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A Photometric and Psychonomic Analysis of Exit Signs and Current Way-Finding Technology

Joseph Whitlock

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A PHOTOMETRIC AND PSYCHONOMIC ANALYSIS OF EXIT
SIGNS AND CURRENT WAY-FINDING TECHNOLOGY

A Dissertation

Submitted to the School of Graduate Studies and Research

in Partial Fulfillment of the

Requirements for the Degree

Doctor of Philosophy

Joseph Whitlock

Indiana University of Pennsylvania

December 2018

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This study examined and evaluated exit signs and related flashing way-finding technology (Linear Strobe™ L-100). The research determined exit sign performance and an observer's preference in two phases. The photometric phase measured and recorded luminance and luminance contrast levels for exit signs (red LED, green LED, blue LED, photoluminescent or PLM, and flashing way-finding at a distance of 100 feet using a photometer across four combined conditions of ambient lighting and obscurity (#1 lights on-no smoke, #2 lights on-smoke, #3 lights off-no smoke, and #4 lights off-smoke). The photometric phase results determined the red and green font had the highest luminance overall and the highest luminance contrast for the green font and flashing. The flashing technology had the lowest luminance levels overall but had the highest luminance contrast when smoke was present (conditions 2 and 4). Observers determined their individual preferences under the same four conditions as the photometric phase and their overall preference regardless of condition. A significant difference was reported for the flashing technology for conditions 2, and 4 and red font for condition 1 ($p = .000$). Thus, flashing way-finding performed better with smoke. Regardless of condition, 72% of males and 54% of females preferred flashing resulting in 63% of all observers preferring the flashing technology overall. Consideration of these results indicated greater luminance levels did not equilibrate to better visibility or overall preference. Flashing was preferred under the conditions with smoke where luminance contrast was highest. Qualitatively, the flashing

technology appears to be enhanced by the smoke concentrations where the traditional exit sign was obscured. This study is important given no research to date has been performed with the Linear Strobe™ as compared to existing exit signs. Exit sign “readability” criterion could become obsolete as the flashing outline of the door is easily perceived as an exit below the smoke layer. This technology should be studied further and considered as a more universal design for children, elderly, color-blind, and prescriptive eye wear users than the traditionally worded “EXIT” sign.

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To my Grandmother Dorothy I will call out from above. Thank you for being the foundation of hard-work and the epitome of tenacity. A factory welder during World War II and a member of the greatest generation, Dorothy went to work every day as a proud member of the working class. Dorothy and many others like her quietly demonstrated to the world how grit and fortitude will ultimately prevail with enduring perseverance.

To my Grandfather Charles, he never had the opportunity to finish a college education. But his great grandchildren look to the skies above and still seek his thirst for knowledge and wisdom.

To my family who endured, tolerated, broke-up, persevered, and yet somehow still supported me during this journey. Your love is my strength. Your love makes me complete. I would like to thank my parents for being the eternal, unwavering foundation of love and support. Eva, Liv, and Gavin may you each follow your dreams. You are all capable of far greater things than you can ever imagine. But first, dream. More importantly, listen to your heart. Do what makes your heart happy. The long, lonely road is the road best traveled where you pass many failures on your way to success. These failures are the true measure of one's success.

And finally, William H. Stone your star burned out too soon. Thanks for believing in me and educating me on the greater things in life. "Ride fast and take chances." Billy, I miss you already.

Lastly, we all get lost at times. Remember those lonely souls out there in the dark and know the smallest candle burns like the sun. Be a light. Be a candle. Be the sun. Be a star to guide me home.

So to my brightest star – know I always look for you and I'm coming home.

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CHAPTER ONE

INTRODUCTION

Background and Significance

Building exit signs are a critical element in any emergency escape. Exit signs are designed to show people the way out. Exit signs denote the escape route that should be taken in an emergency and reduce confusion and delay that may prevent a safe escape.

Historically, failure to quickly escape from fire resulted in death, as seen in several of the fire disasters that took place during the twentieth century. The investigations of the 1903 Iroquois Theater fire in Chicago, Illinois (602 deaths); the 1911 Triangle Shirtwaist fire in New York City, New York (146 deaths); the 1942 Cocoanut Grove nightclub in Boston, Massachusetts (492 deaths); and the 1977 Beverly Hills Supper Club fire in Southgate, Kentucky (165 deaths) revealed many building occupants encountered missing, blocked, unmarked, locked, or obscured exits (Cavallini, Papagni, & Baruffaldi Preis, 2007).

The analysis and history of major fire investigations in the U.S. demonstrated that a quick and safe means of egress from a burning building or related emergency is essential to human survival (Kobes et al., 2010). Most recently gathered data showed that a structure fire occurs nearly every minute in the United States (U.S.) according to the National Fire Protection Association (NFPA). The NFPA's 2015 Annual Fire Loss Report recorded over 501,000 structure fires for the year, resulting in a total of 3,280 civilians killed and another 15,700 civilians injured (Haynes, 2016). The human loss resulting from structure fires in 2015 corresponded to a fatality every two hours and 40 minutes and an injury every 30 minutes.

The NFPA has also estimated total fire losses represent over two percent of the U.S. gross domestic product (GDP) during 2011, which is equivalent to approximately \$330 billion (Haynes, 2016). Human loss, property loss, and the legal liability from fires are very much real concerns for safety professionals and building owners alike. As a result, fire policy experts should be encouraged to revise their collective strategy to reduce fire fatalities and injury. Any strategic plan to do so will require specific knowledge and research to aid code revisions.

Unfortunately, dramatic fire and life safety code revisions frequently require a catalyst in the form of a major catastrophe before fire officials will make improvements to existing fire and life safety standards (Teague, 1991). Historically, considerable time was required before revisions became final. For example, the NFPA committee on Safety to Life formally reviewed the egress and exit issues from the tragic 1911 Triangle Shirtwaist fire. Ultimately, this review resulted in the publication of the Building Exits Code in 1927—over 15 years after the incident occurred (Pauls, 2002).

More recent catastrophes, such as the World Trade Center (WTC) fire and building collapse in New York City, New York in 2001 (2,666 deaths) and The Station nightclub fire in West Warwick, Rhode Island in 2003 (100 deaths) reveal that there is still a gap between existing code requirements and improved protection from fire (NFPA, 2016). Both of these tragedies triggered revisions to existing fire policy and code. However, these unfortunate incidents serve to highlight the fact that many potential gaps remain in our overall knowledge in fire safety and fire code currently. More importantly, improvements in life safety and code revision should not be predicated on resultant fatalities from major fire tragedies.

Exit Sign Requirements

It has been estimated the emergency egress products market for new and renovated buildings is worth \$250 million dollars per year and exit sign market accounting for \$75 million annual sales (Conway & Boyce, 1997). Original equipment manufacturers of exit signs have indicated new exit signs are replacing older units some three to ten years old (Conway & Boyce, 1997).

Building owners are required to install and maintain exit signs. Emergency exit signs are designed to indicate the direction of egress and to designate the doors leading to a stairwell or outside the building envelope. Due to the exit sign's universal importance, several sources of regulation exist in the U.S. establishing the sign's requirements.

As a result, there are many overlapping regulatory bodies. For example, the International Building Code (IBC), National Fire Protection Association's (NFPA) Life Safety Code, Occupational Safety and Health Administration (OSHA) standards, Underwriters Laboratories Standard 924 (UL 924) and the International Fire Code (IFC).

Most exit signs are made with two contrasting colors to ensure visibility. Emergency exit signs usually depict the word "EXIT" or equivalent wording in the local language in green or red letters. According to Konica-Minolta (2017), the international "running green person" symbol is increasing in prevalence and ". . . has been used in many countries, such as Germany, Canada, Australia and parts of Asia Pacific, including Singapore." This symbol was developed by Yukio Ota in 1980 and introduced in 2003 by the International Standards Organization (ISO) 7010 Standard. Ota's running man symbol is depicted in Figure 1.



Figure 1. Yukio Ota’s design of running man pictogram. An international emergency exit symbol introduced for use in 2003 by the ISO Standard 7010. Adapted with permission from the “Emergency Lighting Measurement of Exit Sign, 2012” by Konica Minolta p. 1. Copyright 2012.

In the U.S., the absolute origins of the text-depicted exit sign are unclear. Current U.S. requirements dictate the sign must be labeled with the word “EXIT” and located within the maximum viewing distance rated for the exit sign, or 100 feet (NFPA 101, Life Safety Code, 2015). Each exit sign must have plainly legible letters not less than six inches high, with the principal strokes of the letters in the word "Exit" not less than three-fourths of an inch (1.9 cm) wide.

Another basic NFPA 101 requirement is that where a change in direction exists or where egress is not apparent, a mounted sign is required. A change in direction of egress requires a directional indicator to be provided (known as a chevron) adjacent to the word “EXIT.” NFPA 101 (2018) also requires every exit sign to have such size, color, and design that it is readily visible and contrasts with the background where it is located. Additionally, no other illumination sources that could distract from the exit sign shall be permitted. Exit signs are normally mounted on the door or directly above the door. If the exit sign is mounted adjacent to the door, the sign edge must be within four inches of the doorframe.

Federal, State, and local governments all maintain jurisdictional authority over exit sign placement, performance, maintenance, and operation. The International Fire Code (IFC), the International Building Code (IBC), the National Fire Protection Association (NFPA), and the Occupational Safety and Health Administration (OSHA) all maintain specific language regarding exit signs. OSHA requires a Nationally Recognized Testing Laboratory (NRTL) when testing equipment and products related to safety (OSHA's NRTL program, 2017). Manufacturers are required to submit their exit signs to approved third-party laboratories for certification to a known test standard. Underwriters Laboratories' (UL) 924 Emergency Lighting and Power Equipment standard requires exit signs to be evaluated and laboratory tested at predetermined distances (50, 75, and 100 feet) while the luminance levels are verified during normal operation under clean air condition (ambient lighting and no smoke) and with a back-up power supply (NFPA 101, 2018). After being certified as UL approved, exit signs will be listed as internally illuminated, externally illuminated, self-luminous, or radioluminescent.

Individual states and local governments have additional jurisdictional control over exit sign specifications and performance, with some choosing more stringent requirements. The more progressive states and the larger metropolitan cities have adopted more rigorous requirements.

For example, California was the first state to require low-level exit signs adjacent to exit stairwell doors for new construction in 1989 (California Fire Code, 2007). The idea behind additional low-level signage is that smoke density is greater at the ceiling, and the signage near the floor would be more visible during a fire.

Another example of more stringent regulations is in New York City. After the catastrophic World Trade Center fire and building collapse in 2001, New York City required

photoluminescent (PL) exit signs and photoluminescent markings (PLM). In addition, exit signs are required to be mounted on the exit door or wall near the floor for buildings over seventy-five feet, while all stairs and handrails must be clearly marked with PLM (NYC Local Laws & NYC Building Code, 2004).

PLM perimeter marking is also required for all stair landings and corridors. This improved way-finding was integrated into New York City fire code after investigations from the World Trade Center revealed building occupants were able to evacuate by following the PL exit signs and related PLM in the stairwells (de Vries, 2006). PLM aided egress for building occupants even after the reported widespread power failures and smoke-filled stairwells.

This PLM perimeter marking is also known as “Luminous egress path markings” under Section 1024 in the IBC 2009 (International Building Code, 2009). Continued evolution of incorporating way-finding into related code and regulations will require further testing and validation.

Exit signs in use today are internally powered or externally powered with new advances in technology compounding our decisions for code compliance with existing requirements. Internally powered signs are operated by alternating current (standard electric) or direct current (batteries), or, more simply, sign illumination comes from within the sign. Whereas, externally illuminated exit signs can receive their illumination by the building’s ambient lighting. The self-luminous exit sign signs can be operated by tritium. PLM exit signs light are powered by the sun or existing light sources and then that energy is re-emitted during low light conditions or darkness. Whether internally or externally powered, commercially available exit signs and the related way-finding technology are illuminated by many sources. Some of the more commonly

found sources available commercially include incandescent, fluorescent, light-emitting diode (LED), light emitting capacitor (LEC) or electroluminescent, photoluminescent (PLM), and radioluminescent sources (P. Boyce, 1993).

Exit Sign “brightness” is determined by illuminance and luminance. Illuminance refers to light levels imposed on the exit sign surface as measured in foot-candles (lux). While luminance refers to the amount of light emitted from the exit surface and is measured in foot-lamberts (fL) or candela/meter² (cd/m²). The required luminance levels are found in OSHA 1910.37 (2018), NFPA 101 (2018), and UL 924 (2018). OSHA (2018) requires the exit sign to be illuminated by five f-c (54 lux) minimum by a reliable light source and be distinctive in color. If the exit sign is self-luminous or electroluminescent, then the surface may be illuminated to a minimum of 0.06 fL (0.21 cd/m²).

NFPA 101 (2018) also has similar illumination requirements; however, the exit sign luminance requirements must be located in the respective listing requirements under UL 924 Standard for Emergency Lighting and Power Equipment. Consequently, for internally illuminated exit signs, the UL 924 (2018) illumination requirement of 5 f-c (54 lux) is similar to OSHA. Luminance requirements are found in UL 924 (2018) and are listed as no point on the exit sign element surface can be less than 8.57 cd/m² (2.50 fL) for normal power conditions.

Exit sign luminance may be tested and determined in the observation visibility test or in the luminance measurement test (UL 924, 2018). The observation visibility test requires observers with good visual acuity and dark condition acclimation to correctly identify signs in random order. While the luminance measurement test is performed with a calibrated instrument (photometer or spectroradiometer) measuring luminance (cd/m²) in prescribed locations.

In addition to externally and internally illuminated exit signs, recent technology has been developed which utilizes light emitting diodes, or LEDs, integrated into the doorjamb and along the floor and wall corner (see Appendix A). This new technology also flashes. While both the NFPA 101 (2018) and the UL 924 (2018) reference exit sign flashing performance requirements, neither are specific to new technology. However, flashing exit signs do not appear to be commonplace in the U.S. according to this researcher's observations.

Though, the UL 924 (2018) listed test method can determine the flashing rate, flashing rate, flashing rate stability, light pulse duration, and duration between successive light pulses for exit signs. However, this testing method is not specific to this technology.

But this new technology is part of a more recent development in fire safety and public signage known as way-finding (Passini, 1984). Consideration for exit signs to perform in conjunction with the environment to aid humans' sense of location is a notion developed under the concept of way-finding (Karimi, 2015). Way-finding in most literature denotes how humans perceive and process information to reach their destination related to their surrounding spaces (Zwaga, Boersema, & Hoonhout, 2003). This study will focus on LED exit signs, PLM exit sign, and flashing LED way-finding.

But even with compliance directives and specific regulatory language regarding exit sign placement, sign positioning, font size and spacing, placement, back-up power supply, operation, and maintenance, many gaps still exist between current literature, actual field conditions, and the testing lab. Some of those gaps will be explained next as the basis for the proposed research questions.

Statement of the Problem

The simple, universal exit sign is expected to operate twenty-four hours per day, and usually not much attention is given to exit signs until they are needed during an actual fire or emergency. Exit sign performance may deteriorate dramatically during structural fires where smoke easily obscures one's vision, yet current independent laboratory testing does not take this consideration into account when certifying exit signs (Bierman, Raffucci, Boyce, & DeCusatis, 1996; Boyce, 2014; Jouellette, 1988). Therefore, a gap of knowledge exists between third-party certification specifications and actual field conditions. This notion deserves further scrutiny, how does our currently available exit signs and related way-finding technology perform today? Performance should be examined especially under the conditions of smoke and no lights.

When needed, exit signs aid in the rapid egress from buildings or related structures. But another confounding factor to consider is buildings are becoming taller and more complex in design at the same time humans become bigger and less fit (Bukowski, 2008, p. 179-180). Therefore integrating optimal exit sign visibility with revised Life Safety measures becomes more critical.

In addition, current way-finding technology has not been compared to types of exit signs currently being used in the field. To integrate exit sign optimization, additional research is required to determine optimal exit sign design characteristics such as font color or effects of flashing.

Despite the reality of smoke easily obscuring signs in an emergency, there is logic that has dictated why exit signs historically have been mounted above individuals trying to exit (Boyce, 1993). Other building occupants in their mode of egress, or even the building's

furnishings, might easily obscure exit signs mounted lower to the floor. Another advantage of ceiling mounted exit signs is that they are less prone to damage and regular maintenance issues.

However, exit signs installed in the U.S. are not currently tested and certified under conditions found during emergencies. For example, during power outages and fires with resultant smoke concentrations is when exit sign performance is the most critical to survival. Exit sign design and operation should be based on experimental research (Rea, Clark, & Ouellette, 1985). In addition to testing current exit sign designs representing emergency conditions, further research is needed to verify optimal exit sign font colors and whether a flashing effect will provide increased exit sign conspicuity (Boyce, 2014; Collins, Dahir, & Madrzykowski, 1993). Some literature suggests exit sign font color is based on cultural familiarity and previously established safety colors without evidence-based research to support these conclusions (Boyce, 2014).

The question of effective exit sign flashing has also been proposed previously by subject matter experts and is of particular interest in the no lighting, smoke condition due to the scattering of light (Boyce, 2014, p. 320). The no light, smoke condition may enhance the flashing effect or may result in decreased visibility due to light scattering.

So herein contains the challenge: mounting exit signs near the ceiling makes logical sense, but in reality the signs can be difficult to see during an emergency, especially during a fire where smoke easily obscures the sign or even the individuals' vision. This resultant smoke layer near the ceiling makes it difficult to locate the nearest exit to escape.

As stated previously, exit sign performance is ensured by independent laboratory certification where equipment is verified as performing to required specifications. However,

testing conditions do not resemble actual conditions when an exit sign is needed most—such as with no lighting and smoke present, which calls into question the effectiveness of the current certification process and code requirements. Researchers have suggested red font exit signs are not optimal and additional research is needed to determine color and type (Rea, Clark, & Ouellette, 1985).

Advances in lighting technology require improvements in life safety requirements. This researcher predicts future exit sign and way-finding technology will integrate optimal color selection and flashing into the next generation of exit signs. The researcher predicts these improvements will increase our response times, especially when needed during no light and smoke conditions.

Purpose of the Study

The human dark-adapted vision responds differently to colors in the dark as compared to the day-time. So, how humans respond to the specific wavelengths of light is of particular interest. The exit sign font colors red, green, and blue will be examined to determine a preference. In addition, the PL exit sign and flashing way-finding technology will be evaluated.

Loss of visibility during a fire due to smoke or power failure can impede one's escape. Therefore, another goal of this research is to experimentally evaluate the selected exit signs and new way-finding technology with special attention given to no light and smoke conditions.

Many options exist today for commercially available exit signs; however, current technological advances have not been studied overall. Consequently, this study will account for a newly available exit technology.

The overall goal of this study is to examine and evaluate three exit sign colors (red, green, and blue), one PL exit sign, and a way-finding flashing technology installed around the door jamb.

The luminance values and the observers' preference for each these five exit types were examined under a total of four conditions (lights and no lights and no smoke and smoke).

Objective data is critical for informed decisions regarding human behavior and survival during an emergency or fire. The data collected was used to contribute to our collective knowledge as safety researchers. It is anticipated the research results and collected data will lead to overall improvements in Life Safety technology, fire policy, and technology certification.

Research Questions

The research questions posed by this study include:

1. Which exit sign experimentally has the highest level of luminance under each of the four investigated conditions?
2. Which exit sign experimentally has the highest luminance contrast under each of the four investigated conditions?
3. Which exit sign type is preferred under the combination of ambient lighting and obscurity across all four investigated conditions?
4. Which exit sign type is preferred overall regardless of conditions?
5. Is there an association between participants' exit sign preferences and their genders?
6. Will exit sign luminance levels correspond to the observers' exit sign preference across all four investigated conditions?

Hypotheses

A set of hypotheses and experimental data has been developed to answer the research questions as the following:

1. Luminance Level

The luminance level of each exit sign was measured three times across all four investigated conditions to determine the arithmetic mean. The luminance level data will be recorded as descriptive statistics.

2. Luminance Contrast Level

The luminance contrast level of each exit sign was measured three times across all four investigated conditions to determine the arithmetic mean. The luminance contrast level data will be recorded as descriptive statistics.

3. Observer's Exit Sign Preference (Lighting and Obscurity)

Under each of the four investigated conditions, the following hypotheses were postulated:

H₀: There is no significant difference between the observer's overall preferences of exit signs across all four conditions.

H₁: There is a significant difference between the observer's overall preferences of exit signs across all four conditions.

4. Observer's Overall Preference

H₀: There is no significant difference between the observer's overall preferences of exit signs regardless of the conditions.

H₁: There is a significant difference between the observer's overall preferences of exit signs regardless of the condition.

5. Gender

H₀: There is no association between gender and participants' perceived perception regarding the exit signs.

H₁: There is an association between gender and participants' perceived perception regarding the exit signs.

6. Luminance Level and Observer's Preference

H₀: There is no significant difference between the exit signs' average luminance level across all conditions and the observer's preference.

H₁: There is a significant difference between the exit signs' average luminance level across all conditions and the observer's preference.

Definition of Terms

The definition of terms found throughout the study is listed below:

Candela/meter² or cd/m^2 : the international unit that determines the power emitted from a specific source within a known angle. This unit is usually associated with the luminance measurement as the intensity of light emitted from a source as luminous intensity per unit area of light travelling in a given direction.

Chevron: the directional arrows located on either side of an exit sign. The chevron may be indicating a left or a right turn on the escape route via < for left or > for right. This chevron marking is vital in determining an occupant's escape route.

Color-blindness: vision color deficiency when an individual is unable to differentiate the colors of red, green, or blue, or a mix of these colors. Most color-blind problems are genetic and are usually present at birth. The most commonly used Ishihara color blindness test consisting of

colored dotted plates with colored dotted numbers or symbols is frequently used to determine the red-green color deficiency.

Consensus Standards: the specific standards agreed upon by the Standard's members, usually reflecting academic, legal, professional, manufacturing, and related parties interested in standard development, implementations, and revision. The varied membership contributes to all parties with a related interest being represented in common language and standards development.

Common safety consensus standards include; NFPA, NEC, ANSI, etc.

Deuteranopia: one of the two most common conditions of color-blindness. In deuteranopia, one is less sensitive to green light. The deutan color vision deficiency is the most common color blindness and is found in approximately 5% of the male population.

Electroluminescent or EL: the high frequency discharge through a gas or phosphor-coated surface illuminating the sign's background or font. Electroluminescent exit signs are noted for being more efficient than LED exit signs.

Emergency Exit: designated doorway out of a building, vehicle, tunnel, sea vessel, or aircraft. Designated exits are required by code for quick evacuation during emergencies such as fire or power failure. When alternate exits are designated, emergency exits may be blocked or cut-off from fire, while an alternative emergency exit is provided.

