HUMAN-ENVIRONMENTAL INTERACTION:

POTENTIAL USE OF PUPIL SIZE FOR OFFICE LIGHTING CONTROLS

By

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Dedication

This thesis is dedicated unconditionally to my family. The thesis can not be realized without their insistently support. My dad didn’t have a chance to see the completion of this thesis, but without him, I would not receive the opportunity to receive great education and start this thesis. My mom, sacrificed even more, bearing the sorrow and loneliness, to support me to finish all the thesis work.

Thank you dad, thank you mom! I love you forever.

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Abstract

The goal of this research is to establish a visual environment diagnostic model based on the occupant's physiological responses for detecting improper ambient lighting conditions, a major contributing factor to visual stress and work productivity in office workplace environments. The human body, as a biological mechanism, naturally minimizes the effects of ambient environmental stressors using its physiological autonomous nerve system. This system enables a human's pupils to dilate and contract, depending on visual sensations affected by the ambient lighting conditions. An extensive experiment using human subjects will be conducted in an environmental chamber on the University of Southern California campus. All parametric data including human pupil sizes and lighting parameters will be categorized by age and ethnic origin, to investigate and determine the most common features of pupil sizes per visual sensation among individuals. Lighting parameters, including illuminance (lux), luminance (cd/m2), and lighting-color-temperature (K), will be controlled and maintained for each volunteer subject based on his/her task-type (computer-based or paper-based), which is most typical in the current office environment.

This study will provide unique knowledge concerning how an occupant via his/her physiological signal, i.e. pupil size can interact with the visual (lighting) environment. The research outcome will be potentially applicable in reality to diagnose the lighting quality in workplace environments, and to integrate an occupant's pupil size information for the visual environmental controls.

Hypothesis

Lighting design in the office building is always a crucial part for the whole indoor environment quality. At present, in the US, most office buildings have adopted guidelines that were empirically developed, primarily by the IESNA (Illuminating Engineer Society of North America). But these guidelines that were empirically developed, mainly based on a conventional paper-based bask-dominant environment. However, a computer-based work has become the most popular task in the office since personal computer's prosperity existed this 20 years. In this case, current guidelines are not fit for the new working task. Furthermore, lighting simulation programs and High-Dynamic Range (HDR) have also been used for detailed investigations such as lighting design and glare analysis. However, human physiological features are not considered in any of these current approaches. Regarding the biological function, pupil size could be potentially used in the research to establish a visual quality assessment tool based on measuring an individual's pupil size so as to ensure one aspect of visual comfort in the built environment.

Chapter 1: Introduction of Study

Buildings have consumed almost 40% of all the energy consumption in the United States. The number seems to be larger when it talks about the whole world. However, among all types of buildings, the commercial or office buildings occupy large ratio of energy consumption. Lighting, as one of the most important key components in the indoor environmental quality, nearly the most significant one for the office environment, has a great relationship in energy consumption as well as huge effect on human health and productivity.

Designing good lighting conditions attracts favorable attention from both architect and engineering. Architects would have artistic lighting for a better presentation of the design: highlighting details, dividing zones, creating a unique atmosphere and so on. While, for engineers, their job is to ensure there is at least enough lighting for occupants to accomplish their work. The occupants do not need to pay extra focus on getting right position for better lighting, or feel tired due to improper lighting environment, which could be either too dark or too bright while causing problems like glare. Demands from architects and engineers need realistic solutions. Design guidelines or strategies are most appreciated especially when they could ensure basic lighting level for high productivity as well as strengthen architecture artistic highlights. Maintaining most ideal lighting environment is very impressed these days in the industry and academia.

1.1 - Problem

Although great effort has been made for better indoor environment quality, most indoor environmental components are managed based on pre-defined human comfort formulas and not on the actual building occupants' needs. Typically, environmental formulas are attained by calculations and adopted to system industry standards and guidelines. As a result, an individual‘s comfort is easily affected negatively, and unsatisfactory ambient conditions end up with affecting the occupants’ work productivity and environmental health. Lighting, of all of these factors, is most significantly related to the occupants’ visual comfort, which is instantly affected and is easily vulnerable due to its immediate sensitivity. Recent studies have reported that 65% of building occupants express that their workplace lighting conditions as inappropriate. These occupants also report that they have considerable glare problems in their workplaces, which can lead to serious visual stress(Irlen 1991). Despite its significance, most office buildings have adopted empirically developed guidelines established mainly by the Illuminating Engineering Society of North America (IESNA). Overall, these guidelines were designed mainly based on general paper-based task environments which suggest that lighting guidelines may not satisfy each individual lighting preference, and may result in unnecessary glare. Current technical tools, such as lighting simulation and photo-based analysis (i.e. High Dynamic Range image) have no functional feature to estimate a user's visual sensations in real time.

There are many lighting simulation software used in Building Information Modeling (BIM) for daylight, including Ecotect, Radiance, Daysim and 3ds Max. Ecotect is mostly used for early daylighting design, for the second stage, Radiance could provide more accurate daylighting analysis; Furthermore, Daysim offer functions to control daylighting with presenting performance at the same time. While, 3ds Max will create outstanding daylighting visualization so as to explain lighting condition more directly. For artificial lights, there is less choice, however, 3ds Max and AGI are considered as a good one.(“Lighting Analysis in BIM | Sustainability Workshop” 2014) Figure 1.1 shows a simulation interface in the software.

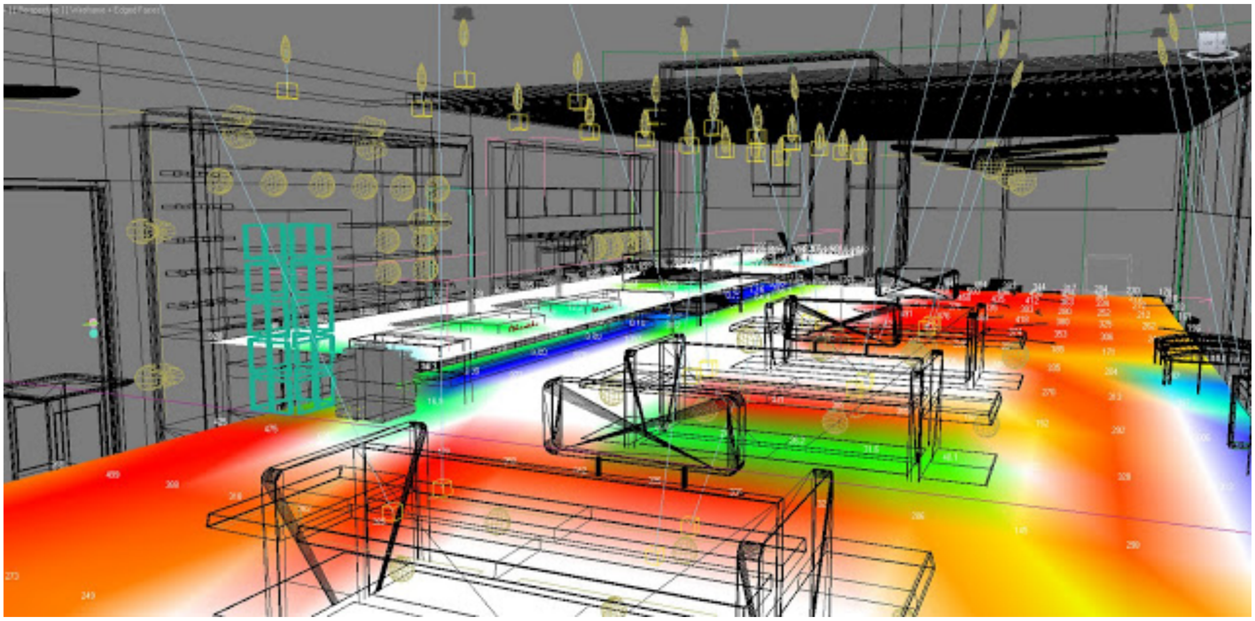


Figure 1.1 View in a Lighting Simulation Software: Autodesk 3DS MAX

(“Light+Architecture: Lighting Simulation Software: Autodesk 3DS MAX” 2011)

Another popular tool in lighting design is High Dynamic Range (HDR) image. HDR could achieve a higher dynamic range of luminosity and represent more accurately than commonly used digital images by mostly merging multiple low dynamic range (LDR) or standard dynamic range (SDR) photographs. HDR is good because of containing huge amount of information. However, it takes too much time and effort to collect enough images, which are also not cost efficient for public use. Figure 2 presents a comparison between HDR image and normal image.

Figure 1.2 Normal Image vs. HDR Image

(“6 Tips for Taking Better Macro Photos with the iPhone Camera” 2012)

What’s worse, neither of the two major tools can obtain real time function to estimate occupants’ visual sensation. That is another reason figuring out a new way for aiding lighting design and control is highly demanded.

1.2 – Physiological Response

The human body has an autonomic function that regulates its physical responses to minimize any environmental stress, such as hot or cold temperatures, or excessively bright. For example, depending on the intensities of various stressors, the skin on a human body could sweat or control the surface body temperature to balance heat losses or gains caused by ambient thermal conditions, and pupil sizes could shrink or dilate in response to variations in light. Therefore, this research adopted human pupil sizes as a feasible physiological signal to estimate visual sensation conditions (based upon the principle of reverse engineering) that could illustrate subjective lighting sensations as a function of objectively measured physiological signals. The result would be a novel method for visual quality assessment, such as a lighting simulation program and high-dynamic images, as compared with conventional methods that have primarily depended on pre-assumed human environmental reactions, instead of real human physiological responses.

1.3 – Pupil Size

Located in the central iris of human eye, the pupil is a hole which allows light to come into the retina (Cassin & Solomon, 1990). It always shows black as the light coming into the pupil are absorbed by the tissues or absorbed within the eye after diffuse reflections. The anatomical pupil serves as aperture and iris as the aperture stop. The iris is consisted mainly of smooth muscle, surrounding the pupil. Iris controls the amount of light entering the pupil by changing its size.

The pupil gets narrower in the light but wider in the dark. The diameter gets to 3 to 5 mm when exposed to bright and respectively, to the maximum of 4 to 9 mm. Age is believed to have significant effect on maximal pupil size. For instance, the diameter of the pupil could be 4mm to 9 mm when in a dark environment at age of 15. However, the average pupil size decrease at a non-steady rate when human is older than 25.("Event Horizon Volume 3 6 Aging Eyes and Pupil Size" 2014; Winn et al. 1994) More information would be discussed more to indicate the importance and possibility of using pupil size for the lighting control and improving human health.

1.4 – Objective

The first purpose of this research is to establish a relationship between lighting conditions and human pupil size, especially, the correlation between the illuminance levels and pupil size change. By understanding effect of lighting condition on the pupil size, the possibility of adopting pupil size serving as an indicator for the use of automatic lighting control could be discussed.

The second objective of this study is to understand the variation of human pupil sizes among different physiologically categorized people and to investigate the difference between raw pupil sizes and normalized data. Human subjects differentiate from each other due to physiological features. So does pupil. Pupil of people could behave significantly differently from each other under the same lighting condition which indicates a various demand for the lighting. Therefore, to check the variation of human pupil sizes is also very important to the study.

The third aim is to establish a visual quality assessment tool based on reading an individual pupil size in order to demonstrate the potential use of pupil size for assuring visual comfort in the office environment. Visual quality assessment depends seriously on huge amount of pupil size data in different lighting environments and also a great variety of human subjects. With the established visual quality assessment tool, it will be easier to judge satisfactions or comfort feeling level of set lighting condition. As there are different requirements from individuals, an optimal control strategy for office lighting setting would be decided based on e basis of all occupants in that space. These strategies will help maintain a comfort lighting condition.

Meanwhile, practicing all related devices and software used in the project could be another objective. Learning graphic programming in LabVIEW would benefit author a lot in future engineering work. Furthermore, physical installation and related lighting device and of course Mobile Eye XG would consolidate strong foundation of research skills related to lighting.

Chapter 2: Background Research

This chapter reviews previous studies and other sources relevant to lighting parameters discussion and the use of pupil size in the lighting design area. Reviewing the potential benefits and problems associated with pupil size and other important factors will help determine the scope of the work in the study. Background information pertinent to the main areas of this thesis was studied to help understand lighting parameters and function of pupil size as well as its potential use in lighting design and control.

2.1 –Human Health and Productivity Corresponding to Lighting Environment

In order to understand better about the importance of proper-designed lighting in the office environment, many studies have been conducted to investigate the correlations between human health and productivity and different lighting conditions. A study conducted by Cornell University (Hedge, Sims Jr., and Becker 1990) reported some findings of the offices which use computers regarding the relationship of productivity, satisfaction and visual health of employees and office lighting conditions in the background research. Complaints about light were collected from 68% of workers in their offices based on the information provided by The American Society of Interior Designers. A better lighting was demanded by 79% of VDT (Video Display Terminal) users according to a study of Silicon Valley. A Louis Harris study in 1989 pointed out eyestrain ranked as number one health hazard in the office which is ahead of radiation and asbestos. All dissatisfaction discussed above is difficult to ignore which indicates potential lighting problems. Better office lighting should be worked out to maintain the visual comfort for the human subjects.

Not only in the surveys dissatisfaction was given to the lighting, but also other researchers explained how lighting influence productivity. “We know that lighting affects people psychologically and physiologically."(Dilouie 2003) Visual impression occupies 80 to 85 percent of the entire process of learning about the world. However, perception depends on lighting that makes it possible to for the visual purpose. Since people spend a large portion of their time indoor, lighting is in charge of human being's predominant perception of the world. It has been long claimed that some lighting design methods are better as the lighting quality can improve employees' satisfaction. Nowadays, it is much harder to evaluate worker productivity in offices, making satisfaction more important than before serving as a metric. Regarding the important role in assessing performance and productivity of participant in the experiment, a satisfaction survey was given to each participant in the experiment during the whole project.

2.2 – Achieving Better Lighting Environment and Design Methods

Many researches have been done to figure out better lighting methods in the office including changing the lamp type, workplace layout, color temperature, illuminance and many other potential elements in lighting control.

In the Cornell Study (Hedge, Sims Jr., and Becker 1990) as mentioned above, it was designed to decide if applying a lensed indirect uplighitng system or a parabolic downlighting would create any difference in the "visual comfort, satisfaction, health or productivity of computer workers". The research reported twice frequent complaints of tired eyes and concentration problems in the indirect uplighting group than the parabolic group. Furthermore, it was more bothersome in the parabolic than in the lensed indirect, and visual discomfort problems under parabolic lighting conditions cut into worker productivity.

And in the research set up by Craig Dilouie, the effect of different forms of realistic office lighting on the performance and health of employees in the offices was studied (Dilouie 2003).

Variables in the study included personal control for lighting, room surface brightness and so on. The study concluded that direct/indirect fixtures was reported more comfortable than lensed and parabolic troffers; People reported better lighting quality, satisfaction and showed higher performance of attention and productivity when there was a dimmer for them to control; People showed positive attitude to the job and working environment when they felt more satisfied with lighting quality; Better task ability would be achieved by improving visibility in the lighting and task conditions.

In summary, the study conducted by Dilouie found that people would feel more satisfied when it was brighter on non-task room surfaces and private dimming control was available to set preferred light levels for the occupants themselves. Satisfaction with lighting rate would result in more focused attention, positive attitude and higher productivity during the work. Results also indicated that more than 25% were not satisfied with standard lighting. It also concluded that by combining direct/indirect lighting with private dimmer and perimeter wallwashing, lighting was reported most comfortable and greatest satisfaction and motivation in a large amount of population, that served as a great option for the owner to achieve economic benefits as well as healthy and productivity.

Besides the type of lighting and the availability of a personal control, other lighting parameters studies drew a great attention in the lighting research field, and among those researches, the color spectrum or color temperature has been put the most attention as it is believed to have the closest correlation with the human visual comfort and productivity.

A report done by the Pennsylvania Power and Lighting Company (PP&L) pointed out that there was a high error rate in the N3 Drafting Department which was caused by employees were not doing to their best because of the inadequate cool-white fluorescent light. There is a finding as follows: A form of indirect glare which is also known as a veiling reflection was created due to the light bounced off the surface of that task into employees' eyes form overhead fixtures. A change was applied and new selected full spectrum lighting could behave more efficient than the previous system as it uses less electricity and last longer. Those costs came out to be minor compared to the productivity improvements after modernization. The new lighting reduced veiling reflections, which resulted in 13% increase in the employees' work productivity. The benefit of improved productivity was estimated as $235,290 per year. Furthermore, a number of errors in their work were reduced as well. In addition, absenteeism rates seemed to be reduced after the new lighting systems were installed, and lower eyestrain and fewer headache rates were reported also. The baseline benefits with better lighting were projected to save $ 255, 929 per year in PP&L(Deneen 2004). Therefore, using full spectrum lighting could be one way of improving visual comfort and employee productivity.

Dr. Same Berman, conducted an application of the theory that by enhancing scotopic side of light (blue light) which was believed to be energy efficient and increase visual accuracy. (Berman 2000) He reported a lighting experiment results in his article: a demonstration was set up for the purpose of testing how the new finding on rod sensitivity affected vision and brightness. "Conventional fluorescent lamps were used to compare the vision effects of a high color temperature lamp (scotopically enhanced), and therefore higher bluish output, with a low color temperature lamp (lower bluish output, scotopically deficient)". Intel facilities staff observed that under the scotopically rich lighting, people could see better and that this lighting would be perceived as brighter even though a light meter would display the opposite, which is exactly what PGE had tried to show. Intel realized that with scotopically rich lamps, they would achieve larger energy saving by reducing the number of lamps and meanwhile maintain or improve prior vision and brightness conditions. (Berman 2000)

Renowned pediatrician Doris Rapp, MD, stated in her, “Is This Your Child’s World?”(Rapp 1997), that natural light should be the best lighting for not only schools but also anywhere else. However, in lots of places, students spend more than 6 hours a day under the fluorescent lights which are in a cool white color. The productivity of students could be decreased because of the emitted radiation and X-rays from fluorescent lights, which also caused health problems such as eyestrain, fatigue and depression sometimes among students. A research proved that by replacing fluorescent lights with full-spectrum lighting would decrease those health problems significantly which was about 33%. So, full spectrum lighting were encouraged and focused more in both daily activities and research aspects (Rapp 1997). Based on Dr. Rapp statements, full spectrum must be chosen if fluorescent lighting must be used. With the recent invented lighting products with the blue spectrum, it is possible for companies to change lighting environment in the office.

2.3 – Human Pupil Sizes and the Potential Use

Only over the past a few years have researchers discovered the role of pupil size in vision and importance of designing appropriate interior lighting to maintain visual acuity. Many researches have investigated for spectrum controls. Scotopically enhanced lamps, which favor the blue-light wavelength, reduce pupil size. According to Professor Dr. Sam Berman, “At typical interior light levels, smaller pupils will contribute to better vision. The present lighting practice often calls for reducing pupil size by raising light levels, which is not efficient and fails to utilize the response of the rods to control pupil size.” (Berman 2000)

In a joint program which was cooperated by Lawrence Berkeley Laboratory and University of California, San Francisco, human responses to electric lighting were studied. Significant differences in pupil size occurred when subjects were exposed to indirect high-pressure sodium (HPS) lighting as compared with indirect incandescent lighting when the light intensities were photopically matched. The two lighting systems applied roughly the same spatial luminance distribution. By observing difference in pupil size, the spectral power distribution of the two lighting systems were claimed to have effect on visual performance and other aspects of visual systems function.

Pupil size was recognized to have considerable influence on the visual system ability to achieve higher resolution of details which is also known as visual acuity and on depth of field as well. (Leibowitz 1952), and spatial contrast sensitivity function (B. Y. F. W. Campbell and Green 1965). It was observed that depth of field decreased inversely when pupil diameter increased (F. W. Campbell 1957). It was also noted that larger pupil allowed more retinal luminance in a steady ambient luminance environment (Luckiesh and Moss 1934; Ferguson and Stevens 1956). Thus, improvement in visual acuity could be achieved by control of pupil size independent of light condition depending on the specific factors of the visual task (Eastman and McNelis 1963). Larger pupil could be realized under a scotopically deficient lamp and was believed to have better performance than under another lamp which had more scotopic lumens.

On the other hand, studies of contrast sensitivity (B. Y. F. W. Campbell and Green 1965; B. Y. F. W. Campbell and Gubisch 1966) showed a steady reduction in this quantity with increasing pupil size. Further studies were encouraged to show that there are preferred pupil sizes in the everyday world of visual tasks, the results here should lead to a new dimension for improving the quality of our lighting environment.

But given the controversies within vision science, and the importance of pupillary response to vision and lighting design, further testing on other lighting will be necessary to see how much effect other factors of lighting and human could have on the pupil. When such additional information is available, the general principles governing this part of visual efficiency will have a more ensured base.

There were other researches who investigated environmental and physiological factors affecting pupil size. It was indicated that pupil size decreased linearly as a function of age at all illuminance levels. Significant effect of age on pupil size was still shown at the highest illuminance level. The change rate of pupil diameter caused by age was about 0.043 mm per year at low illuminance level and about 0.015 per year at high illuminance level. "In addition, the variability between pupil sizes of subjects of the same age decreased by a factor of approximately two as luminance was increased over the range investigated. Pupil size was found to be independent of gender, refractive error, or iris color (P >0.1)."(Winn et al. 1994)

Although those previous studies showed independent of gender, a validation still needs to be done. Other human subject factors, such as ethnic origin, myopic condition, and age should also be tested (again) to figure out their potential effects on pupil size.

2.4 – Conclusions for Background Research

The existing researches related to this topic are still very limited. However, the those researches have already explained the importance of proper lighting conditions in the office environment which significantly affect employees' visual comfort, health and productivity and indicate the potential use of pupil size in the future lighting research. Although there were studies on environmental and physiological factors affecting human pupil size and there were researches using pupil size for a lighting study. Those studies were mostly focused on improving visual comfort by controlling spectrum. No one previously studied correlations between illuminance, luminance and human pupil size and applied it to lighting design and control, which is very critical in today's building environment, where people spend more than 90% of their time, for their visual health and work productivity.

Chapter 3: Methodologies

Methodology of the research will be introduced into details in this chapter. First, the scope of work will be given explaining the main procedure of the research and selected variables; Second, a description of experimental chamber will be presented to give a whole idea of the environment where the experiments were conduced; Third, research tools and software used in the research will also be presented with detailed explanation and index; other preparations including taking IRB course and preliminary study will be discussed in the end.

3.1 - Scope of Work

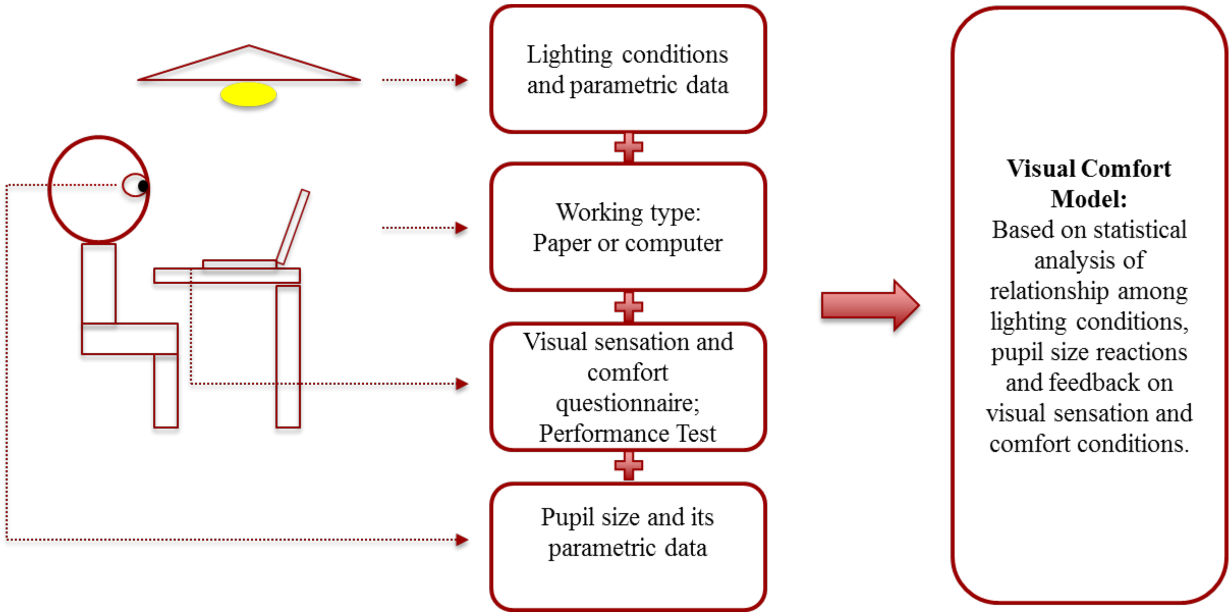


Figure 3.1 Conceptual diagram of the research methodologies

The experiment was conducted in a well-designed and equipped chamber, which is based on the requirements of experiments, on the basement level of Watt Hall on University of Southern California campus.

