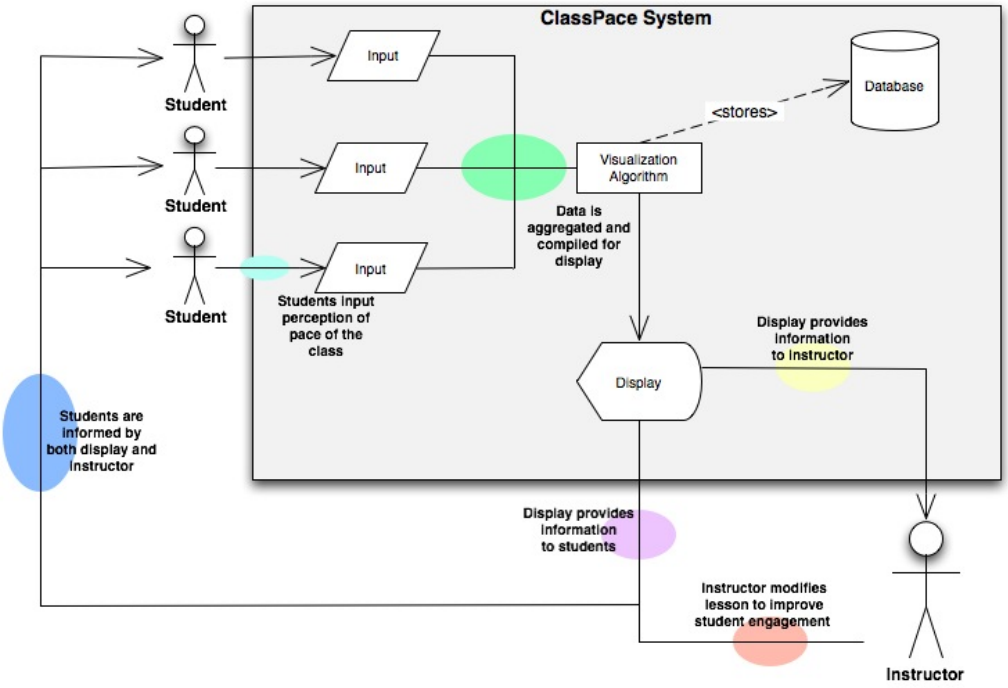


Figure 20: *ClassPace* System

Figure 20 illustrates the flow of information in the classroom and the ways in which ClassPace can assist. ClassPace facilitates the flow of information between the students and the teacher.

Due to the additional lines of communication provided by the ambient communication capabilities of the Smart Lighting prototype, the system works to facilitate learning. Future testing will reveal the results of this hypothesis.

Conclusion and Recommendations

After the successful installation of the user-customizable fluorescent lighting system, new avenues exist for the growth of Smart Lighting. While LEDs are generally considered to be the next step for energy-efficient lighting, many commercial options are still scarce for LED lighting systems. Though the fixtures generally do consume less energy, the amount of lighting produced is also substantially less than with current fluorescent lights. Thus energy consumption for a room lit by LEDs would require nearly twice as much energy as the same room lit by fluorescent LEDs. Therefore, LEDs are currently not an ideal choice for a general lighting solution.

However, LEDs do show preliminary promise in close uses (such as task lighting) due to their attenuation patterns: While fluorescent light seems to possess an inversely proportional relationship to distance from the light source, LED lighting is more linear. This would suggest that using LED lighting is more applicable in situations closer to the source such as task lighting (or as in display lighting where they are used now).

Avenues for growth of Smart Lighting exist beyond simple illumination, as well. Lighting can be used in ambient communication applications. By being reflective of information or proactive actors in a situation, lighting has many possibilities. To be better used in a proactive manner, the ways in which lighting can be used are examined: color, actuation, etc. Some existing claims correlate color to emotion and while preliminary tests conducted in this area confirm such a relationship, it does not link colors to previously linked emotions. Thus, preliminary research shows possibilities for uses of Smart Lighting as a form of ambient communication but further research must be conducted in this area to clearly define such methods.