Escape lighting: any of the lighting or related technology present along an escape route used to increase visibility during fire conditions or power failures.

Escape route: the quickest and safest route used during an emergency. Usually required to be designed or designated per code requirements.

Exit sign: sign containing the wording or symbols to designate an emergency exit, or escape route. This sign is required by code and regulations. Exit signs may be illuminated by photoluminescent materials, electric sources, batteries, or tritium.

Externally illuminated: exit sign having the source of illumination from outside the unit or a sign legend that is illuminated. Externally illuminated signs shall be illuminated by not less than 54 lux (5 foot-candles) at the illuminated surface and shall have a luminous contrast ratio of not less than 0.5. Some exit signs are illuminated from ambient lighting and can be powered by a back-up circuit in the event of an emergency.

Feet (ft): the US customary and imperial unit of length. Research results are presented as feet. Previous research literature was converted from meters and presented as feet. The conversion is 1 foot = .3048 meters or 3.2808 meters to 1 foot.

Incandescent: light bulb in which a wire filament is heated to produce luminance. This type of light bulb was used with earlier exit signs.

Internally illuminated: exit sign or way-finding technology having the illumination source contained within the unit. For example, exit signs that are powered by alternating current, batteries, capacitors, or radioluminescence (tritium-sourced).

International Organization for Standardization: an independent, non-governmental organization consisting of national standards groups found world-wide with representatives working for agreed upon voluntary international standards.

Light-emitting Capacitor or LEC: the LEC lamp emits photons when the electroluminescent polymer is charged electrically and produces light. This technology is used for exit signs. No heat or ultraviolet radiation is produced by LEC lights.

Light-emitting Diode or LED: low voltage is supplied to a semiconductor material to produce visible light. This light source uses semiconductors and electroluminescence and is capable of producing white light or other colors in the color spectrum.

Luminance: the measurement of the amount of light emitted from, passing through, or reflected from a particular surface from a solid angle, or the luminous power concentration perceived by the human eye. Luminance indicates the intensity of light emitted from a source as luminous intensity per unit area of light travelling in a given direction.

For exit signs, luminance will quantify the brightness of the sign in one of the common units for luminance. Candela/square meter (cd/m^2) is the SI unit for luminance. Foot-lambert (fL) is the U.S. unit. 1 foot-lambert (fL) equals $1/\pi$ candela/square foot, or $3.426 \text{ cd}/\text{m}^2$.

Luminance contrast: measures an object's relative brightness compared to its background on a scale of zero to one with the nearer to one being more visible. UL 924 references luminance contrast as the contrast between the exit sign letters or picture and the rest of the sign.

National Recognized Testing Laboratory (NRTL): OSHA term used to describe the third-party organizations capable of providing testing and certification of any products described within the OSHA regulations. Testing and validation is generally performed within the U.S. consensus standards or U.S. standards organizations such as NFPA, UL, or ASTM.

National Institute of Standard and Technology (NIST): founded in 1901 as the National Bureau of Standards to standardize weights and measures. Operating under the U.S.'s Department of Commerce, in 1988 the organization's name was changed to the National Institute of Standard and Technology. NIST continues to function as a measurement standards laboratory seeking to promote the U.S.'s innovation and competitiveness.

Obscurity: a measure of legibility of an exit sign or difficulty in recognizing the exit sign due to smoke. There is no known standard to effectively evaluate exit signs with known smoke concentrations. Smoke concentrations from fire produce widely variable conditions depending on materials present, temperature, air velocity, etc.

Occupational Safety and Health Administration (OSHA): formed in 1971 under the U.S. Department of Labor to promote the health and safety of employees in the 50 states and related territories. Employers are required to comply with specific regulations, while employees are required to comply with their employer's safety rules, which may be stricter than OSHA's regulations.

Organic Light Emitting Diode (OLED): a newer lighting technology found in exit signs. A light-emitting diode where an emissive electroluminescent layer consists of an organic compound and produces light when electrical current is applied. Either fluorescence or phosphorescence is utilized to produce light.

Path-lighting: Life Safety Code requires Emergency or escape lighting to emit one foot candle of light at any point in the building and 0.1 foot candle of light along the emergency exit path at floor level for buildings. Different path-lighting requirements exist for airplanes, sea vessels, and buildings.

Photoluminescence or PL: specific luminescence produced by phosphor excitation from a known source such as the sun or other light source.

Photoluminescent materials or PLM: any of the signs or markings containing photoluminescence as their source of illumination. Examples include: exit signs, hand-rail markings, stair markings, and related markings designed to improve visibility and aid way-

finding. Usually refers to the materials in which the phosphor surface is excited by photons and released as visible light. Exit signs require a minimum charging illumination to continually illuminate during darkness or low-light conditions.

Photometer: an instrument, usually portable, capable of measuring visible light. Photometers are commonly used to measure various types of light such as luminance intensity, luminance contrast, and luminous flux. Exit sign compliance in the U.S. requires specific testing methods with the UL 924 Standard for Safety Emergency Lighting and Power Equipment.

Photopic Vision: the range of human vision during the day where the cones are more sensitive to light than the rods and easily adapt to changing light levels. The cone's sensitivity adjusts toward the longer wavelengths of light. Overall, the rods are responsible for red, green, and blue color sensitivity and produce the high resolution vision.

Protanopic: one of the two most common conditions of color-deficiency affected by limited functioning red cone or protan where one is less sensitive to red light. The color red appears as black and is thought to affect approximately one percent of males.

Psychonomics: word origin is "the science of laws of the mind" related to the discipline of scientists concerned with how humans think and interact as related to their internal and external environment. Psychonomics is the field aligned with the Psychonomic Society and is an approach to psychology related to experimental psychologists.

Radioluminescent: the luminescence excitation created by the impact of radioactive particles interacting with phosphor material. Radioluminescent exit signs are most commonly associated with tritium or H^3 . Radioluminescent exit signs are traditionally used in locations where and electrical source was unavailable or unreliable. Manufacturers have listed a 20-year life span for

radioluminescent exit signs, and each unit is required to be marked with an expiration date. Tritium exit signs have special disposal and handling requirements under the U.S. Nuclear Regulatory Committee.

Scotopic Vision: the range of human vision where the rods are more sensitive than the cones. In darkness, the rod sensitivity adjusts toward shorter wavelengths of light. Overall, the rods are not sensitive to color but do detect motion well.

Strobe light: also known as a strobe, this is when a light flashes at a regular frequency and intensity, typically between one to two hertz or one to two flashes per second.

Tritium: the radioactive hydrogen isotope H^3 containing one proton and two neutrons with three times the mass of hydrogen. Tritium is commonly used to illuminate exit signs in locations without electricity.

Visual acuity: a common vision test to measure one's ability to discriminate and discern letters or numbers at defined intervals in accordance with the American Optometric Association. The Snellen chart test is commonly used in the US; while in European-based studies, the visual acuity test is referred to as the Landolt test. Either test may be performed to determine visual acuity. A visual acuity test is normally required to participate in observational studies where visual preferences are denoted, especially when the readability and visibility of signs to observers is being tested.

Way-finding: the cognitive and physical process utilized to locate, follow, or navigate a path through and to a known location. Usually, way-finding is thought of as the physical design, formation, or related components of a system in place to assist and guide humans through their

environment. Way-finding is commonly associated with the evacuation maps, symbols, or technology designating escape routes to safety.

Assumptions

This research has the following assumptions:

1. All participants fully comprehend each question.
2. Participants respond to questions and ratings honestly and to the best of their abilities to reflect their true perceptions.
3. Participants are unaware of the intended methodologies and will not intentionally bias any of their responses.
4. The survey instrument used in this study includes ratings that accurately measure the perception of visibility of observers during the psychonomic phase of evaluating exit signs under the conditions of lighting and obscurity.
5. The observers participating and rating exit signs during the psychonomic phase are representative of the general public viewing exit signs.

Limitations

This research has the following limitations:

1. The participants in this study were limited to visitors, students, faculty, staff, and alumni (18 years and older) located at Wright State University's main campus located in Dayton, Ohio.
2. There were different participants in each group with no participant being in more than one group.
3. Research parameters were inherently constrained and limited by the researchers' design to simulate field conditions.

4. This study's participants did not participate in life-threatening or actual emergency conditions representing worst-case fire scenarios with smoke or related emergencies due to obvious ethical and welfare concerns.
5. The perception survey was only available in English. English, as a second language, or non-English speaking participants may have had difficulty fully comprehending directions. Otherwise, participants were asked if they could read and write and to ask for assistance on the survey if they had any questions.

Delimitations

The following delimitations have been identified:

1. The data collected was delimited to visitors, students, staff, faculty, and alumni of a Mid-western university campus located in Dayton, Ohio.
2. The data collected was delimited to the participants with good visual acuity and no color-blindness within selected study participants.
3. The research was delimited to the current exit sign and way-finding equipment commercially available.
4. The photometric testing of luminance levels was conducted in an underground tunnel beneath the Wright State University campus to simulate escape routes commonly found throughout the campus.

Summary

The purpose of this research was to determine if there is a significant photometric difference between current exit signs and related way-finding technology. Specifically, a red LED, a green LED, a blue LED, a PLM, and a way-finding flashing LED were evaluated. This

study investigated how an observer's preferences correlate to the exit sign photometric values under lighting conditions of ambient light and no light, and obscuration conditions of smoke and no smoke. These conditions are referred to as #1 lights on-no smoke, #2 lights on-smoke, #3 lights off-no smoke, and #4 lights off-smoke.

Luminance levels and luminance contrast levels were recorded to establish a photometric baseline for all five exit sign categories for each of the four investigated conditions.

In addition, observers were asked to select their overall exit sign preference regardless of the investigated conditions.

This study examined the association between the participant's exit sign preferences and his/her gender. The research question postured, will gender be a determinant in the observer's preferences across all the conditions or will the human spectral efficiency be the same for male and female?

Of particular interest is the performance of exit signs with smoke when egress to safety is more important given the danger of heat and toxic or irritating smoke. Although occurring less frequently, the most important condition is no power with a fire (with smoke). This condition is known as lights off and smoke.

Specifically, this study examined the human preference for exit signs under specific conditions to help verify compliance with existing regulations may not be adequate for those trying to escape during an actual emergency or fire. This study seeks to evaluate new way-finding technology not previously examined. The flashing way-finding technology presents the door perimeter and floor edge as an outline of the exit and does not rely on the traditional exit sign placement to inform occupants of the exit location.

CHAPTER TWO

LITERATURE REVIEW

Introduction

A review of the literature has been conducted to determine the history related to exit signs and, specifically, whether prior research has been conducted on exit sign performance under the proposed conditions. Of particular interest is exit sign performance under the no power with smoke conditions. This review provides the logical reason and general approach for the research design. Knowledge gained from the review aided in the formulation of the research questions and hypotheses.

Research into exit signs and way-finding technology has been conducted for over 60 years. This literature review references research going back to the 1960s to provide a broad overview of the quantitative research into exit signs and way-finding technology in buildings, non-buildings, and virtual reality.

Building-related research involves hotels, retail stores, apartment building evacuation, and underground shopping malls. Non-building research includes Navy and maritime evacuations, aircraft lighting and signage, rail passenger car emergency signage, train and subway train evacuation, road tunnel evacuation, smoke concentration standards, mobility impaired evacuees, photoluminescent materials, psychonomics, way-finding, and computer modeling.

The lessons learned by fire and safety professionals from the catastrophic building fires during the early 1900s in the U.S. resulted in the development or revision of fire safety standards for commercial buildings (Lista, 1995; Sutherland, 2011; & Teague, 1991). In addition to

building evacuation experiments, there is a history of evacuation-related research conducted on Navy ships, trains, cruise ships, aircraft, and within highway tunnels. From the original simple exit signs to the wide variety of exit signs available today, all research demonstrates that exit signs are integral to escape from buildings under emergency conditions.

To improve human survivability during building fires, researchers focused on how to mobilize occupants quickly during the 20th century, and many resultant theories have followed (Kuligowski, 2016). Many individuals have dedicated their careers to improving human performance during a fire or emergency. Others have specifically contributed to the body of knowledge regarding exit sign visibility and appearance in the pursuit of saving lives.

Quantitative Research

The earliest research efforts into exit sign visibility evaluated exit signs compared to the resultant smoke from various building materials in a smoke test structure. Bono and Breed (1966) used a photoelectric cell five feet from the floor to record exit sign visibility. The test structure measured 32 feet long, 12 feet wide and 14 feet high and was constructed of fire resistant materials (Bono & Breed, 1966). As materials burned in an adjacent furnace, the furnace's exhaust stack entered the smoke test structure where three rows and two columns of exit signs were mounted. The photoelectric meter used by Bono and Breed (1966) evaluated the middle exit signs' visibility on a scale from zero to five, where zero indicated entirely unobscured and five indicated totally obscured. The number scale corresponded to percent density. Number one represented 20% density going up to number 5 representing 100% density. Observers also recorded the visibility of the middle row of exit signs without any other luminance in the room. Both visual and photographic measurements were recorded. Traditional

building materials were being replaced with synthetic and plastic compositions, and researchers noted differences in smoke density between these materials. Bono and Breed concluded that building smoke would quickly obscure exit signs, and exit signs were not visible with the resultant black smoke, especially with the increased smoke density observed from the newly developed plastic building materials being introduced at the time. Their research suggested room volume, airflow, and ventilation all affect smoke density and the time required to obscure exit signs. Bono and Breed (1966) did not provide the number of subjects or photometric measurements. Although the researchers commented that there was no discernable difference between exit sign colors red and green.

Research into the minimum exit sign font size and maximum viewing distance variables for visibility did not focus on real fire incidents, though many researchers evaluated exit sign visibility in both clear and obscured conditions (Schooley & Reagan, 1980). Schooley and Reagan (1980) compared visual angle, visual acuity, and background luminance levels. Their conclusions resulted in identifying five areas that should be used to determine exit sign legibility:

1. Font height, width, and spacing
2. Font luminance and background luminance
3. Viewing distance to sign
4. Luminance contrast throughout this distance
5. Age and visual acuity of observers

Schooley and Reagan (1980) evaluated early exit signs using incandescent bulbs and a tritium-powered sign. Five human subjects entered a viewing tunnel (400 feet long, 12 feet high, and 10 feet wide) illuminated at various luminance levels and obscurity conditions. A smoke

candle was used to obscure the viewing area. In the clear condition, 225 feet was the maximum visibility distance, and the maximum legibility distance was 125 feet. Smoke concentrations in the viewing tunnel reduced legibility to 40 feet. The researchers Schooley and Reagan (1980) found the tritium-powered sign performed favorably compared to the incandescent bulb signs. Schooley and Reagan (1980) commented that the smoke candle did not provide consistent smoke concentrations and ultimately contributed to greater variability during the research. Also, one observer was reported as being protanopic, or having difficulty seeing longer wavelength light, and would have had difficulty seeing red-lettered exit signs. Another stated goal of this research was to reduce electrical consumption and promote energy conservation (Schooley & Reagan, 1980). The researchers found increasing luminance did not improve legibility and, above a certain luminance output, legibility seemed to actually decrease.

Signage symbols and the need for exit sign standardization provided the impetus to test preferences of observers (Lerner, 1981). A density filter on the slide projector was used to replicate smoke conditions. Researchers commented that the small sample of symbols produced a discrimination bias because observers could quickly recall previous symbols.

Lerner and Collins (1983) studied symbol recognition with smoke concentrations to determine visibility thresholds. Smoke concentrations were simulated using density filters over a sign's light. The experiment consisted of 108 symbols and 42 observers evaluating their preferences once they were familiarized with nine random symbols from a set of 18. Of the 108 total symbols, 18 were exit-type symbols. Symbol familiarity and non-familiarity amongst observers can account for some variability. Researchers concluded that viewing degradation increased symbol recognition errors (Lerner & Collins, 1983). Furthermore, their research noted

observers widely recognized the person at the open door symbol as an exit, and they recommended fire officials should adopt the symbol as such. Lerner and Collins (1983) also recommended the word EXIT combined with the symbol should be evaluated for use in highway transportation specifications.

Rea, Clark, and Ouellete (1985) performed a comprehensive review of exit signs with clear visibility and visibility obstructed by smoke within a viewing chamber. These researchers examined sign type effectiveness within the viewing chamber while human subjects within a viewing booth recorded their observations. Sign type, visibility, detectability, and readability were the research criteria. Fluorescent lighting five feet high from the floor of the booth provided ambient lighting of seventy-five lux within the viewing booth. For this study, sixteen human subjects remained seated behind a window in the viewing booth and recorded if the exit sign seventeen feet away was detectable and readable. Then researchers added smoke to the booth, and observers recorded detectability and readability to determine critical smoke density. The research and analysis of Rea et al. (1985) determined that to obscure exit signs, higher concentrations of smoke were required. Or, conversely, the greater the sign luminance, the more visible exit signs were in higher smoke-densities. Ambient illumination from the fluorescent lighting has been observed to decrease sign visibility overall. For some exit signs evaluated in the Rea et al. (1985) study, this decreased visibility due to illumination was much greater for some than for others. When the fluorescent lighting was turned off, the signs became more visible from the reduction in scattered light. Rea et al. (1985) concluded that the readability of low contrast exit signs was greatly reduced compared to high contrast exit signs. Rea et al.

(1985) also contended that a sign with higher luminance will be recognized even if high smoke density decreases readability.

Irritating smoke can also decrease internally illuminated exit sign visibility and resultant walking speed (Jin & Yamada, 1985). In a small room measuring 16 feet by 13 feet, Jin and Yamada (1985) evaluated 12 test subjects on their visual acuity with a Landolt's ring test chart while the subjects were experiencing highly irritating smoke. Eye blink rate was recorded as an indicator of eye irritation. This research established a linear relationship between visibility at sign obscuration threshold and smoke concentration. Jin and Yamada (1985) also used a corridor 65 feet in length with white and black smoke to determine the visibility of exit signs of 2,000 cd/m^2 and 500 cd/m^2 . Test subjects reduced their walking speed overall by 33% due to smoke concentration. In both experiments, smoke concentrations were found to decrease exit sign visibility. Smoke irritation was discovered to decrease exit sign visibility. Test subjects experiencing the irritating physical effects of smoke had greatly reduced overall visibility.

In another study conducted by Jouellette (1988), 12 human subjects observed three trans-illuminated lettering on opaque exit signs. Smoke concentrations with and without ambient illumination were compared to exit sign lettering and background. Observers 6 ½ feet from the exit sign adjusted the brightness of the sign. Joulette (1988) utilized emergency lighting luminance of one half lux in this research to represent the minimum emergency lighting conditions. Emergency lighting required during an emergency decreased exit sign readability consistent with the study conducted by Rea et al. (1985) that showed resultant scattered light from ambient lighting sources decreases sign readability.

The National Institute of Standards and Technology also reviewed exit signs in smoke and clear conditions with varied luminance levels noted (Collins et al., 1993). A total of 12 exit signs consisting of incandescent, fluorescent, and electroluminescent varieties were evaluated. Results showed exit signs with greater than 70 cd/m² average luminance required greater smoke concentrations to become obscured. Higher luminance levels were found to correspond to greater visibility, contradicting several earlier findings. Collins et al. (1993) showed their study and conclusion contradict the earlier findings of Schooley and Reagan (1980).

In another study evaluating exit sign colors, Wong and Lo (2007) found observers preferred green exit signs when English and Chinese words for EXIT with directional indicators in red and green colors were provided for evaluation. Test criteria for the 30 observers in Wong and Lo's (2007) study included graphics, colors, luminance levels, and age of the observer. Wong and Lo (2007) commented that observers preferred two mounted exit signs instead of the traditional one sign as well as for green-colored exit signs.

Navy and Maritime Evacuation and Signage

Edmondo and Macey (1968) formulated the early foundation for exit signs and emergency egress when they evaluated the effectiveness of lighting and directional signs aboard Navy ships. They reviewed the photometric output of various light sources and required human subjects to escape a smoke-filled maze using these same light sources. A total of 15 observers evaluated light sources in smoke. A quartz-iodine light was determined to be the most visible, even though it was not approved by the U.S. Navy specifications—then the U.S. Navy battle lantern. After selecting the most visible light source, subjects navigated a smoke-field maze using markers and lights. The slowest times and greatest navigation errors occurred on the path

with no markers. The subjects using the Navy battle lantern had the quickest times to exit and the fewest course errors. The retro-reflective tape on ladders and hatches was recommended to improve egress. Path arrows were used to direct subjects through the escape route and were thought to be an improvement. The researchers concluded that the retro-reflective tape mounted on a ship's hatchways and ladders in conjunction with the Navy battle lantern would improve pathway visibility for Navy personnel.

The 1974 International Convention for Safety of Life at Sea (SOLAS) Maritime Convention adopted the International Maritime Organization (IMO) resolution calling for low-location lighting on passenger ships, and independent research, shows low-level lighting systems aid overall response times (Heskestad, 1999).

The impetus for low-level lighting systems was provided by the *Scandinavian Star* fire where 159 passengers perished aboard the ferry elicited an urgent response to improve escape during emergencies at sea. Overall, several Norwegian researchers conducted five separate large-scale experiments with over 300 human subjects total (Heskestad, 1999). Research criteria focused on human movement speed and escape path success as a probability. The International Organization for Standardization (ISO) maintains specifications for ISO 15370 Ships and marine technology - Low-location lighting (LLL) on passenger ships for use and demarcation on board passenger ships with greater than 36 passengers. This ISO standard was developed as a result of several maritime disasters where existing emergency lighting and signage proved to be inadequate (Simpson, 1996).

Aircraft Emergency Lighting and Signage

In 1979, the U.S. Department of Transportation (DOT) funded research to focus on aircraft signage readability in smoke-filled aircraft (Rasmussen, Garner, Blethrow, & Lowrey, 1979). In this DOT-funded research, human subjects viewed exit signs from a defined distance of 76 inches with various background luminance levels and smoke obscurity levels. Background luminance levels from 31 cd/m² to 158 cd/m² were utilized with the Rasmussen et al. (1979) study concluding that the lowest background luminance level required only a slight smoke density for the signage to become obscured. The three highest background luminance levels required similar levels of smoke density to become obscured. These levels, while similar to each other, were significantly higher than those required to obscure the lowest background luminance level. Research results show estimated smoke concentrations could reduce exit sign luminance and visibility from three to eleven percent of clear air without smoke. Rasmussen et al. (1979) examined sign width and height as a condition of visibility. Subjects evaluated signs based on width and height, and the findings of this study showed that larger signs required greater smoke densities compared to smaller signs to become obscured. Researchers suggested increasing the sign size above a certain threshold did not readily increase the sign's readability. The study confirmed that the Federal Aviation Administration, or FAA, sign recommendation of 89 cd/m² would allow for the visibility of signs in smoke densities between three to three and half total optical density.