A desk was placed against the south wall of the room. 16 LED dimmable lamps were installed above the workstation as the light source that were also controlled by a manual dimmer for creating different lighting intensity on the desk. Two chairs were placed beside the desk, one for the participant, the other for student investigator. The chamber was modified or rearranged based on the experiment plan. The dimmable LED lamps were changed based on demand of different color temperature. For paper-based task in the experiment, the central part of the desk was left with enough space for participants' working, while, for computer-based task, a monitor plus a keyboard and a mouse were placed on the central section instead.

The chamber has high acoustic insulation and absorption for unfavorable noise, the thermal condition maintained constant and indoor air quality is ensured by a ventilated fan on the ceiling, fresh air is provided. A ceiling lighting fixture is installed for general daily work in the chamber and serves as aided light source.

This is a human subjects experiment, and only one person can participate in the experiment at one time. There is no specific way in selecting participants. But an effort has been made to achieve a balanced ratio in human characteristics such as gender, age, myopic condition as well as eye color. Participant was informed of the whole procedure of the experiment and their main task as well as some restrictions during the experiment. Each experiment took about 1.5 hours to conduct. During the entire process, the participant was asked to carry out a typical type of office work separately using paper-based and computer-based tasks. Every five minutes, the participant was asked to respond to a series of questions regarding their visual sensations and comfort conditions. At the same time, pupil size and lighting parametric data were automatically collected and saved in a computer-based data acquisition server. Detailed information will be explained in Section 3.3 and 3.4. Based on the collected data of lighting environment conditions, pupil size reactions, and feedback on visual sensation and comfort conditions, a visual comfort model was developed for future lighting designs and individual control purposes using a statistical tool.

3.1.1 – Lighting Parameters

Illuminance, luminance and color temperature were selected as indicators for the lighting conditions and environment in the experimental chamber. As one of basic lighting components that represent the lighting environment condition, illuminance has been examined in several studies (Veitch and Newsham 1998; Manav 2007). It is also included in most design guidelines and as an indicator of energy consumption. Instead of selecting a single visual location for the data record, overall luminance provides a better understanding of average performance for a certain area in a typical office environment. Many previous studies have also used luminance as one of the critical lighting parameters. Color temperature, which has been studied as another significant lighting parameter having a substantial relationship to the productivity, is also considered in this project. (Oi and Takahashi)

- Illuminance: “One lumen of luminous flux, uniformly incident on 1 m^2 (ft^2) of area produces an *illuminance* of 1 lux (footcandle [fc]). Illuminance is normally represented by the letter E. It is the density of luminous power, expressed in terms of lumens per unit area. If consider a lightbulb as analogous to a sprinkler head, then the rate of water flow would be the lumens, and the amount of water per unit time per m^2 (ft^2) of floor area would be the lux (footcandles). Thus, the SI unit, lux, is smaller than the corresponding I-P unit, footcandles, by the ratio of square meters to square feet. That is, 10.764 lux = 1fc.” (Grondzik, Kwok, Stein, & Reynolds, 2010, p. 472)
- Luminance: “Luminance is normally defined in terms of intensity; it is the luminous intensity per unit of apparent (projected) area of a primary (emitting) or secondary (reflecting) light source. Thus, its units are candela per area. While SI unit of luminance

is candela per square meter (cd/m^2), sometimes referred to as the nit." (Grondzik, Kwok, Stein, & Reynolds, 2010, p. 473)

- Color temperature: "The color of the light radiated is related to its temperature. By developing a blackbody color temperature scale, we can compare the color of a light source to this scale and assign to it a *color temperature* – that is, the temperature to which a blackbody must be heated to radiate a light similar in color to the color of the source in question. Temperature is measured in Kelvin, which is a scale that has its zero point at -460°F". (Grondzik, Kwok, Stein, & Reynolds, 2010, p. 514)

Illuminance was measure in lux, luminance was measured in cd/m^2 and color temperature in Kelvin. The settings were decided based on the consideration of the possible ranges of individual lighting parameters in office environments in the U.S. (Choi, Loftness, and Aziz 2012). As typical illuminance level in the office is 400 lux for paper based task. The range from 50 to 1400 lux should cover the preferences of most occupants. For light color temperatures, two conditions with warm light (2700 K) and daylight (5000 K) were selected. These are the most frequent work types in a typical workplace. Typical range and interval for the experiment is summarized in Table 3.1.

Table 3.1 Settings for lighting parameters

Illuminance:	50 – 1400 lux, 150 lux interval
Luminance:	Lowest (cd/m^2): 2.05 (min), 21.23 (max), 8.67 (ave), 14.3 (UGR) Highest (cd/m^2): 2.22 (min), 581.61 (max), 278.92 (ave), 10.4 (UGR)
Color temperature:	Warm: 2700 K – 3000K; Daylight: 5000K – 6500K

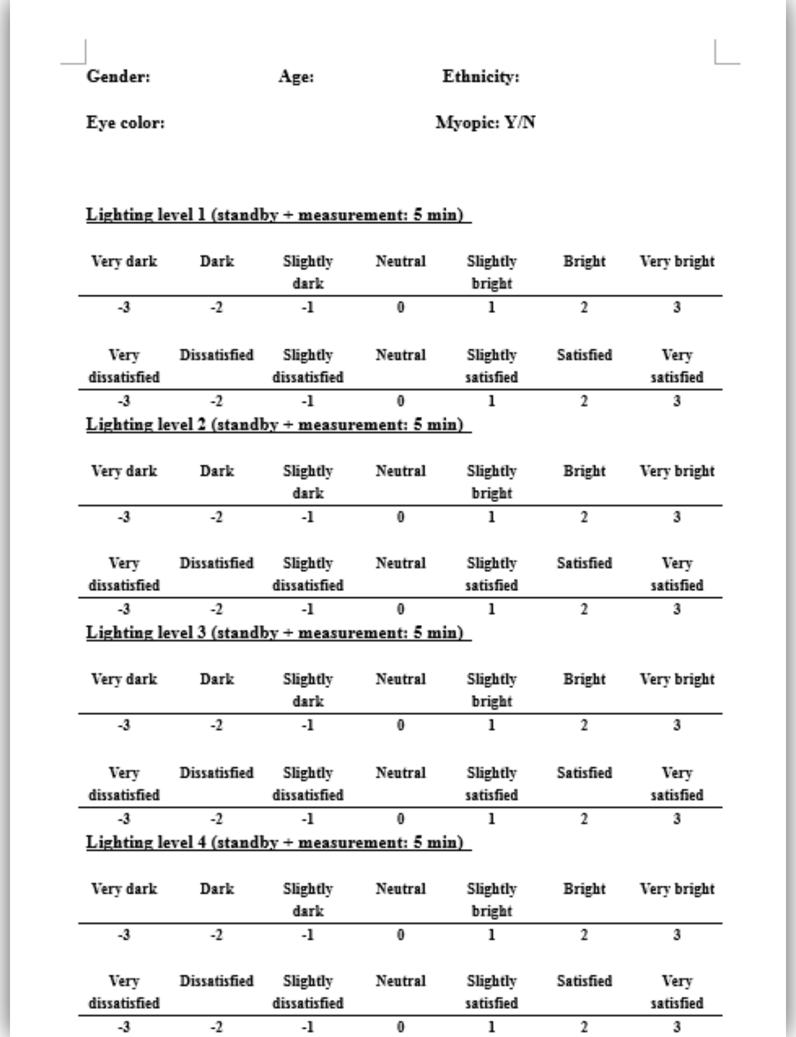
3.1.2 – Task Types

Two task types were selected for the human subject experiments: paper-based task and computer-based tasks. The computer based task consisted of reading and typing. The same material was supplied to all of the subjects in both digital and printed forms. While, in paper-based task, the reading material was printed out and provided to participants. All other settings and experiment procedure were kept same with the computer-based task.

3.1.3 – Questionnaire and Performance Test

A survey questionnaire was used for collecting participants' identification information and feedback on their perceived visual sensations and comfort conditions. Collected identification information included age, gender, ethnicity, eye color and myopic condition. Age, gender and ethnicity are most common parameters collected and taken into consideration when conducting a human subject involved research project, especially in the domain of visual comfort studies (Sivaji et al. 2013). Eye color and myopia are two parameters more directly connected to lighting studies. All of these parameters are believed to have an effect on physiological responses of human pupils (Sivaji et al. 2013). Those parameters will be used for grouping the participants for data analyses to investigate the correlations between physiological and environmental conditions in this study.

For visual sensation and comfort condition surveys, a 7-point scale was applied to the answers of the questionnaire. Background research indicated a 7-point scale is better than 5 point scale to give a higher resolution for answers without excessive complication (Sauro 2014). Previous studies indicate that applying more than an 11 point scale has a diminishing benefit. Since there are only 10 change steps of lighting levels generated during the experiment, 11 would be too many for the participants. An example of an error or bias that could be introduced by the scale is that participants might simply pick one option adjacent to the previous one for the newer level without much considerate thinking or judging. A 7-point scale has been widely used for thermal comfort research asking for satisfaction levels. This scale consists of both enough essential options and distinctions between options. It provides neutral level at the central point and two other directional sections for positive and negative points. And in each section, there is highly extreme and slightly effective levels and one moderate between them. This type scale could facilitate participants' report on their perceived visual sensations and comfort conditions. An example of the questionnaire shows how it was organized (Figure 3.2).



Gender: **Age:** **Ethnicity:**

Eye color: **Myopic: Y/N**

Lighting level 1 (standby + measurement: 5 min)

Very dark	Dark	Slightly dark	Neutral	Slightly bright	Bright	Very bright
-3	-2	-1	0	1	2	3

Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied
-3	-2	-1	0	1	2	3

Lighting level 2 (standby + measurement: 5 min)

Very dark	Dark	Slightly dark	Neutral	Slightly bright	Bright	Very bright
-3	-2	-1	0	1	2	3

Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied
-3	-2	-1	0	1	2	3

Lighting level 3 (standby + measurement: 5 min)

Very dark	Dark	Slightly dark	Neutral	Slightly bright	Bright	Very bright
-3	-2	-1	0	1	2	3

Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied
-3	-2	-1	0	1	2	3

Lighting level 4 (standby + measurement: 5 min)

Very dark	Dark	Slightly dark	Neutral	Slightly bright	Bright	Very bright
-3	-2	-1	0	1	2	3

Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied
-3	-2	-1	0	1	2	3

Figure 3.2 Sample Section of Designed Questionnaire

To assess the participants' visual acuity as their work productivity in each lighting condition, simplified performance tests were conducted during the experiment with simulating individual's typical light office work. Participants were also invited to complete four performance tests at different lighting levels, including brightest (1400 lux), darkest (50 lux), moderate (800 lux) and optimal level. The optimal level was selected at the end of each experiment based on their preferred lighting condition. The neutral sensation with the highest satisfaction level was believed as the optimal level, but it varied depending on the participants.

A selected performance test was a simple reading and typing work. The same reading material was given in a text file to each participant. Meanwhile, another blank text was open for typing purpose. These two text files were displayed on the monitor at the same time with same settings in a font size and background color. The evaluation was conducted in two parts: typing speed and error rate. Total typed characters were counted as typing speed, and typos were accumulated to estimate an error rate based on the total character number.

3.1.4 – Pupil Size Parametric Data

As discussed in Chapter 2, the pupil tracking device ASL Mobile Eye-XG was used for collecting pupil size and its parametric data of human subjects. Each participant was asked to wear this sensory device for the entire experimental time period (Figure 3.3).

Figure 3.3 Participant Wearing ASL Mobile Eye-XG Device

Due to the presetting defined in the device, the pupil size was measured and collected at 30 Hz, and a very large amount of data was collected from each test. The data process and analysis procedure were conducted using the Microsoft Excel and Minitab Statistical Package software, and the details would be discussed in Chapter 4. The pupil size was shown in pixels for illustrating and comparing purposes. Since human pupil sizes vary depending on people, the study normalized the collected data per individual participant to estimate a changing rate of the size per lighting condition and compared to those physiological changes between different test participants or their physiological groups. The normalization process will be discussed in Chapter 4.

3.2 - Experimental Chamber Setup

An experimental chamber was used for the human subject experiment. It simulated a private closed office workplace which would be dedicated to only one user without being affected by other neighbor workplace environmental conditions, and that allowed controlled lighting conditions. Other indoor environmental quality components, such as thermal, air and acoustic conditions were monitored and controlled to be maintained at constant levels as only human physiological responses and lighting environments were being studied.

3.2.1 – Chamber Design

With a financial support from the USC School of Architecture, a room was provided for the experiment. The room is located on the basement floor of Watt Hall, and the area is about 15 m^2. As the windowless room is located on the basement level of a high-mass building, it is not significantly affected by external thermal and acoustic conditions. The chamber consists of two interior spaces; one is a test room for a participant, and the other is a monitor room for an investigator. This physical division helps the participant concentrate on the test without being distracted.

The chamber was composed of two parts: A Test Room and a Monitor Room (Figure 3.4). For the purpose of reducing other effects on the participant, an individual room was designed for a participant to take a test while the investigator in stationed in the Monitor Room for supervising the experiment and offering any help if needed. The division between the rooms has a large window that occupies more than half of the area to be used so as to allow the investigator's view through for a monitoring purpose. Light can leak through the window but there is no effect on the performance of the participant, since light source is located in the test room. The interior wall of the chamber was painted plain white, which does not cause any glossy refection and is a typical interior color in an office environment.

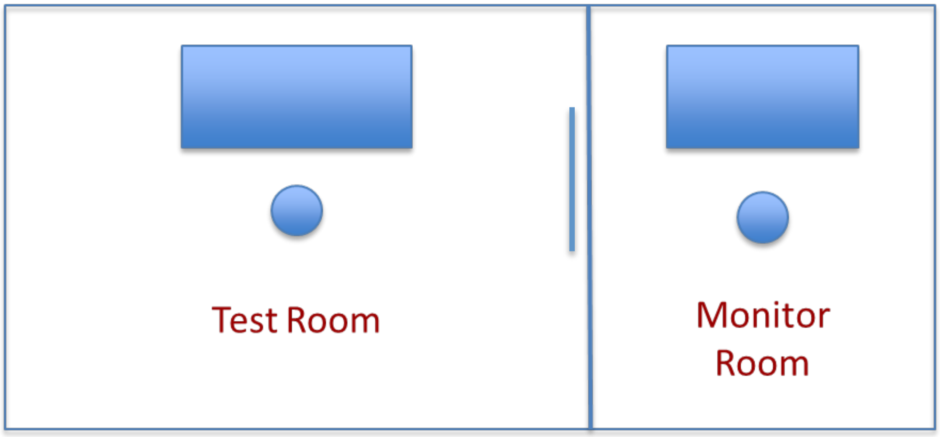


Figure 3.4 Diagrammatic plan of Modifying Chamber

3.2.2 – Lighting Fixtures

There are two types of light sources in the chamber. Fluorescent lamps were originally installed on the ceiling for the purpose of strengthening the light when needed. The second source is the primary light source for the experiment. The light source adopted in the experiment is a Philips dimmable LED lamp. Each lamp provides up to 530 lumens for luminous flux and 2700 K color temperature. For the earlier pilot study – a paper based task, 12 lamps were used. Later, 3 more lamps were added to achieve a higher lighting illuminance level on the work surface. For the second round of the experiment, the installed LED light bulbs were replaced with a similar type of lamps, which emit 5000 K color temperature. Figure 3.5 shows the lamp adopted in the chamber test.

Figure 3.5 Dimmable LED Lamp

3.3 – Research Tools and Sensor Devices

A detailed description of all research tools and sensor devices used in the research will be given in this section.

3.3.1 – Sensory Devices: Illuminance Meter, Luminance Meter and HDR camera

Three illuminance meters were used to measure and collect lighting intensity data (Figure 3.6). They were evenly distributed on the desk so that measure data could reflect more precisely. Illuminance meters are powered by batteries and could output 0-5V analogue signals to a data acquisition device (DAQ), which has a functionally featured with a signal conversion to illuminance value and data storage.

The HDR camera (Model: Nikon COOLPIX 8400) (Figure 3.7) with a fisheye lens was also used for estimating luminance data is. The settings for the camera are summarized in Table 3.2.

Table 3.2 Settings for COOLPIX 8400 in “M” mode

White balance	Sunny
Best shot selector	Off
Image adjustment	Normal
Saturation control	Normal
Image quality	Normal
Image size	8M (3264 x 2448)
Sensitivity	100 ISO
Image sharpening	Off
Lens	Fisheye
Exposure option (AE lock)	Off
Auto bracketing	Off
Noise reduction	Off

With the same settings, four photographs for each illuminance level were taken to calculate luminance levels. Each image was taken with different individual aperture and exposure time settings, which are summarized in Table 3.3.

Table 3.3 Aperture and Exposure Time Settings

COOLPIX 8400

Aperture	Exposure Time
3.8	1/2
3.8	1/15
3.8	1/125
3.8	1/1000

All the images taken in each lighting condition, mainly driven by illuminance, were processed using the Photolux 2.1 software to calculate luminance for each illuminance level. Highest, lowest, average and UGI were also estimated as representatives for the luminance performance based on the use of the processed image images.

For a calibration purpose, the Cooke cal-SPOT 401 luminance meter was used (Figure 3.8). The measured luminance with a high resolution was compared with the estimated by the Photolux software. The study confirmed that there were minimal discrepancies between the measured and calculated values.

Figure 3.6 OMEGA HHLM-1

Figure 3.7 Coolpix 8400

Figure 3.8 Cooke cal-SPOT 401

3.3.2 –DAQ device

Another essential device adopted in the chamber for data acquisition was the NI USB 6008 (Figure 3.9). It was connected with all the illuminance meters in the chamber and also transmitting collected data into a laptop through cable. All the data were displayed in real time on the laptop by a programmed data collection interface developed using in the LabVIEW software. More detailed information could be figured out in section 3.4. Data were also automatically saved into a selected file with being labeled with detailed information including date, time, etc.

Figure 3.9 NI USB-6008

3.3.3 –ASL Mobile Eye XG

An essential device is ASL Mobile Eye XG that was used for detecting, measuring and collecting pupil size data from participants (Figure 3.10). The device consists of three major elements: a laptop computer with related software installed, monitor and special-designed glasses with cameras. Three components were connected and working together for pupil size parametric data acquisition. Participants were asked to wear the sensory glasses during the whole experiment process. Some adjustments were applied to each participant to achieve the best display in the laptop. There are two cameras on the glasses, one is for capturing images of the pupil, while the other is for monitoring the view seen by the human subject. The pupil size data was automatically saved to the laptop and it can be exported as a csv file for future analysis in MS Excel and Minitab 16.

Figure 3.10 ASL Mobile Eye XG

(Head Mounted Eye Tracking See the World Through Different Eyes)

The final layout of the chamber and locations of all devices are shown in Figure 3.11.

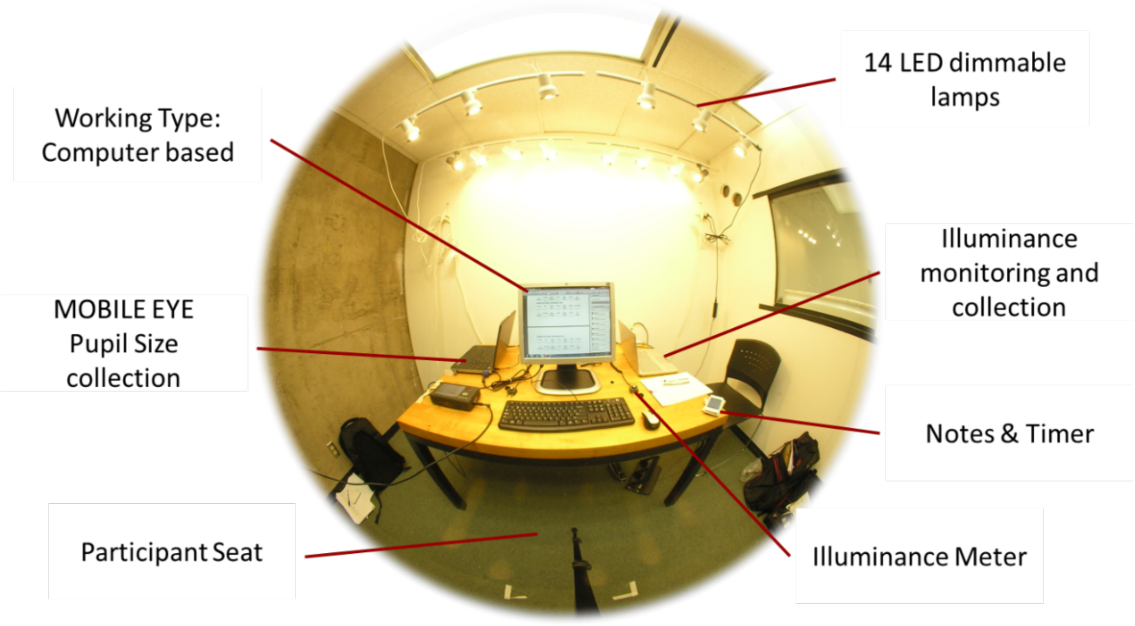


Figure 3.11 Fisheye View of the Chamber

3.4 - Adopted Software

Many software tools were adopted or programmed for this project. A challenge at the beginning of the project was identifying a program to efficiently collect illuminance data. Later, for the purpose of luminance analysis and data processing, other software were adopted.

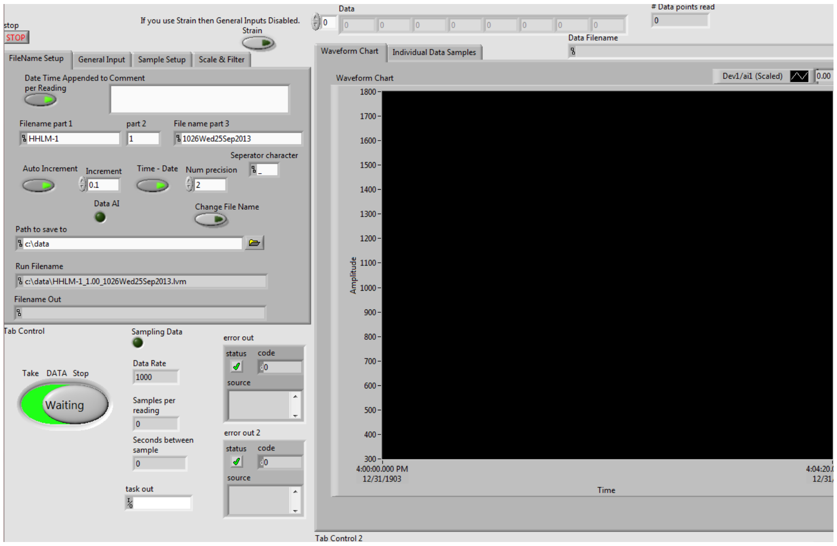
3.4.1 – LabVIEW

LabVIEW is a graphical programming platform that allows users to develop different programs with desired functions related to data collection, processing and storage. It offers great compatible connections to many data acquisition hardware which makes it easier to use than other similar software.

LabVIEW software is ideal for any measurement or control system, and the heart of the National Instrument design platform. Integrating all the tools that engineers and scientists need to build a wide range of applications in dramatically less time, LabVIEW is a development environment for problem solving, accelerated productivity, and continual innovation." (LabVIEW System Design Software) The best attraction of this software is its significant advantage in data acquisition researches. It has very good connections to DAQ sensor devices. A core data collection, processing and storage tool was programmed in LabVIEW platform.