Appendix

Arduino Code

Computer-Controlled On/Off Switch

This code controls whether or not the lamp is controlled on or off. This code controls the circuitry detailed in Figure 4.

```
/*
 * Nicholas Galano
 *
 * Turn a light on/off using MOSFET control
 *
 */

//Variable Definition
int outPin = 11; //Light sensor analog pin input #
int inPin = 2; //input pin
int buttonState = 0; //

void setup() {
  pinMode (outPin, OUTPUT); //sets digital pin for output
  pinMode (inPin, INPUT); //sets digital pin for input
}

void loop () {
buttonState = digital Read (inPin);
if (buttonState == HIGH) { //If the button is pressed
  digitalWrite(13,HIGH); //Actuate the light (High Voltage -> turns on mosfet -> closes
relay)
  }
}
```

Dimmer PWM Cycle

This code outlines the manual PWM cycle utilized for controlling the TRIAC for the LED luminaire dimmer. This code controls the circuitry detailed in Figure 6.

```
/*
 * Nicholas galano
 *
 * Manual PWM Output
 * Test the Digital IO ports for ability for custom duty cycle
```

```
 *
 */

float T = 100/12; //Period
float duty = 0.25; //initialize duty cycle (from 0 - 1)
float a = 0; //initialize duty time
float b = 0; //initialize off time

int controlPin = 7; //Digital Pin

void setup(){
  pinMode(controlPin, OUTPUT);
}

void loop(){
  a = duty*T; //set duty cycle time
  b = T - a; //set off cycle time
  digitalWrite(controlPin,HIGH); //turn on
  delay(a);
  digitalWrite(controlPin,LOW); //turn off
  delay(b);
}
```

Sample Color Wash Cycle for Ambient Color Display

This code showcases the color wash ambient display by cycling through the color wheel. This code is used to control the circuit exhibited in

```
/*
 * LED Color Mixing
 * Nick Galano
 * BEST Lab
 *
 * 3-1-09
 *
 * Show Color Mixing Capabilities
 *
 */

//Variables
int redpin = 9;
int greenpin = 10;
int bluepin = 11;
```

```
int redval = 0;
int greenval = 254;
int blueval = 120;

int rindex = 0;
int gindex = 0;
int bindex = 0;

void setup() {
  pinMode(redpin, OUTPUT);
  pinMode(greenpin, OUTPUT);
  pinMode(bluepin, OUTPUT);
}

void loop() {
  if (rindex == 0) {
    redval=redval+1;
    if (redval == 255) rindex = 1;
  }
  if (rindex == 1) {
    redval=redval-1;
    if (redval == 1) rindex = 0;
  }

  if (gindex == 0) {
    greenval=greenval+1;
    if (greenval == 255) gindex = 1;
  }
  if (gindex == 1) {
    greenval=greenval-1;
    if (greenval == 1) gindex = 0;
  }

  if (bindex == 0) {
    blueval=blueval+1;
    if (blueval == 255) bindex = 1;
  }
  if (bindex == 1) {
    blueval=blueval-1;
    if (blueval == 1) bindex = 0;
  }
```

```
    analogWrite(redpin,redval);
    analogWrite(greenpin,greenval);
    analogWrite(bluepin,blueval);
    delay(80);
  }
```

Color-Emotion Test

Sample Colors Tested

Sky Blue	Orange	Magenta
Green	Red	Yellow

Sample Survey

Demographic Information:

Are you color blind? Y N
Gender? M F
What Country did you grow up in?

Emotions to be selected:

- Energetic
- Focused
- Excited
- Friendly
- Cheerful
- Calm
- Relaxed
- Ready
- Other: ________________________

Respondent Results

Color

emotion	Pale Blue	Orange	Magenta	Green	Yellow	Red
energetic		7	9	8	7	3
focused	2	3	2	6	1	9

excited		3	12	2	3	9
friendly	2	4	4	3	7	1
cheerful		6	5	6	8	
calm	21	3		5	4	1
relaxed	12	3		2	2	2
ready		3	3	4	3	3
OTHER	1	4	1	1		8

Table 4: Respondent Results of Color-Emotion Test

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