Overall, aircraft cabin volumes are reduced and can rapidly fill with smoke. The location of lighting and emergency signage is critical to passenger escape times. Aircraft emergency lighting and exit signs mounted near the ceiling and near the floor were evaluated with smoke

concentrations to evaluate the escape times between the locations (Chesterfield, Rasmussen, & Dillon, 1981). The experiment used 220 human subjects in a cabin simulator for a series of six evacuations. The total evacuation times were recorded as the average evacuation rate for ceiling lights, aisle lights, and cabin smoke. Chesterfield et al. (1981) established that evacuation times are reduced with emergency lighting and exit signs located near the floor. These researchers also commented the use of actual smoke was chosen over filtered goggles to simulate smoke. Their reasoning was due to the fact that the smoke layer stratification created by actual smoke is not accurately replicated by the filtered goggles.

High temperatures and heavy smoke concentrations from aircraft fuel and interior materials create special requirements for aircraft signage and lighting. Wide-body aircraft emergency interior lighting was evaluated in a fire environment to determine effectiveness (Demaree, 1982). Research results demonstrated significant smoke stratification results quickly, and emergency lighting visibility in the top third of the cabin is greatly reduced (Demaree, 1982). Ceiling lighting was obscured in 68 seconds, whereas floor lighting became obscured after 158 seconds with the same smoke concentrations. Lower smoke concentrations and reduced cabin temperatures were confirmed in the lower third of the cabin. Armrest lighting had greater visibility than the ceiling and bulkhead lighting. Demaree (1982) demonstrated lighting should be placed at or below the passenger seat armrests to increase visibility and survivability. This research concluded that maximum visibility would be obtained by installing floor-mounted electroluminescent lighting.

Railroad Passenger Car Emergency Signage

The American Public Transportation Association (APTA) provided guidance to the Federal Railroad Administration recommending PLM signs and markings following a passenger rail crash in 1996. The crash investigation revealed that when passenger rail cars are disconnected, the exit signs and related markings are not illuminated due to the lighting failure from the resultant power loss (Force, 2007). Exit signs and related markings are required for passengers, train personnel, and emergency responders.

Currently, the Standard for Emergency Signage for Egress and Access of Passenger Rail Equipment requires PLM markings and exit signs (Force, 2007). In addition, the Standard for Low-Location Exit Path Marking for passenger rail cars requires the low-location emergency path markings (LLEPM) to help passengers locate exits during low-light conditions, darkness or when smoke obscures overhead lighting.

Train and Subway Train Station Evacuation

Shiwakoti, Tay, Stasinopoulos, and Woolley (2016) analyzed train passenger knowledge of emergency exit signs, evacuation maps, and assembly areas in a Melbourne, Australia train station. Train passengers were asked to complete questionnaires to determine their overall knowledge of and perceptions for a safe and effective evacuation. Questionnaires totaling 1,127 were received and analyzed. Remarkably, 43% of the passengers did not know the exit locations, 59% did not know where evacuation maps were located, and 67% did not know where the assembly areas were located.

Additionally, Yoon, Lee, and Yee (2013) evaluated subway stations underground and found that these stations shown presented unique fire and emergency conditions. In Japan, 292

human subjects evacuated a large subway station when a simulated fire aboard the subway train occurred (Yoon et al., 2013). When the subway train door opened, the evacuation time started and total evacuation times were recorded. Video cameras were installed throughout the subway station to record the test subjects' activities. Yoon et al. (2013) found female test subjects were 23% slower in evacuating on average as compared to males. The test subjects without prior information on escape routes were 18% slower overall. It seems if walking with others you had slower evacuation times as, passengers with companions were reported to be 29% slower than solo passengers.

Road Tunnel Evacuation

Highway tunnel fires and emergencies create an especially hazardous environment for drivers. In Sweden, 29 human subjects drove one half mile into the Göta tunnel and encountered a simulated accident with pre-recorded information boards, audible alarms, and a flashing green strobe light used to determine the drivers' exit decision-making process (Nilsson, Johansson, & Frantzich, 2009). The test subjects' activities were recorded by 15 video cameras with views of the exits, vehicles, and drivers. Evacuation times started when the test subjects stopped their vehicles. In addition, questionnaires regarding the emotional process they went through during the test were completed by each test subject. In this study an acoustic aid was evaluated in addition to signage and messaging. This acoustic signal was preferred over the pre-recorded message due to the participant's difficulty in verbal comprehension of the pre-recorded message. The green flashing light may be helpful, but other test subjects driving did not notice the lights at the exits. The researchers Nilsson et al. (2009) discovered other drivers have a significant impact and influence on other drivers when seeking refuge.

In the U.S., Higgins, Carlson, Rozyckie, and Miles (2016) performed similar research in a simulated tunnel environment using a large pole barn building and simulated smoke. The goal was to determine the most effective messaging and delivery methods, optimal signage, and technology. The dynamic message sign was used to communicate emergency information to drivers while different signage and pathway markings were provided. Flashing and strobing pathway lighting and audio beacons were preferred by participants. The visibility distance of the PLM signage was less than the internally illuminated signage. Smoke obscuration greatly reduced participants' visibility across all sign technologies. Higgins et al. (2016) noted that participants did not have difficulty recognizing the word "EXIT," directional arrow, and distance from exit in feet. In addition to the traditional exit signs, the running man pictogram evaluated and was correctly, or partially, understood by the majority of participants.

Retail Store and Apartment Building Evacuation

Retail stores provided researchers with actual evacuation performance metrics for employees and customers (Shields & Boyce, 2000). No prior knowledge was provided to staff of four retail stores in the United Kingdom to assess real-world conditions during an evacuation. After the evacuation alarm sounded, approximately 50 closed-circuit television cameras (CCTV) were utilized to study test subjects' (employees and customers) movements. Test subjects were provided questionnaires to complete after the test. Many confounding variables were present in this experiment; however, Shields and Boyce (2000) concluded that staff training is paramount to successful evacuations.

The evacuation times for approximately 150 occupants within four apartment buildings was recorded during the summer and fall months in 1993 for each building (Proulx, 1995). The

apartment buildings were each six to seven stories high, were erected in the 1980s, and were chosen to determine building occupant evacuation times and movement. The researcher communicated with limited mobility occupants prior to the evacuation to determine their actual participation abilities. Then, one week prior to the evacuation, written notices were provided to all of the buildings' occupants. In two of the four apartment buildings, 25% of occupants reported an inability to hear the alarm. Due to their difficulty hearing the alarm, average occupant time to evacuate was nine minutes. In the other buildings where the alarm was heard, evacuation times were under three minutes. The researcher Proulx (1995) observed limited mobility occupants went to their balcony; but, could not hear the rescue personnel knocking at their door.

Underground Shopping Mall

Competing signs and lighting can be a problem for reading exit signs, and in Japan three different exit sign sizes were used to determine conspicuousness of emergency exit signs (Jin, Yamada, Kawai, & Takahashi, 1991). In the first study conducted by Jin et al. (1991), 33 participants in an underground shopping mall with competing ambient lighting sources were asked to evaluate exit sign conspicuousness from 32 feet to 197 feet at six pre-determined distances. In a second study, the research participants used the same pre-determined distances and observed a flashing exit sign compared to a non-flashing exit sign. These observations were made with normal and varying ambient lighting levels. Jin et al. (1991) concluded that exit sign conspicuity is increased by larger exit sign size, increased luminance, and flashing.

Flashing Light Conspicuity

Early research on the effect of flashing show conspicuity increases when compared to similar luminance sources. Gerathewohl (1957) designed a study to look more closely at flashing. The study involved the observer's response time between flash frequencies, flash durations, and brightness contrasts. Observers viewed 120 signals in various patterns and their mean time between test signal appearances was recorded using a push button. Upon conclusion of the study, Gerathewohl (1957) observed a significance between contrast and frequency. The researcher's data demonstrated as brightness contrast increases, conspicuity increases. At low contrast, conspicuity increases as flash frequency increases.

Although this early study with flashing was performed with now obsolete lighting technology, the observations and principles of flashing should still be accurate today when determining whether electroluminescent flashing technology is preferred over traditional exit signs.

Smoke Density Standardization and Smoke Simulation Software

The ability to recognize an exit sign is greatly reduced, if not eliminated entirely, with enough smoke concentration present to obscure the signage. It is well established in literature that smoke can easily obscure exit signs with the expected resultant visibility degradation (Boyce, 1993). Therefore, it is critically important to replicate and quantify smoke conditions in research environments and during testing conditions. A physical model is not presently deployed and applied to testing and validation. Robust performance standards for testing in smoke conditions have not been applied, but would be very valuable to future research efforts.

Bierman, Raffucci, and Boyce (1996) recognized this need and concentrated their efforts at exit sign degradation in smoke while attempting to standardize smoke generation characteristics and variability. They developed and validated the foundation to verify two other existing models used for general imaging in the atmosphere. Exit sign visibility was recorded with a photometer while smoke was generated within a chamber. A formula was then generated using particle diameter, absorption, and scatter coefficient of smoke. It was suggested that the validity of their methodology to measure sign luminance is dependent upon the sign format and smoke density. Unfortunately, the exit sign must be the only source of illumination and therefore the test may be somewhat limited in application.

Defined smoke concentrations are required when testing exit sign visibility, and because of this validation of smoke generation technology is needed (Mulholland, Johnsson, Fernandez, & Shear, 2000). Mulholland et al. (2000) successfully developed a smoke concentration meter using a helium-neon laser. The technology and methodology were developed at the National Institute of Standard and Technology (NIST) for both small-scale and large-scale applications. The research of Mulholland et al. (2000) focused on a total mass of smoke per collection period for applications or studies in visibility reduction, smoke-detector performance, or fire-retardant chemical.

The American Society for Testing and Materials (ASTM) has developed several smoke density or obscuration test methods as well (Smith, 1979). For example, ASTM D2843-16 covers measuring smoke density from the burning or decomposition of plastics. However, none of the standards that have been referenced are specific to exit sign obscuration simulating real fire conditions. The ASTM manual describes specific smoke obscuration test methods but there is no

correlation to other test methods related to exit sign visibility performing under true field conditions specifically.

At this time, there are no physical test methods currently available to validate exit signs and related escape markings to simulate smoke during real-time fire conditions. This void needs attention to improve future research efforts. Certainly, future smoke test methods and standards could be developed and validated.

Other research has used simulation technology instead of physical smoke generation. Smoke-Sim© is the name of the software created by the Lighting Research Center of Rensselaer Polytechnic Institute (Boyce, 1993). This simulation has the potential to eliminate the variability associated with actual combustion processes used to test products or perform research under replicated smoke conditions. Smoke-Sim© and related software are designed to eliminate the need for burning materials to simulate fire conditions while reducing the human health effects from smoke inhalation during tests.

Rubini, Zhang, and Moss (2007) introduced methodology from their quantitative simulation of visibility through a smoke laden environment. Their research examined direct illumination, indirect illumination from surfaces and particle scattering. Their work resulted in a publicly available Visibility Simulation Tool (VST) to determine human perception and visibility in smoke laden environments. From their published work, their photorealistic renderings of a long corridor with illuminated exit signs in smoke and clear conditions appear to be very life like. Again, both the VST and Smoke-Sim© both provide viable alternatives for the need to replicate quantifiable and reliable smoke conditions to test Life Safety products and the human response to those conditions.

Mobility-Impaired Evacuees

Historically, there is limited exit sign-related research on mobility-impaired or visually impaired individuals. Early research demonstrated the need for greater precautions for group home residents (Jones, Van Hasselt, & Sisson, 1984). This research focused on teaching fire safety skills to blind and mildly intellectually disabled students and highlighted the additional study needed for at risk groups. Proulx and Pineau (1996) discussed limited-mobility building occupants in their earlier apartment building evacuation research and then focused on additional research to perform a comprehensive review of existing literature. This review of evacuation strategies focused on current issues, legal requirements, and strategies that should be adopted.

Rubadiri, Ndumu, and Roberts (1997) conducted research to model and predict mobility-impaired persons. An evacuation route experiment was performed with five disabled full-time students attending the University of Central Lancashire. One test subject without disabilities also participated. Observers and a video camera recorded mean evacuation times. Their data was combined to add to an earlier framework for predicting human movement and behavior (Rubadiri et al., 1997).

Color Normal and Color Deficient Observers

Research has also been conducted to determine the difference in exit sign recognition for color normal and color deficient observers (Eklund, 1999). A total of 16 human test subjects were asked to correctly identify exit sign orientation. Of the 16 test subjects, eight were pre-tested and identified as color normal, and the remaining eight were pre-tested and identified as color deficient. Testing equipment projected exit signs at one-fourth scale of their actual size with luminance contrast and background colors being controlled by the researcher. After a

practice trial run, the test subjects viewed 600 actual signs at their own pace to determine exit sign's orientation. Overall results for all observers showed that a green exit sign on a matte black background is the most recognizable configuration regardless of ambient illumination or ability to perceive color.

Visual Acuity and Visually Impaired

The majority of literature and research studies have used individuals with good visual acuity. The idea being those with good visual acuity could quickly discern and evaluate exit sign characteristics compared to visually impaired individuals. Good visual acuity in many studies was represented as being 20/40 or 20/50 measured at 20 feet with no color deficiency. The UL 924 observation visibility test method for candidate exit signs being tested uses observers with good visual acuity rated as 20/40 or better as determined by a standard eye chart (see Appendix B).

Some researchers recognized the need to include the overall population and their study included visually impaired participants (Cook, Wright, & Webber, 1999). Researchers Cook et al. (1999) reported their study performed in the United Kingdom involved thirty visually impaired individuals while recording their speed of movement under different lighting systems. The different types of emergency lighting and way-finding systems used in the study were; miniature incandescent way-finding, LED way-finding, PLM way-finding, normal overhead lighting, and overhead emergency lighting. Individuals were chosen to walk a route and low-light-sensitive video cameras captured their time. Overall, the results showed the mean walking speeds for visually impaired individuals compared to those with good visual acuity are generally

very similar. The study concluded that overall way-finding systems are preferred and found to be useful. The PLM way-finding system rated last and the normal overhead lighting rated first.

Visual Acuity Results for Americans

Recently, the National Institutes for Health (NIH) conclude when a study revealed 94% of Americans 12 years and older have good vision while 6%, or 14 million Americans, are considered visually impaired (Vitale, Cotch, & Sperduto, 2006). During this NIH study, a mobile examination vehicle obtained visual acuity results from approximately 14,000 participants between 1992 and 2002. The Snellen 20/50 line was presented first with at least four of the five symbols being required to be read correctly to advance to the next line with smaller symbols. An individual was considered visually impaired with 20/50 or worse in the better-seeing eye.

Of the 14 million visually impaired Americans, 11 million have visual impairment that can be corrected with glasses or contact lenses. The remaining three million visually impaired Americans cannot improve their vision with glasses or contact lenses.

Although no specific research involving exit signs and participants with visual impairments was located, visual acuity and our ability to see exit signs with and without prescription eyewear is an important variable. This is of particular note when considering that while an individual is sleeping and a fire occurs, their glasses or contact lenses cannot always be worn or located quickly.

Human Visibility and Color Sensitivity

Humans are thought to obtain 80% of their environmental information through their visual system (Pulat, 1997). To understand exit sign visibility, we must first characterize the mechanics of human vision as determined by the visible light segment of the electromagnetic

spectrum. The human response to this very narrow range of visible light is represented by the 380 nm (violet) to 780 nm (red) wavelengths of light on the electromagnetic scale between ultraviolet light and infrared light (Boyce, 2014). The human eye is composed of photoreceptors known as rods and cones (Pulat, 1997). These photoreceptor rods and cones absorb electromagnetic wavelength energy in this visible light range to determine human spectral sensitivity and discern colors as seen in Figure 2.

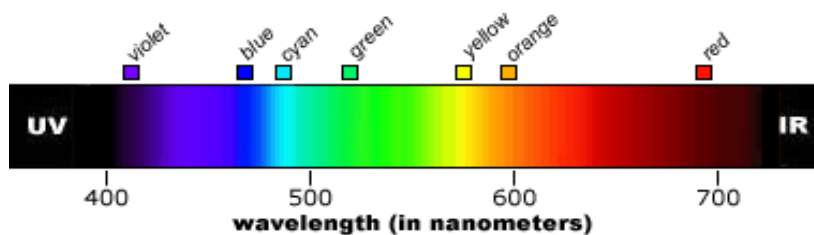


Figure 2. Electromagnetic energy spectrum showing visible light in nanometers. Adapted with permission from *Handprint*, by B. MacEvoy, 2015. Retrieved November 12, 2018 from <https://handprint.com/LS/ CVS/color.html>. Copyright 2015 by Bruce MacEvoy. Adapted with permission.

However, the human visual system response is not the same across the entire 380-800 nm of wavelengths of light on the electromagnetic visible light scale. In 1896, Max Schultze proposed the theory of duplex vision by describing vertebrate eyes having two types of photoreceptor cells with different sensitivities for dim light and bright light with color detection varying between (Ingram, Sampath, & Fain, 2016).

Therefore, brightness and the resultant colors are not perceived the same and account for the differences in the human spectral sensitivity (Pulat 1997). The cones are sensitive to color and allow humans to discern colors, and will accordingly activate to the illuminance from a standard candle reflecting upon a standard white sheet of paper. Meanwhile, the rods will

respond to luminance levels equilibrated to the illuminance resulting from sole full moon with no other sources of luminance.

The human visual system is actually contained and optimized by the luminance level received by the retina within the human eye by three distinguishable luminance ranges (Pulat, 1997). The cones are activated during the day for photopic vision or daylight vision. The rods are activated during very low illumination for scotopic or night-time vision. The range between scotopic and photopic vision is known as the mesotopic vision, where a combination of rods and cones are utilized.

Consequently, the human visual system takes advantage of the amount of daylight luminance present to differentiate colors. During the day time, the human eye maximum sensitivity is 555 nm (yellow-green), while night time vision or photopic vision has maximum eye sensitivity at 507 nm as in depicted Figure 3. This difference in maximum eye sensitivity is known as the “Purkinje shift” and is designated where the human color sensitivity varies with changing incoming light levels (Pulat, 1997, p. 85).

The Purkinje effect is attributed with the differences in the human visual system for scotopic and photopic vision. Decreased luminance levels elicit a different response at the lower wavelengths of light level as depicted by the maximum sensitivity of humans to light (555 to 507 nm) as seen in Figure 3.

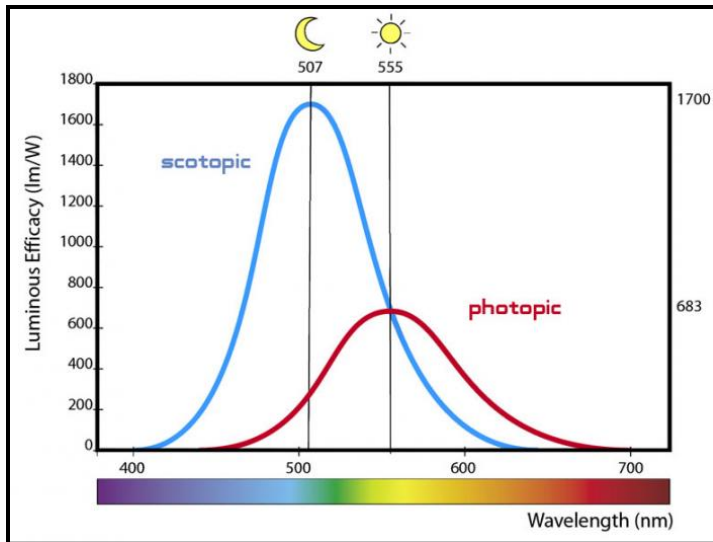


Figure 3. Luminous efficacy of scotopic and photopic vision showing peak sensitivity. Adapted from Primalence of Sweden, 2018. Retrieved June 14, 2018 from http://www.primalenceuk.com/light_vision. Copyright 2018. Adapted with permission.

This ability to perceive wavelengths of light differently at night time or in darkness was important to our survival from a human evolution perspective (Williamson & Cummins, 1987). Human survival was predicated on quickly and accurately determining threats to our existence. Different times throughout our day demanded different responses to light and movement to accurately identify threats or food. Of the photoreceptors in the human eye, the rods are more numerous than the cones and are adapted to our night-time vision, or scotopic vision.

The Young-Helmholz theory describes the cones as maintaining three types of pigments sensitive to color; red, green, and blue catching pigments (Pulat, 1997, p. 83). The red, green, and blue catching pigments within the rods and cones maintain a selective absorption of wavelength of light. This sensitivity toward the shorter wavelengths of light accounts for the perceived brightness of green leaves in the twilight. Overall less sensitive to color, the rods are more plentiful in our peripheral vision and detect motion much better - which was thought to be

essential to detect danger from movement more quickly in our periphery (Williamson & Cummins, 1987). According to Williams and Cummins (1987), this effect occurs approximately at the 555 nm wavelength of light for the human light-adapted vision and for dark-adapted vision approximately at the 507 nm wavelength. Consequently, during the daylight, human vision is most sensitive to a broader range of wavelengths. During the night, or periods of darkness, human vision is most sensitive to blue – green wavelengths. In between these two luminance levels, is region known as mesopic vision (Pulat, 1987). Here the spectrum of visible wavelength of light steadily decreases until the human vision system approaches the scotopic range. As a result, humans will perceive fewer colors as illumination levels steadily decrease as depicted below in Figure 4.

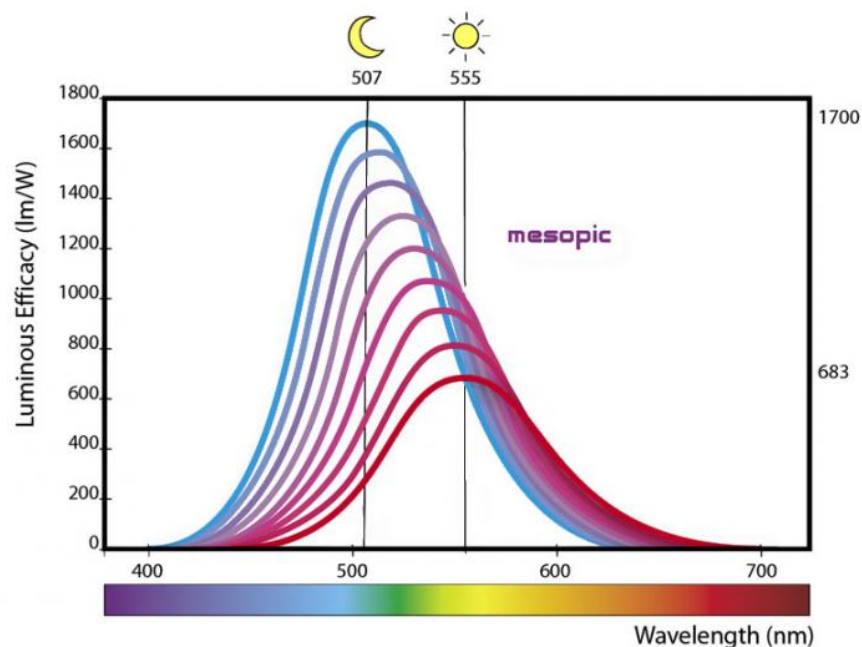


Figure 4. Wavelength of light used for mesopic and scotopic vision. Adapted from *Prismalence of Sweden*, 2018. Retrieved January 11, 2018 from http://www.prismalenceuk.com/light_vision. Copyright 2018. Adapted with permission.