3.4.2 – Programming Logic

Signals transmitted from DAQ sensor are ranging from 0 – 5V. Based on the instructions of illuminance meter, formula was used and programed to calculate illuminance. The calculated illuminance was displayed on the laptop. The user can also set intervals and choose desired channels according to the project purpose. The file name was created using the current date and time. Figure 3.12 and Figure 3.13 present appearance and graphic programming icons in the LabVIEW. The interface was modified and developed based on the previous product provided by Professor Joon-ho Choi.



If you use Strain then General Inputs Disabled.

Filename part 1: HHLM-1

part 2: 1

File name part 3: 1026Wed25Sep2013

Seperator character: _

Increment: 0.1

Num precision: 2

Path to save to: c:\data

Run Filename: c:\data\HHLM-1_1.00_1026Wed25Sep2013.lvm

Data Rate: 1000

Samples per reading: 0

Seconds between sample: 0

Figure 3.12 Front Panel of Designed Program in LavVIEW

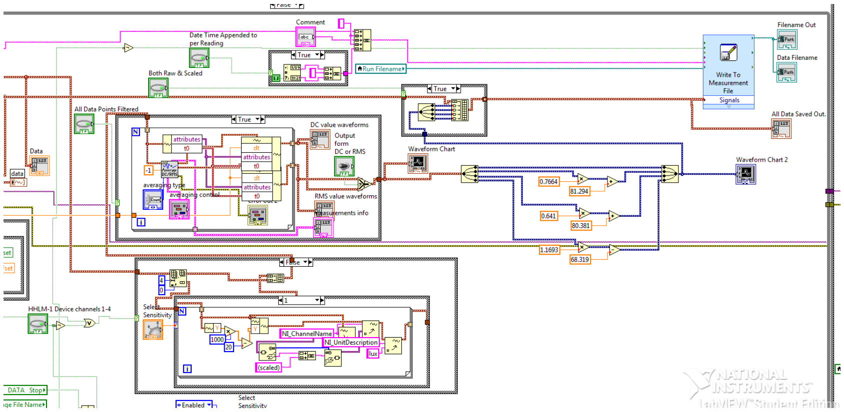
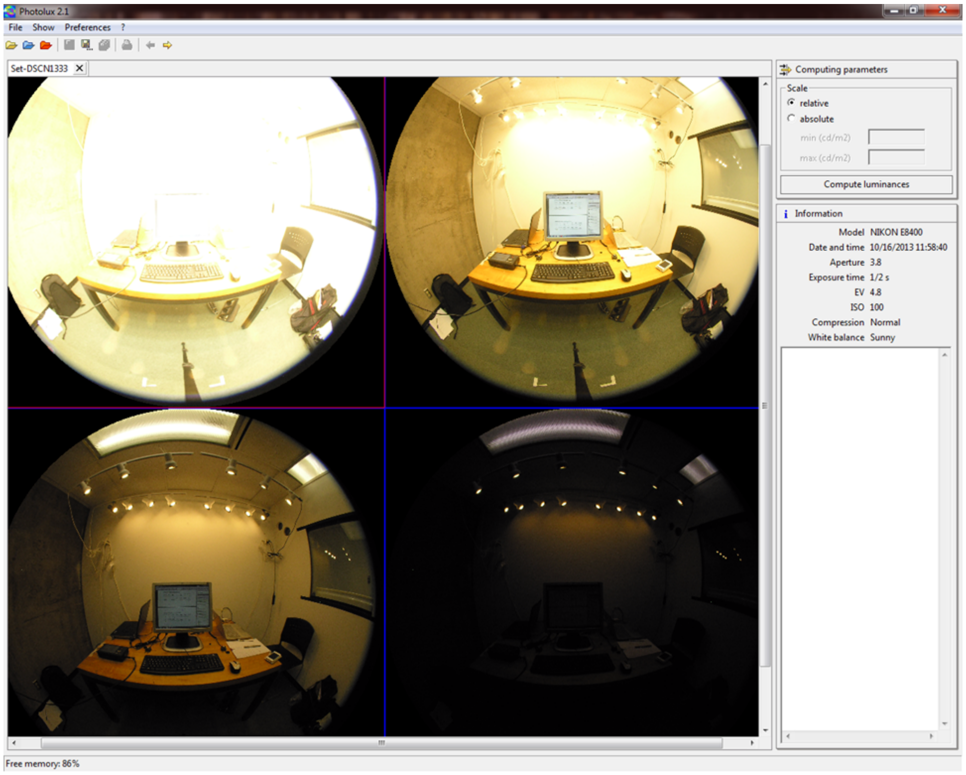


Figure 3.13 Block Diagram of Designed Program in LabVIEW

3.4.3 – Photolux 2.1

Since the luminance meter could only measure one spot at a time, a better way of estimating luminance level for a specific area would be needed. An HDR camera was selected for this purpose. In addition, Photolux was adopted for calculating luminance of a specific view of participant by combining all four images taken at different aperture and exposure settings into single file and conducting analysis (Figure 3.14 and Figure 3.15).



Model NIKON E8400
Date and time 10/16/2013 11:58:40
Aperture 3.8
Exposure time 1/2 s
EV 4.8
ISO 100
Compression Normal
White balance Sunny

Figure 3.14 Four images taken at different exposure settings for same illuminance setting displayed in Photolux before combining.

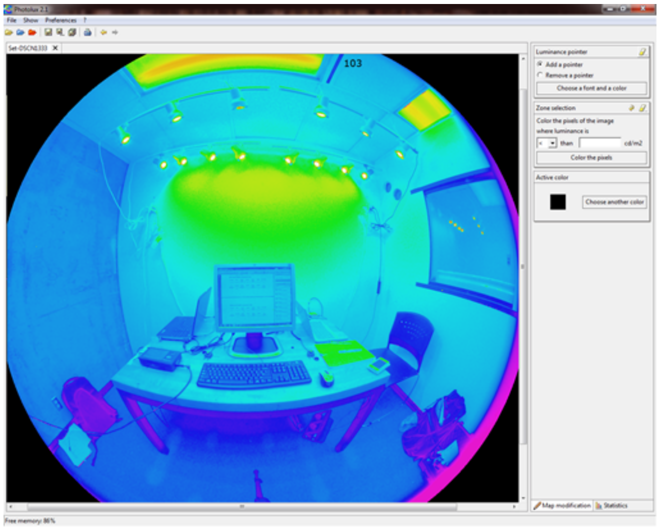
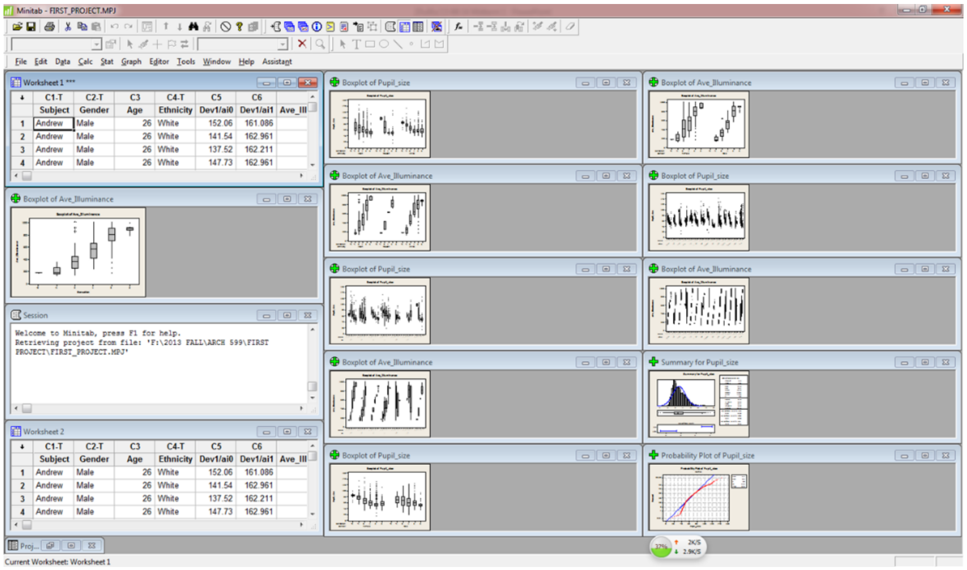


Figure 3.15 Processed and analyzed image after combining four images taken at different exposure settings for same illuminance setting in Photolux.

Four pictures of lighting environment in the chamber were taken under the settings shown in Table 3.3 of Section 3.3.1. With different aperture and exposure time, the image could have different reflection of the lighting performance in the chamber. After combing these four images, a overall explanation of the lighting performance of the chamber could be calculated and shown in Figure 3.15. This image could comprehensively present the illuminance and luminance of the chamber.

3.4.4 – Minitab

After the data acquisition process, statistical analysis was applied to datasets to determine correlations between parameters. Minitab was chosen to finish the objective. Minitab is a statistics package. It was developed at the Pennsylvania State University by researchers Barbara F. Ryan, Thomas A. Ryan, Jr., and Brian L. Joiner in 1972. Minitab began as a simple version of OMNITAB, a statistical analysis software made by NIST; the documentation for OMNITAB was published 1986, but there has been no apparent development since then. (OMNITAB 80) Minitab is an easy to learn statistical analysis software. It provides a considerable functions for statistical analysis including T-test, correlations, regression, ANOVA, etc. It also has strong graphic generators that help explain and present data better. Figure 3.16 presents a sample interface in Minitab.



↓	C1-T	C2-T	C3	C4-T	C5	C6	
	Subject	Gender	Age	Ethnicity	Dev1/ai0	Dev1/ai1	Ave_Ill
1	Andrew	Male	26	White	152.06	161.086	
2	Andrew	Male	26	White	141.54	162.961	
3	Andrew	Male	26	White	137.52	162.211	
4	Andrew	Male	26	White	147.73	162.961	

```
Welcome to Minitab, press F1 for help.
Retrieving project from file: 'F:\2013 FALL\ARCH 599\FIRST
PROJECT\FIRST_PROJECT.MPJ'
```

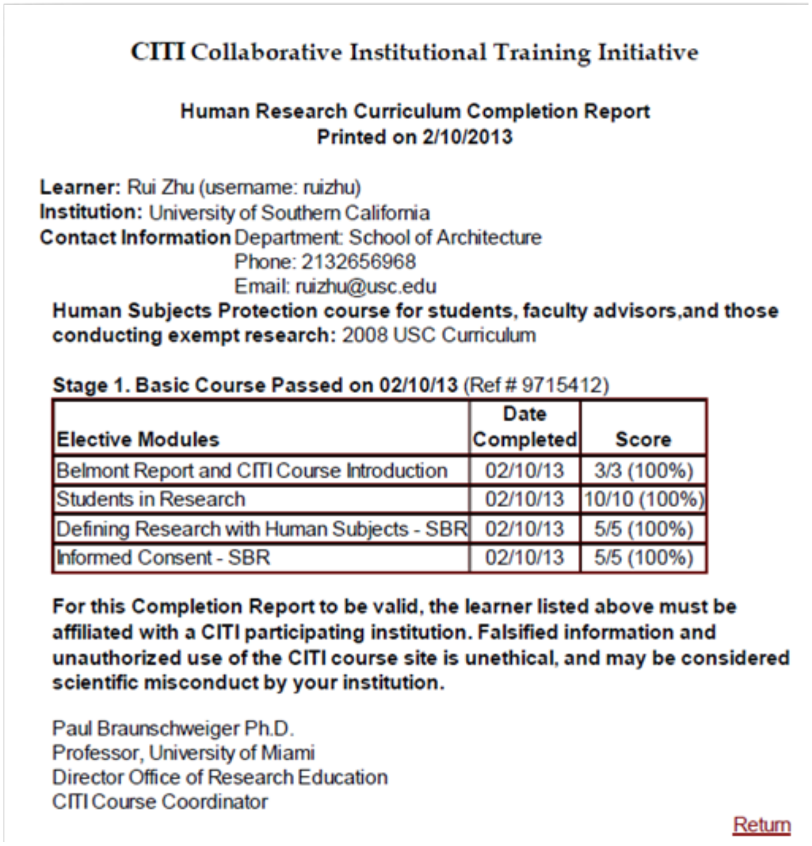
↓	C1-T	C2-T	C3	C4-T	C5	C6	
	Subject	Gender	Age	Ethnicity	Dev1/ai0	Dev1/ai1	Ave_Ill
1	Andrew	Male	26	White	152.06	161.086	
2	Andrew	Male	26	White	141.54	162.961	
3	Andrew	Male	26	White	137.52	162.211	
4	Andrew	Male	26	White	147.73	162.961	

Figure 3.16 Sample interface of Minitab

3.5 - IRB Preparation

An approval from the USC University Park Institutional Review Board (UPIRB) was required for human subject research. Meeting requirements outlined in 45 CFR 46.110 category (4), (6) and (7), the IRB designee determined this research that involves no more than minimal risk. Requirements were all satisfied. Minors are not eligible for inclusion. Approval of this study was granted on 3/17/2013.

As the project manager and student investigator, required courses were taken and related tests were passed so as to be eligible for the experiments. The course completion report is summarized in Figure 3.17.



CITI Collaborative Institutional Training Initiative

Human Research Curriculum Completion Report
Printed on 2/10/2013

Learner: Rui Zhu (username: ruizhu)
Institution: University of Southern California
Contact Information Department: School of Architecture
Phone: 2132656968
Email: ruizhu@usc.edu

Human Subjects Protection course for students, faculty advisors,and those conducting exempt research: 2008 USC Curriculum

Stage 1. Basic Course Passed on 02/10/13 (Ref # 9715412)

Elective Modules	Date Completed	Score
Belmont Report and CITI Course Introduction	02/10/13	3/3 (100%)
Students in Research	02/10/13	10/10 (100%)
Defining Research with Human Subjects - SBR	02/10/13	5/5 (100%)
Informed Consent - SBR	02/10/13	5/5 (100%)

For this Completion Report to be valid, the learner listed above must be affiliated with a CITI participating institution. Falsified information and unauthorized use of the CITI course site is unethical, and may be considered scientific misconduct by your institution.

Paul Braunschweiger Ph.D.
Professor, University of Miami
Director Office of Research Education
CITI Course Coordinator

Figure 3.17 Human Research Curriculum Report

3.6 – Preliminary Study and Results

Before starting actual experiments in the chamber, practice with the devices and software was done. Pilot studies were conducted in the spring semester of 2013 for the purpose of learning the system and to practice the methodology of conducting the experiments. A group of 13 students participated in the pilot study. The demographic information is summarized as follows: eight females (age: 26.3±2.12) and five males (age: 25.6±1.52), and eight Asians and five Caucasians. Test methodologies consisted of different settings for illuminance in a paper-based task setting.

In the pilot study, ten different levels of illuminance, following order of lowest to highest, were tested in the workstation setting of the chamber. The pilot study focuses on investigating the relationship between lighting intensity at the workstation surface and the user's pupil sizes. At that time, the room was only equipped with 12 units of 9W-LED lights on the ceiling surface and data acquisition device, which include lighting sensors, lighting controller, and a computer for purpose of displaying and collecting data. The generated lighting intensity (lux) on the workstation surface ranged from 150 to 1050 lux with a 100 lux interval. The test had a two-minute stand-by period in each lighting level to allow pupil adjust to a new lighting level, and a one-minute data collection time frame for lighting intensity and pupil size measurement. The overall range of deviations was approximately ±10 to 25 lux in the test. At the end of each lighting step, the subject was asked to report the visual sensation using a seven-point scale questionnaire: (-3) very dark; (-2) dark; (-1) slightly dark; (0) neutral; (+1) slightly bright; (+2) bright; (+3) very bright. The results for preliminary test will be explained in Chapter 4.

This preliminary test indicated several problems. The first one was that the generated lighting intensity could not satisfy the desired range. In that case, two more same type dimmable LED lamps were installed in the chamber that finally could generate more than 1400 lux in the chamber. The second problem was about a time interval between each illuminance level. Three minutes total was questioned by some professionals and suggested not enough time for the human pupil finishing adjusting the new lighting level. For the official experiments, the time interval was raised from 2-minute standby, 1-minute measurement to 3-minute standby and 2-minute measurement. Empirically based on pilot study, 5 minutes should be enough for adjustment in this research whose interval is 150 lux between each level. The third problem was complaints from participants about glare. Because there is a tilted glass fixed on the glasses to reflect pupil to the camera for tracking purpose, the tilted glass can reflect light from lamps located above the participant in some case which caused serious glare problems with a result of lower comfort conditions. In order to solve this problem, modifications by installing light-shields were applied to the chamber at beginning of fall semester 2013.

In order to solve the glare problem, several methods were implemented. First, changing the location the desk was tested. The seat of the participant was relocated to achieve different angles avoiding strong reflection of the light source so as to resolve glare problem. The desk was moved to the opposite side of the chamber, so that the participant would face away from the light source and thus block the glare. Unfortunately, this resulted in enlarging the distance between workspace and light source, and the light intensity projected on the desk was reduced below the acceptable level of 1400 lux.

Later, realizing that the camera installed on the glasses blocked some of the reflection inspired the idea of a creating a shade for the glasses. A small paper board was attached to the top of camera; this expanded blocking area and solved the problem. An ordinary baseball-style cap could also be adopted for the same purpose. Using either the paper board or the cap could resolve the glare problem and would not affect actual light source from working area.

3.7 – Experiment Rounds

After finishing all preparations, three rounds of experiments were conducted within one year. To maintain a statistical significance in the study, at least 20 human subjects were sampled per each round of the designed experiments. The different rounds of the experiments were defined based on the task-type modes and lighting color temperatures. The settings for three rounds are summarized in Table 4.

Table 3.4 Different Experiment Rounds

Round No.	***One***	***Two***	***Three***
Working Type	Computer based	Computer based	Paper based
Color Temperature	Warm	Daylight	Daylight

Since computer based task and daylight are mostly used in office, these two settings account for 2/3 of the whole experiments.

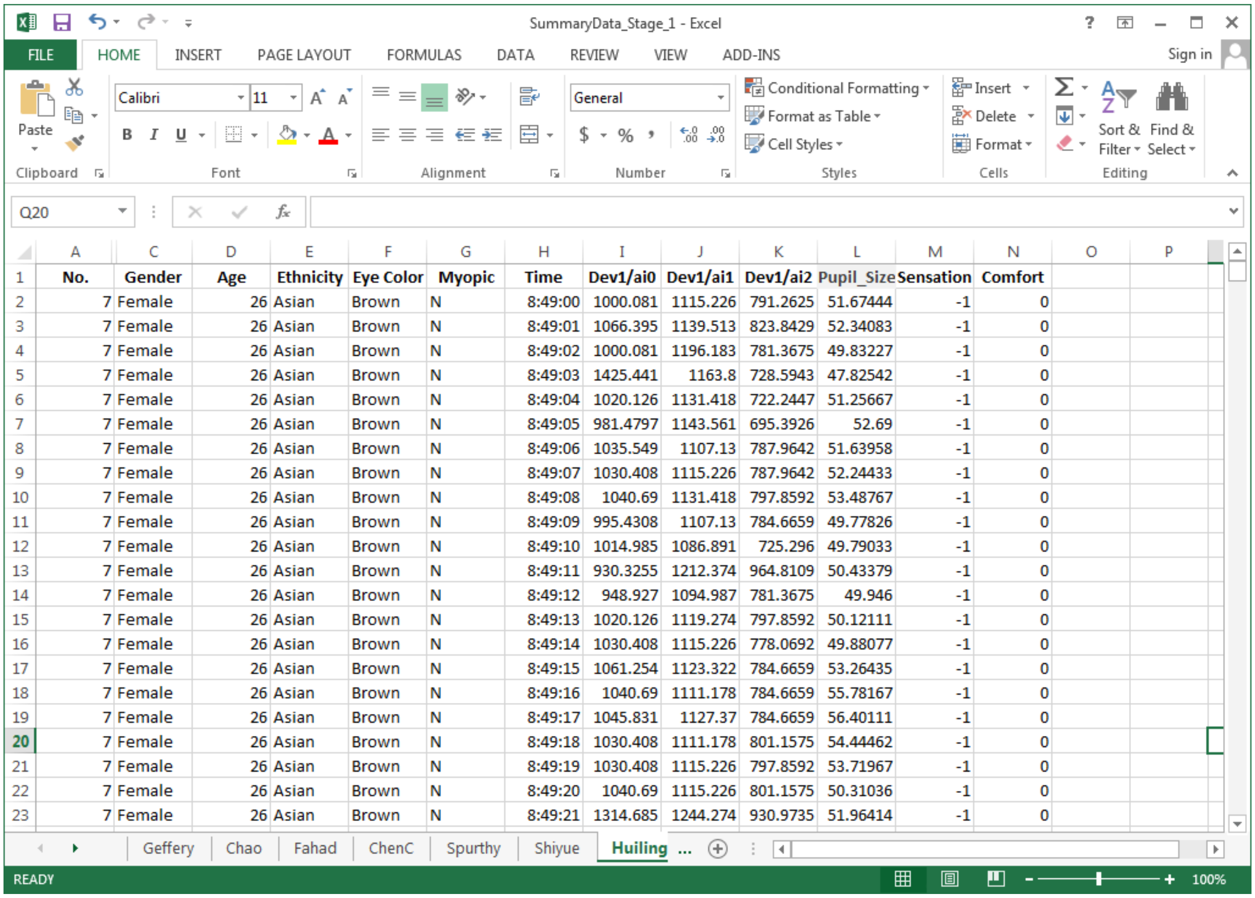
For the demographic characteristics of the participants, the ideal combination would be balanced populations in ethnicity (e.g. 50% Caucasians and 50% Asians), age groups (younger than 30 years old and 30 or older), and gender. However, due to the limited environment condition, the balanced population ratio was not able to be achieved in this research. The demographic information of the test participants of each round are summarized in Chapter 4.

No food or drink was allowed during the experiment to maintain a consistent physical condition across the participants. Although caffeine didn’t appear to cause irregular pupil behavior, each subject was asked not to consume caffeinated food or drink at least one hour before the experiment so as to avoid any potential effect (Wright et al. 1997),. The participant was expected to arrive 30 minutes earlier before experiment starting to remain in a stable metabolic rate. A detailed explanation about the process was given to the participant and questions were allowed to ask if there were any. Most of conversations between participant and investigator were minimized to avoid any erroneous data collection, such as facial expression changes affecting pupil size detection. Necessary time alerts and reminders were offered to the participants during the experiment. The participant was seated at the table with the classes and asked to perform the tasks (Figure 20).

Figure 3.18 Images taken for some participants in the experiment

3.8 – DATA Analysis

When each round accomplished, summarizing collected data and analyzing data was applied. The parametric data about pupil size, illuminance, luminance, responses to questions and subject personal information were processed and combined into a single dataset for each participant that resulted in a tab in the Excel spreadsheet. Figure 21 shows the sample dataset in Excel spreadsheet. Minitab was used for statistical analysis. The results and analysis would be discussed in Chapter 4.



	A	C	D	E	F	G	H	I	J	K	L	M	N
1	No.	Gender	Age	Ethnicity	Eye Color	Myopic	Time	Dev1/ai0	Dev1/ai1	Dev1/ai2	Pupil_Size	Sensation	Comfort
2	7	Female	26	Asian	Brown	N	8:49:00	1000.081	1115.226	791.2625	51.67444	-1	0
3	7	Female	26	Asian	Brown	N	8:49:01	1066.395	1139.513	823.8429	52.34083	-1	0
4	7	Female	26	Asian	Brown	N	8:49:02	1000.081	1196.183	781.3675	49.83227	-1	0
5	7	Female	26	Asian	Brown	N	8:49:03	1425.441	1163.8	728.5943	47.82542	-1	0
6	7	Female	26	Asian	Brown	N	8:49:04	1020.126	1131.418	722.2447	51.25667	-1	0
7	7	Female	26	Asian	Brown	N	8:49:05	981.4797	1143.561	695.3926	52.69	-1	0
8	7	Female	26	Asian	Brown	N	8:49:06	1035.549	1107.13	787.9642	51.63958	-1	0
9	7	Female	26	Asian	Brown	N	8:49:07	1030.408	1115.226	787.9642	52.24433	-1	0
10	7	Female	26	Asian	Brown	N	8:49:08	1040.69	1131.418	797.8592	53.48767	-1	0
11	7	Female	26	Asian	Brown	N	8:49:09	995.4308	1107.13	784.6659	49.77826	-1	0
12	7	Female	26	Asian	Brown	N	8:49:10	1014.985	1086.891	725.296	49.79033	-1	0
13	7	Female	26	Asian	Brown	N	8:49:11	930.3255	1212.374	964.8109	50.43379	-1	0
14	7	Female	26	Asian	Brown	N	8:49:12	948.927	1094.987	781.3675	49.946	-1	0
15	7	Female	26	Asian	Brown	N	8:49:13	1020.126	1119.274	797.8592	50.12111	-1	0
16	7	Female	26	Asian	Brown	N	8:49:14	1030.408	1115.226	778.0692	49.88077	-1	0
17	7	Female	26	Asian	Brown	N	8:49:15	1061.254	1123.322	784.6659	53.26435	-1	0
18	7	Female	26	Asian	Brown	N	8:49:16	1040.69	1111.178	784.6659	55.78167	-1	0
19	7	Female	26	Asian	Brown	N	8:49:17	1045.831	1127.37	784.6659	56.40111	-1	0
20	7	Female	26	Asian	Brown	N	8:49:18	1030.408	1111.178	801.1575	54.44462	-1	0
21	7	Female	26	Asian	Brown	N	8:49:19	1030.408	1115.226	797.8592	53.71967	-1	0
22	7	Female	26	Asian	Brown	N	8:49:20	1040.69	1115.226	801.1575	50.31036	-1	0
23	7	Female	26	Asian	Brown	N	8:49:21	1314.685	1244.274	930.9735	51.96414	-1	0

Figure 3.19 Data Analysis Process

This chapter presents detailed information about the scope of the research, experimental chamber, research tools, adopted software and other preparation and procedure of the project. By being acquainted with the methodology of this research, it would be easier to understand the results and discussion coming in the next chapters.

Chapter 4: Study Results

After a pilot study and following the completion of each round of experiments, all data were collected for analysis. In this chapter, the pilot study results are summarized and briefly discussed. Then, data is presented about each individual's preferred range of lighting environment and their pupil size based on the visual sensation levels. The overall pupil size range of all the subjects in each round of chamber experiments is also summarized. The displayed data is all raw data without any processing such as standardization.

4.1 – Pilot Study Results

Figure 4.1 summarizes the ranges of illuminance per visual sensation for all individual study participants. Volunteer subjects showed different levels or ranges of illuminance with the same sensation level. For example, the subject #01 illustrated around 400 lux as a "neutral" level while illuminance between 200 and 700 lux were reported as a "slightly dark" or "slightly bright" condition by the test participants. However, the subject #03 reported 170 lux as a "neutral" condition (i.e. satisfied), but the range from 250 lux to 1000 was "(slightly) bright" for the subject. The data in Figure 4.2 confirms individually different preferences on illuminance. Illuminance ranges perceived by the test subjects were aggregated at each visual sensation level in the figure. The illuminance range of the subjects' neutral sensation widely ranged from 140 lux to 700 lux, and "bright" sensations were reported with conditions between 250 lux and 1000 lux.

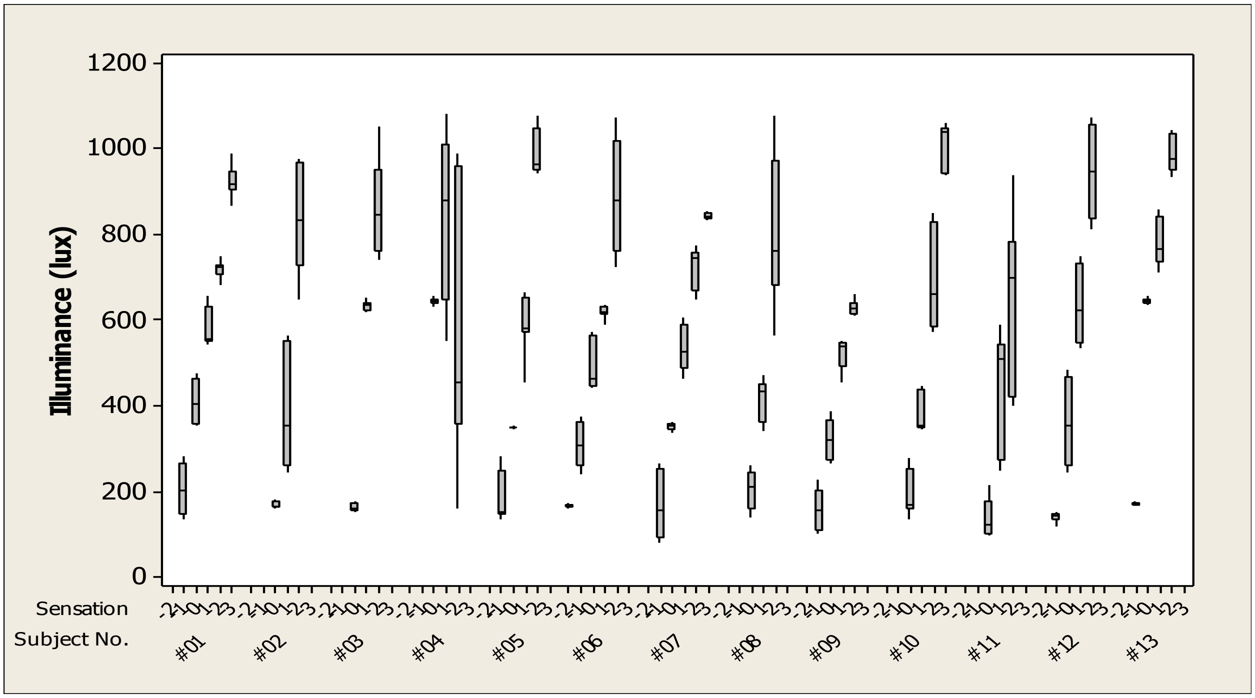


Figure 4.1 Illuminance range per visual sensation of each individual (Pilot study).

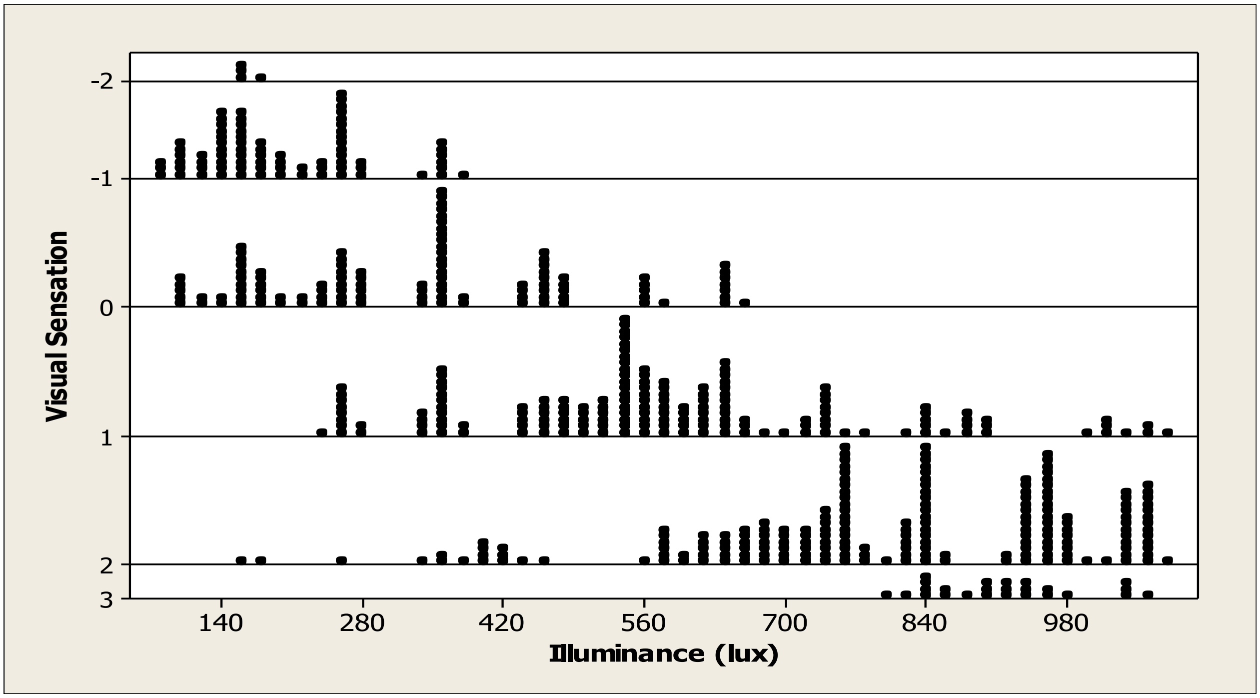


Figure 4.2 Overall illuminance distribution per visual sensation of all individuals (Pilot study).

Measured pupil sizes also showed various features per individual test subject. Some subjects showed relatively small ranges of pupil size changes between the visual sensations, but others generated large variations in their pupil sizes across the visual sensations. Currently, the only reason could be came up is individual physiological characteristics. To reduce the deviations by personal physical conditions, the collected pupil size data were standardized per individual subject by using the following equation:

$$Standardized\_Pupil\_size(\%) = \left(\frac{Pupil\_size(i) - Pupil\_size(neutral\_sensation)}{Pupil\_size(neutral\_sensation)} \right) \times 100$$

where i is a visual sensation.

Individually standardized values by the equation showed more stability with reduced deviations across the subjects (Figure 4.3) than the raw data of pupil sizes. As shown in Figure

4.3, the confidence intervals of each subject show more consistency between the different sensations across the test subjects. In addition, the standardized data showed clear ranges of confidence intervals between the different sensations. These results illustrate the potential of pupil sizes to characterize visual sensation.

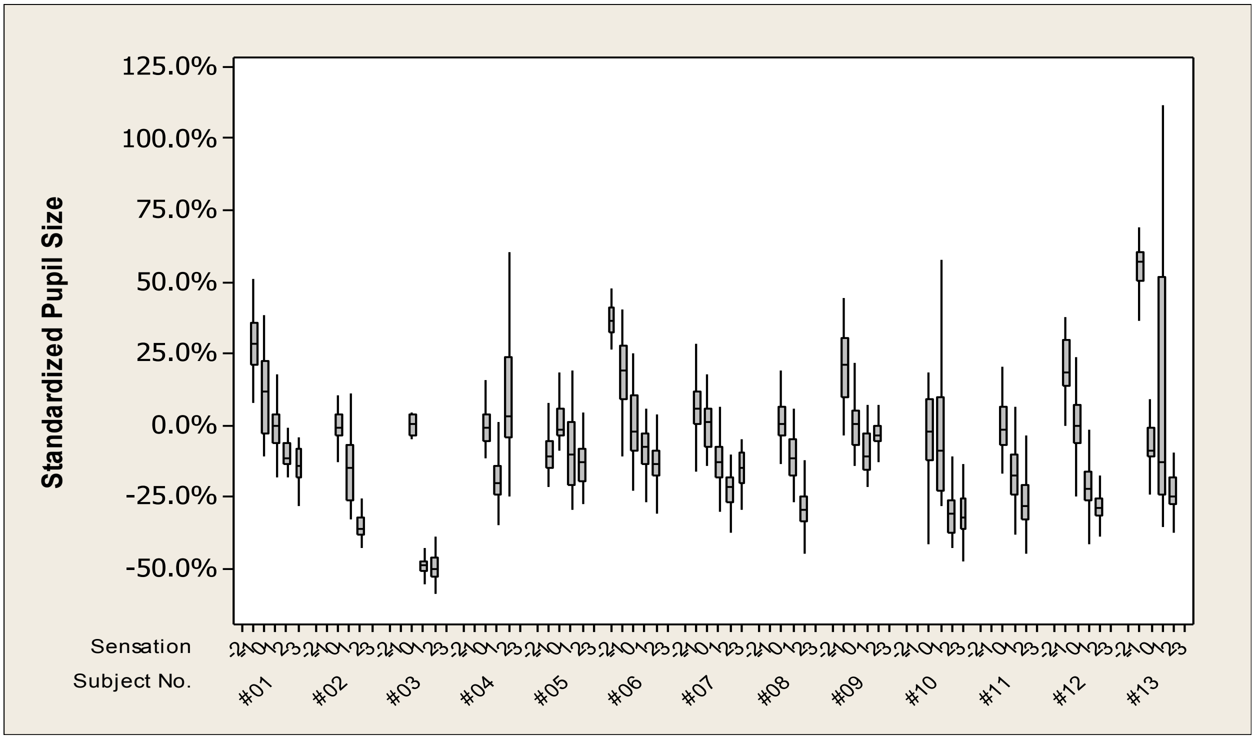


Figure 4.3 Ranges of standardized pupil size per visual sensation of each individual (Pilot study).

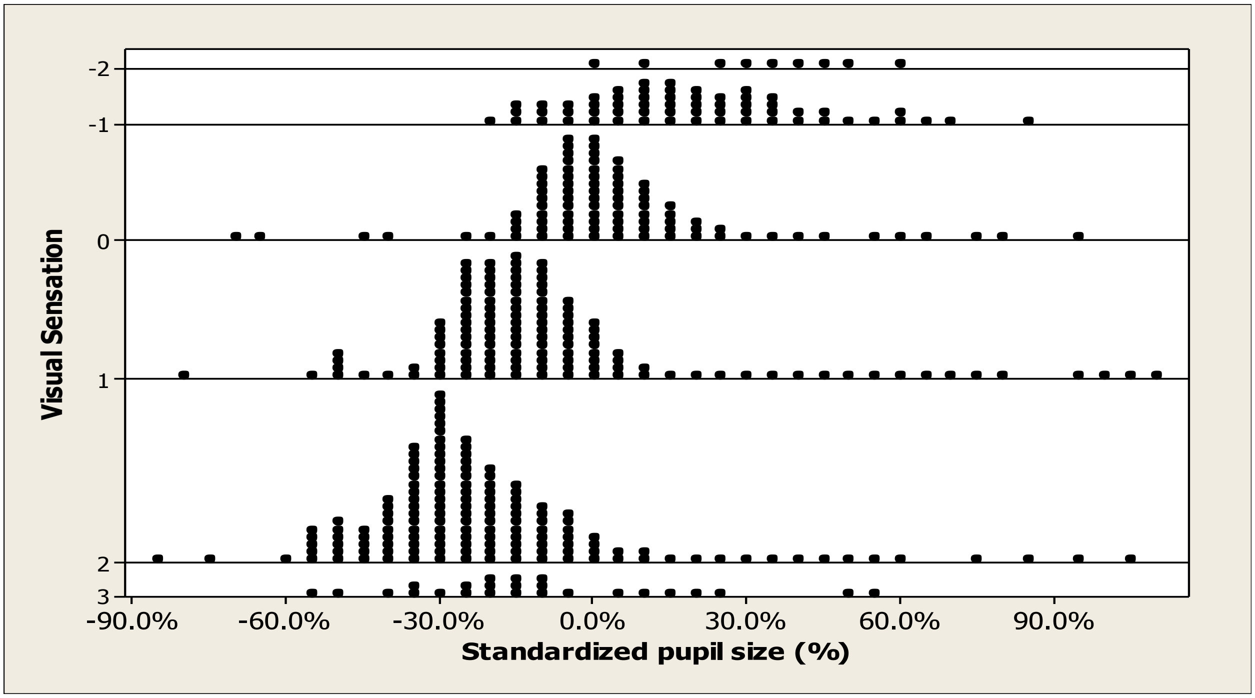


Figure 4.4 Overall standardized pupil size distribution per visual sensation of all individuals (Pilot study).

The standardized pupil sizes per individual subject were combined to find a common feature across the subjects. Overall distributions of standardized data in Figure 4.4 are clearly shaped like a typical normal distribution in each visual sensation, and the pupil size ranges seem distinctly differentiated from each other. The ANOVA (analysis of variance) test in Table 4.1 (left) shows that those distributions are clearly set apart from each other with a statistically significant p-value of 0.000.

The confidence interval (CI) of the variance of standardized pupil size distribution of each visual sensation level is evidently separated from each other, so it is enough to show a visual sensation by reading the ranges of the CIs (Table 4.1- left). A stepwise regression formula also shows the significant contribution of standardized pupil size to predict the visual sensation (Table 4.1- right) with a significant p-value, and a R-sq value increase in the stepwise regression.

The stepwise regression generated a high R-sq of 70.25, which indicates a higher predictive potential increase of standardized size than the actual pupil size adopted in the step 3. Therefore, standardized pupil size can be used as a critical single predictor to estimate an actual visual sensation.

Table 4.1 Results of ANOVA with standardized pupil size data (left) and stepwise regression based on the data of standardized pupil size, actual pupil size and illuminance.

```
Source       DF        SS       MS       F      P
Sensation     5  117.3903  23.4781  729.80  0.000
Error      5452  175.3949   0.0322
Total      5457  292.7853

S = 0.1794   R-Sq = 40.09%   R-Sq(adj) = 40.04%


                             Individual 95% CIs For Mean Based on
                             Pooled StDev
Level     N     Mean   StDev  ---+---------+---------+---------+-
-2       30   0.3504  0.1078                          (---*--)
-1      747   0.1739  0.1900                     (*
 0     1033   0.0126  0.1322              (*
 1     1555  -0.1362  0.1959        *)
 2     1908  -0.2437  0.1860  (*
 3      185  -0.1645  0.1554     (-*)
                             ---+---------+---------+---------+--
                             -0.20      0.00      0.20      0.40
```

```
Step                         1        2        3
Constant               -0.9174  -0.7539  -1.7840

Illuminance (lux)      0.00326  0.00280  0.00294
T-Value                 106.30    78.19    81.89
P-Value                  0.000    0.000    0.000

Pupil size (Stand.)             -0.994   -1.555
T-Value                         -22.70   -28.70
P-Value                          0.000    0.000

Pupil size (Abs.)                        0.01435
T-Value                                  16.83
P-Value                                  0.000

S                       0.643    0.614    0.599
R-Sq                    67.44    70.25    71.72
R-Sq(adj)               67.43    70.24    71.70
Mallows Cp              825.0    285.2      4.0
```

4.2 – First Round Results: Low light color temperature condition, Computer task type

As mentioned in Chapter 3 Methodology, color temperature used for the first round was 2700 K, which was included in the “warm” temperature range, and the selected work type was a computer-based task. The remaining variables for the experiment were maintained consistently for each experiment in the different rounds. The overall ranges of the air temperature, relative humidity, and CO2 during the experiment were 23.5± 0.7℃, 33±2.5%, and 620 ± 35ppm, respectively. 20 volunteers participated in the first round experiments. Information about the human subjects is summarized in Table 4.2.

Table 4.2 Demographic information of human subjects (First round)

First Round (Computer + Warm)							
Gender		***Age***		***Eye color***		***Myopic***	
Male	Female	<25	>=25	Blue	Brown	Yes	No
12	8	11	9	4	16	9	11
60%	40%	55%	45%	20%	80%	45%	55%

Similar procedures applied in the pilot study were adopted for displaying the collected raw data. First, the preferred range of illuminance per visual sensation of each participant in the first round is all displayed (Figure 4.5). Although the all subjects show very different patterns, they still share a similar general trend: a sensation increases when illuminance increases. That also demonstrates the basic physiological ability of perceiving the light and visual acuity performance. Furthermore, several subjects have even very similar patterns, e.g. Subject no. 10, 11 and 19. That creates the possibility of grouping people for further analyses to determine the similarities that could commonly found in a certain subject group defined in this research.

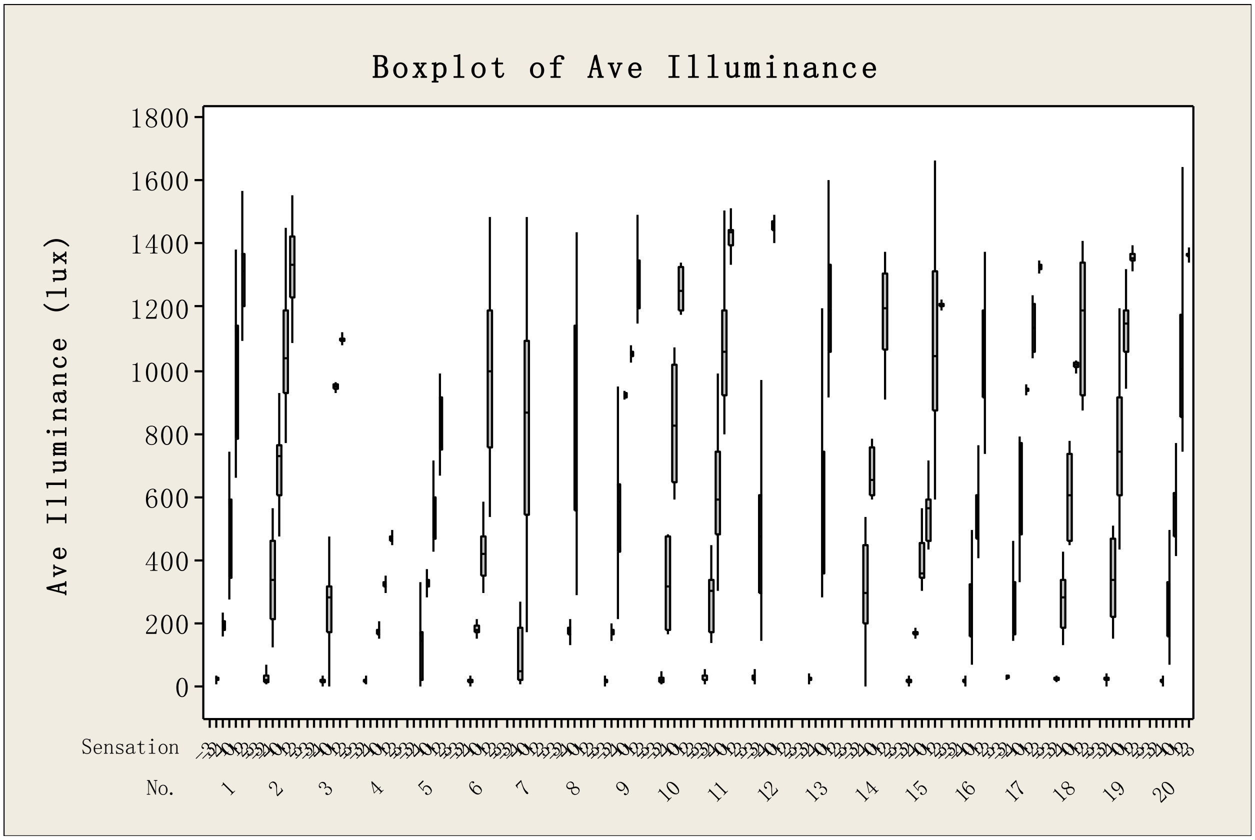


Figure 4.5 Illuminance range per visual sensation of each individual (First round).

One more step into the analysis of raw data about preferred range for each sensation was conducted (Figure 4.6). Overall preferred illuminance distribution per each sensation is shown. Based on the distributions, the general preferred range could be identified. For -3, it lasts from 0 to 300 lux; for -2 and -1, it lasts from 0 to about 1000; for 0, it is from 0 to 1600; for 1 and 2, it is from 300 to 1600, while for 3, it is 1200 from 1500. There are some data points beyond the designated highest illuminance level, which is 1400 lux. It was because some extra electric current caused in the transmission between illuminance meter and DAQ sensor. But these data points are very few compared to the remaining amount of data and thus are not expected to have a significant effect on the results and analysis, which will be discussed in Chapter 5.