The literature review revealed that exit sign visibility has been studied extensively for over 50 years. However, this complex body of research regarding how humans responded during fires in regard to optimal exit sign font color has not been clearly validated (Boyce, 2014, p. 320). As modern buildings become larger and more complex, resulting in greater human occupancies, the effectiveness of emergency exit signs and related way-finding systems becomes even more critical. Yet conflicting jurisdictional authority in the U.S. has commonly required red and green font color for exit signs.

Based on the Purkinje effect, the researcher has proposed blue-green exit sign font colors during low-light and green-yellow during the day time. The researcher has hypothesized modern exit signs and way-finding could be further improved by taking advantage of how humans perceive both color and movement during emergency conditions of no lighting. As Williams and Cummins (1987) validated human sensitivity to movement in no light conditions, could this attention to movement be enhanced by flashing exit signs?

Good visual acuity is dependent upon several factors but visual acuity is further demarcated by the photopic and scotopic regions of human vision. The scotopic region, or night vision, is weaker for red wavelength light and stronger for blue wavelength light (Williamson & Cummins, 1987). These known attributes of the human visual system are in in direct conflict with existing fire code where red font exit signs are required.

In addition, the condition of no lighting during an emergency is especially important when one considers that humans are able to adapt and change their spectral luminous efficiency. When ambient light is nominal, such as experienced during no light conditions, the optimal color

is known to be blue-green. Yet research has not validated an optimal color for a specific smoke density (Rea et al., 1985).

Could flashing way-finding technology supersede this notion of optimal color? Perhaps optimal colors are not relevant if flashing alone is preferred. Or could flashing exit signs have an optimal color? To date, research has been conducted in highway tunnels and retail settings with improved visibility being reported (Jin, Yamada, Kawai, & Takahashi, 1991; Nilsson, Johansson, & Frantzich, 2009). However, this flashing is from older style lighting technologies and newer electroluminescent technology has not been represented in current research.

Light Scattering and Absorption

The Beer-Lambert's law is applied to both liquids and smoke (Wampfler, 1966). Smoke particles scatter and absorb light and this effect is important to understand when considering the effectiveness of exit signs. This known principle will depend on the type of smoke produced. Heavy black smoke behaves differently than thin white smoke. The aerodynamic diameter of the smoke particle and the resultant concentration ultimately determine how light behaves. How light is mechanically reflected, diffused, and absorbed can be complex. However, this understanding can be simplified by looking at the combined effect of scattering and absorption known as Beer-Lambert's law (Wampfler, 1966):

$$I = I_0 e^{-Ad}$$

I = light propagating a distance d through a uniform medium

I_0 = unattenuated luminous intensity (cd) at distance d (m) equal to zero

A = absorption coefficient

Generally, the higher the luminance levels, the “brighter” the exit sign may appear in air without light scattering resulting from smoke particles. Thus, increasing luminance levels will ultimately decrease apparent luminance and exit sign visibility in smoke according Beer-Lambert’s law. Conceptually, understanding Beer-Lambert’s law can help reduce exit sign luminance equally without reducing distortion. However, researchers have suggested scattering of light may cause confusion easily when exit signs are needed during smoke conditions (Malvern, 1986).

Obscurity from smoke particles increases both scattering and absorption and makes exit sign visibility difficult (Oullette, 1988; Rea et al., 1985). Yet exit sign obscurity is difficult to quantify and convert easily from the field to the lab setting (Rubini et al., 2007). Increasing exit sign luminance does not seem to increase visibility due to scattering and absorption (Schooley & Reagan, 1980; Webber & Aizlewood, 1993).

Photoluminescent Materials

Photoluminescent materials (PLM) are made of inorganic, phosphorescent materials such as strontium aluminum. The PLM crystals are photoluminescent due to their ability to absorb light photons, store their energy, and re-emit this energy as visible light. When exposed to light, the PLM is charged, then the light source is removed, and these PLM pigments are released as luminescence or light.

PLM markings were evaluated and compared in a four-story building with favorable results (Proulx, Kyle, & Creak, 2000). Results indicated PLM exit signs perform similarly to incandescent exit signs. The researchers Proulx et al. (2000) recommended increasing PLM use

and applications due to their increased luminance for improved visibility overall. The PLM used on handrails, around doorjambes, and on stair edging is often referred to as way-finding.

Averill, Mileti, Peacock, Kuligowski, & Groner (2005) examined the evacuations resulting from the World Trade Center towers catastrophe and revealed that the addition of photoluminescent materials and way-finding in the stairwells did contribute to the occupants' safe evacuation. The installation of photoluminescent materials and way-finding was prompted by the earlier 1993 World Trade Center bombing when investigations revealed that many exit signs were dark, and path lighting back-up power was not working. Similar investigations into the World Trade Center tower evacuation provided the impetus for N.Y.C. to require PLM markings and signage (de Vries, 2006).

Ouellette (1993) observed smoke density and the charging source had a strong correlation to exit sign illumination. Internally-illuminated sourced signs observed during this research had the required visibility in the lab. However, it should be noted, building owners must be aware of the luminance levels when installing PLM or PLM exit signs, as those luminance levels and duration are related to the charging luminance available. Overall, the PLM were shown to be a viable option for Life Safety code requirements.

Jeon and Hong (2009) utilized a subway station with 103 test subjects to determine human behavior during an evacuation with PLM signs and smoke concentrations. Their research focused on determining exit sign visibility while smoke conditions were simulated by covering the participant's eyes or by wearing tinted goggles. Evacuation times, evacuees' speed, and evacuation route choice were evaluated. The test subject's evacuation times did increase with PLM signs and markings, but only when signage was provided at regular intervals (Jeon &

Hong, 2009). These regular intervals were measured to be shorter than the participant's walking pace or gait.

Fire Alarm-Related Concerns for At-Risk Populations

Hoskins and Helmberger (2017) conducted research to understand how persons with autism spectrum disorders and epilepsy may respond to the sounds and lighting related to fire alarm signals. This is of particular interest as applied to exit signs and emergency signaling in general. Fire notification systems traditionally consisted of annunciators which flash rapidly to warn occupants of a fire in the building or related occupancy. Parents of special needs students and educators in the U.S. responded to a survey related to the needs and challenges of special education classroom evacuation. For hearing impaired individuals, the strobe light is critical and functions to signal that a fire has occurred (or that evacuation is required). This flashing light notification has disadvantages when students are sleeping or when students cannot view the fire notification (annunciators). Hoskins and Helmberger (2017) concluded that fire notification systems for special education facilities should be redesigned to be more inclusive. Hoskins and Helmberger (2017) also indicated that future research and further study is needed to expand our limited knowledge for at-risk populations during evacuations. But Hoskins and Helmberger (2017) highlighted that changing the color of strobe lights, elongating the lights, decreasing strobe frequency are all possible solutions.

Psychonomics

Human behavior during fire, or the study of how humans respond during an emergency, focuses on "people's awareness, beliefs, attitudes, motivations, decisions, behaviors, and coping strategies in exposure to fire and similar emergencies" (Kuligowski, 2013, p. 2070). Our overall

ability to evacuate a building quickly to escape from fire is related to our behavior and how we process information presented.

Founded in 1959, the Psychonomic Society emerged from researchers using a scientific approach to psychology and primarily deals with how humans process information in different situations (Dewsbury & Bolles, 1995). Research is still limited in determining how human ability and human behavior interact to allow an individual to escape effectively from a burning building. The Psychonomic Society and its members are developing new strategies to test previous assumptions, including how humans react to spatial cues such as exit signs during stress (Smeets, Otgaar, Raymaekers, Peters, & Merckelbach, 2012). Researchers in this field have contributed to our understanding of human behavior by evaluating how humans make decisions in respect to the existing environmental cues during a fire. Smeets et al. (2012) have recommended more integration of engineering and human psychology in order to maximize the possibility of individuals being able to escape during a fire (Sime, 1995).

Way-Finding

Way-finding has many connotations, but how humans navigate their surroundings is the most simplistic. Architects have incorporated way-finding principles into building design and master planning (Passini, 1984). How building occupants circulate and move, or navigate, throughout a building is an important component of way-finding.

Architects and urban planners first used this concept to aid city dwellers in finding their way around urban centers. Developed in the late 1970s, this concept is essentially how humans spatially orientate themselves in their environment, and how they perceive information related to their environment (Passini, 1996). International symbols and related standards are being

developed to aid humans' way-finding ability in buildings. This concept is most dominant in European countries where standardization is important due to the many different languages and culture barriers commonly encountered when traveling (Passini, 1996).

How emergency information is conveyed is a subset of critical way-finding information. How humans choose their escape route, and their decision-making criteria involved, is still being refined as determined by the paths chosen to escape a hotel. Way-finding research with 83 evacuations was conducted in a hotel during the night to determine how smoke concentrations affect escape routes with low-level signage (Kobes et al., 2010). Exit signs are but one component of an emergency evacuation. But do lower-level exit signs expedite egress during smoke conditions? Pre-existing knowledge of the building layout had an influence on escape route choice over any other variable. Otherwise, exit signs placed lower to the floor had a positive effect on escape route choice. Interviews and assessments post-evacuation of test subjects contained conflicting information. The researchers, Kobes et al. (2010), found real-time observation of test subjects provided greater reliability and accuracy than just recording the times of hotel evacuation participants.

Way-finding effectiveness and related research has been conducted in train stations, airports, hospitals, hotels, ferries, and university buildings (Allison, 2007; Corlett, Manenica, & Bishop, 1972; Fewings, 2001; May, 2004; Shiwakoti et al., 2016). Effective signage, markings, and routes are essential in how humans navigate those environments. Research has also shown that even with effective way-finding systems in place, humans may still be unaware of critical information. For example, in a train station located in Melbourne, Australia many occupants were not aware of the building exits or designated escape routes (Shiwakoti et al., 2016).

A comprehensive literature review of wayguidance systems was performed examining PLM safety way-finding (Tonikian, Proulx, Bénichou, & Reid, 2006). The review resulted in studies demonstrating PLM could be an acceptable alternative to conventional lighting systems. PLM has low maintenance requirements, does not rely on power sources, easy installations, and relatively low costs overall.

Low-level lighting way-guidance systems did perform better than conventional systems. When smoke was used, studies showed PLM when was seen below the smoke levels did provide increased visibility. Results also found low luminance levels as a factor for its low visibility. However, PLM specifications were limited making several of these results difficult to compare objectively. Thus additional studies are required to effectively compare all way-finding systems and related technologies.

Heskestad's (1999) research focused on five large studies with way-finding performance as the goal. Overall, human performance was improved with various technology employed. However, research has shown that way-finding needs to be improved for "next-generation" experiments to verify direction and exit performance. Also, cost-benefit considerations must be incorporated into these studies to demonstrate the need for revisions to fire codes (Heskestad, 1999). This research also pointed to the potential use of tactile systems or directional notches on handrails being comparable to low location lighting in effectiveness. It was also noted that performance specifications are missing, and much more work must be done for exit sign visibility and recognition.

Behavioral Computer Modeling

Traditional studies have utilized human subjects to observe and evaluate exit signs and related way-finding technology. However, new research has evolved to incorporate computer modeling. Using computer models to predict egress and help improve building egress, recent research has attempted to model human behavior during an evacuation or escape from a building (Fang et al., 2010; Pires, 2005; Tang et al., 2009). Human subjects observed under actual fire conditions risk injury and undue stress, whereas computer modeling and simulation provides more efficient and safer outcomes. As computer modeling and simulations improve, future virtual environments will improve research models.

Research with competing volunteers and a virtual reality methodology to model escape route choices during two situational variables in way-finding virtual environments has indicated visibility, brightness, and signage does have an effect on the volunteers' escape route (Vilar, Rebelo, Noriega, Duarte, & Mayhorn, 2014). A total of sixty-four university students were randomly assigned to the two groups to navigate a virtual hotel environment scenario. Vilar et al., (2014) gave participants a task to complete, and participants were then required to escape using routes with signs and without signs. The escape performance was higher for emergency conditions than for everyday conditions.

Occhialini et al. (2016) demonstrated that neurological activity and quantification of study participants can be translated to exit sign effectiveness in Ancona, Italy at the Università Politecnica delle Marche. Virtual tests or Animated Virtual Scenes (AVS) with 32 participants under six scenarios with exit signs recorded the human perception of each scene presented as exit signs within a building. Tests were conducted in both real world scenarios and in AVS. The

study reinforced determining the perception of exit signs with reflective or PLM used in the real world scenarios as applied in the AVS.

Occhialini et al. (2016) observed that researchers could examine the unconscious detection of the participant before the conscious detection. During black-out conditions, participants had lower sample variance, suggesting participants were focusing only on the exit signs with no relative distractions. The researcher recommended and concluded that in order to obtain more accurate results, studies should increase sample sizes and add exit sign variables such as color, shape, message, and related variables. It should be pointed out that participants in Occhialini's study were confined to a seated position in front of a monitor. Occhialini et al. (2016) also discussed the fact that an improved and more natural virtual presence should be developed for future studies to reflect the participants' natural postures and reactions.

Way-Finding App

Recently, a unique way-finding app using electronic devices was developed using augmented reality (AR) and pedometry to allow users to evacuate buildings (Ahn & Han, 2011). Researchers Ahn & Han (2011) developed this app to utilize existing smartphone sensors and smartphone users' walking velocity in combination with building tags to reveal the optimal, least crowded evacuation routes. These researchers reported that this app does not use the Global Positioning System (GPS) indoors or the Radio Frequency Identification Wi-Fi-based positioning systems due to poor reception indoors and other common sources of interference. Instead, the app relies on a commercial image labeling Web service known as IQ Engines. While the operational reliability still needs to be confirmed, this electronic version of way-finding has enormous potential for future electronic way-finding systems. With directions to exit in hand,

this app may indeed alleviate many concerns regarding safe evacuation from fixed exit signs. Certainly, additional evacuation smart apps can be expected as technology and operational efficiency improves.

In another way-finding app study, researchers developed an automated direction setting algorithm (ADSA) for a smart exit sign system (Cho, Lee, & Lee, 2015). In this study, researchers were able to improve space types into nodes thereby providing directions to the shortest safe evacuation route. Cho et al. (2015) tested ADSA by comparing existing algorithms thorough scenario-based simulations of test cases.

Like the previously mentioned smoke generation software, this way-finding app technology breaks several widely held conventions and has promise for future use. Concurrently, it is these electronic app developments that hold the most promise for future Life Safety improvements as we become more reliant on their everyday use.

Limitations of the Current Body of Knowledge

The preceding review of literature represented the diverse body of knowledge related to the photometric and psychonomic exit sign evaluations. There is a wide body of knowledge regarding how humans perceive and respond to exit signs. The literature review related to exit signs, way-finding technology, and our resultant escape routes identified important gaps in research foci regarding exit signs and way-finding technology practices. However, an overall lack of centralized research and understanding still exists between encountered field conditions and current lab testing requirements (Boyce, 2014, p. 320). This researcher has concluded there are still several gaps present in the validation of our knowledge and understanding how humans can perceive information related to exit signs and way-finding.

For example, the exit signs installed in the U.S. are not required to be tested and certified under simulated conditions to represent field conditions, especially those conditions found during an emergency or fire. For example, power outages and fires with resultant smoke concentration conditions are precisely why exit signs are required and when exit sign performance is most critical. Yet the conditions of heavy smoke preclude the assumptions of how humans perceive Life Safety information during no smoke conditions. Smoke generation is difficult to control and assess. The literature review did not provide any known approved smoke generation methodologies explicitly for exit sign testing.

This researcher has proposed virtual reality and simulated computer applications will become more common and aid Life Safety requirements in the future. As we improve the virtual “presence” in evacuation modeling, researchers will be able to test more assumptions more quickly. Yet this field of study is still developing.

This researcher has also proposed electronic devices and their resultant apps will evolve more quickly than other Life Safety components. Further, our reliance on these devices will provide impetus, and the platform, for the next generation of “electronic” egress.

Humans are susceptible to movement and to shorter wavelengths of light during periods of darkness due to inherent scotopic vision attributes. Yet what is the exit sign’s optimal color? Should blue, purple, or near UV wavelengths prove more effective during no light conditions? How do humans synthesize a flashing exit sign during the no light condition?

There is flashing technology available utilizing electroluminescent wire rope approximately two mm. in diameter that flashes around the perimeter of the doorjamb. During a fire, this flashing can still be seen while an exit sign above the door may become obscured. This

technology uses a shorter wavelength of light and flashes. There is a gap in our knowledge as current research has not considered this technology as a viable alternative or enhancement to current exit sign placement.

As discussed previously, little research is available to demonstrate the optimal exit sign font color humans prefer. Similarly, a single incandescent strobe light has been used in previous research to aid escape. But further research is needed to capture the way-finding technology now available.

Contributions of This Study

The ultimate goal of this study is to improve human cognition and our response to escape during an emergency. The most basic tenet in fire safety is the ability to get out of a building quickly and safely. Exit signs and related way-finding technology increase the human ability to detect, process, and respond quickly to a fire or an emergency. The presence, operation, and maintenance of exit signs can be easily overlooked, and exit signs are often ignored until an emergency requires their use. Building owners and property managers alone cannot be relied upon to provide completely safe structures (Chertkoff & Kushigian, 1999). Improving exit markings, exit signals, and human cognition will decrease overall human response time and thus promote human survivability during a fire or emergency (Ozel, 1993).

The intent of this study is to determine the observer's preference for LED exit signs (red, green, and blue), a PLM exit sign, and flashing way-finding technology. Also, which exit sign type is preferred under the four simulated conditions - obscurity (no smoke and simulated smoke environment) and lighting conditions (ambient light and no light)? Is there a correlation between

the exit sign luminance levels or luminance contrast levels compared to the observer's preference?

Red and green font colored exit signs are common in the U.S. but how does the PLM exit sign or flashing way-finding technology compare to the commonly found exit signs under the four simulated conditions? This study will seek to answer that question and seek to further our understanding of exit sign performance.

The flashing LED way-finding technology is a cable mounted around the entire door jamb and thus can possibly be seen even when smoke accumulates near the ceiling. In addition, the flashing can be seen when approaching the door from the side and not directly. This technology may have the advantage of being easily recognized when flashing and not affected by the light scattering and absorption compared to exit signs mounted or obscured in the smoke layers.

Current research is needed to verify optimal exit sign font color and whether the flashing effect associated with an exit sign and way-finding technology will provide optimal conspicuity (Boyce, 2014, p. 320). Does exit sign font color affect our visibility? Does flashing way-finding technology affect our visibility? This study will attempt to answer those questions and further advance our understanding of exit sign performance. It is anticipated this work will improve the Life Safety Code, advance our understanding of way-finding, and help save lives overall.

CHAPTER THREE

METHODOLOGY

Exit Sign Pilot Study

The researcher conducted an early pilot study where twelve individuals rated a red LED exit sign, a PLM exit sign, and flashing way-finding technology in without any lighting. Only the exit sign provided any luminance during the no lights condition. The original research intent was to more closely examine the PLM exit signs and related products under three conditions. Exit signs were mounted at ceiling and floor height. A pole barn structure with an office complex and storage was used at night time with no overhead lighting and white smoke was generated while the individuals evaluated the visibility of each exit sign type. The observers were asked to rate the signs under light, no light, and no light with smoke. Three groups of four individuals selected the most visible exit sign type. The smoke condition was generated using three smoke candles. Results showed the majority of the participants preferred the flashing way-finding technology when used with the red exit sign, used with the PLM exit sign, or as an exit by itself. From this pilot study, the researcher refined the conditions to be tested, the sequence of testing, and the exit sign options to be evaluated.

Introduction

This research study was conducted in two phases – photometric and psychonomic. The photometric phase experimentally measured and recorded the luminance and luminance contrast levels for the four exit signs (red LED, green LED, blue LED, PLM, and the way-finding flashing LED) when comparing the combination of obscurity conditions (simulated smoke

environment) and lighting conditions (ambient light and no light) at a predetermined distance of 100 feet.

The psychonomic phase consisted of observers rating the visibility of the same exit signs under the same four conditions. This phase determined the overall preferred exit sign and whether the observer's preferences for exit signs (red LED, green LED, blue LED, PLM, or way-finding flashing LED) were in agreement with the photometric results.

This study was based on the following research questions:

1. Which exit sign experimentally has the highest level of luminance under each of the investigated conditions?
2. Which exit sign experimentally has the highest luminance contrast value under each of the investigated conditions?
3. Which exit sign type is preferred under the combination of the conditions of ambient lighting and obscurity across each of the investigated conditions?
4. Which exit sign type is overall preferred by the observers regardless of the condition?
5. Is there an association between the participants' exit sign preferences and their gender?
6. Will exit sign luminance levels correspond to the observer's exit sign preference under the obscurity and lighting combination conditions?

Research Population

Study participants were comprised of volunteers aged 18 years and older from the general campus population where anyone could choose to participate on a voluntary basis. Anyone from the university community including students, staff, faculty, and the general public may have

received research flyers via community bulletin board postings and university-wide email announcements. The study flyers consisted of basic information and communicated the basis for the study and general study requirements. The flyers also communicated that participant identity, and personal and related information would remain anonymous.

Exclusion and Inclusion Criteria

Participation was open to all members of the university community without exclusion criteria except for age and visual acuity restrictions. Participants were verified to be 18 years old or older to participate in this study by providing a driver's license or student identification card. All participants were given a general visual acuity test to determine visual acuity and color blindness. As indicated from previous studies in the literature review, exit sign testing usually required subjects to have a minimum visual acuity threshold to participate in the visibility tests.

For this research study, a 20/40 minimum visual acuity was achieved by 47 participants and five participants had a visual acuity worse than 20/40. One participant was confirmed as being color deficient by being unable to discern red or green and failing to recognize numerals and characters from the Ishihara color plates.