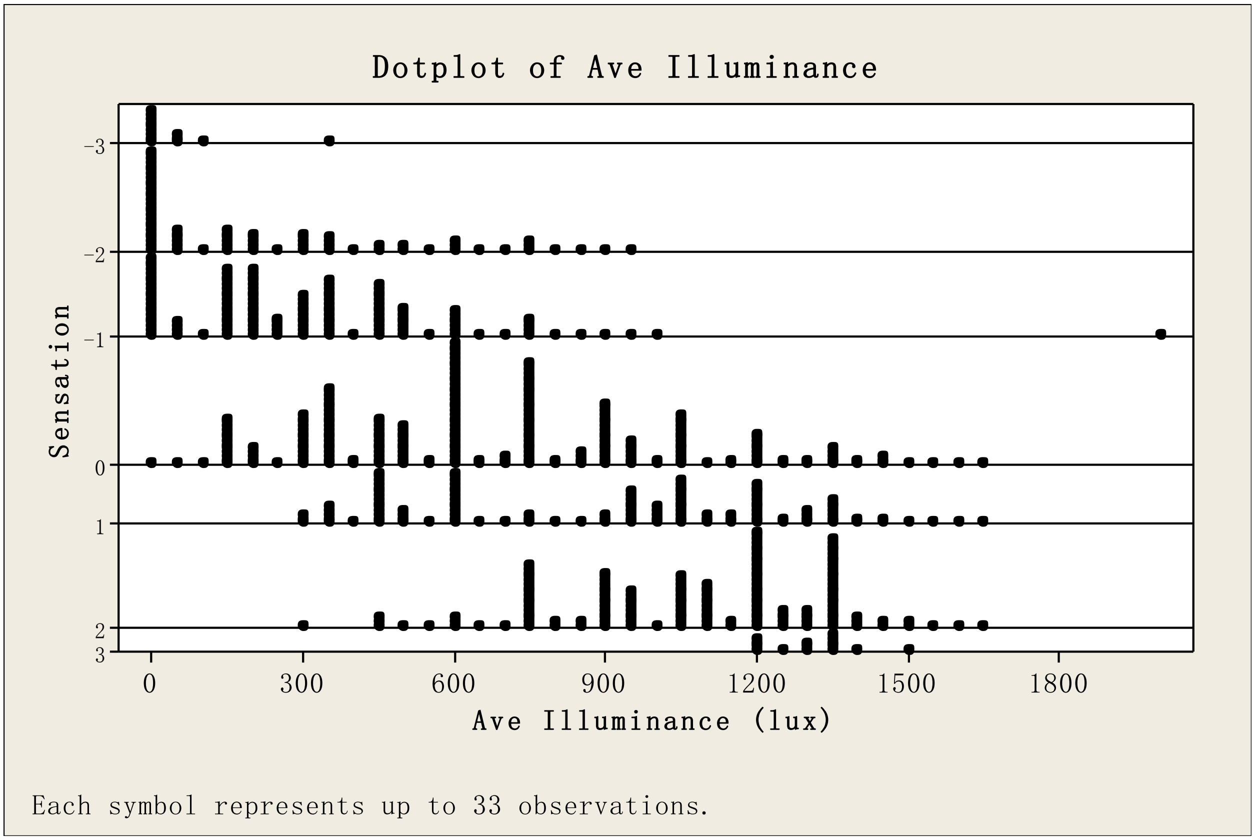


Figure 4.6 Overall illuminance distribution per visual sensation of all individuals (First round).

The pupil size of each participant was collected and totally 1200 pupil size data per person was recorded for a one-hour experiment. Ranges of original pupil size per visual sensation of each individual are plotted (Figure 4.7). Due to physiological characteristics of each individual, they have wide ranges of pupil sizes even in a same visual sensation, No. 6 shows 30 to 80 pixels in the pupil sizes, while No.1 generates around 40 to 50. Due to individually different pupil sizes and their change rates, it is difficult to find a generalized pattern among the test subjects. However, at least all individuals still share similar trends in patterns. Pupil size decreases when sensation increases, which could also be recognized in daily time.

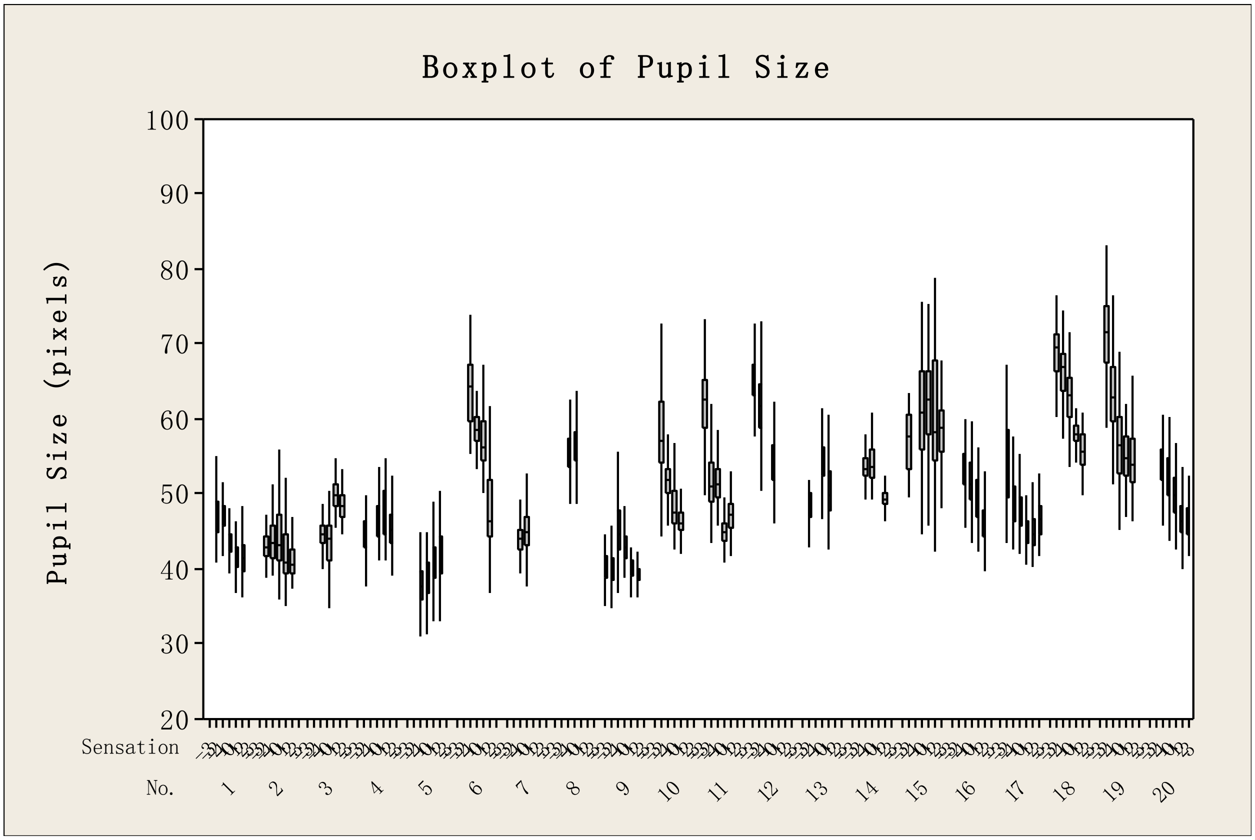


Figure 4.7 Ranges of original pupil size per visual sensation of each individual (First round).

The original pupil size of all individuals were combined and plotted (Figure 4.8). Pupil size doesn't follow a normal distribution per visual sensation since the physiological difference among human subjects, which indicates the importance of standardization process of the pupil size.

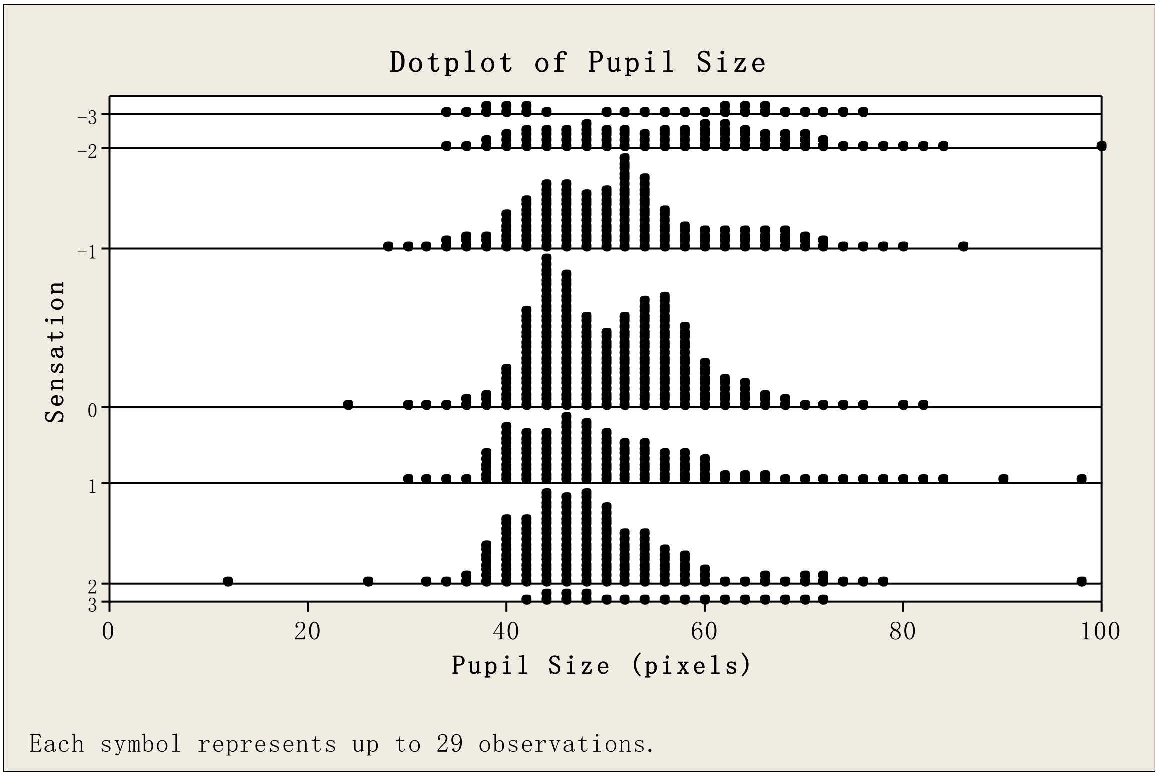


Figure 4.8 Overall original pupil size distribution per visual sensation of all individuals (First round).

4.3 – Second Round Results: High light color temperature condition, Computer task type

The color temperature used for the second round was 5000 K, which was included in the "daylight" defined range, and the selected work type was a computer-based task. Compared with the first round, other variables for the experiment were kept same for each experiment, except the lighting color temperature in the second round test. Again, 20 volunteers participated in the first round experiments. Information about the human subjects is summarized in Table 4.3.

Table 4.3 Demographic information of human subjects (First round)

Second Round (Computer + Daylight)							
Gender		***Age***		***Eye color***		***Myopic***	
Male	Female	<25	>=25	Blue	Brown	Yes	No
12	8	8	12	5	15	7	13
60%	40%	40%	60%	25%	75%	35%	65%

Same as the first round, boxplots of illuminance range per visual sensation of each individual (Figure 4.9), overall illuminance distribution per visual sensation of all individuals (Figure 4.10), pupil size range for each individual (Figure 4.11) and overall pupil size distribution of all individuals (Figure 4.12) were generated based on the experiment data of the second round. Compared to the findings in the first round experiments, similar findings about illuminance-sensation patterns and pupil size-sensation pattern were revealed. The raw data are summarized in Figures 4.9 to 4.12.

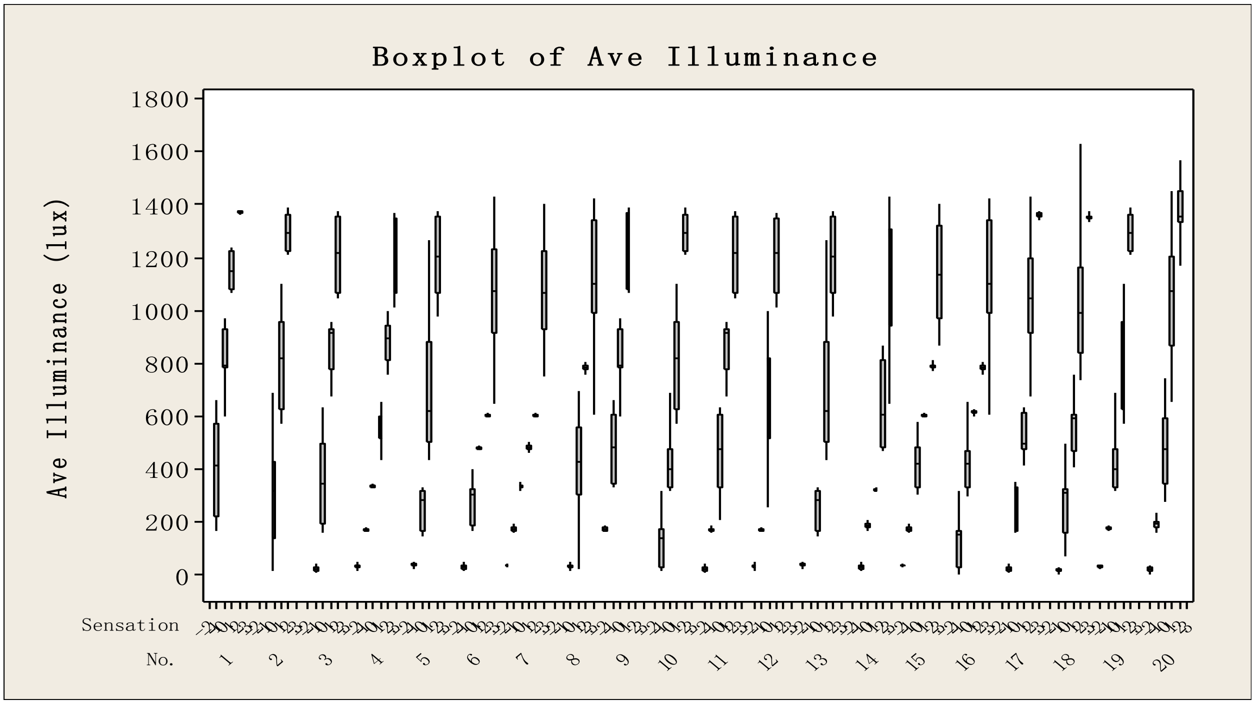


Figure 4.9 Illuminance range per visual sensation of each individual (Second round).

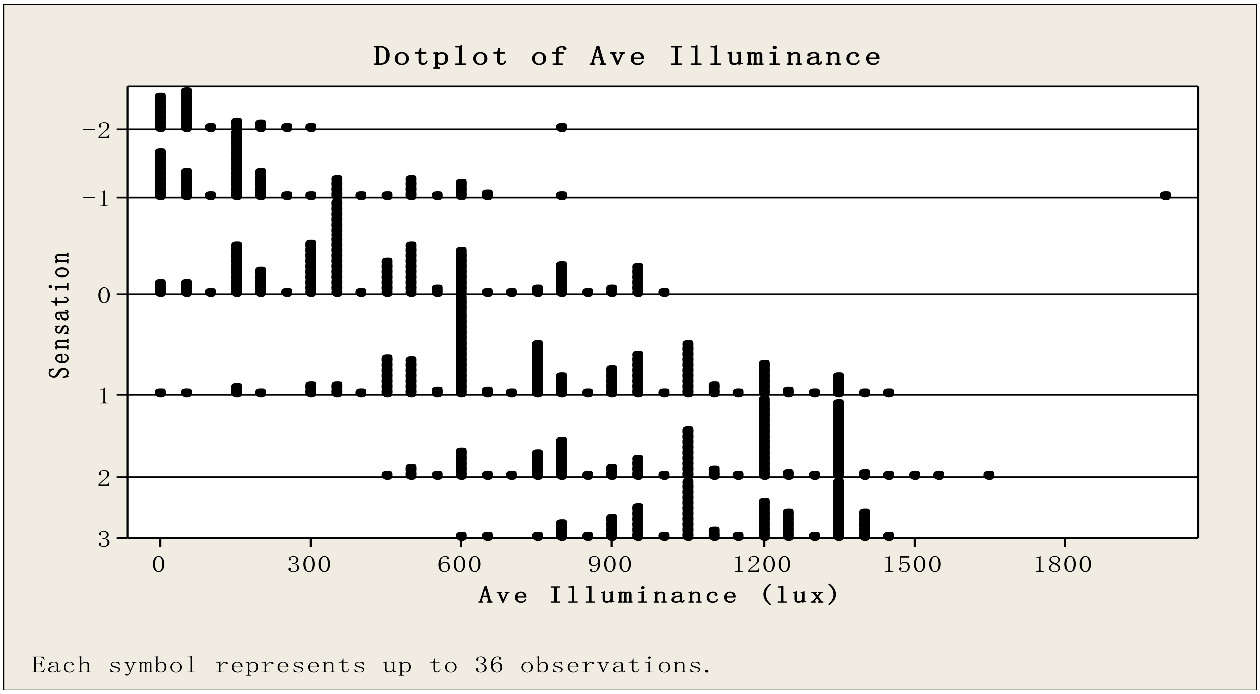


Figure 4.10 Overall illuminance distribution per visual sensation of all individuals (Second round).

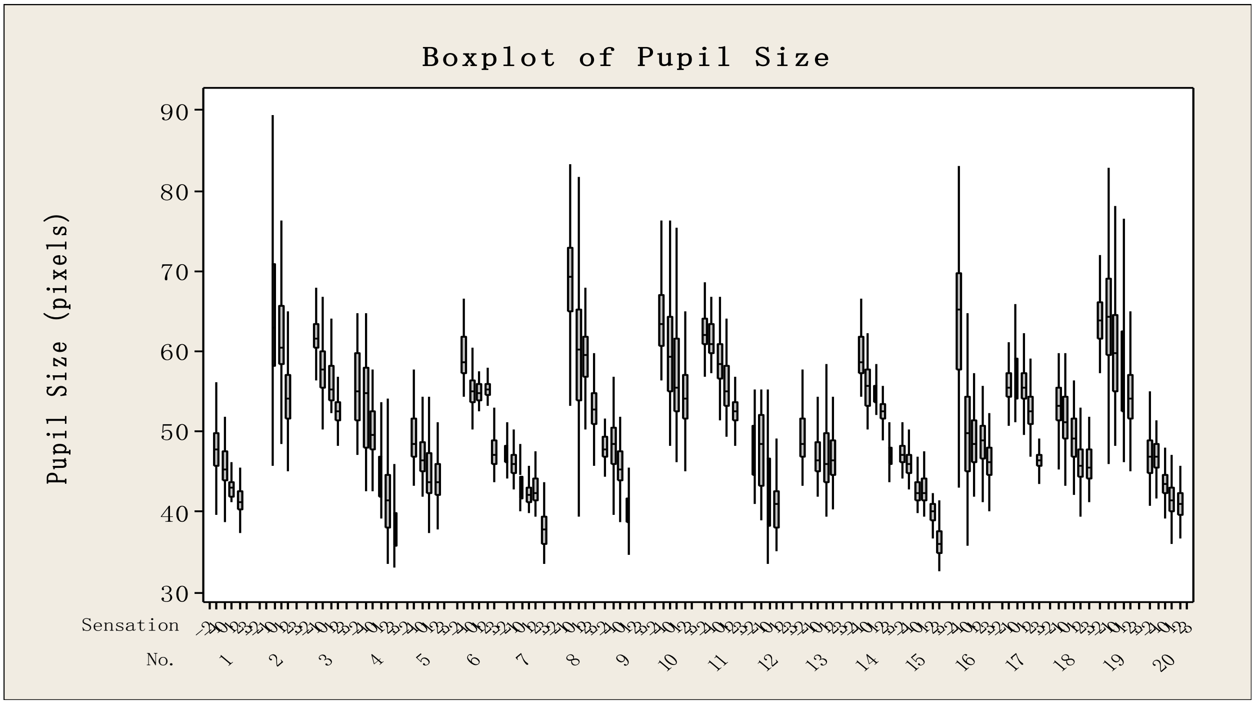


Figure 4.11 Ranges of original pupil size per visual sensation of each individual (Second round).

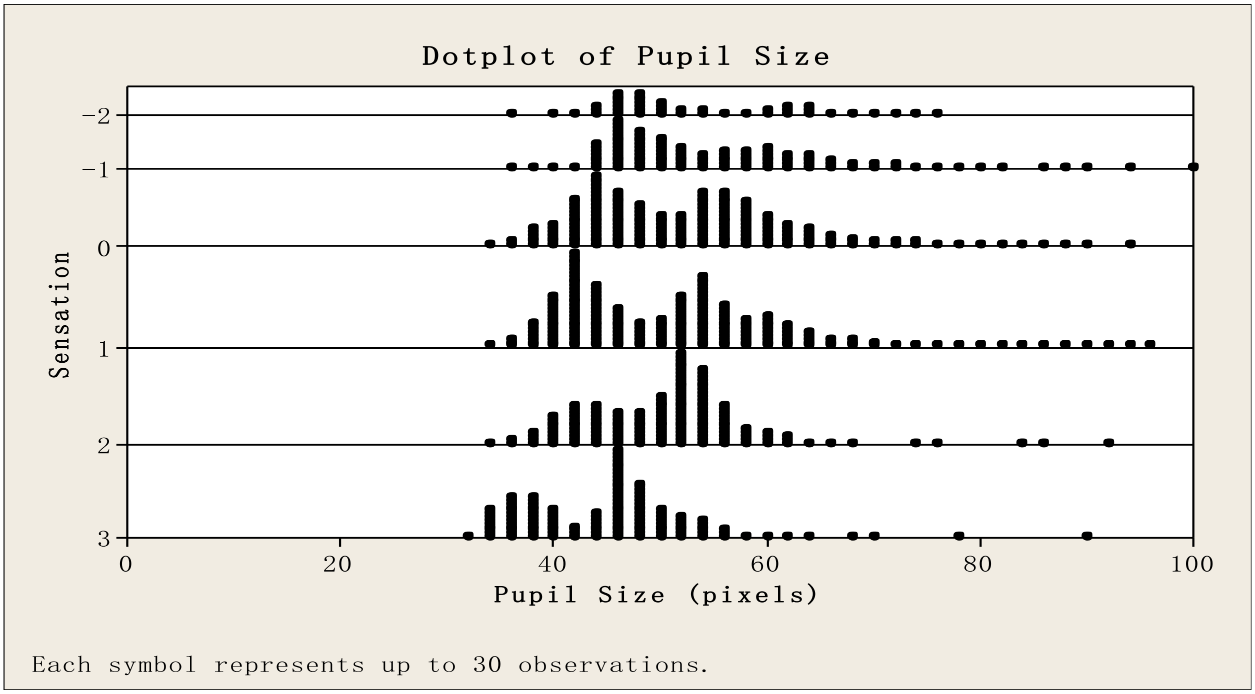


Figure 4.12 Overall original pupil size distribution per visual sensation of all individuals (Second round).

4.4 – Third Round Results: High light color temperature condition, Paper task type

The color temperature used for the third round was 5000 K, which was included in the “daylight” defined range. However, the selected work type was a paper-based task. Other variables for the experiment except the task type were kept same in the third round experiment, compared to the second round. 20 volunteers participated in this round. Information about the human subjects is summarized in Table 4.4.

Table 4.4 Demographic information of human subjects (Third round)

Third Round (Paper + Daylight)							
Gender		***Age***		***Eye color***		***Myopic***	
Male	Female	<25	>=25	Blue	Brown	Yes	No
11	9	7	13	6	14	9	11
55%	45%	35%	65%	30%	70%	45%	55%

In a same way adopted in the previous rounds, boxplots of illuminance range per visual sensation of each individual (Figure 4.13), overall illuminance distribution per visual sensation of all individuals (Figure 4.14), pupil size range for each individual (Figure 4.15) and overall pupil size distribution of all individuals (Figure 4.16) were generated based on the experiment data of second round. Similar findings about trend of illuminance-sensation pattern and pupil size-sensation pattern were revealed compared to the first and second found experiments. The data distributions are summarized in the following figures.