Research Design

The purpose of this research was to determine photometric differences in LED exit sign font colors, PLM exit sign font colors, and flashing way-finding technology as compared to the human preference for exit signs. The study was conducted in two phases: photometric and psychonomic. During the photometric phase the luminance values were measured three times under known conditions and the arithmetic mean value was calculated and reported for the three values. Specifically, the five exit sign types were quantitatively evaluated by measuring the

luminance levels (cd/m^2) and luminance contrast (0 to 1) under the combination of lighting conditions (ambient light and no light) and obscurity (no smoke and simulated smoke conditions) at a viewing distance of 100 feet.

These lighting and obscurity conditions are categorized and defined in the four investigated conditions:

1. Lights On and No Smoke condition represents the ambient lighting from a regularly functioning electrical circuit and no smoke or other visibility issues are present. The installed overhead ambient lighting illuminates the pathway and visibility to evacuate is not obscured by smoke.
2. Lights On and Smoke condition is represented by functioning overhead ambient lighting. Visibility is greatly affected by lighting when the resultant scattering and absorption of light is redirected by the smoke particles.
3. Lights Off and No Smoke condition is represented by a power failure or power shutdown where observers could locate exit signs to evacuate the building. There is no obscurity from smoke or other particulates. Visibility was limited and the only source of light is from the exit signs or way-finding technology.
4. Lights Off and Smoke condition is represented by a power failure or power shut-down where observers would rely on exit signs and way-finding technology to evacuate safely. Visibility for this condition can be obscured by smoke and the resultant scattering and absorption of light from the smoke particles. This condition might not be common but is the most critical for survival as the building lighting or back-up power systems are not working properly.

For this study, it should be noted emergency, or escape lighting was intentionally not utilized. Only ambient overhead lighting was present during the lights on conditions. The lights off conditions allowed the exit sign as the only source of illumination. Otherwise, no other visible lighting was present during the study. OSHA does not have specific regulations addressing emergency lighting other than 29 CFR 1910.37 (b) (1) stating, “Each exit route must be adequately lighted so that an employee with normal vision can see along the exit route” (OSHA, 2018).

By NFPA code, emergency lighting is required and minimum luminance requirements are provided (NFPA 101, 2018). The addition of emergency light sources or emergency lighting compounds the problem of light scattering and reduces readability of exit signs as confirmed by the earlier work and conclusions of Rea et al. (1985).

During the psychonomic phase, participants rated their preferences for the same five exit sign types under the same combination of conditions of lighting and obscurity at the distance of 100 feet as detailed above.

Each participant was asked to rate the visibility of each exit sign type by completing the exit sign visibility form using a 5-point Likert scale to rate the exit signs with 1 being the least visible and 5 being the most visible (see Appendix C). Participants also provided their overall most preferred exit sign regardless of the investigated conditions. Upon completion, participants placed the visibility form in a collection tray for later review and tabulation by the researcher.

Research Setting

The research was conducted at Wright State University in Dayton, Ohio. A significant feature of the university campus is the many underground tunnels historically used as utilities

access. These utility tunnels are present today and are currently connecting many buildings on campus as a mode of egress. Research was performed within a selected tunnel connecting the student dormitory to the Student Union. This tunnel measures 108 ft in length and is currently not open to the public. During the study, the concrete tunnel was accessed by observers at one end and secured between research study activities. The total viewing distance between observer and the exit sign measured 100 ft. Dimensions and a schematic of the tunnel are provided in Appendix D.

Smoke Generation

The literature review revealed a gap in fire safety and related research as smoke generation has not been effectively standardized; additionally, the conditions of ambient lighting and non-smoke require additional validation. Previous studies have utilized different methodologies to simulate obscured visibility. A simple method used in previous studies to simulate smoke conditions was the theatrical “fog generator” machine. For this study, a fog generator was utilized and positioned near the location of the exit signs and opposite of the observer as seen in Appendix E.

The fog machine was placed on a stool approximately six feet above the floor to simulate smoke rising from heat and flames. A heating element within the machine heated a liquid mixture containing 70% propylene glycol and 30% distilled water to aerosolize droplets resembling grey smoke. Some previous studies had smoke generation technology using real smoke from various materials, which can be a health and property risk (Rubini et al., 2007). More commonly the theatrical smoke or haze equipment and related products have been utilized. For this study, the smoke equipment manual operation button was pressed four times to maintain

the approximate relative density during each smoke condition. Without air movement, smoke density was maintained throughout the tunnel. Between trials the tunnel maintained a high velocity fan rated at 7,000 cubic feet per minute, (CFM) which moved residual smoke away from the observers and exhausted outside the building.

Exit Sign Colors and Flashing

Throughout the U.S., the majority of exit signs have been installed with red and green font colors. The blue font color was selected for this research study because lower wavelength colors may be viewed more easily in the dark by humans (Boyce, 2014). According to Pulat (1987), the biological and evolutionary logic for this human vision enhancement is known as the Purjinke effect. The researcher postulated by taking advantage of the Purjinke effect, exit signs and way-finding can be optimized for the purpose of life safety. The researcher formulated the shorter wavelength light and flashing light should be evaluated for exit signs especially during no power conditions.

In addition, the psychological and physical factors of human vision must be combined with the ageing, corrective vision, and color-deficient segments of the human population to improve our overall understanding of exit sign visibility. For example, while individuals are sleeping, prescription eyewear and contact lenses may not be easily located when they are awakened during an emergency and need to evacuate quickly. These psychophysical factors and corrective vision dependency can delay the human response and decrease our ability to quickly evacuate or discern exits for escape.

The researcher has postulated that flashing light and lower wavelength light could address the constraints of the ageing, those with corrective vision, and the color-deficient

population while improving the overall human cognitive perception of emergency egress. For this study, the exit sign LED font colors of red, green, and blue were selected. The red, green, and blue were primary colors utilized while the PLM exit sign appeared to be a lighter green. The flashing way-finding was reported by the manufacturer to be a shorter-wavelength of light in the violet – UV range at approximately 395 nm. Although, color measurements and precise color discrimination was beyond the scope of this research.

LED Exit Sign

The internally illuminated exit sign used during this study was created using a standard exit sign cover mounted over an aluminum box. The LED exit sign met the UL 924 specifications of 6-inch font height and 0.375 inch spacing with a stroke width 0.75 inch. The sign cover was painted flat white and illuminated by an LED tape light wrapped within a fabricated aluminum container designed by the researcher. The exit sign dimensions measured 14 inches by 12 inches. From inside the aluminum box, the exit font letters were covered by a thin sheet of lightly frosted see-through plastic.

The LED tape light was manufactured by Patriot Lighting® and was powered by a single phase 120-volt receptacle, as seen in Appendix F. The exit sign font color was changed by an infrared remote control and the researcher used the remote to quickly change the LED font color between the colors red, green, and blue during the study.

Photoluminescent Exit Sign

The externally illuminated photoluminescent exit sign was created using an illuminating epoxy coating manufactured by Foxfire© epoxy delivery system as seen in Appendix G. The word “EXIT” was outlined by thick-film tape and the epoxy coating was applied to an aluminum

sheet painted white. After allowing the epoxy coating to cure, the tape was removed. The exit sign's dimensions measured 14 inches by 11 inches. The externally illuminated exit sign was powered by the overhead lighting within the tunnel. The PLM exit sign met the UL 924 specifications of 6-inch font height and 0.375 inch spacing with a stroke width 0.75 inch. Prior to conducting the trials, the overhead lighting was measured to confirm luminance levels. This type of exit sign required absorbed electromagnetic energy from the overhead lighting provided and then this energy is re-emitted as light when the overhead lighting was turned off.

The tunnel lighting provided an average of 35 f-c which exceeded the manufacturer's minimum ambient lighting recharge requirement of 5 f-c. The PLM exit sign was mounted in place directly over the internally illuminated LED exit sign during the study.

Flashing Way-Finding Technology

The flashing way-finding technology is a product offering from Light Saver Technologies, Inc. known as the Linear Strobe™ L-100. The way-finding technology has a two mm diameter electroluminescent light strand that was glued around the door perimeter and a compact electronic console mounted directly atop the doorjamb above the door as seen in Appendix H. The LED light strand was held in place with clear silicone adhesive. The unit's console dimensions are 7-½ inches in length by 1-½ inches wide. The electronic console is powered by a nine-volt battery and was activated by using a tone similar to a smoke detector alarming. When the console detects a signal from a smoke detector, the Linear Strobe will begin flashing. During the study, a dog whistle was used which also triggers the Linear Strobe™ L-100 to begin flashing. The dog whistle could not be heard by the participants and did not interfere

with the study. According to the manufacturer, the LED light strand emits light at the near ultraviolet wavelength and flashes twice approximately every two seconds.

Photometric and Luminance Level Data Collection

Luminance and luminance contrast are referenced in the UL Standard 924 requirements to certify exit signs. Both measurements were applied to the two exit signs used in this study. Luminance is the photometric equivalent of how humans perceive brightness. Luminance measurements were recorded in candela per meter squared or cd/m^2 . The photometer determined actual luminance variations as opposed to human perceptions of luminance or exit sign brightness.

Photometers are generally small, handheld light meters designed to record photometric human-perceived brightness as luminance from light sources or as light striking a surface measured in the units of cd/m^2 or fL. The photometer used for this study measured luminance over the range of 0.0001 to 299,900 cd/m^2 (Konica Minolta, 2013). The photometer can measure a small area on the exit sign at considerable distance through a viewfinder. When light energy from an object enters the lens and strikes the silicon photocell, this energy is converted to an analog electrical current after being filtered to match the Commission Internationale de L'Eclairage (CIE) luminosity response (Konica Minolta, 2013).

For internally and externally illuminated exit signs, 5 f-c (or 54 lux) must be illuminated to the surface of the sign. For self-luminous or electroluminescent exit signs, such as the PLM exit sign, a minimum luminance of at least 0.21 cd/m^2 or (0.06 fL) are permitted. For internally illuminated exit signs, the blue font did not meet UL 924 (2018) luminance requirement of 8.57 cd/m^2 (2.50 fL) for conditions 2 and 4. However, for this study, the minimum luminance value of

0.21 cd/m² was used as the minimum luminance threshold for all exit signs and way-finding technology.

For this study, the Konica-Minolta© LS-100 photometer was used to measure luminance levels and luminance contrast as seen in Appendix I. Luminance was measured by the factory-calibrated photometer using a luminous intensity standard lamp calibrated the Electro Technical Laboratory of the Japanese Ministry of International Trade and Industry. The photometer was mounted on a tripod for stability and measurement repeatability. The photometer's lens focal adjustment was locked to maintain the same angle of measurement. Measurements were recorded 100 ft from the exit signs in the opposite end of the tunnel. The luminance values were measured from the normal viewing angle to the face of the exit sign of zero degrees (0°).

The UL 924 standard specified photometry measurement locations. These locations consisted of 20 points on the sign letters and 23 points on the sign background. These locations were measured as demonstrated in Figure 5.

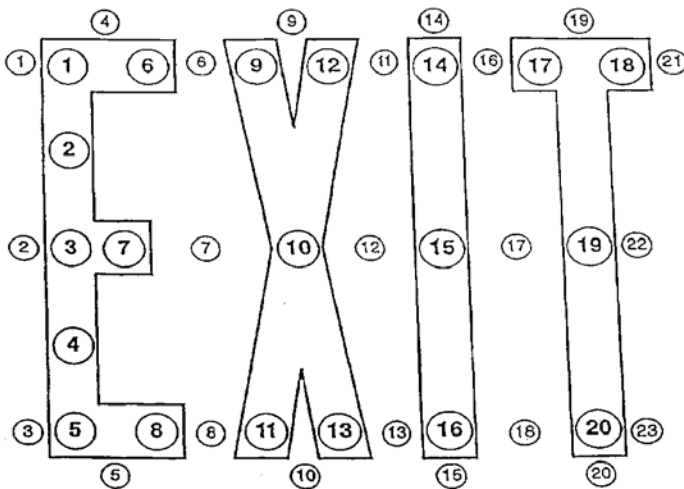


Figure 5. Measurement points of luminance for font and background positions. Adapted with permission from the *Underwriters Laboratories 924, Standard for Emergency Lighting and Power Equipment, Edition 10*. Copyright 2018 by Underwriters Laboratories.

These 20 points of luminance on the font letter were averaged for an overall sign luminance. Luminance values were measured and recorded three times and averaged for each of the four signs under the four investigated conditions.

Unlike the standard exit sign, the researcher could not locate similar luminance measurement specifications for this new technology. The UL 924 Standard (2018) does list testing criteria for flashing rate, stability, and duration but this method was specific only for flashing exit signs.

To determine the luminance values of the flashing way-finding technology, eight points along the lighting cable around the door and 12 points along the wall were measured around the perimeter of door next to the LED light strand.

However, regardless of the exit sign type, luminance is still considered to be the luminous intensity per unit area or a measure of the flux emitted from, reflected by, a flat and generally uniform surface (Boyce, 2014). Luminance values under the four conditions were the primary focus of this research. Conversely, luminance contrast is an important consideration when evaluating exit sign visibility and the values were collected separately for the exit sign types.

Luminance contrast measures an object's relative brightness compared to its background. The UL 924 standard references luminance contrast as the contrast between the exit sign letters or picture and the rest of the sign.

The luminance contrast formula is represented as:

$$C = (L_g - L_l) / L_g$$

Where,

C = luminance contrast

L_g = greater luminance (mean luminance of either legend or background)

L_l = lesser luminance (mean luminance of either legend or background)

Luminance contrast or C was recorded from zero to one. When C is closer to one, the assumption is that the exit sign font is more visible compared to the ambient background.

Luminance contrast is another criterion for exit sign visibility. The luminance contrast value of .5 or greater is required for exit signs (UL 924, 2018; NFPA 101, 2018). The luminance contrast compares the exit sign's brightness of font to the sign's background of the sign. The closer to one is indicative of the sign's font being more visible compared to the sign's background.

The luminance and luminance contrast levels from each of the LED exit signs (red LED, green LED, blue LED), PLM, and way-finding flashing LED located around the door were measured for the four different conditions at a fixed distance of 100 ft. These conditions are ambient lighting (lights on or lights off) and obscurity (smoke and no smoke) measured as lights on-no smoke, lights on-smoke, lights off-no smoke, and lights off-smoke. From the three distances tested and certified by the UL 924 (50, 75, and 100 ft), the maximum viewing distance of 100 ft was chosen to accommodate the study site and participants.

Psychonomic Data Collection

Upon arrival to the experiment site, the experimental procedure was explained to the participants. Participants were then asked to sign the IRB consent form as seen in Appendix J. After receipt of the IRB consent form was confirmed, participants were asked to complete a

simple visual acuity and color blindness test. UL 924 specifies observers have 20/40 visual acuity as determined by a standard eye chart. The Snellen eye chart was used to determine and record visual acuity. An example of the Snellen eye chart is available in Appendix B. From several previous studies, good visual acuity was defined as 20/40 at 20 ft on the Snellen chart (Ouellette, 1988; Schooley & Reagan, 1980). The Snellen chart was presented at 20 ft and participants were asked to read a series of letters and numbers. On the chart there is also a red and green bar to indicate color blindness. A second test utilized the Ishihara plate tests, or more commonly referred to as the color deficiency test, and the test was performed to indicate color recognition of red and green. The chart contained color plates presented as a red or green number against a similar red or green background combination with the goal being to recognize the number presented. Failure to clearly recognize or discern the number from the background indicates color blindness. An example of an Ishihara color plate is available in Appendix K.

After establishing visual acuity, participants assembled outside the study area before entering the tunnel. Again, expectations and the instructions to complete the survey were communicated to each participant. In addition, prior to entering the tunnel to begin the study, the facility emergency information and the communication methods to stop the study were conveyed to each participant.

After determining visual acuity, the participants entered the tunnel. The exit sign visibility rating and questionnaire was distributed to collect the participants' ratings of each of the four exit sign types and way-finding technology of ambient lighting (on and off) and obscurity (no smoke and smoke) as represented by the following four conditions: lights on-no

smoke, lights on-smoke, light off-smoke, and lights off- no smoke. A copy of the survey instrument can be found in Appendix C.

A 5-point Likert scale was used to rate the exit signs with 1 being the least visible and 5 being the most visible. While developing the self-administered exit sign survey and questionnaire, the researcher examined the surveys used from the previous research to ensure consistency with historical studies. From the literature review and associated studies, the researcher could not establish a consistent survey tool commensurate with exit sign visibility and recognition. For this study, the exit sign visibility form was designed to focus on whether an exit sign was visible, recognizable, and perceived as an exit sign under the lighting and obscurity conditions for each exit sign and way-finding technology presented.

In addition to the psychonomic data collection, demographic information such as age, gender, visual acuity, and color blindness was gathered.

To establish a baseline measurement of ambient lighting illumination, the existing overhead lighting was measured using an illuminance light meter (#840021) by SPER Scientific© (see Appendix L). Tunnel lighting was provided by LED (T5) lights mounted overhead at approximately 11 feet high. Measured tunnel illuminance was averaged from the light fixtures resulting in 35 ft-c throughout the length of the tunnel. The overhead lighting was controlled and turned off for a no light condition where the only source of luminance was from the single exit sign or flashing way-finding technology. This condition was to simulate a power outage with no other light source available.

Upon entering the tunnel, the participant was asked to rate the exit signs (LED red, LED green, LED blue, and PLM exit sign, and flashing way-finding electroluminous) under the four investigated conditions standing a distance of 100 feet from the exit sign.

To optimize the study and decrease observation time, the sequential order of lighting and obscurity conditions were:

1. lights on and no smoke,
2. lights on and smoke,
3. lights off and no smoke,
4. lights off and smoke, and;

Between conditions 2 and 3, observers were given a minimum of five minutes to acclimate to the darkness. During this time the smoke was evacuated with a high volume ventilation fan. The internally illuminated exit sign was mounted above the door. The LED exit sign was designed to switch from red, green, or blue color font via an infrared remote. The externally illuminated exit sign (PLM) was placed over the mounted exit sign and the LED switched off. When the flashing way-finding technology was being viewed, the PLM exit sign was reversed to a white only background to match the wall surface.

Power Analysis

A power analysis of the exit sign visibility survey responses was conducted using the software, G-Power version 3.0.1, to validate the appropriate study sample size. This analytical software determines the statistical power of the study to determine an effect. More simply, the software can calculate the probability of accepting the alternative hypothesis H_1 when it is true.

The researcher first calculated the effect size using the following guidelines from Cohen (1988); medium effect size = .3. The next step was to calculate the minimum sample size required using the G-Power calculator settings of Chi Square (χ^2) and Goodness of fit tests: Contingency tables. With the effect size of .3, alpha of .05, power of .8, and degrees of freedom of 4, the G-Power calculator determined the total sample size to be 133.

Statistical Analysis

The survey instrument was created using Microsoft Word© 2013, and the data were recorded using Microsoft Excel© 2013. The data from the study were analyzed using the IBM Statistical Package for the Social Sciences© (SPSS) version 24 software package. The variables were examined using both descriptive statistics and inferential statistics to answer the researcher's five hypothesized research questions. All inferential statistical tests were analyzed using an alpha (α) level of .05 to test significance. The .05 alpha (α) level represents the probability the researcher will reject the null hypothesis when the null hypothesis is true (Rubin, 2012).

Descriptive Statistics

Descriptive statistics were used to summarize the luminance and luminance contrast values for each exit sign and way-finding technology. Descriptive statistics were used to generally summarize the participants' demographic data, such as age, gender, prescriptive eye wear for the analysis of trends. These descriptive statistics were included as the analysis of the mean, the minimum and maximum, and standard deviation. Descriptive statistics were used to answer Research Questions 1, 2, and 6.

Research Question 1 – Which Exit Sign Experimentally has the Highest Luminance Level Under Each of the Investigated Conditions?

The researcher proposed the exit sign luminance levels could be higher for some exit signs and way-finding technology under each of the four investigated conditions. The luminance value for each exit sign and way-finding option was measured three times under the four conditions using the calibrated Konica-Minolta© photometer. The photometer camera captured and measured luminance levels of each exit sign type. Measurements were captured for each exit sign type and way-finding technology under the four conditions and recorded as cd/m^2 . Those results were presented as the arithmetic mean of highest luminance values for each of the four conditions as descriptive statistics.

Research Question 2 – Which Exit Sign Experimentally has the Highest Luminance Contrast Level Under Each of the Investigated Conditions?

The researcher proposed exit sign luminance contrast levels could be higher for some exit signs and way-finding technology under the four conditions. The luminance contrast level closer to one indicates a greater visibility of the exit sign font compared to the background as referenced in the Photometric and Luminance Level Data Collection section.

The photometer camera captured and measured luminance contrast levels of each exit sign type. Measurements were captured for each exit sign type and way-finding technology under the four conditions and recorded as cd/m^2 . From the formula presented on page 69 ($C = (L_g - L_l) / L_g$), the luminance contrast levels were calculated from three separate occasions. Those results were presented as the arithmetic mean of luminance contrast values for each of the four conditions as descriptive statistics.

Research Question 6 – Will Exit Sign Luminance Levels Correspond to the Observer’s Exit Sign Preference Under the Obscurity and Lighting Combination Conditions?

The researcher proposed there is an agreement between the experimental measurements and the subjective results. Will the luminance level measurements outcomes correspond to the observer’s overall preference outcomes under each of the four investigated condition. Higher luminance levels should increase exit sign visibility during light off and no smoke. Exit sign obscurity from smoke is affected by light scattering and absorption. But does exit sign color or way-finding flashing increase visibility?

Inferential Statistics

Inferential statistics were primarily used to answer our research questions. For all tests, an alpha (α) level of .05 was used to determine statistically significant differences. The .05 represented the probability of rejecting the null hypothesis when the null hypothesis is true (Rubin, 2012).

Friedman Test

The Friedman Test is a non-parametric alternative to the one-way repeated measures analysis of variance (ANOVA) and is used for testing the difference between several related samples (Pallant, 2013). The Friedman Test is used to determine statistically significant differences between distributions of three or more groups or conditions. It is used when the measurement dependent variable does not meet the normality assumption and the equality of variance assumption of a One-Way ANOVA with repeated measures. The Friedman Test does not assume data are normally distributed and that the variation within the groups is equal, or meets the assumption of homoscedasticity.

Research Question 3 - Which Exit Sign Type is Preferred by Observers Across all Four Conditions?

The Friedman Test was used to answer Research Question 3. The researcher postulated there could be differences in the observers' preference of exit signs methods across the four investigated conditions. Overall, the Friedman Test was used to determine if statistically significant differences were present between the 47 observers' ratings for the four exit signs and the way-finding methods under the four conditions. The null hypothesis is the mean ranks of the groups (exit sign type) across each of the four investigated condition are the same.

Variables

The independent variable was the exit sign type and investigated condition type. The exit sign type is a fixed effect variable with five levels; red, green, blue, PLM, and flashing. The lighting and obscurity condition is a fixed effect variable with four levels as the following:

1. Lights on and no smoke,
2. Lights on and smoke,
3. Lights off and no smoke, and;
4. Lights off and smoke.

The dependent variable was the observers' rating of the exit sign type. A Likert scale of one (1) to five (5) with one (1) being the least visible and five (5) being most visible was used to rate the exit sign type across the four conditions.

Assumptions for the Friedman Test include:

Assumption 1: The dependent variable is ordinal or continuous. In this research, the dependent variable is the observers' rating, which is an ordinal variable.

Assumption 2: The independent variable is two or more categorical independent groups.

Assumption 3: No relationship exists between observations in each group or between the groups.

Assumption 4: Each group distribution has a similar shape or variability. One group cannot be skewed, and this assumption was verified by comparing the medians of the independent variable. If different shaped distributions exist, the test only examines mean ranks.

If the Friedman test results indicate a significance difference ($p \text{ value} \leq .05$), a post-hoc analysis will be performed using the Wilcoxon signed-rank test.

Wilcoxon Signed-Rank Test

The Wilcoxon signed-rank test is considered the nonparametric test option to the dependent t-test because there is no assumption of normality in the data or equality of variance. It is used when comparing two related samples, matched samples, or repeated measurements on a single sample to assess whether their population mean ranks differ.

Research Question 4 – Which Exit Sign Type is Preferred Overall by the Observers Regardless of the Investigated Conditions?

The researcher postulated there could be differences in the observer's overall preference for exit signs and way-finding technology across the four conditions. The null hypothesis

suggests the proportion of observer's preferences should be the same across the conditions. Will the observer's overall preference be significant for one or more of the exit signs?

Variables

The independent variable was the exit sign type, which is a fixed variable with five levels; red, blue, green, PLM, and flashing. The dependent variable was the observer's overall preference, which is a nominal variable.

One Sample Chi-Square Test - Goodness-of-Fit Test

The One Sample Chi-Square test, also referred to as the Goodness of fit test, is a nonparametric statistical test used to determine if the distribution of cases (e.g., participants) in a single nominal variable follows a known or hypothesized distribution (Laerd, 2018). It is hypothesized the proportion of cases in each group of the categorical variable is not equal or different than the expected value. The categorical variable here is the exit sign and it consists of five exit sign types (red LED, green LED, blue LED, PLM, and flashing). The participants were asked to select their overall exit sign preference regardless of the lighting and obscurity condition (#1 lights on-no smoke, #2 lights on-smoke, #3 lights off-no smoke, and #4 lights off-smoke) to determine if there are significance differences in participants' preference.

According to the Laerd Statistics (2018) and their Chi-Square test tutorial, the Chi-Square test has four assumptions to test and verify. The first test is when the two variables must be measured as nominal (categorical). The second test of independence is determined when there is independence of observations; whereby, no relationship exists between the participants. The third test is determined if the nominal variable is mutually exclusive. And, the final test is there must be five expected frequencies in each group of the nominal (categorical) variable.

With all test assumptions determined as true, the Chi-square Goodness of fit test was performed. This test was used to answer Research Question 4 to determine whether the observers' overall exit sign preferences have the same distribution from a categorical variable of exit sign types.

Cramer's V Statistical Test

Cramer's V test determines the strength of a relationship with the value of the correlation coefficient. The test was used to measure the strength of association between two nominal variables or a nominal variable and an ordinal variable by providing a value between 0 and ± 1 with 0 indicating no association and ± 1 indicating a strong association (Cohen, p. 222, 1988; Corbett, 2001; Rubin, p. 212, 2012). The measures of association do not assume randomly sampled data. Cramer's V test can be used post-test to analyze the association after a chi-square test has determined significance. The values adapted from Corbett in interpreting measures of association are presented in the Table 1 below and offer guidance when interpreting the strength of relationships from the Cramer's V test.

Table 1

Measures of Association from the Cramer's V Test

Relationship Strength	Very Weak	Weak	Moderate	Strong
Cramer's V Score	< .10	.10 to .19	.20 to .29	≥ 0.30

Adapted from *Statistical power and analysis for the behavioral sciences* (p. 222), by J. Cohen, 1988. Hillsdale, NJ: Lawrence Erlbaum Associates. Copyright 1988 by Cohen.

Cramer's V test was used here to measure the association between gender (female-male) and participants' perceived perception of the exit signs presented in Research Question 5.

Research Question 5 - Is There an Association Between Participants' Exit Sign Preference and Their Gender?

The researcher postulated there could be differences in the observer's preference for exit signs and way-finding technology based on their gender. Will an observer's preferences vary based on their gender?

Variables

The categorical, independent variable was the participant's gender, which is a fixed effect variable with two levels: males and females. The categorical, dependent variable was participants' overall selection of their preferred exit signs regardless of the four investigated conditions. This is a fixed effect variable with five levels; Red LED, blue LED, green LED, PLM font, and flashing.

CHAPTER FOUR

RESULTS

Introduction

The survey instrument developed for this study was distributed to participants who volunteered from the general campus community to participate in the psychonomic phase of the research. A total of 53 participated in the study; however, six participants were excluded from the study due to incomplete or illegible results. This resulted in a total of 47 completed surveys.

Descriptive Statistics

A total of 47 individuals completed the survey instrument as directed to participate in the psychonomic phase of this study. Participants were asked their age and gender, and whether they wear prescriptive aids such glasses or contacts.

The participants reported their ages ranging from 19 to 72 years of age and corresponding with an overall average age of 24 years of age and standard deviation (S.D.) of ± 11.1 , as presented in Table 2.

Table 2

Participants' Demographic Data

Gender	No. of participants	Mean Age \pm S.D.
Male	25	24 \pm 11.3
Female	22	23 \pm 11
Total	47	24 \pm 11.1

Participants also self-reported their gender. Of the 47 participants, 25 (53.2%) were identified as male and 22 were female (46.8%) as shown in Table 2 above.

A total of 16 participants (34%) were recorded as wearing contacts or glasses. The visual acuity of each participant was determined with a Snellen chart at 20 feet prior to entering the tunnel. Each participant was asked to correctly identify corresponding letters and colors on the Snellen eye chart to determine visual acuity and to discern colors. A total of 42 participants were recorded as meeting the visual acuity of 20/40 or better in both eyes. The visual acuity of 20/40 as determined by a standard eye chart is required in the UL 924 Standard observation visibility test. The 20/40 visual acuity is also similar to the visual threshold to maintain an operator’s license. Five participants did not meet the minimum visual acuity requirements. The Snellen chart contained a red and green line to indicate color deficiency. If participant could not discern red or green lines correctly, then color plates were used to confirm color-blindness. One participant was confirmed to be color-deficient and had a known color-blindness condition which was verified using the Ishihara color plates (see Appendix K).

A summation of those observers in this study is provided in Table 3 below.

Table 3

Visual Acuity and Prescriptive Wear

	No. of participants	Visual Acuity \leq 20/40	Prescriptive Wear	Color Deficient
Male	25	23	7	1
Female	22	19	9	0
Total	47	42	16	1

Inferential Statistics

Research Question 1: Photometric Results - Luminance

Which exit sign experimentally has the highest level of luminance under each of the investigated conditions? The luminance levels were recorded three times from the LED exit sign (red, green, blue), the PLM exit sign, and the flashing way-finding at a fixed distance of 100 ft under the four different environmental conditions (lights on-smoke, lights off-smoke, lights on-no smoke, and light off-no smoke). The luminance levels were averaged for each exit sign type and flashing technology are graphically represented in Figure 6.

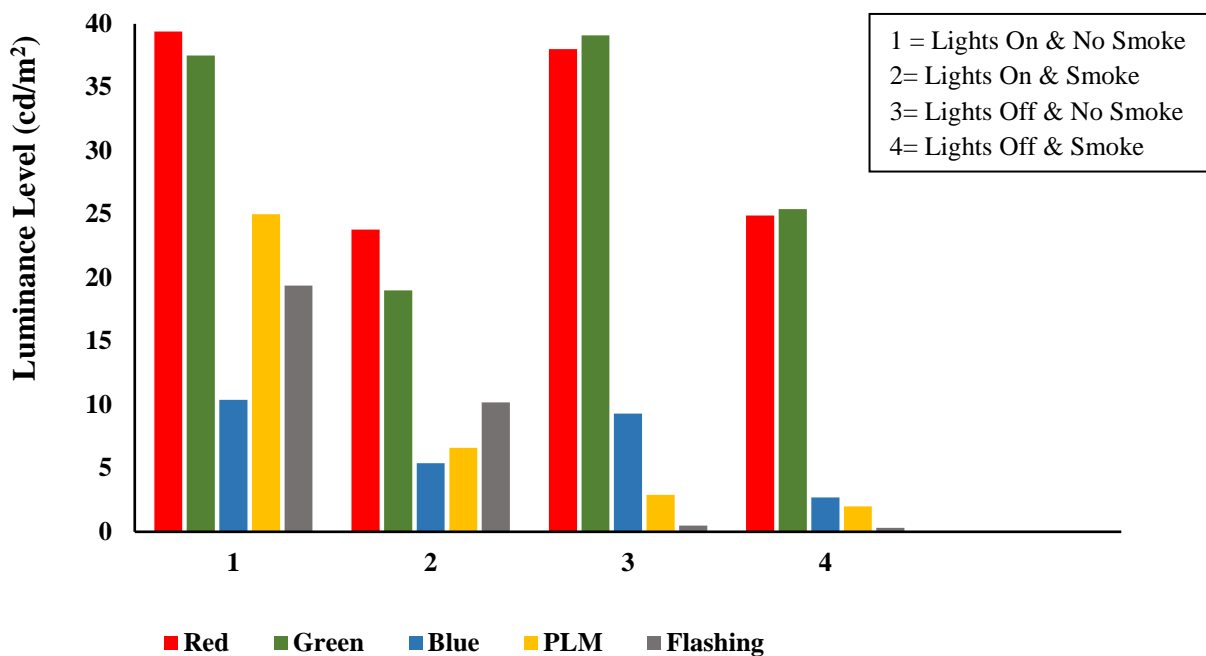


Figure 6. Exit signs luminance values (cd/m^2).

For internally illuminated exit signs, the minimum surface luminance value should not be less than 8.57 cd/m^2 (2.5 fL) according to the UL 924 Standard (2018). For self-luminous and

electroluminescent exit signs, such as the PLM exit sign used in this study, the 0.21 cd/m² (0.06 fL) is the minimum luminance value allowable by OSHA (2018) and UL 924 (2018). All exit signs and way-finding technology tested were recorded as greater than the 0.21 cd/m² minimum luminance for self-luminous exit signs threshold.

The results indicated the red LED exit sign has the greatest luminance level under condition one and two. While the green LED exit sign has the greatest luminance level under condition three and four. Overall, the red LED has the highest luminance level.

Research Question 2: Photometric Results - Luminance Contrast

Which exit sign experimentally has the highest level of luminance contrast under each of the investigated conditions? The luminance contrast levels were recorded three times from the LED exit sign (red, green, blue), the PLM exit sign, and the flashing way-finding at a fixed distance of 100 ft under the four different conditions (lights on-smoke, lights off-smoke, lights on-no smoke, and light off-no smoke). The luminance contrast values were averaged for each exit sign type. Luminance contrast denotes the exit sign's relative "brightness" compared to the exit sign's background from a scale of zero to one. A value closer to one equilibrates to the exit sign being generally more visible due to its font having greater contrast. However, a minimum luminance contrast of .5 is required per the UL 924 and NFPA 101 (2018). The exit sign luminance contrast values are graphically presented in Figure 7.

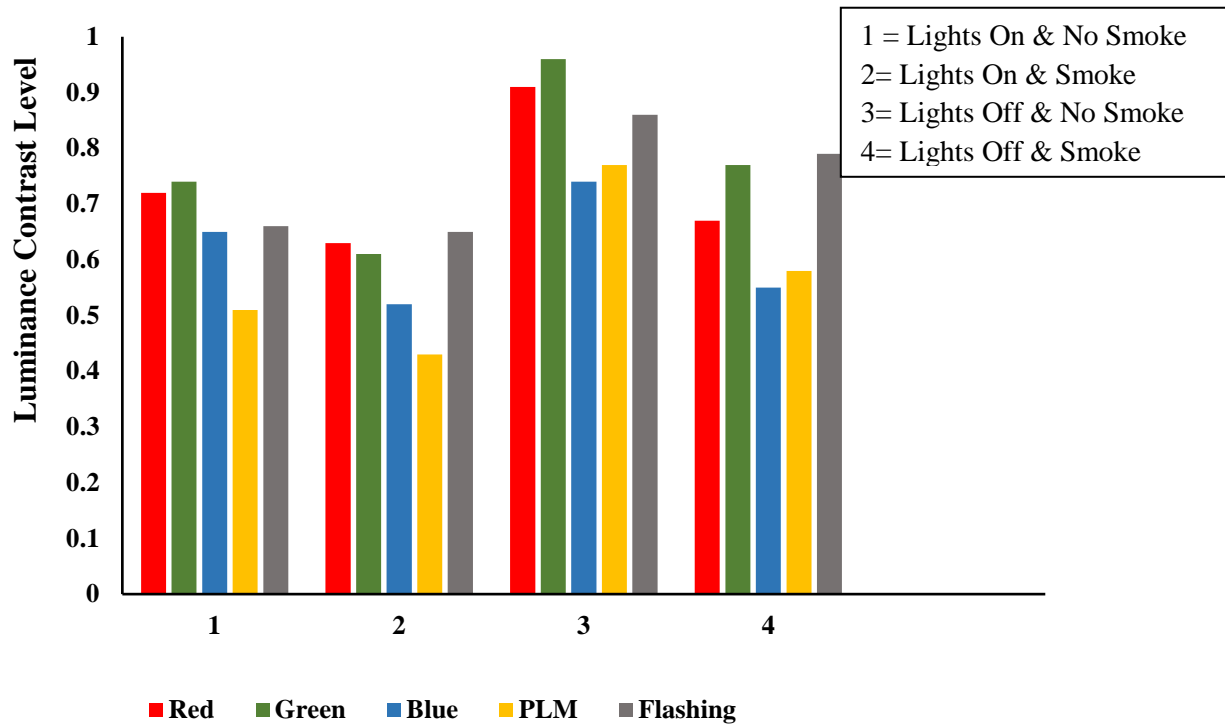


Figure 7. Exit signs luminance contrast values (0-1).

The results for luminance contrast indicate the green LED has the greatest contrast for conditions one and three. Under conditions two and four, the flashing way-finding technology has the greatest luminance contrast values. Of all the signs tested, only the PLM exit sign was recorded as less than the required .5 luminance contrast minimum under condition 2. Overall, the green LED has the greatest average luminance contrast followed by flashing and red, respectively.

Psychonomic Phase Results

Research Question 3: Observer's Exit Sign Preference

Which exit sign type is preferred by observers across all conditions? A Friedman test was performed to determine if there were significant differences in the participant's preference for an exit sign under each of the four conditions.

The results indicated a significant difference for the red font exit sign under the condition 1 (lights on and no smoke). The results also indicated significant differences for the flashing type under conditions 2 (lights on and smoke) and 4 (lights off and smoke) with $p < .000$. Table 4 below provides a summary of the Friedman test mean ranks and significance.

Table 4

Friedman Test Mean Ranks

	N	Red	Green	Blue	PLM	Flashing	Sig.
1. Lights On & No Smoke	47	<u>3.48</u>	3.33	2.97	3.13	2.09	.000*
2. Lights On & Smoke	47	2.70	3.22	3.02	2.38	<u>3.69</u>	.000*
3. Lights Off & No Smoke	47	2.75	3.19	3.02	2.75	<u>3.30</u>	.182
4. Lights Off & Smoke	47	2.98	2.78	2.48	1.89	<u>4.87</u>	.000*

Bold & underline = highest mean rank/condition

* significant at α level of .000

Since the Friedman Test showed significant differences across three of the four light-smoke conditions, a post-hoc analysis using the Wilcoxon signed-rank test on the different combinations of related groups was performed for these three conditions. A Bonferroni adjustment on the results from the Wilcoxon tests was performed because multiple comparisons were conducted. With five exit sign options or groups, the α level of .05 was divided by 10 producing a new significance level of .005. The Wilcoxon results are shown below in Tables 5, 6, and 7 respectively.

Table 5

Wilcoxon Signed-Rank Test Results Condition 1 (Lights On & No Smoke)

	Red	Green	Blue	PLM	Flashing
Green	.235				
Blue	.063	.002			
PLM	.000	.000	.009		
Flashing	.000	.000	.000	.000	

Note. Bold is significant at α level of .005

Table 6

Wilcoxon Signed-Rank Test Results Condition 2 (Lights On & Smoke)

	Red	Green	Blue	PLM	Flashing
Green	.065				
Blue	.509	.197			
PLM	.946	.180	.616		
Flashing	.001	.018	.006	.002	

Note. Bold is significant at α level of .005

Table 7

Wilcoxon Signed-Rank Test Results Condition 4 (Lights Off & Smoke)

	Red	Green	Blue	PLM	Flashing
Green	.000				
Blue	.009	.106			
PLM	.000	.000	.000		
Flashing	.000	.000	.000	.000	

Note. Bold is significant at α level of .005

Research Question 4: Overall Preferred Exit Sign

Which exit sign type is preferred overall by the observers regardless of the investigated conditions? Each observer provided their overall exit sign preference across all four conditions. The Chi Square Goodness of fit test was performed to determine the significance between the observer's preferences regardless of the investigated conditions with the results presented below in Table 8.

Table 8

SPSS Results for the Association Between Best Sign Preferred Overall

	Observed N	Expected N	Residual	χ^2	df	P value
Red	1	9.4	-8.4	62.255	4	.000*
Green	10	9.4	.6			
Blue	5	9.4	-4.4			
PLM	1	9.4	-8.4			
Flashing	30	9.4	20.6			
Sum	47					

* Significant at α level of .00001

The Chi Square Goodness of fit test ($\chi^2 = 62.255$, $df = 4$, $p = .000$) indicated there is a strong and significant correlation between the observers' overall exit sign preference regardless of the investigated conditions with $p < .000001$. The flashing way-finding technology was determined to be preferred overall by observers.

Research Question 5: Association Between Participants' Preference and Gender

Is there an association between participants' exit sign overall preferences and their gender? A Cramer's V test was performed to determine if there was a significant correlation between the participant's overall preference and their gender regardless of the environmental conditions. At the end of the study, observers were asked to list their most preferred exit sign

type overall regardless of the environmental condition. Of the 25 male participants, 18 selected flashing as best overall and of the 22 female participants, 12 selected the flashing as best overall. These preferences resulted in 72% of males selecting flashing and 54% of females selecting flashing as their overall preferred exit sign. These results are summarized in Table 9.

Table 9

Best Sign Selected by Gender

		Red	Green	Blue	PLM	Flashing	Total
Gender	Male	0	2	5	0	18 (72%)	25
	Female	1	8	0	1	12 (54%)	22
	Total	1	10	5	1	30 (63%)	47

The Cramer’s V test results using the cumulative data from Table 11 showed a significant correlation between gender and the exit sign type preferred. Using SPSS, the Cramer’s V value of .498 and corresponding significance of .020 was calculated.

The .498 value from the Cramer’s V analysis ($p = .02 < .05$, $\phi = .498$) indicated a strong association between gender and overall exit sign preference. According to Corbett (2001), any value greater than .30 indicates a strong relationship between variables. Therefore, a strong association relationship does exist between the observer’s gender and preference. This indicates that both genders have a preferred exit signs which is the flashing.

Research Question 6: The Photometric Versus The Psychonomic Phase Results

Will exit sign luminance levels correspond to the observers’ exit sign preference across all four investigated conditions? The results from Research Questions 1, 2, and 4 were used to answer research question 6. Condition 3 was determined not be significant and was not

considered. While figure 4, Luminance level, indicated that the green LED and red LED are the best choice overall, figure 5, Luminance contrast, showed that green, flashing, and red were the exit signs with the highest contrast, respectively. The luminance and luminance contrast levels contradicts the findings of the psychonomic phase where the participants preferred the flashing light exit sign overall, see Table 4 and Table 10.

Higher luminance contrast levels did correspond to observer preference. The most important result is condition #2 and #4 with smoke present, where flashing was preferred overall. These findings are highlighted in Table 10.

Table 10

Photometric Results vs. Psychonomic Results

	#1 Lights & No Smoke	#2 Lights & Smoke	#3 No Lights & No Smoke	#4 No Lights & Smoke
Luminance (cd/m ²)	Red (39.4)	Red (23.8)		Green (25.4)
Luminance Contrast (0-1)	Green (.74)	Flash (.65)		Flash (.79)
Subject Preference	Red*	Flash*		Flash*

*Significant at p = .000

The red exit sign font was found to have higher luminance under Conditions #1 and #2. The green font had a higher luminance for Condition #4 and higher luminance contrast for Condition #1. The luminance contrast values indicate the Linear Strobe™ flashing technology to be higher for conditions with smoke. The flashing technology resulted in the best preference by observers across all of investigated conditions, especially obscurity under the two smoke conditions. Overall, the observers selected the flashing technology as their preferred exit sign regardless of the investigated conditions.

CHAPTER FIVE

DISCUSSION AND CONCLUSIONS

In the United States, exit signs must be tested and certified by a Nationally Recognized Testing Laboratory (NRTL) to known performance specifications and testing criteria (UL 924, 2018). The UL 924 Standard for Emergency Lighting and Power Equipment has existed since 1958. Yet paradoxically, exit signs are not currently required to be tested under conditions with smoke. Even more critical is the emergency condition of no light and smoke when escape is critical due to decreased illumination and obscurity.

Today many exit sign varieties, font colors, and luminance levels are available for installation and use. It is intuitive to believe current exit sign requirements and related standards are based on validated technical specifications. However, conclusive research for the complex human perception of exit signs and way-finding methodology is not apparent and many gaps in knowledge exist still today (Boyce, 2014; Jouellette, 1988).

The purpose of this study was to determine whether the primarily red and green exit signs consistently found throughout the U.S. can be enhanced through revised font color or by flashing, especially under the conditions of no light and smoke. Exit signs observed under emergency conditions are when way-finding is needed the most and escaping quickly is critical to human survival.

To date, research has not validated the optimal exit sign font color preferred by humans or whether flashing increases human cognition during the conditions of no lighting and smoke (Boyce, p. 320, 2014). The Linear Strobe™ L-100 from LightSaver Technologies, Inc. was the flashing way-finding technology utilized throughout this study. Comprehensive studies

comparing current exit sign technologies to date have not been conducted using the Linear Strobe™ L-100.