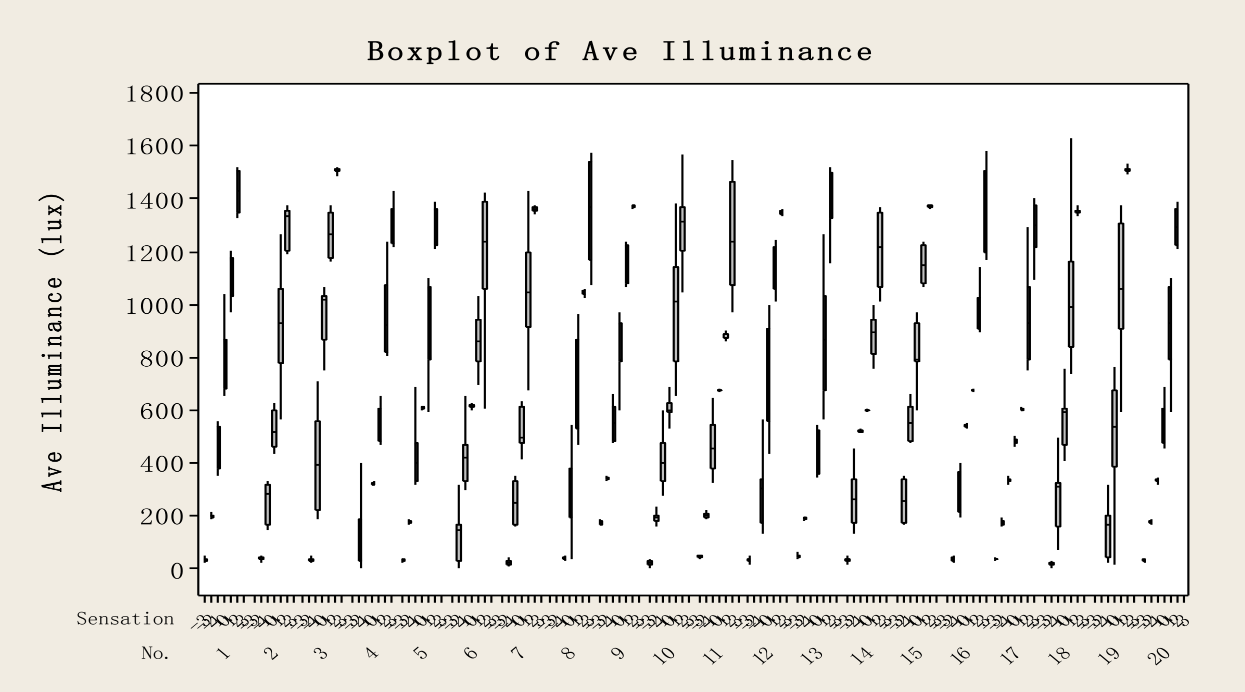
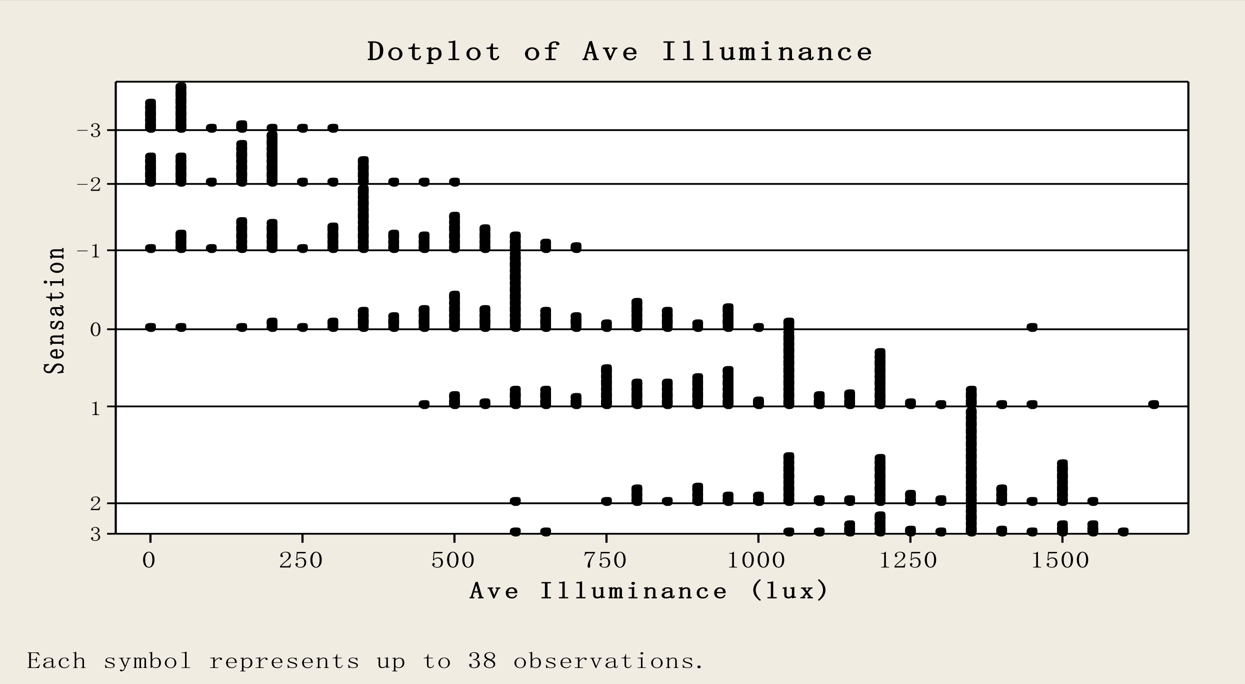


Figure 4.13 Illuminance range per visual sensation of each individual (Third round).



Each symbol represents up to 38 observations.

Figure 4.14 Overall illuminance distribution per visual sensation of all individuals (Third round).

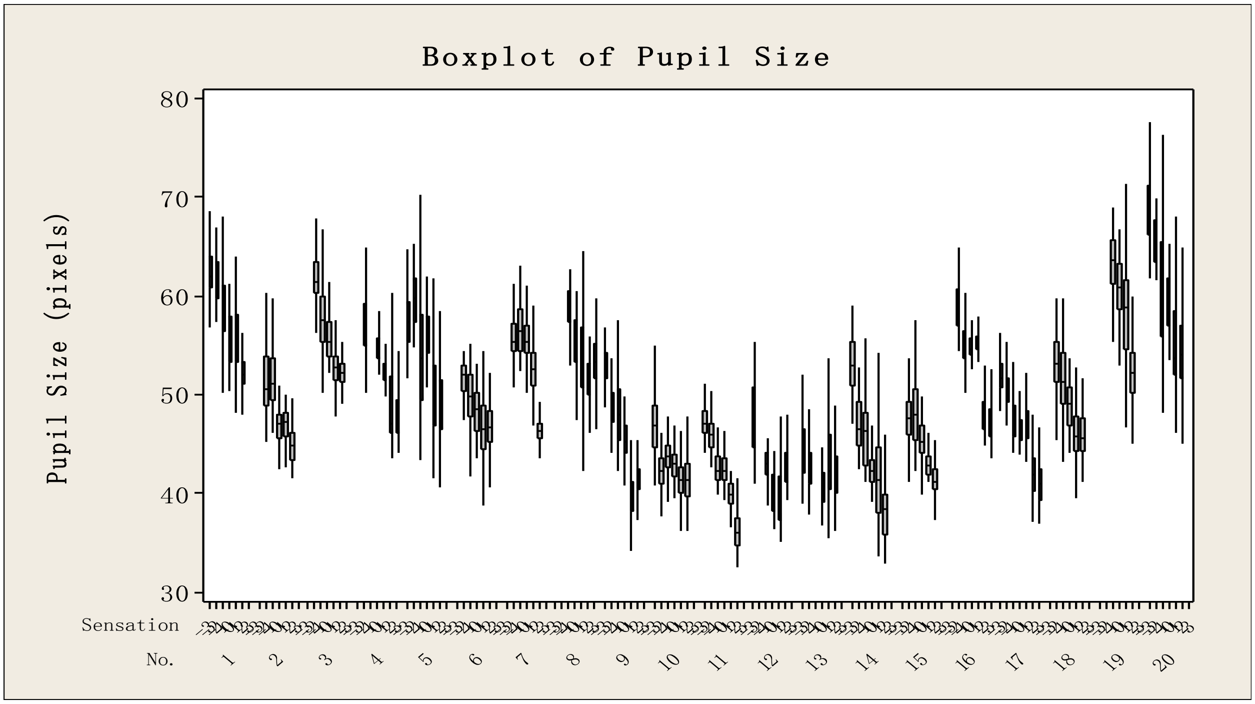


Figure 4.15 Ranges of original pupil size per visual sensation of each individual (Third round).

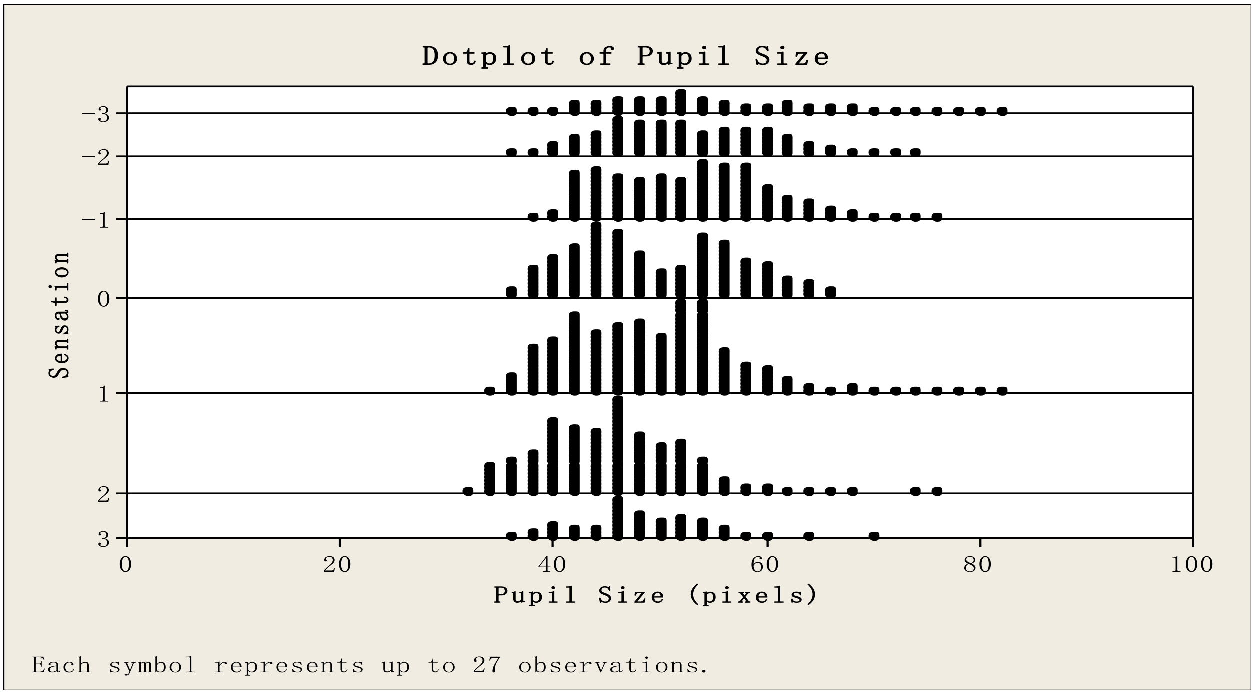


Figure 4.16 Overall original pupil size distribution per visual sensation of all individuals (Third round).

Chapter 5: Data Analysis and Discussion

The pupilometer used the pixel as a metric for measurement. It detected the size of a pupil by the micro-camera facing the subject's eye while tracking the path of eye movement. The raw data of individuals' pupil sizes are not comparable because pupil sizes and shapes vary in different individuals. For this reason, normalized (i.e., standardized) data for each individual was used for data analysis using the formula introduced in the pilot study part.

$$Standardized\_Pupil\_size(\%) = \left(\frac{Pupil\_size(i) - Pupil\_size(neutral\_sensation)}{Pupil\_size(neutral\_sensation)}\right) \times 100 \qquad (5\text{-}1)$$

where i is an eye's response to illuminance.

5.1 – First Round

Figure 5.1 displays the standardized pupil size for each human subject based on their sensations. The individually normalized data shows more stable fluctuations than the raw data pupil size data. As illustrated in the standardization formula above, the pupil size measured at the neutral visual sensation was selected as a baseline. This process relatively flattened the undulation of the measured data per individual. As illustrated in Figure 5.1, most test subjects showed positive change rates with darker perceptions and vice versa with brighter perceptions. However, in the case of No.11, since he reported a "neutral" sensation for the highest illuminance condition, the measure pupil sizes had increased to 60% of the baseline pupil size. On the other hand, Subject No. 20 reported a neutral sensation for the lowest illuminance condition, and the measured pupil sizes had decreased to 25% of the subject's baseline pupil size. In addition, the normalized pupil sizes showed different changing rates per individual and his/her visual sensation. Subject No. 5

and No. 20 showed very mild change slopes as the visual sensations increased, but data for Subjects No. 11 and No. 19 presented rapid changes with irregular patterns.

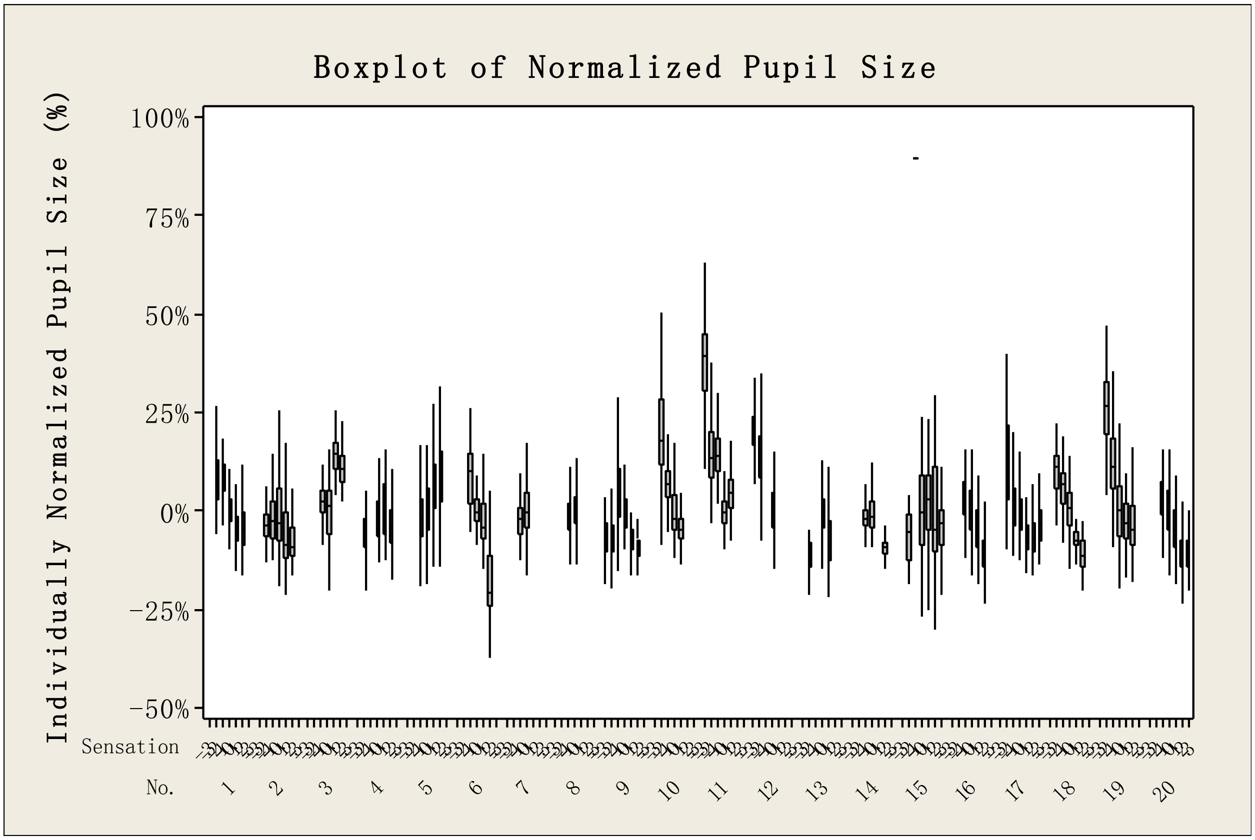


Figure 5.1 Standardized pupil size distribution in each subject's test ("No." indicates a subject ID) (First round).

Figure 5.2 illustrated the pupil size patterns for visual sensations based on the combined data of all individuals. Overall, the standardized pupil sizes decreased while the generated illuminance intensity was increasing. The analysis of variance (ANOVA) test showed a statistically significant p-value that was lower than 0.05 (Table 5.1). This finding is clearly summarized in Figure 5.3. The chart contains basically the same data as Figure 5.2, but it shows a 95% confidence interval for pupil sizes per visual sensation. The interval lines are clearly differentiated from each other, and the length of an interval at neutral sensation is shortest, which indicates that the pupil size for a neutral sensation is more stable than for other sensations.

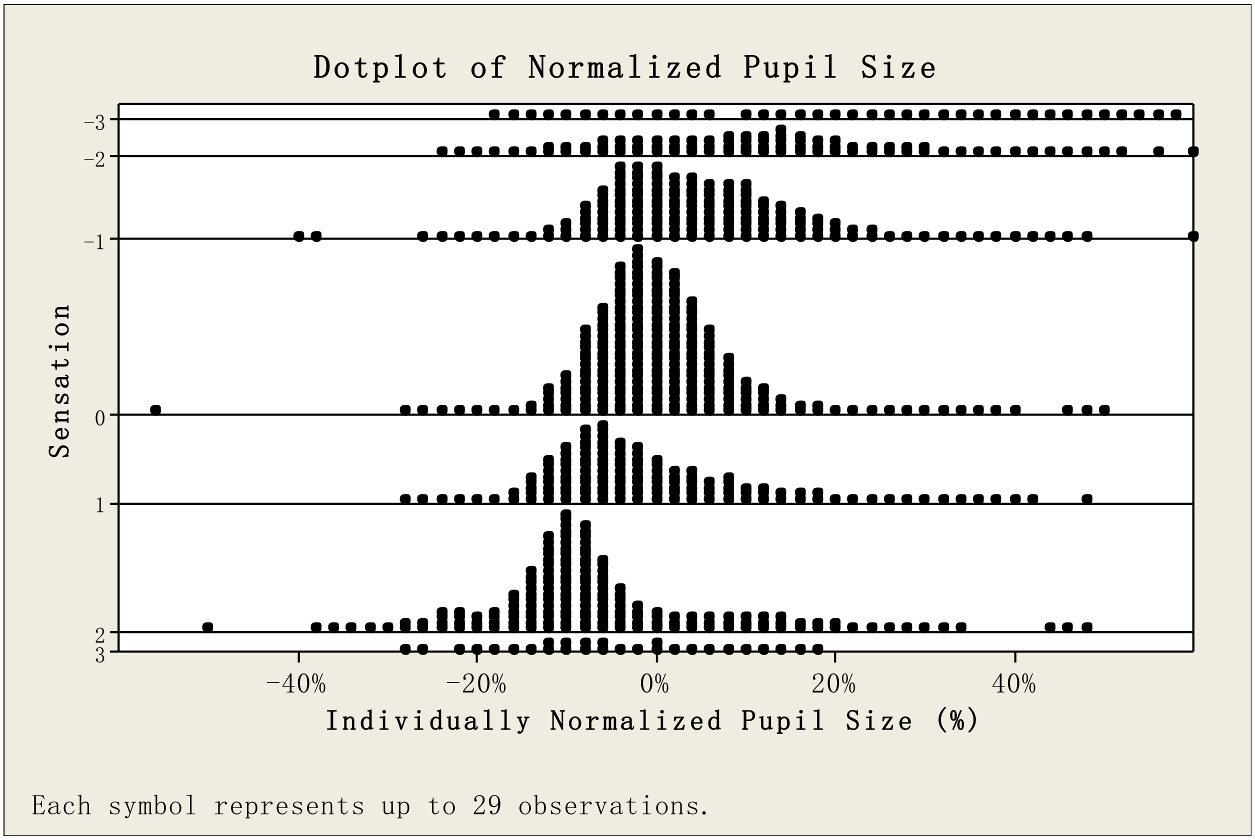


Figure 5.2 Overall standardized pupil size distribution per visual sensation to illuminance intensity (first round).

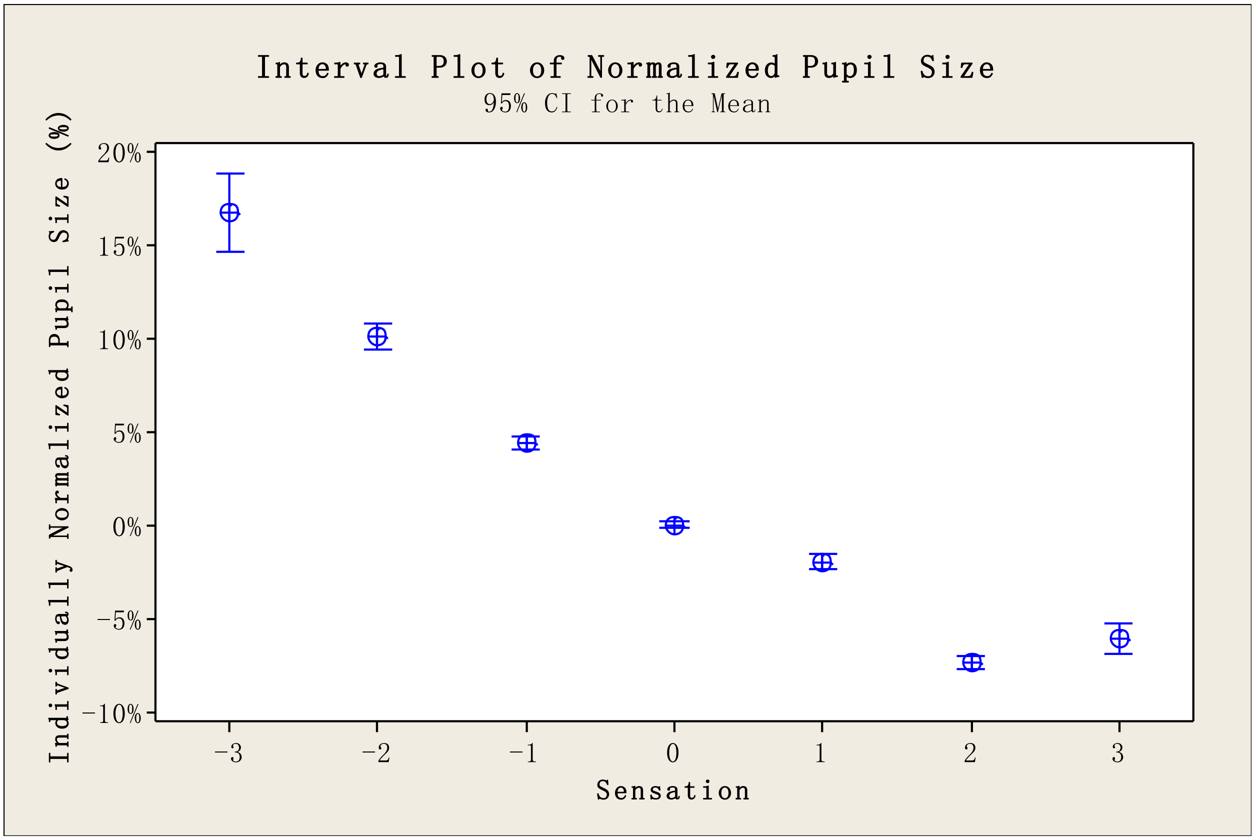


Figure 5.3 Interval plot of standardized pupil size per visual sensation to illuminance intensity (First round).

However, the mean value of sensation 3 is a bit higher than sensation 2, which could indicate a lack of enough data for this level. It is also shown in Figure 5.2, which the distribution of sensation 3 is flat and there is limited number of dots. Similarly, for both sensation 3 and sensation -3, the interval lines are longer than others because of less reported data from experiments. That is also an indication that in the current illuminance range (50 lux – 1400 lux), very few participants considered “very dark” or “very bright.” Another finding is the differences between sensations when reported among “dark” zones are larger than those among “bright” zones.