This study provides an update to the existing body of research related to exit signs, way-finding technology, and how humans escape during an emergency. This study incorporated new flashing way-finding technology not previously considered nor evaluated. It is anticipated this study will function as a benchmark and to serve as an empirical baseline to perform additional research.

Research Questions

This study determined exit sign performance and an observer's preference in two phases. The photometric phase measured and recorded luminance and luminance contrast levels for five exit signs (red LED, green LED, blue LED, photoluminescent or PLM, and flashing way-finding) at a distance of 100 feet using a photometer across four combined conditions of ambient lighting and obscurity (#1 lights on-no smoke, #2 lights on-smoke, #3 light off-no smoke, and #4 lights off-smoke).

Luminance and Luminance Contrast Levels

Results from the photometric phase indicated the highest luminance levels (cd/m^2) were recorded for the red font and the green font. Luminance for red was highest for Conditions 1 and 2 and green was highest for Conditions 3 and 4 respectively. Each of the exit signs were above the minimum $0.21 \text{ cd}/\text{m}^2$ (.06 foot Lamberts) threshold for self-luminous exit signs (OSHA 2018; UL 924 2018). The highest luminance level recorded for the red font was $39.4 \text{ cd}/\text{m}^2$. The most critical condition with smoke was recorded for red with condition 2 and green with condition 4.

The minimum exit sign luminance contrast threshold is .5 and all exit signs were above the minimum threshold except for PLM measured at .43 for Condition 2. The highest luminance contrast levels were recorded for green with Condition 1 and 3 and Condition 2 and 4. The highest luminance contrast levels were for flashing across both smoke conditions (2 & 4). Both luminance and luminance contrast results can be presented in table 11.

It should be noted the concept of using the LED rope cable with remote control was to quickly actuate color changes and eliminate luminance variability between font colors. However, when activated, the blue font did not perform comparably; and, therefore the blue font option did not record luminance and luminance contrast levels comparable to the red and green font option. This variability could not be explained and the researcher's intent was to have similar luminance levels for the LED option.

The PLM exit sign option had low luminance contrast levels overall across most of the conditions. The researcher personally designed and assembled this sign, so variability may exist when comparing to similar PLM exit signs found commercially. Unfortunately, the PLM exit sign did not perform comparably to the red and green font option.

Consequently, the resultant experimental performance variability of the blue LED exit sign and PLM exit sign made experimental comparisons difficult and less than rigorous.

Previous literature suggested greater exit sign luminance would provide greater visibility (Rea et al., 1985) when smoke was present. Intuitively, greater exit sign luminance levels should correspond to greater exit sign "visibility." However, previous research has also suggested merely increasing exit sign luminance does not increase visibility due to scattering and absorption of light (Schooley & Reagan, 1980; Webber & Aizlewood, 1993).

Inversely, the color and the flashing from the Linear Strobe L-100™ may have been enhanced by the higher luminance contrast levels due their inherent sharp contrast with the door jamb. This observation is subjective. But it was known the effect from flashing was preferred by observers for both smoke conditions (lights on and off). In addition, the no light and smoke condition was preferred by observers; the most challenging and difficult egress condition encountered during a fire.

Exit Sign Preference Across Each Investigated Condition

A critical part of this study was to determine which exit sign type is preferred by participants under the combination of all four investigated conditions. Results from the study indicated there is a significant difference ($p < .000$) for conditions 1, 2, and 4 but not 3. Red font was preferred under condition 1, and flashing was preferred under the conditions of smoke regardless of the light status (#2 and #4). The most critical condition (#4) lights off and smoke, flashing was again preferred resulting in the flashing effect being perceived as more visible observers.

Overall Exit Sign Preference Regardless of Condition

Another critical part of this study was to determine the exit sign type preferred overall regardless of conditions. Based on the results of Chi Square Goodness of fit test, overall exit sign preference was found to be significant regardless of investigated conditions ($p \text{ value} = .00001$, $\chi^2 = 62.255$). Based on results, the flashing way-finding technology was the preferred exit sign by the observers regardless of the investigated condition.

Blue font color was anticipated to be perceived better than red and green under the no light condition according to the known Purkinje effect (Pulat, 1987). In addition to the font color

variability, the PLM exit sign was manufactured by the researcher with the potential for variability in the application and curing of the PLM. Unfortunately, the blue and PLM font colors had greater variability than expected.

In addition, previous research has suggested when exit signs are obscured by smoke, the scattering of light may cause increased confusion during egress (Malvern, 1986; Rea et al., 1985). Lighting experts have also questioned what effect flashing may have during no lights and smoke conditions (Boyce, 2014). It was observed that the flashing technology was below the smoke stratification layers and was easily discernable as an exit as noted by the observers in this research study. The Linear Strobe™ can be seen at angles where the flat exit signs cannot be observed due to the illumination created by 360 degree light cable. This angle is effectively reduced to 90 degrees of illumination when installed next to the door jamb. However, this visual angle contributes to an enhanced illuminance by greater reflection from the wall and door trim. This greater reflectance could aid in the overall luminance contrast value determination thus increasing visibility despite lower luminance values.

Qualitatively, the heavy smoke concentration seemed to accentuate the flashing effect. This no light and smoke condition is when human cognition and response would be traditionally delayed as smoke naturally rises to the ceiling. Smoke effectively obscured any mounted exit signs above the door and consequently limited the observer's visibility as compared to the Linear Strobe™.

Association Between Gender and Exit Sign Preference Regardless of Condition

While evaluating results, the researcher investigated whether gender made a difference in the observer's preference. The results from the Cramer's V test indicated a significant correlation

between gender and exit sign type. The Cramer's V value of .498 was reported indicating a strong correlation between gender and exit sign preference based on Corbett's (2001) generally accepted guideline. The significant correlation indicated each gender has a preferred exit sign with both male and female selecting the flashing. This significance is more consistent among males at 72% than females at 54%.

Luminance Correspondence to Overall Preference

The final research question examined the correspondence between luminance levels and overall preference. Luminance levels did not correspond to overall preference and no corresponding trends were noted. However, the luminance contrast levels did correspond to overall preference for the flashing way-finding technology for smoke conditions (worst cases during an emergency). Flashing was ranked the highest by observers during smoke conditions (#2 and #4). Similarly, flashing provided the highest luminance contrast level during the same two smoke conditions.

Results indicated luminance contrast may be more important than luminance level for exit sign performance and visibility especially during the smoke conditions (Conway & Boyce, 1997). The increased contrast levels provided better visibility. In addition, smoke may have contributed to the increased visibility for the flashing effect due to the increased visual angle and scattering of light.

The flashing technology was preferred with the lights on and smoke, where existing ambient lighting would still be functioning. The most critical condition is no lights and smoke where flashing has not been validated to date (Boyce, 2014) as smoke and lights off condition is critically important for egress. The flashing technology was positioned around the door

perimeter, so it was easily detected by observers since it was below the smoke stratification levels compared to the ceiling mounted exit signs. These results are summarized and presented below in Table 11.

Table 11

Luminance Levels vs. Observer's Overall Preference

	Luminance cd/m²	Luminance Contrast (0-1)	Subject Preference
1. Lights On & No Smoke	Red (39.4)*	Green (.74)	Red*
2. Lights On & Smoke	Red (23.8)	Flashing (.65)	Flashing*
3. Lights Off & No Smoke	Green (39.1)	Green (.96)	
4. Lights Off & Smoke	Green (25.4)	Flashing (.79)	Flashing*

* Denotes Significance at .000

Overall, exit sign font color and luminance levels did not correspond to performance. Flashing is a better indicator of visibility where luminance contrast was the highest. This would indicate the flashing has the greatest effect for exit sign visibility especially during the worst case scenarios (condition 2 & 4). This research has challenged the traditional exit sign requirement of readability and visibility with a simpler concept - human cognition and perception is greater for flashing. Therefore, we could eliminate the need for readability during exit sign testing and actual field use.

According to Pulat (1987), the scotopic effect would suggest the green and blue should be visible at no light conditions (see Appendix M). But the blue font and the PLM font did not perform comparably in the experimental phase thus limiting their overall performance.

The researcher observed the simulated smoke concentration was always greater at the ceiling and much less at the ground level. Yet this observation also points to the notion of why

the flashing technology could be seen with greater ease and was preferred overall. Simply stated, the flashing was visible below the smoke layers. Yet the flashing was somewhat enhanced by smoke layers half-way to the ceiling even if the exit sign was obscured. These anecdotal observations demonstrate flashing as an improved exit marking. Existing exit signs can be easily retrofitted with the Linear Strobe™. High hazard areas or occupancies with sleeping areas could benefit from increased exit visibility provided by the flashing.

Conclusions

This study examined six research questions to expand the overall knowledge of the common exit sign and human visual response. The literature review and resultant analysis demonstrated specific gaps existed in the use of flashing way-finding technology, effective font colors, and overall optimal use in emergency conditions (lights off and smoke).

Historically, most of the exit sign research focused on the readability of the exit sign under various conditions. This research challenged that notion and contends attracting human attention in an emergency is required – not readability. During the conditions of a real fire is exactly when exit sign readability becomes difficult whereby smoke obscures the sign font. Given the concept of universal design and way-finding, an aging population, color-blindness, and prescriptive wear use, this research suggests we forgo exit sign readability in exchange for more quickly identified exits and egress. Even if readability were no longer a pre-requisite, the flashing effect would greatly enhance egress times as postulated by subject matter experts (Boyce, 2014).

The most significant finding in this study is 63.8% of the observers preferred flashing way-finding technology overall (30 of 47). In addition, the Linear Strobe™ was seen more easily

during the conditions of smoke. Previous research indicated light may be scattered during smoke conditions causing confusion (Malven, 1986; Rea et al., 1985). However, qualitatively, the smoke seemed to accentuate the flashing effect whereas the ceiling mounted exit signs were simply obscured making readability very difficult.

The following are the major conclusions derived from these research activities:

1. Exit visibility was enhanced by the flashing effect produced by the Linear Strobe™.

Flashing increased the observer's overall visual cognition and response – especially during obscured conditions. In an early pilot study for this research, flashing technology with a green font exit sign was preferred overall. Flashing technology without an exit sign was preferred overall and in smoke conditions with lights on and off. The no lights and smoke condition is especially important in life safety. Therefore, the flashing technology does improve visibility.

2. The relationship between luminance and obscurity was challenged. Traditionally, the results from exit sign studies have shown higher luminance levels corresponded to greater visibility (Collins & et al., 1992; Oullette, 1985; & Rea. et al., 1985). However, flashing with much lower luminance levels was preferred over the traditional exit signs with significantly higher luminance levels. Higher luminance contrast levels may prove more important to visibility than luminance levels when smoke is present, especially when combined with flashing as earlier research indicated without smoke present (Gerathewohl, 1957).

3. Luminance contrast values appear to be more of a determinant than higher luminance levels during obscured conditions (Conway & Boyce, 1997). The Linear Strobe™ had

higher luminance contrast values corresponding to overall preference for smoke conditions.

4. There is a correlation between gender and exit sign preference. The association between gender and exit sign preference regardless of conditions indicates there is a significant correlation between gender and exit sign preference ($p = .02$). Each gender has a preferred exit sign. This preference for both genders is the flashing Linear Strobe™.
5. Quite surprisingly, the UL 924 Standard (2018) requires exit sign testing be conducted under ". . . clear air conditions (and no smoke present)." This does not represent the most critical element of egress such as fire where smoke will naturally rise to the ceiling and obscure traditionally ceiling-mounted exit signs. This study should provide the impetus for testing authorities to certify exit sign and related way-finding products similar to actual fire conditions.

Limitations

Limitations of this study were noted during the study and after the results were finalized.

Those noted limitations are captured below.

1. The variation between LED font colors was not anticipated. The LED exit sign was designed to eliminate luminance and luminance contrast variability between font colors. This unintentional variability is thought to be from the manufacturing process. An improved design has already been implemented and demonstrated in another study.
2. Although adequately simulated, the smoke concentration to obscure the exit signs was not objectively quantified. The pilot study utilized three 10,000 cfm smoke candles while the study generated smoke from a theatrical smoke machine. Neither method effectively

captured the actual smoke concentrations such as measuring optical density with laser designed for such measurements. Such equipment was beyond the scope of this study.

Therefore, light scattering and diffusion properties cannot be characterized adequately.

3. In an actual building fire, emergency lighting is required and during no light conditions this lighting will illuminate the escape route. For this study, ambient lighting and emergency lights were not considered during no light conditions. However, additional building illumination, or emergency lighting, is thought to increase the scattering of light and decrease sign visibility (Rea, Clark, & Ouellette 1985).

4. Exact color measurements were not provided and beyond the scope of this study.

Actual font color is determined by light's composition and how the human eye perceives this electromagnetic energy; but, precise color measurements are important for determining optimal font color. One such method, the precise color measurement for exit sign color is specified by Commission Internationale de L'Eclairage (CIE) x, y chromaticity coordinates. Exact color measurements are critical in determining human luminous efficiency such as those presented on the various scotopic and photopic curves. The question of how the optimal colors are perceived by humans is challenged by the various luminous efficiency curves created with resultant illumination levels (see Appendix M).

5. The study could only solicit the help of 47 volunteers for the study. Time constraints and busy schedules prevented many other volunteers from participating in the study. In consideration of the no shows and cancellations, the study was difficult to schedule with

the participant's schedule and perform. However, larger sample size is preferred. The G-Power analysis showed 133 participants were needed to run this study.

6. The observer's predisposition and familiarity to the already existing red and green color exit signs font installed in most buildings today in the U.S. may have created an inherent bias amongst observers. Observers may have responded to what they are most familiar with as exit signs. In addition, the sequence of exit signs presented and the conditions were not randomized due to ventilation and administrative concerns. These two factors added to the uncontrolled variability in this study.

7. Inversely, observers may have been biased by the flashing way-finding as being entirely new and unique. As such, observers may have selected flashing due to this familiarity versus unique effect. During the study, all observers reported not being aware of the flashing technology or ever seeing this technology prior to the testing.

8. Previous studies with exit sign visibility required good visual acuity similar to the Observational Visibility Test requirements under UL 924 (2018). The study was open to all participants regardless of their vision level; however, most of the participants were reported as having good visual acuity.

Future Research

The following summary points to further research to be considered when evaluating exit signs and way-finding technology.

1. Expand the exit sign font colors evaluated. Research should validate the optimal wavelength of light perceived by humans. Ideally, future studies should be designed to include colored light measurement with spectral sensitivity matching the CIE tri-stimulus

or three-color colorimeter. As MacEvoy (2015) has observed, in no light conditions, optimal font colors would be short wavelengths of light or more blue than the traditional red font colors (see Appendix N). Unfortunately, with the unforeseen LED font color variability, the optimal font color and resultant observer evaluation was not as robust as originally designed.

2. The question of low-light acclimatization should be noted. To capture the full low light vision, observers would have required additional time to acclimate. However, in a true emergency scenario, this would not be possible. Therefore, this researcher opted to have a very limited time (three to four minutes maximum) to acclimate to the no light scenario. This time delay was only to confirm study set-up and observation tunnel was ready. Future research should focus on emergency scenarios without regard to acclimating to the dark to simulate real emergencies where rapid egress is important.

3. Fire code requires flashing annunciators to indicate when a fire is present, or when the manual pull station is activated. But exits may still be difficult to locate if the flashing annunciators interfere with the flashing way-finding technology. For example, how will the Linear Strobe™ function with the flashing annunciators located nearby? Perhaps flashing exit signs could be integrated with flashing annunciators. Coordinated flashing way-finding, exit signs, and markings should be further examined.

4. Future research should look more closely at the flashing and actual color coordinates used in the Linear Strobe™ product. An early pilot study conducted by the researcher with color-blind and legally blind observers indicated the flashing could be discerned. These observers are not adequately represented in exit sign research and these initial

qualitative findings are what prompted this research design and evaluation. Additional research on the optimal wavelength of light is required. The flashing technology was reported by the manufacturer to be a wavelength of approximately 395 nm. Was the color, luminance contrast, or flashing preferred? Or, is it a combined effect overall? The Purkinje effect illustrates how the human eye shifts towards the blue end of the spectrum at low illumination levels. This near-uv wavelength may be significant as during nighttime, or periods of darkness, Pulat (1987) has shown human vision is most sensitive to the lower wavelengths (see Appendix N). As a result, we should examine the lower wavelength of light such as blue-green exit signs being optimal instead of red exit signs. This concept should be further explored and validated to optimize Life Safety.

5. A larger sample size is recommended. The sample size was 47 and additional studies with a larger sample size should be conducted to confirm the results of this research.

6. Future studies should be expanded to incorporate children, elderly, and especially limited-vision observers. The historical research model that emphasizes exit sign readability and including only observers with good visual acuity should be challenged. By continuing to perform studies with observers demonstrating good visual acuity, we are excluding our most vulnerable populations already vulnerable to delayed egress times.

7. Consider conducting research with white, black, and grey smoke to adequately represent field conditions. Research should specify smoke color (black, grey, and white) to reduce variability across studies. Visibility studies with exit signs should reflect the expected fire conditions.

8. In addition, an approved standard for smoke generation and certification should be further explored. The ability to control for smoke concentrations is still necessary to control variability. Whether this standard is for actual flammable combustion and smoke generation or simulated computer modeling for smoke generation, there is a need to standardized smoke generation when testing exit signs and way-finding technology. A precise testing model for smoke generation is critical for accurate exit sign testing and validation. Smoke generation and resultant testing methodology requires further quantification. This concentration measurement must be quantified for further research reliability.

9. Exit sign testing and certification should reflect field conditions during a fire or other emergency. Regardless of the issues associated to smoke simulation, Life Safety components should be tested replicating field conditions. Current exit sign testing methodology should be improved to include the conditions of smoke and lights off. The current UL 924 exit sign testing and certification should be updated to reflect conditions found during a fire. Such as the smoke conditions resulting from actual fires humans may encounter such as the complex obscurity conditions from smoke. Improving our exit sign testing methodology and certification process was another impetus for this study.

10. This study did not consider the aspect of sound to locate an exit and evacuate safely. However, the concept of sound escape guidance has been tested previously and has been shown to be effective (Yamada & Akizuki, 2016). Can future exit sign technology utilize directional sound to help occupants locate exits? Instead of fire alarms (annunciators) merely alerting occupants when activated, an audible alarm could also be used as an

ancillary aid to escape. This is an interesting addition to the traditional exit sign and way-finding selection and can only enhance egress times.

Summary

To summarize, the flashing way-finding technology (Linear Strobe™) performed better with smoke present with lights both on and off. Flashing was also preferred overall compared to LED font colors of red, green, and blue; and PLM font. Luminance contrast was highest for flashing and was noted as a trending factor that may help explain significance. Observers preferred flashing as exit visibility improved during the smoke conditions similar to those encountered during a building fire. Additional research should be conducted with exit sign cognition and way-finding optimization. These future studies should examine the effects of different exit light conditions using participants with marginal visual acuity and good visual acuity.

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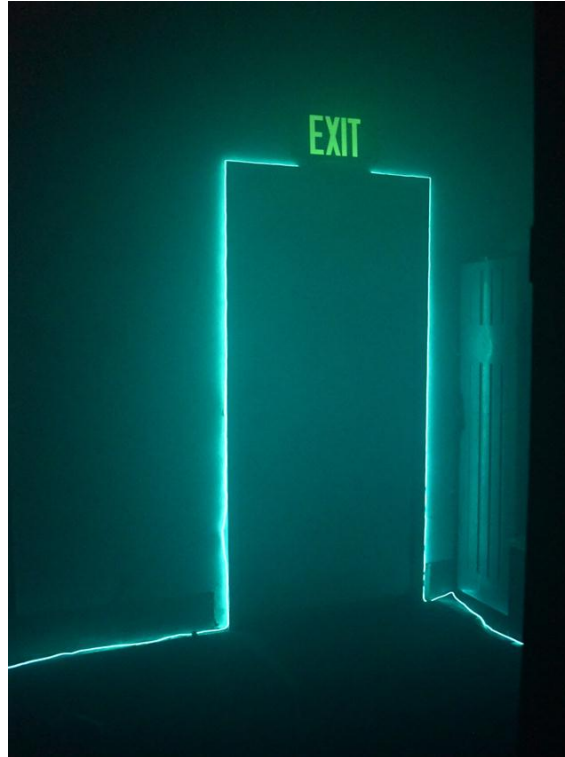
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Appendix A

Linear Strobe™ L-100 Way-Finding Technology

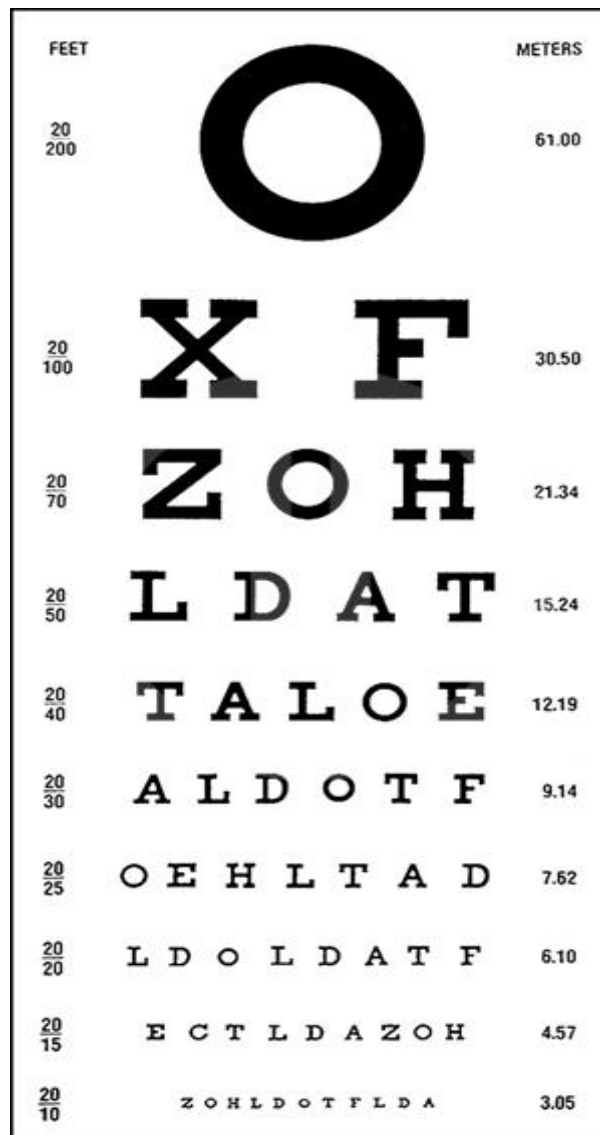


The Linear Strobe™ L-100 Way-Finding Technology by LightSaver Technologies, Inc.