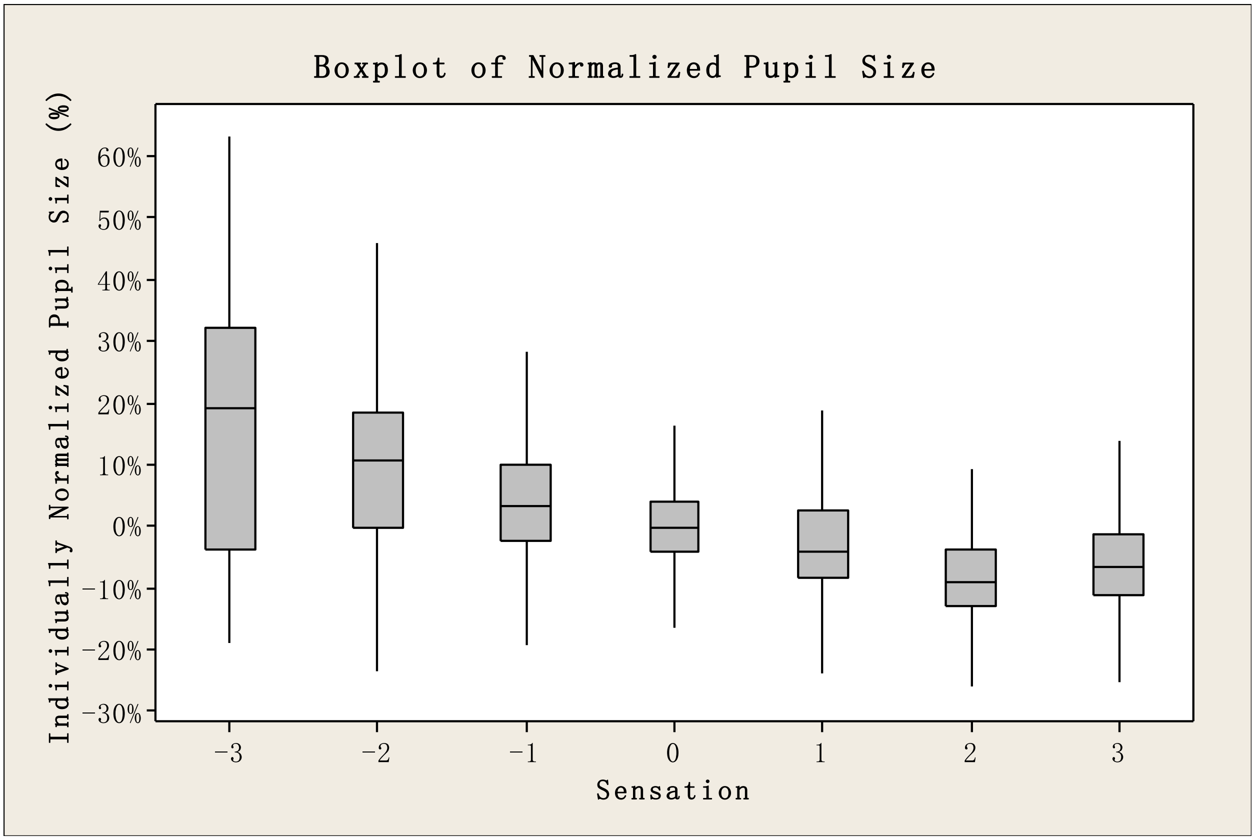


Figure 5.4 Boxplot of standardized pupil size per visual sensation to illuminance intensity (First round).

In addition to Figure 5.2 and Figure 5.3 for the illustration of standardized pupil size distribution, all data was also presented in boxplot chart (Figure 5.4). The line in the boxplot indicating median value for each sensation follows similar pattern as mean value has in Figure 5.3.

Table 5.1 One-way ANOVA test: Standardized Pupil Size versus Sensation

```
Source        DF        SS      MS       F      P
Sensation      6   59.7410  9.9568  957.99  0.000
Error      19680  204.5442  0.0104
Total      19686  264.2852

S = 0.1019   R-Sq = 22.60%   R-Sq(adj) = 22.58%

                                 Individual 95% CIs For Mean Based on Pooled StDev
Level     N     Mean   StDev   -+---------+---------+---------+--------
-3      353   0.1678  0.2029                                   (-*)
-2     1706   0.1013  0.1405                          *)
-1     3909   0.0441  0.0994                  *)
 0     6216  -0.0001  0.0693            *
 1     3120  -0.0198  0.1100        *)
 2     4073  -0.0741  0.1091   *)
 3      310  -0.0607  0.0737    (*-)
                               -+---------+---------+---------+--------
                              -0.070     0.000     0.070     0.140

Pooled StDev = 0.1019
```

To check the consistency of pupil size changes per visual sensations for individuals, the study conducted comparison tests between subject groups of different physiological characteristics, (i.e., eye color, age, gender, and myopic conditions). Since the study adopted 20 human subjects for the chamber experiments, the data for individual sensations were regrouped from a 7-point scale to a 3-point scale to keep the scope of data at a level for statistical significance in the data analysis. Therefore, visual sensations of -3 (very dark), -2 (dark) and -1 (slightly dark) were grouped into “dark,” and visual sensations of +1 (slightly bright), +2 (bright) and +3 (very bright) were grouped into “bright.”

Figure 5.5 shows the interval plot of normalized pupil size with a 95% confidence interval for the mean value in eye color groups. Figure 5.6 indicates four quartile distributions of data and comparison sets illustrate a similar pattern between two eye color groups. Each eye color group showed larger normalized pupil sizes at the dark sensation and smaller pupil sizes at the bright sensation. Since the neutral sensation was reported in different illuminance levels, depending on the participants, the pupil sizes were also measured in some ranges at the neutral condition.

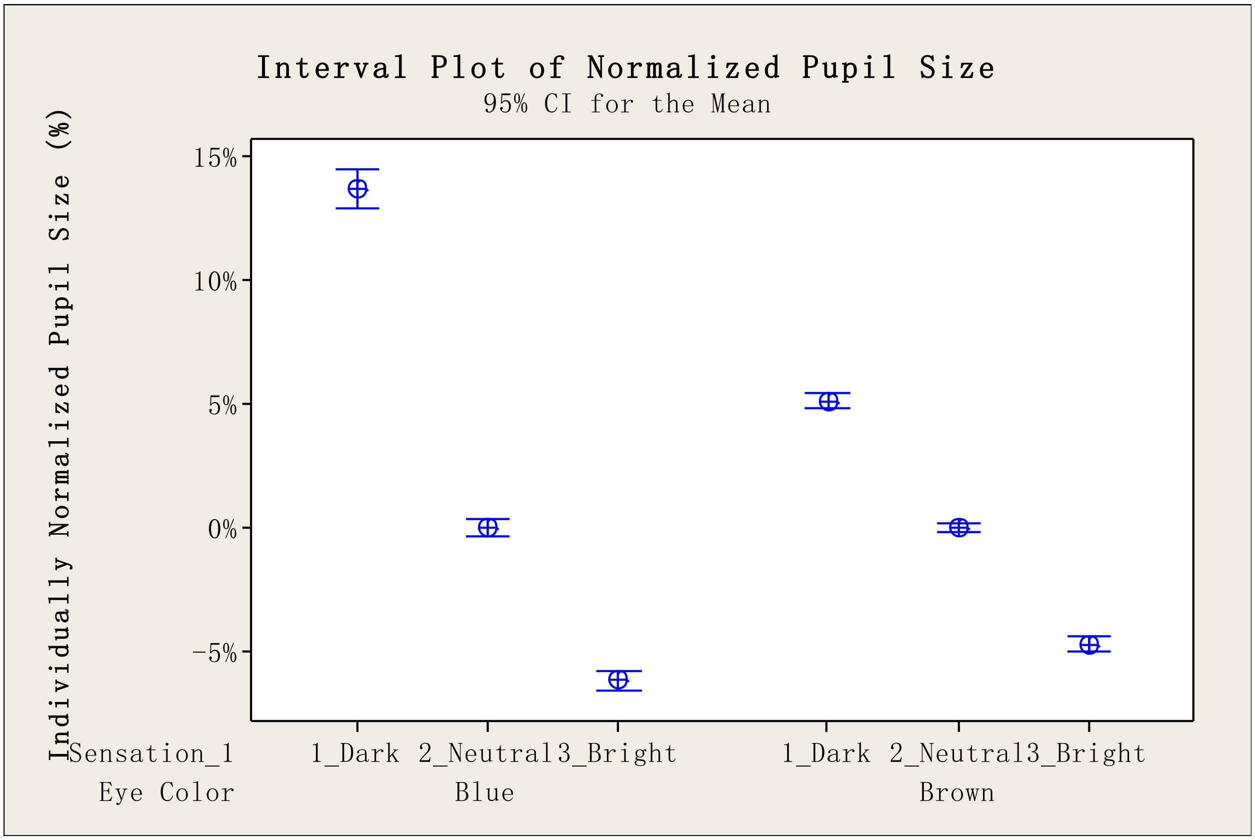


Figure 5.5 Interval plot of comparisons of overall standardized pupil size per visual sensation between eye color groups (first round).

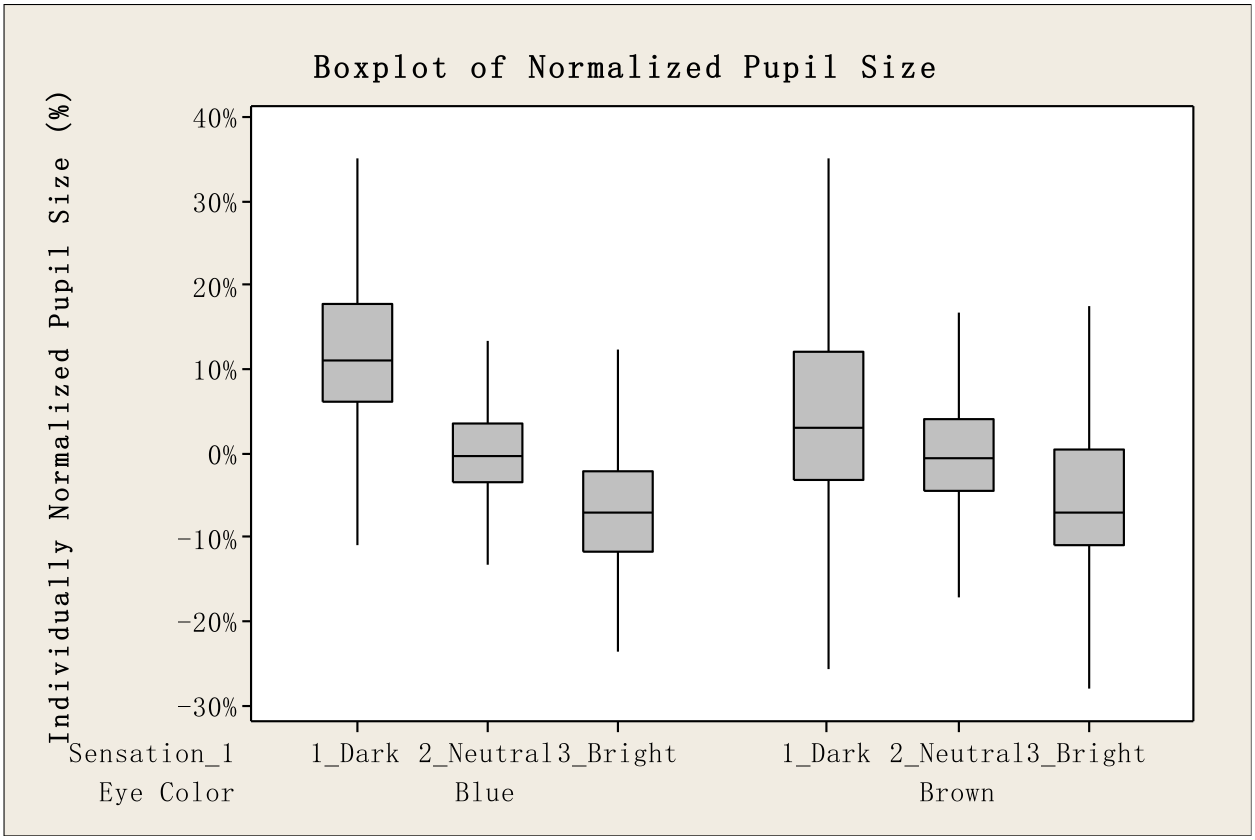


Figure 5.6 Boxplot of comparisons of overall standardized pupil size per visual sensation between eye color groups (first round).

The analysis of variance (ANOVA) test (Table 5.2) reported significant differences of pupil size in each group. The comparisons presented that average pupil size change compared with natural level was about 13.6% at dark and -6.2% at bright in the blue eye color group and respectively 5.1% and -4.7% in the brown eye color group. The ANOVA test showed a p-value of 0.000, which is smaller than 0.05 in the level of 95% confidence. These statistical findings support the concept that the visual sensations can be matched with normalized pupil sizes across the test subjects, and the findings are also commonly applicable to the eye color groups.

Table 5.2 One-way ANOVA test: Standardized Pupil Size versus Sensation between Eye Colors

ANOVA for Blue

```
Source          DF         SS          MS          F
P
Sensation_1      2   28.66370   14.33185   1553.16
0.000
Error         4130   38.10969    0.00923
Total         4132   66.77339

S = 0.09606    R-Sq = 42.93%    R-Sq(adj) = 42.90%

Level          N       Mean      StDev
1_Dark      1171    0.13628    0.13431
2_Neutral   1040    0.00000    0.05357
3_Bright    1922   -0.06172    0.08544
```

```
Individual 95% CIs For Mean Based on Pooled StDev
Level        -+---------+---------+---------+--------
1_Dark                                           (*)
2_Neutral                 (*)
3_Bright      (*
              -+---------+---------+---------+--------
              -0.060     0.000     0.060
0.120

Pooled StDev = 0.09606
```

ANOVA for Brown

```
Source          DF         SS          MS          F
P
Sensation_1      2    24.9154    12.4577   1125.10
0.000
Error        15551   172.1886     0.0111
Total        15553   197.1040

S = 0.1052    R-Sq = 12.64%    R-Sq(adj) = 12.63%

Level          N       Mean     StDev
1_Dark      4797     0.0510    0.1177
2_Neutral   5176    -0.0001    0.0721
3_Bright    5581    -0.0473    0.1188
```

```
Individual 95% CIs For Mean Based on Pooled StDev
Level        -------+---------+---------+---------+--
1_Dark                                             (*)
2_Neutral                         (*)
3_Bright     (*)
             -------+---------+---------+---------+--
                 -0.030     0.000     0.030
0.060

Pooled StDev = 0.1052
```

The subjects were also grouped by age for the comparison of pupil sizes. Figure 5.7 and Figure 5.8 illustrate the changing pattern in normalized pupil size at various visual sensations per age group. The Illuminating Engineering Society of North America (IESNA) has also categorized human ages into three groups for recommending different levels of illuminance: younger than 25; 25 to younger than 45, and 45 or older. Therefore, since the range of the test subjects' ages were from 19 to 40, the subjects were divided into two groups: junior and senior, based on the age 25 as a threshold and considering a sample size balance between the groups.

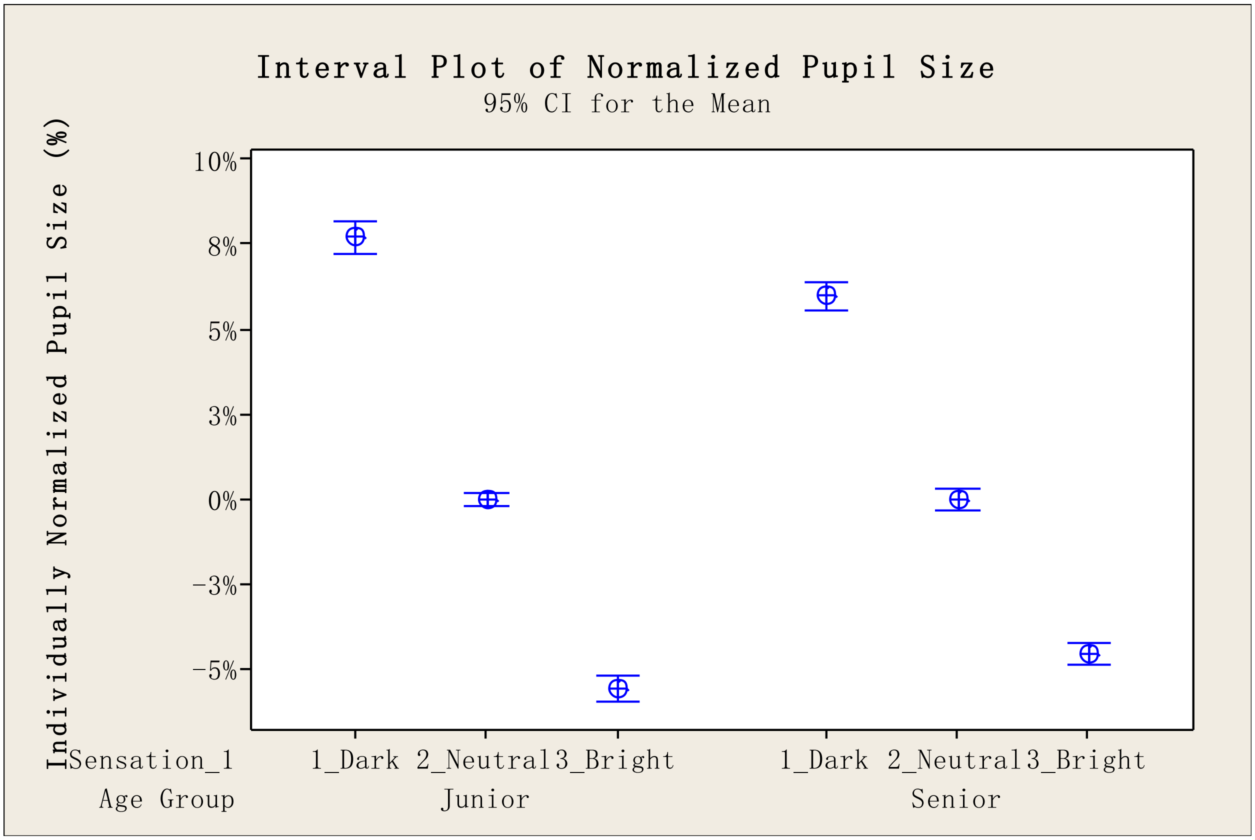


Figure 5.7 Interval plot of comparisons of overall standardized pupil size per visual sensation between age groups (first round).

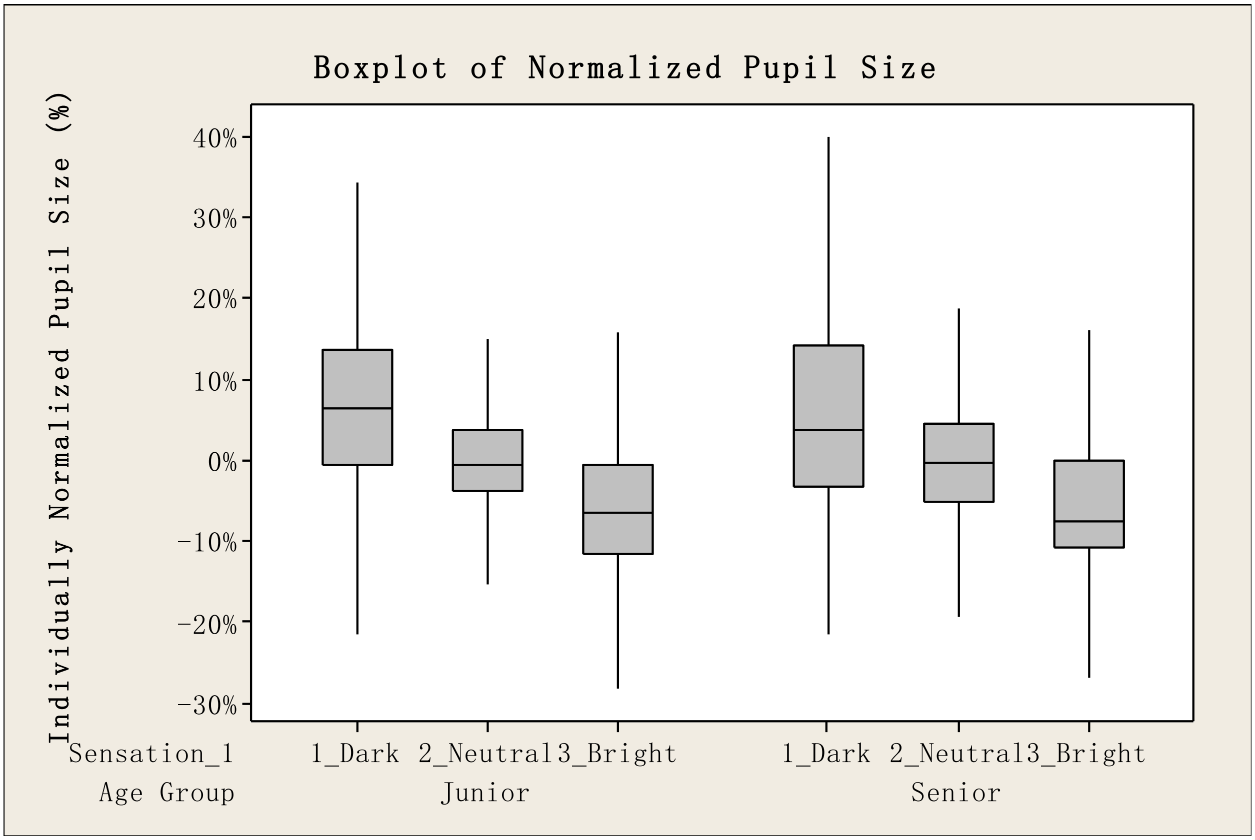


Figure 5.8 Boxplot of comparisons of overall standardized pupil size per visual sensation between age groups (first round)

The average pupil size change compared with natural level was about 7.7% at dark and -5.6% at bright in the Junior group and respectively 6.0% and -4.5% in the Senior group. The ANOVA test (Table 5.3) showed a p-value of 0.000, which is smaller than 0.05 in the level of 95% confidence. These statistical findings support the concept that the visual sensations can be matched with normalized pupil sizes across the test subjects, and the findings are also commonly applicable to both the junior and senior groups.

Table 5.3 One-way ANOVA test: Standardized Pupil Size versus Sensation between Age Groups

```
ANOVA for Senior
Source          DF        SS       MS        F
P
Sensation_1      2   18.5696   9.2848   845.42   0.000
Error         8878   97.5027   0.0110
Total         8880  116.0723

S = 0.1048   R-Sq = 16.00%   R-Sq(adj) = 15.98%

Level          N     Mean    StDev
1_Dark      3218   0.0598   0.1242
2_Neutral   2176  -0.0002   0.0789
3_Bright    3487  -0.0454   0.0993

Individual 95% CIs For Mean Based on Pooled StDev
Level            ------+---------+---------+---------+---
1_Dark
(*)
2_Neutral                            (-*)
3_Bright         (*)
                      ------+---------+---------+---------+---
                    -0.030        0.000         0.030         0.060

Pooled StDev = 0.1048
```

```
ANOVA for Junior
Source          DF        SS        MS          F
P
Sensation_1      2   28.7980   14.3990   1303.89
0.000
Error        10803  119.2991    0.0110
Total        10805  148.0971

S = 0.1051   R-Sq = 19.45%   R-Sq(adj) = 19.43%

Level          N     Mean    StDev
1_Dark      2750   0.0770   0.1270
2_Neutral   4040  -0.0000   0.0636
3_Bright    4016  -0.0558   0.1208

Individual 95% CIs For Mean Based on Pooled StDev
Level             -------+---------+---------+---------+--
1_Dark
(*)
2_Neutral                                 (*)
3_Bright      (*)
                        -------+---------+---------+---------+--
                      -0.035         0.000        0.035
0.070

Pooled StDev = 0.1051
```

The myopic condition was also selected for grouping the test subjects. The pupilometer, adopted for pupil size measurement in the study, has two wearable features. The embedded camera to face the user's eye could be re-attached to the subject's sunglasses frame from the original pupilometer goggle frame.