Appendix B

Snellen Visual Acuity Eye Chart



Source:

Adapted from the Ophthalmic News and Education Network©, 2018. Retrieved January 11, 2018 from <https://www.aao.org/image/snellen-chart>. Copyright by the American Academy of Ophthalmology. Used with permission.

Appendix C

Exit Sign Visibility Rating Form

Please provide a rating best representing the visibility of each Exit Sign Selection using a scale of 1 to 5 with Strongly Disagree being 1 to Strongly Agree 5.

EXIT SIGN TYPE	Exit Sign Red	Exit Sign Green	Exit Sign Blue	Exit Sign PLM	Door Jamb LED
CONDITIONS					
Lights On & No Smoke					
Lights Off & No Smoke					
Lights On & Smoke					
Lights Off & Smoke					

1. Not Visible at all nor recognizable as exit
2. Barely Visible as exit but unsure
3. Somewhat Visible but Perceivable as an exit
4. Visible and Perceivable as an exit
5. Easily Visible and Easily Recognized as exit

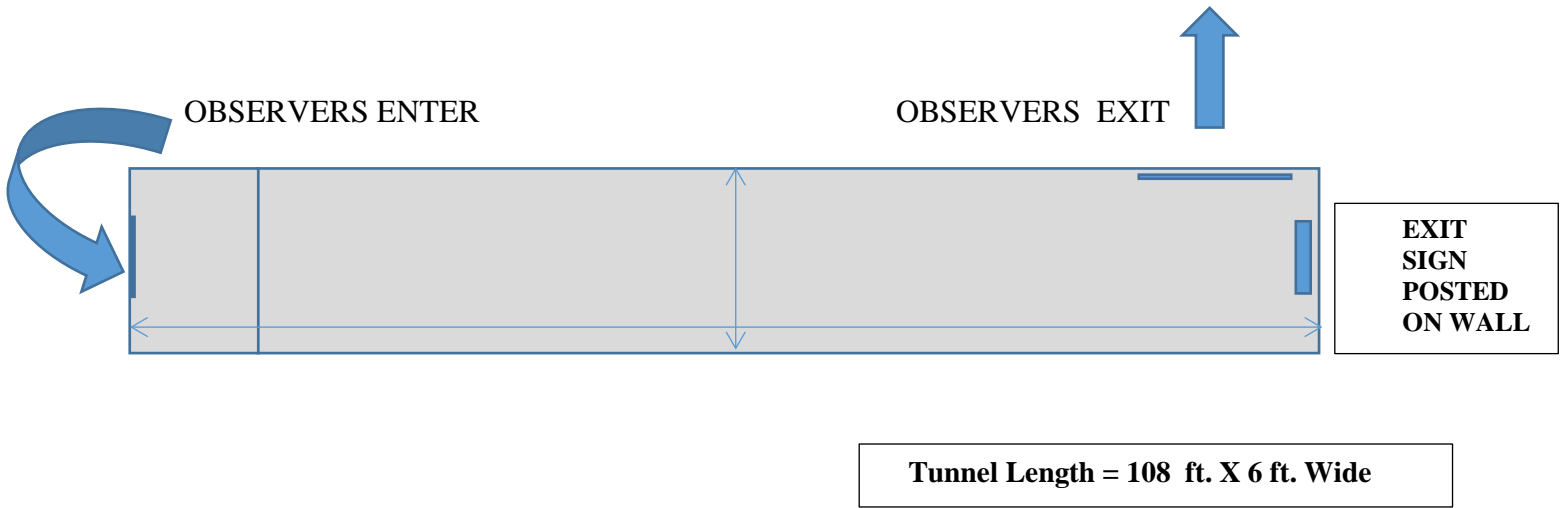
Select Best Exit Sign Overall and Why?

Select Worst Exit Sign Overall and Why?

M/F Age:
Color Blindness: Y/N

Prescription Glasses/Contacts/Surgery: Y/N
Minimum Visual Acuity: Y/N

Appendix D
Tunnel Schematic



Appendix E

Simulated Smoke Generator



Picture of smoke generator used to simulate smoke conditions.

Appendix F
LED Exit Sign



LED exit sign design and remote used to change font colors.

Appendix G

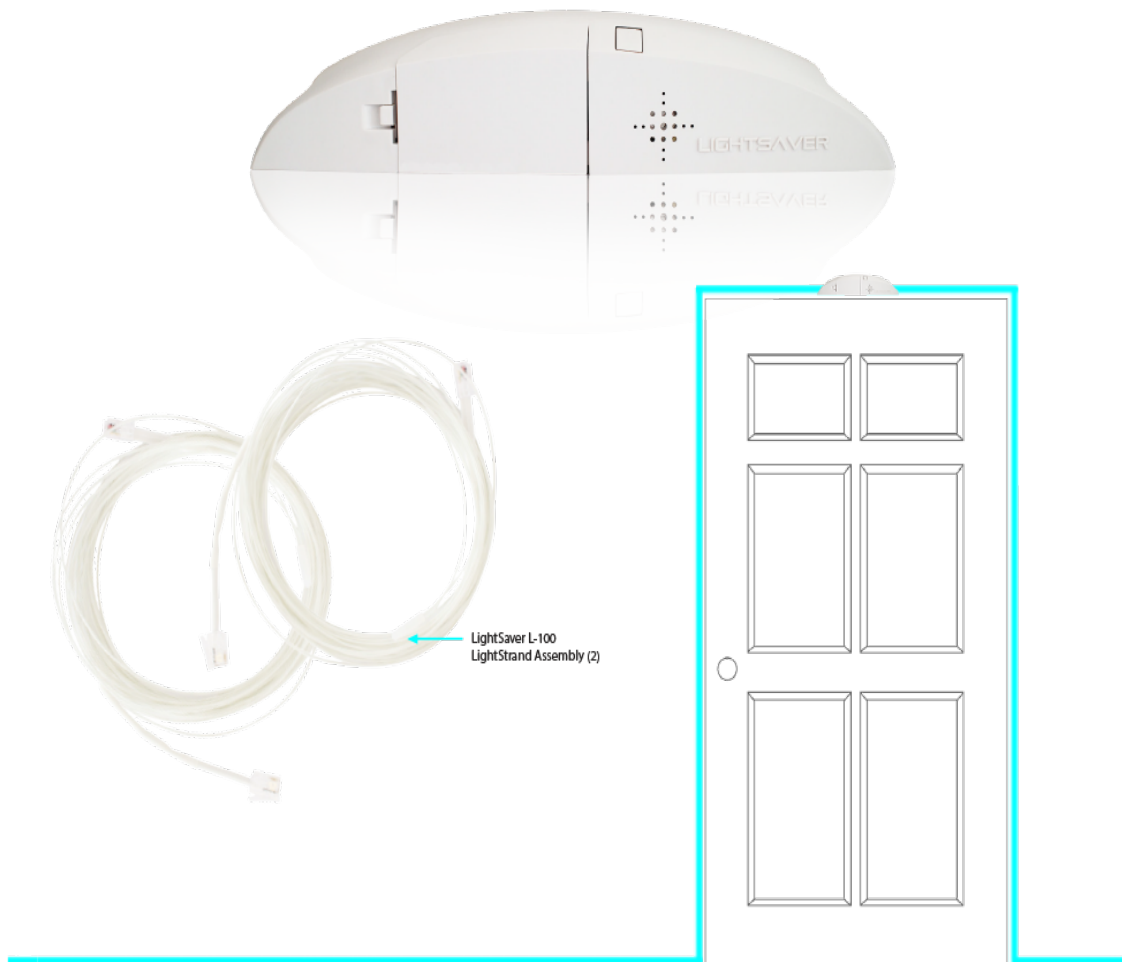
Photoluminescent Exit Sign



Photoluminescent Exit Sign using epoxy coating by MN8 Foxfire©.

Appendix H

Linear Strobe™ Model L-100



Adapted from the LightSaver Technologies©, 2018. Retrieved April 17, 2018 from <http://www.thelighthatsaveslives.com/product/lightsaver-l-100/>. Copyright by LightSaver Technologies. Used with permission.

Appendix I

LS-100 Photometer



The Konica-Minolta© LS-100 photometer used to measured luminance levels and luminance contrast.

Appendix J

Informed Consent Letter

Dear Study Participant,

Thank you for your response to our Exit Sign Research Project. Your participation will assist Safety Professionals determine the optimal exit sign and related technology. This study is being conducted by Joseph Whitlock, a doctoral student with Indiana University of Pennsylvania. Data and information from this study will be required for dissertation research. In addition, results may be published in scientific journals or presented in scientific meetings.

The Indiana University of Pennsylvania Institutional Review Board has approved this study for the Protection of Human Subjects (724.357.7730).

Your participation is voluntary. All required responses would remain anonymous. Name, gender, visual acuity, physical limitations, or related health conditions will remain anonymous.

Total time to participate is estimated to be 20 minutes. There are no known health risks. Theatrical “smoke” will be generated but a clear glass partition will separate the observer’s side from the point of generation 100 feet away. A safety Data Sheet will be available on-site. At any time during the study you may stop. Future participation is your decision.

Your informed consent is required prior to the study. Where consent has been provided, at any time you may choose to stop and withdraw from the study. Be advised the rating form is anonymous and once your rating form is submitted you may not withdraw from the study because the forms have no identifiers or means to identify study participants.

If you have any questions, or need additional information, please contact me at any time with the following university email: ZTCT@iup.edu.

Please indicate your consent and agreement decision by checking the appropriate area below.

- I provide my consent and agree to participate in this study.
- I do not provide my consent and disagree to participate in this study.

- Best Regards,

Joseph Whitlock
Doctoral Student, Safety Sciences
Indiana University of Pennsylvania
937.502.5521

Dr. Majed Zreiqat,
Assistant Professor and Dissertation Chair
Indiana University of Pennsylvania
724.357.3017

Appendix K

Ishihara Color Plate Example



A



B

- A. Demonstration of the Ishihara color plates to determine color blindness.
- B. close-up of #5 and #3 color plate.

Adapted from the Ophthalmic News and Education Network©, 2018. Retrieved June 14, 2018 from <https://www.aao.org/eye-health/diseases/how-color-blindness-is-tested>. Copyright by the American Academy of Ophthalmology. Used with permission.

Appendix L

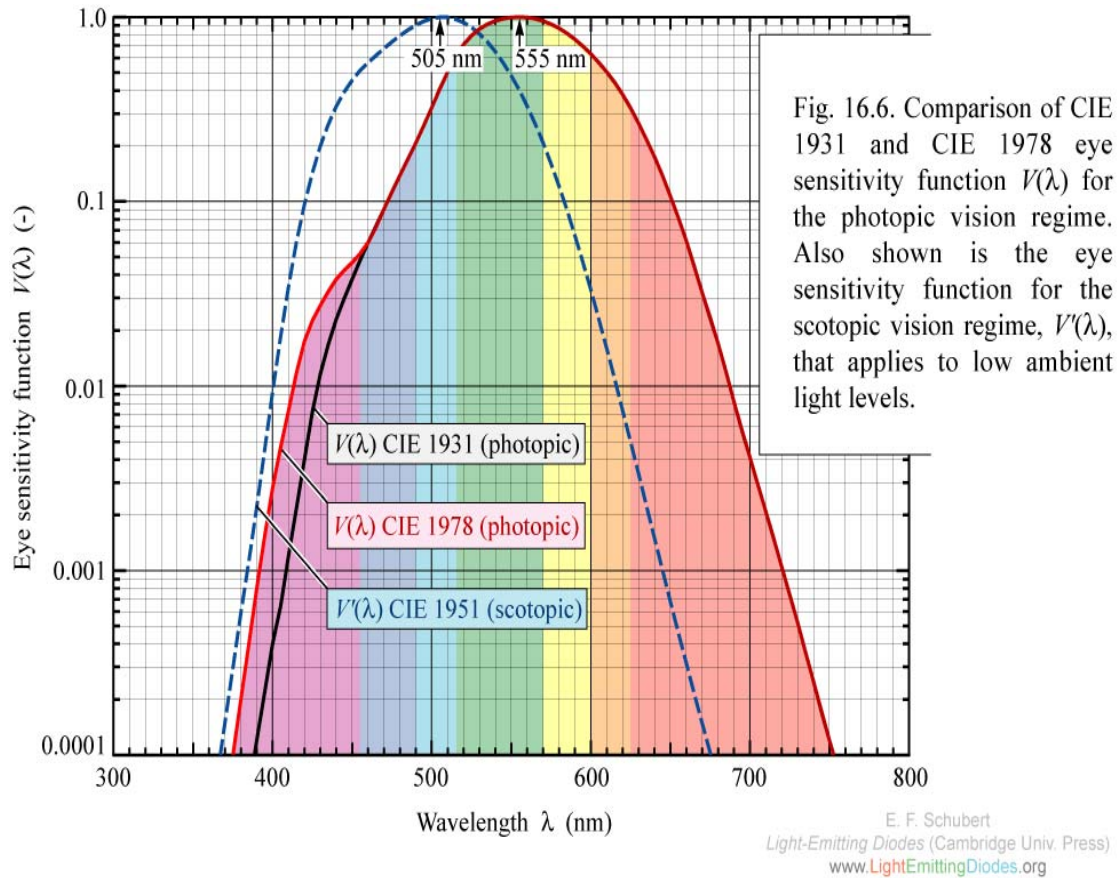
Illuminance Light Meter



Light Meter (#840021) by SPER Scientific© used to measure background illuminance.

Appendix M

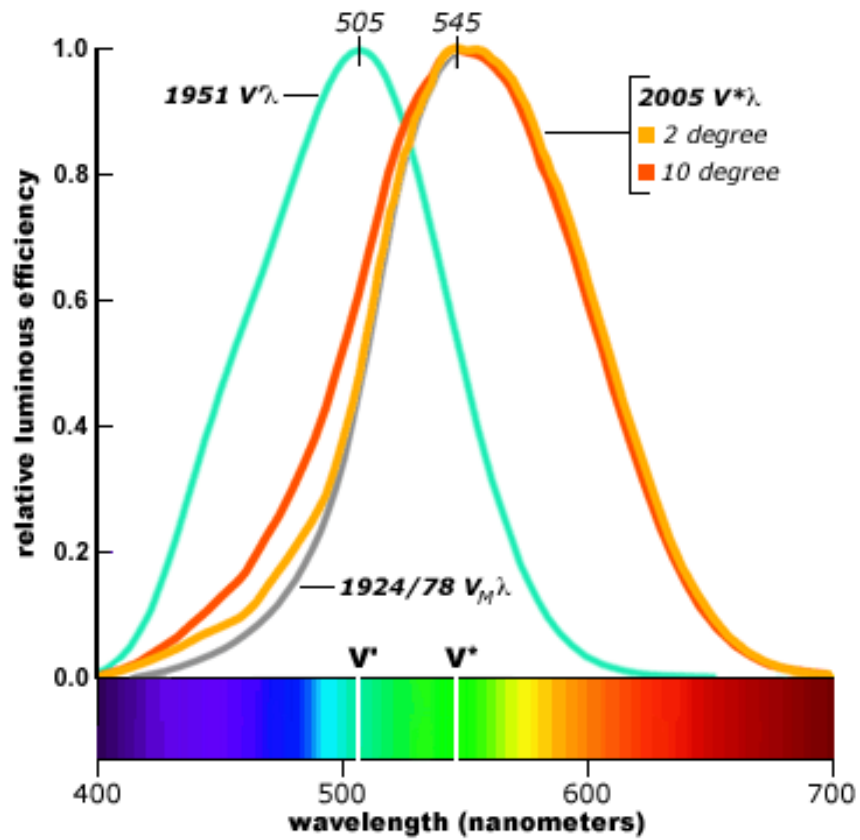
Photopic and Scotopic Eye Sensitivity Function



Adapted from Schubert, 2018. Retrieved April 17, 2018 from <https://www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/Sample-Chapter.pdf>. Copyright by E. F. Schubert. Used with permission.

Appendix N

Photopic and Scotopic Luminosity Function Comparison



Comparison of Photopic & Scotopic Luminosity Functions - photopic function 2° and 10° quantal cone fundamentals of Sharpe, Stockman, Jagla & Jägle (2005), compared with the CIE 1951 scotopic function and the Judd-Vos 1978 photopic function.

Adapted from Handprint, by B. MacEvoy, 2015. Retrieved June 14, 2018 from <https://www.handprint.com/HP/WCL/color1.html>. Copyright 2015 by Bruce MacEvoy. Used with permission.

Appendix O

Copyright Permissions

RE: PhD Dissertation use request

Debra Marchi <dmarchi@aao.org>

Dear Joseph,

No formal permission request is needed. Hopefully this email suffices that you have permission to use the image (I've attached it). Also, please use the following credit line:

© 2018 American Academy of Ophthalmology

Thank you.

Debra Marchi
Administrative Assistant
American Academy of Ophthalmology
655 Beach Street
San Francisco, CA 94109
O: +1 415.447.0269
dmarchi@aao.org
aao.org

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From: Joseph Whitlock <ztct@iup.edu>
Sent: Monday, November 12, 2018 6:47 PM
To: Debra Marchi <dmarchi@aao.org>
Subject: Re: PhD Dissertation use request

Debra,

Yes, please.

Those images of color plate 5 and 3 work just fine. thank you, joe

From: Debra Marchi <dmarchi@aao.org>
Sent: Monday, November 12, 2018 6:01:18 PM
To: Joseph Whitlock
Subject: RE: PhD Dissertation use request

Dear Joseph,

Unfortunately, the Academy does not own copyright to that figure. Copyright belongs to shutterstock. If you would like to purchase it, here's the [link](#).

However, we do own copyright to this [color testing image](#). Would you like me to grant you permission for it?

Ishihara Color Plates Figure from the American Academy of Ophthalmology.

KONICAMINOLTA Customer Contact:Please check No.G034606

WeiHua Ng <weihua.ng@konicaminolta.com>

Dear Joseph,

Thank you for your email.

Yes, you may cite and reference our "Emergency Lighting Measurement of Exit Signs" web article in your PhD dissertation.

Thanks.

Regards,

Wei Hua

Marketing Executive

Konica Minolta Sensing Singapore Pte Ltd

10 Teban Gardens Crescent Singapore 608923

T:6563 5533 D:6895 8685 F:6560 9721

<http://sensing.konicaminolta.asia/>

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--Your Question--

Category : Corporate Information

Question: I am seeking permission to cite and reference your "Emergency Lighting Measurement of Exit Signs" web article located at <https://sensing.konicaminolta.asia/wp-content/uploads/2017/08/Emergency-Lighting-Measurement-of-Exit-Sign.pdf> in my PhD dissertation regarding exit sign evaluation. thank you in advance, joe

--Customer Information--

Name : joseph whitlock

Mail : ztct@iup.edu

Address : 4239 brewsters run court

City: bellbrook

State/Province/Region: ohio

ZIP/Postal Code: 45305

Country: USA

Tel : 937.502.5521

Company : Indiana University at Pennsylvania

Job Title : researcher

Running Man pictogram from Konica Minolta.

Snellen Eye Chart Permission

Debra Marchi <dmarchi@aao.org>

Dear Joseph,

Please feel free to use the image in your PhD dissertation. Please use the following credit: © 2018 American Academy of Ophthalmology. Thank you.

Debra Marchi

Administrative Assistant

American Academy of Ophthalmology

[655 Beach Street](http://655%20Beach%20Street)

[San Francisco, CA 94109](http://San%20Francisco,%20CA%2094109)

O: +1 415.447.0269

dmarchi@aao.org

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Snellen Eye Chart Figure from the American Academy of Ophthalmology.

Re: Permission Request

Bruce MacEvoy <macevoy@handprint.com>

Wed 10/24, 9:55 PM

Joseph Whitlock;

Whitlock, Joseph C. <joseph.whitlock@wright.edu>

granted; thanks for asking, although permission not needed. see the FAQ on citing materials.

best,

bruce

On Oct 23, 2018, at 7:36 PM, Joseph Whitlock <ztct@iup.edu> wrote:

Absolutely love your website and materials!!!!

I am finishing my dissertation of exit sign font colors and would like formal permission to use your EM spectrum and scotopic/photopic efficacy chart.

Of course I would fully cite your work only with your permission.

sincerely, joe whitlock, phd candidate

Electromagnetic Spectrum Scotopic & Photopic Luminance Efficacy Chart from Bruce MacEvoy.

Nov 13, 2018 at 1:45 PM

Absolutely Joe: by all means please feel free to use the graphics and if you need others, just ping me and we would gladly forward over to you.

-Jerry

On November 13, 2018 at 10:02 PM "Whitlock, Joseph C." <joseph.whitlock@wright.edu> wrote: Jerry

At editor found out I omitted you approval to use this image below:

Will you grant me permission to use your image below in my dissertation?

Thanks in advance, joseph whitlock, PhD candidate

Linear Strobe figure from LightSaver Technologies.

Fwd: Primalence Contact form [joseph whitlock - joseph.whitlock@wright.edu]

Reply all |

Wed 11/7, 9:52 AM

Hi Joseph,

Thank you for asking. Absolutely no problem. Please just mention us somewhere.

If you want to discuss the figures or tell me about your paper, you can contact me on email and we can set up a time to talk on the phone.

My father was involved in the base research regarding visibility.

Best regards

Daniel Björk

International Sales Manager

Hörnåsvägen 64, SE-89440 Överhörnäs, Sweden

Office: +46 660 84335 (7), daniel@primalence.se

www.primalence.com

Vidarebefordrat brev:

Från: Fareed Ishani <fareed@btconnect.com>

Ämne: FW: Primalence Contact form [[joseph whitlock](mailto:joseph.whitlock) - joseph.whitlock@wright.edu]

Datum: 7 november 2018 15:44:38 CET

Till: Daniel Björk <daniel@primalence.se>

Hi daniel,

Can you please respond to this.

Thanks

fareed

----- Original Message -----

Subject: Primalence Contact form [[joseph whitlock](mailto:joseph.whitlock) - joseph.whitlock@wright.edu]

Date: 2018-11-05 02:51

From: primalenceuk.com <noreply@primalenceuk.com>

To: webby@primalenceuk.com

name

joseph whitlock

email

joseph.whitlock@wright.edu

tel

9375025521

message

I am writing to seek permission to use your photopic and scotopic

figures in my PhD dissertation. Those figures are found here:

http://www.primalenceuk.com/image_display?ppid=936&ccid=1174&blid=6&k=1

thank you in advance, joseph

Scotopic & Photopic Comparison Chart and Scotopic & Mesopic Chart from Primalence of Sweden.

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Name: Joseph Whitlock
Title: PhD Candidate
Date: 11.05.2018

AGREED AND ACCEPTED BY:
UNDERWRITERS LABORATORIES INC.



Name: Richard Olesen
Title: Standards Manager
Date: Nov. 11, 2018

Luminance points of measurement figure from Underwriters Laboratories.