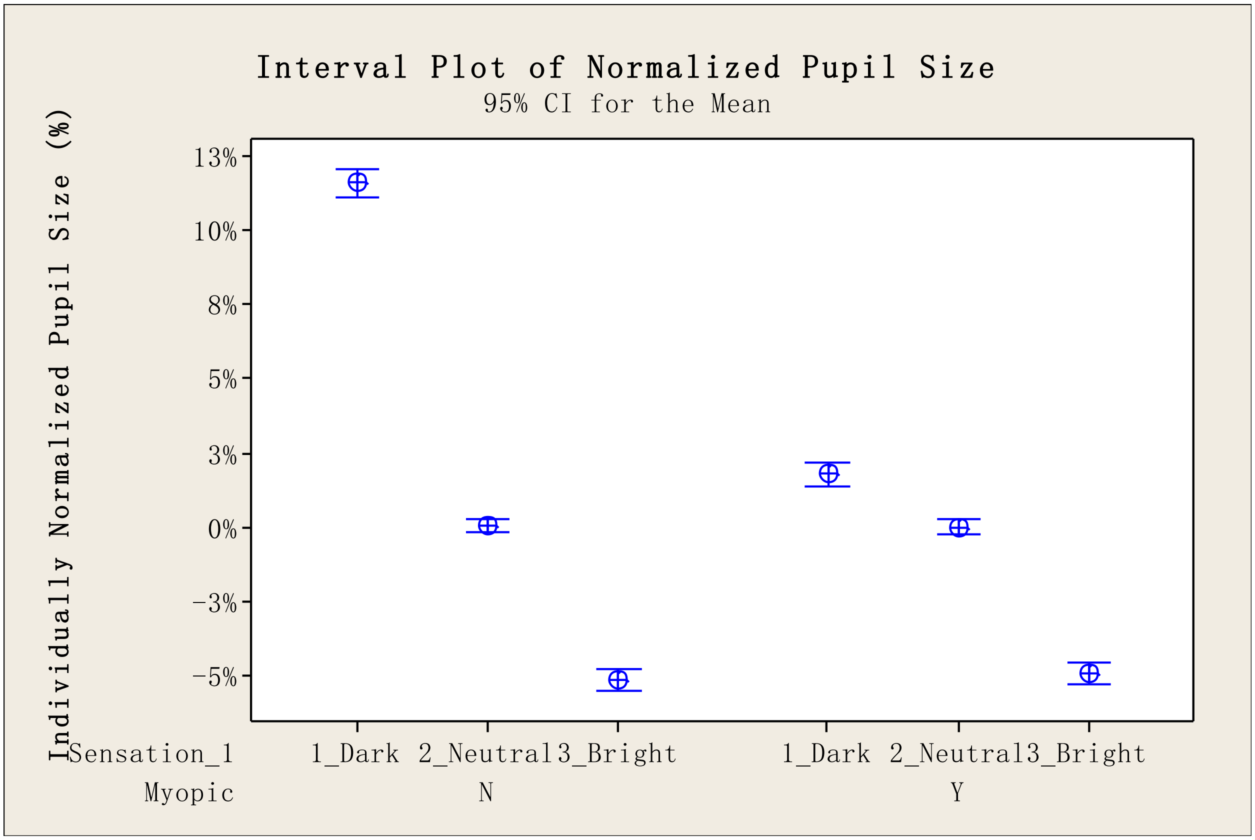


Figure 5.9 Interval plot of comparisons of overall standardized pupil size per visual sensation between myopic groups (first round).

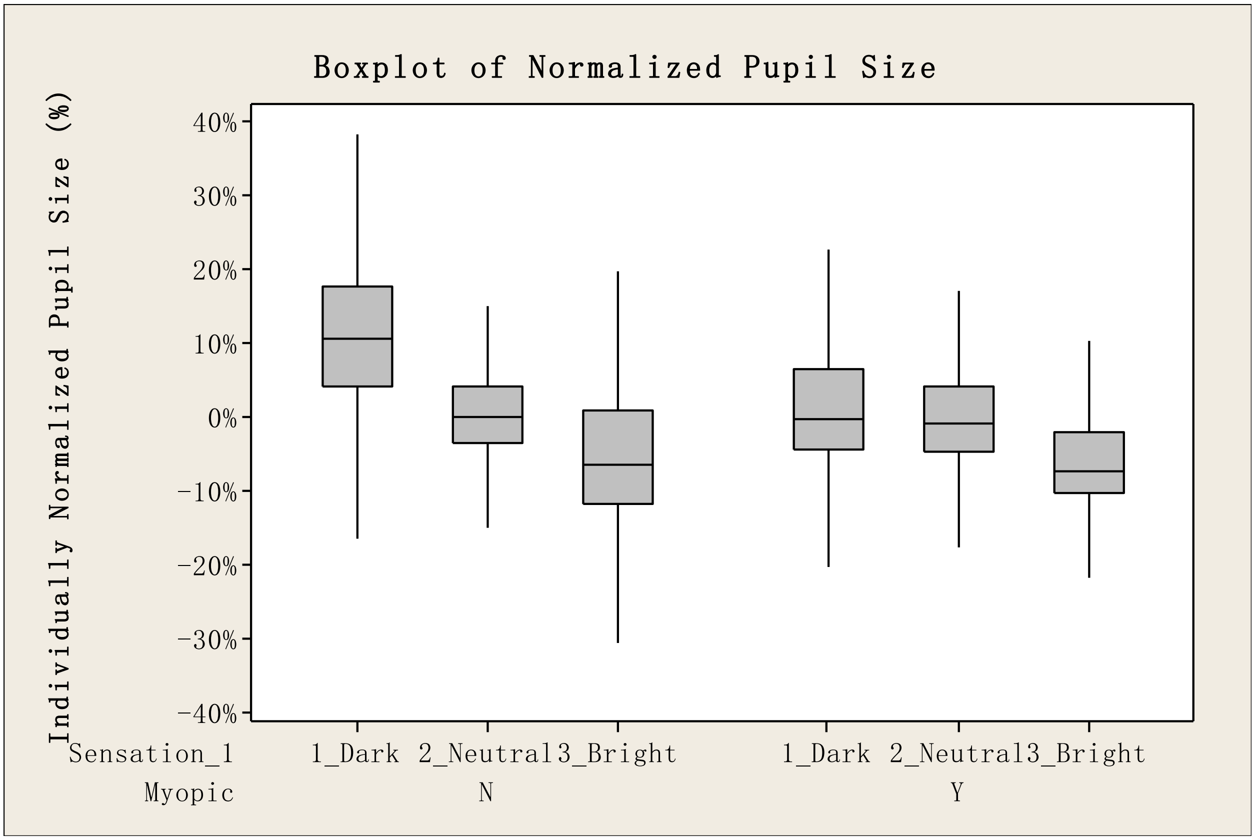


Figure 5.10 Boxplot of comparisons of overall standardized pupil size per visual sensation between myopic groups (First round)

Figure 5.9 and Figure 5.10 show the comparison between the myopic (“Y”) and non-myopic (“N”) groups. The average pupil size change compared with natural level was about 12% at dark and –5.2% at bright in the “N” group and respectively 1.8% and -5.0% in the “Y” group. The ANOVA test (Table 5.4) showed a p-value of 0.000, which is smaller than 0.05 in the level of 95% confidence. These statistical findings support the concept that the visual sensations can be matched with normalized pupil sizes across the test subjects, and the findings are also commonly applicable to both the myopic condition groups.

Table 5.4 One-way ANOVA test: Standardized Pupil Size versus Sensation between Myopic Groups

ANOVA for N	ANOVA for Y
Source DF SS MS F P Sensation_1 2 52.9331 26.4666 2201.96 0.000 Error 11052 132.8398 0.0120 Total 11054 185.7729 S = 0.1096 R-Sq = 28.49% R-Sq(adj) = 28.48% Level N Mean StDev 1_Dark 3057 0.1155 0.1264 2_Neutral 3110 -0.0000 0.0642 3_Bright 4888 -0.0517 0.1207	Source DF SS MS F P Sensation_1 2 6.60785 3.30393 405.61 0.000 Error 8629 70.28856 0.00815 Total 8631 76.89641 S = 0.09025 R-Sq = 8.59% R-Sq(adj) = 8.57% Level N Mean StDev 1_Dark 2911 0.01755 0.10363 2_Neutral 3106 -0.00017 0.07414 3_Bright 2615 -0.04961 0.09168
Individual 95% CIs For Mean Based on Pooled StDev Level -+---------+---------+---------+-------- 1_Dark (*) 2_Neutral (*) 3_Bright (* -+---------+---------+---------+-------- -0.050 0.000 0.050 0.100 Pooled StDev = 0.1096	Individual 95% CIs For Mean Based on Pooled StDev Level -------+---------+---------+---------+-- 1_Dark (-*) 2_Neutral (-*-) 3_Bright (-*-) -------+---------+---------+---------+-- -0.040 -0.020 0.000 0.020 Pooled StDev = 0.09025

The data was also grouped by genders and was shown in Figure 5.11 and Figure 5.12. The average pupil size change compared with natural level was about 6.8% at dark and –5.3% at bright in the female group and respectively 6.8% and -4.8% in the male group. The ANOVA test (Table 5.5) showed a p-value of 0.000, which is smaller than 0.05 in the level of 95% confidence. These statistical findings support the concept that the visual sensations can be matched with normalized pupil sizes across the test subjects, and the findings are also commonly applicable to both the myopic condition groups.

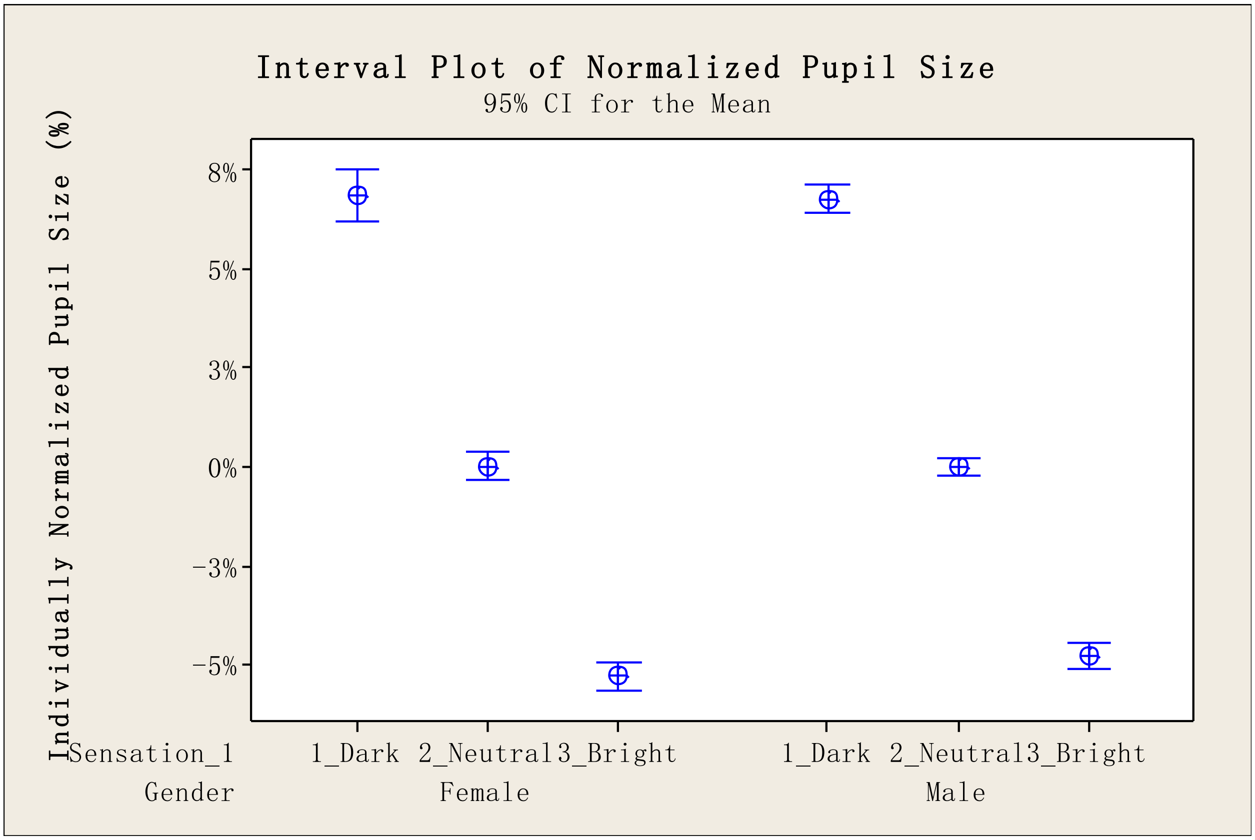


Figure 5.11 Interval plot of comparisons of overall standardized pupil size per visual sensation between gender groups (first round).

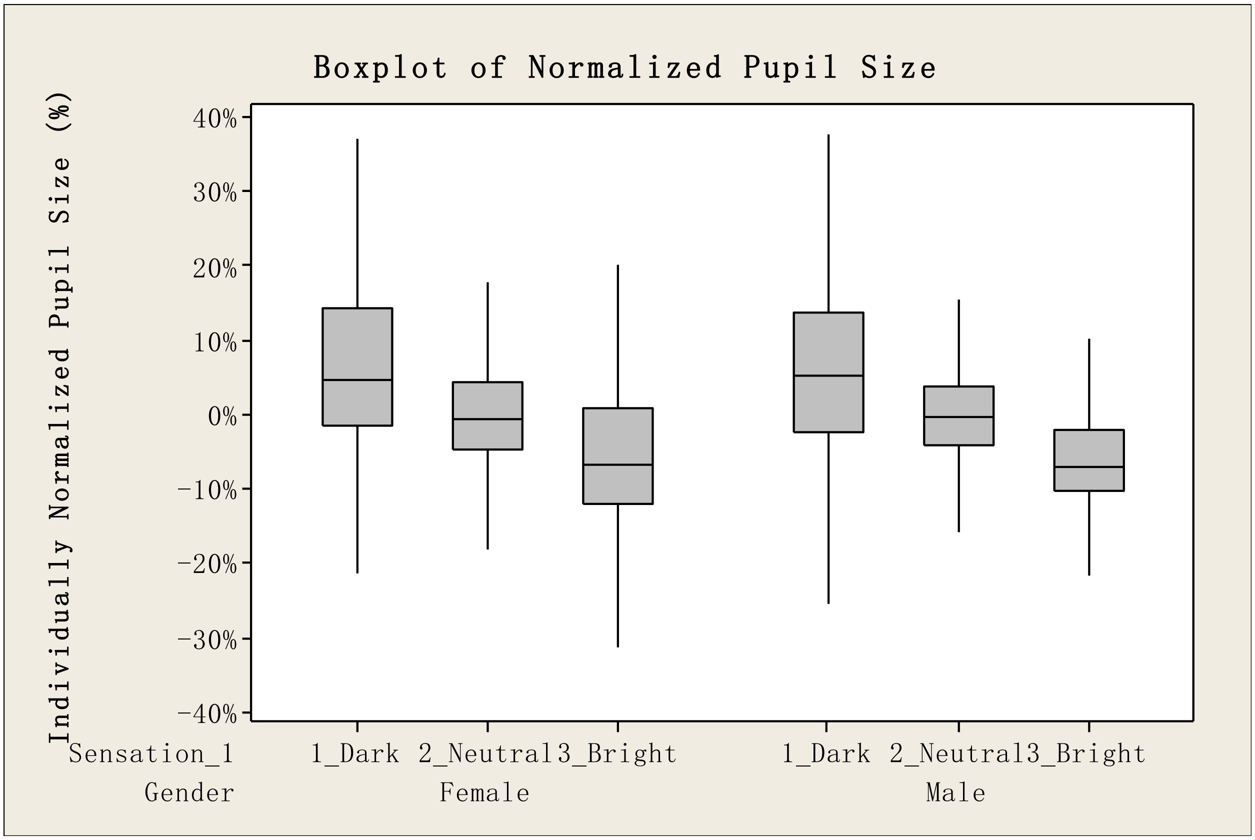


Figure 5.12 Boxplot of comparisons of overall standardized pupil size per visual sensation between gender groups (first round)

Table 5.5 One-way ANOVA test: Standardized Pupil Size versus Sensation between Gender Groups

ANOVA for Female

```
Source          DF        SS        MS       F
P
Sensation_1      2   16.8548   8.4274   658.09   0.000
Error         7767   99.4629   0.0128
Total         7769  116.3177

S = 0.1132    R-Sq = 14.49%    R-Sq(adj) = 14.47%

Level          N      Mean    StDev
1_Dark       1451    0.0683   0.1284
2_Neutral    1859   -0.0000   0.0756
3_Bright     4460   -0.0530   0.1207
```

ANOVA for Male

```
Source          DF        SS        MS        F
P
Sensation_1      2    25.5214   12.7607   1289.11
0.000
Error        11914   117.9353    0.0099
Total        11916   143.4568

S = 0.09949    R-Sq = 17.79%    R-Sq(adj) = 17.78%

Level          N       Mean     StDev
1_Dark       4517    0.06756   0.12495
2_Neutral    4357   -0.00012   0.06648
```

	3_Bright 3043 -0.04801 0.09624
Individual 95% CIs For Mean Based on Pooled StDev Level ------+---------+---------+---------+--- 1_Dark (-*) 2_Neutral (*) 3_Bright (*) ------+---------+---------+---------+--- -0.035 0.000 0.035 0.070 Pooled StDev = 0.1132	Individual 95% CIs For Mean Based on Pooled StDev Level -----+---------+---------+---------+---- 1_Dark (*) 2_Neutral (*) 3_Bright (*) -----+---------+---------+---------+---- -0.035 0.000 0.035 0.070 Pooled StDev = 0.09949

5.2 – Second Round

Second round adopted same procedure of data analysis with first round. Standardization of pupil size and grouping sensations into “Dark”, “Neutral” and “Bright” based on physiological features were applied.

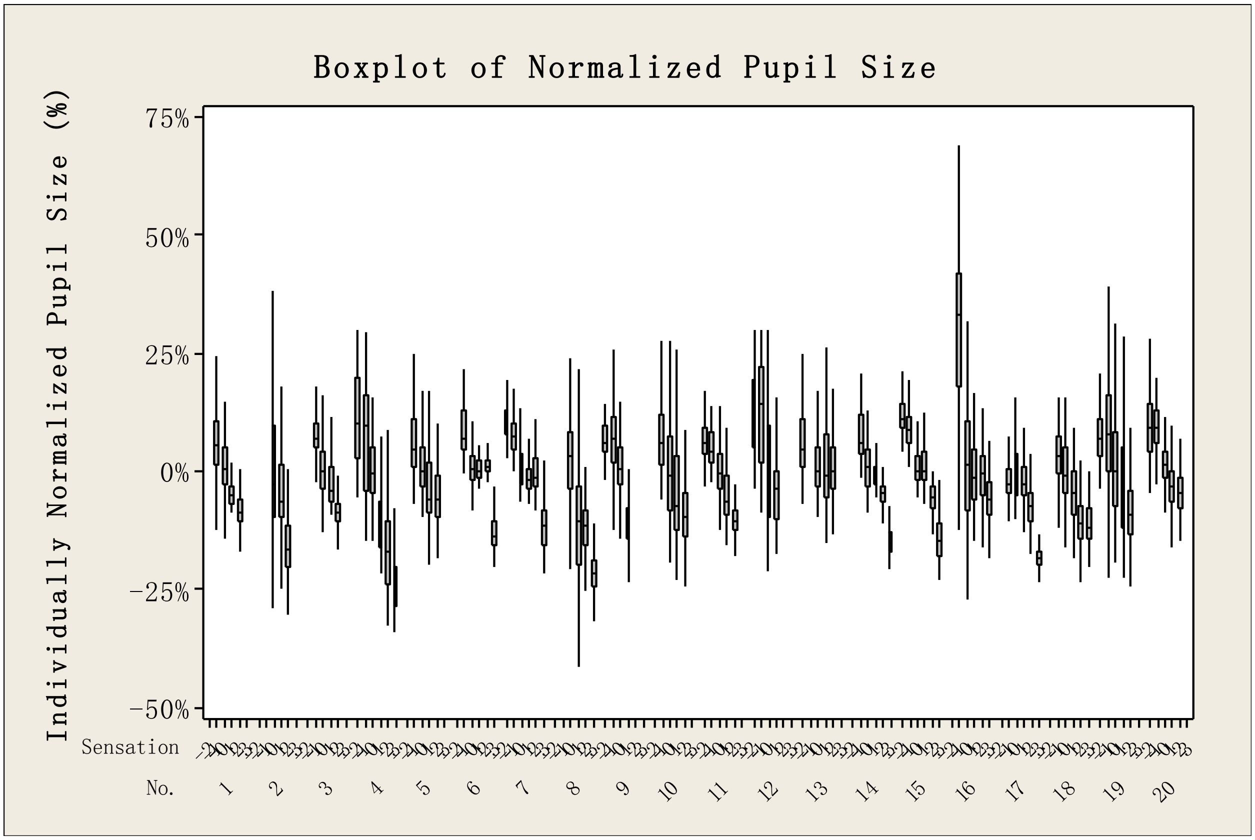


Figure 5.13 Standardized pupil size distribution in each subject's test ("No." indicates a subject ID) (second round).

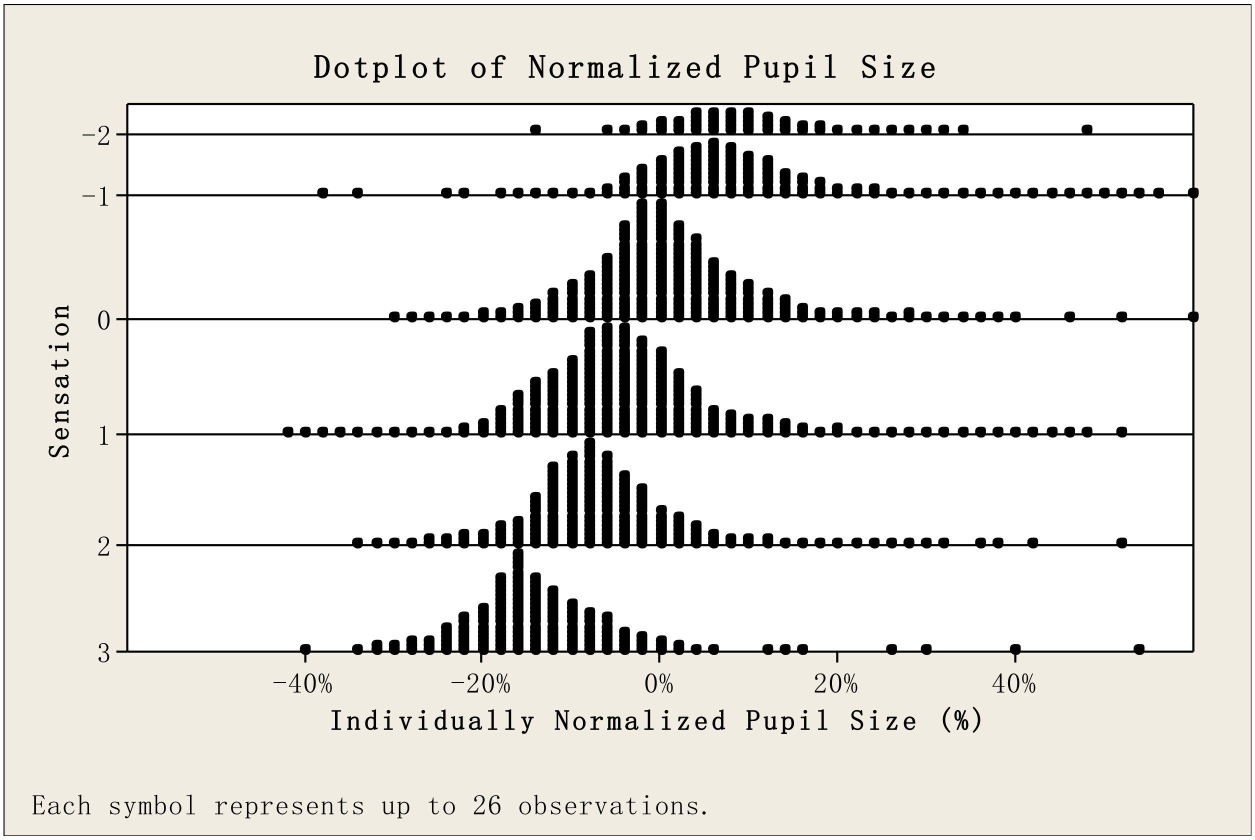


Figure 5.14 Overall standardized pupil size distribution per visual sensation to illuminance intensity (second round).

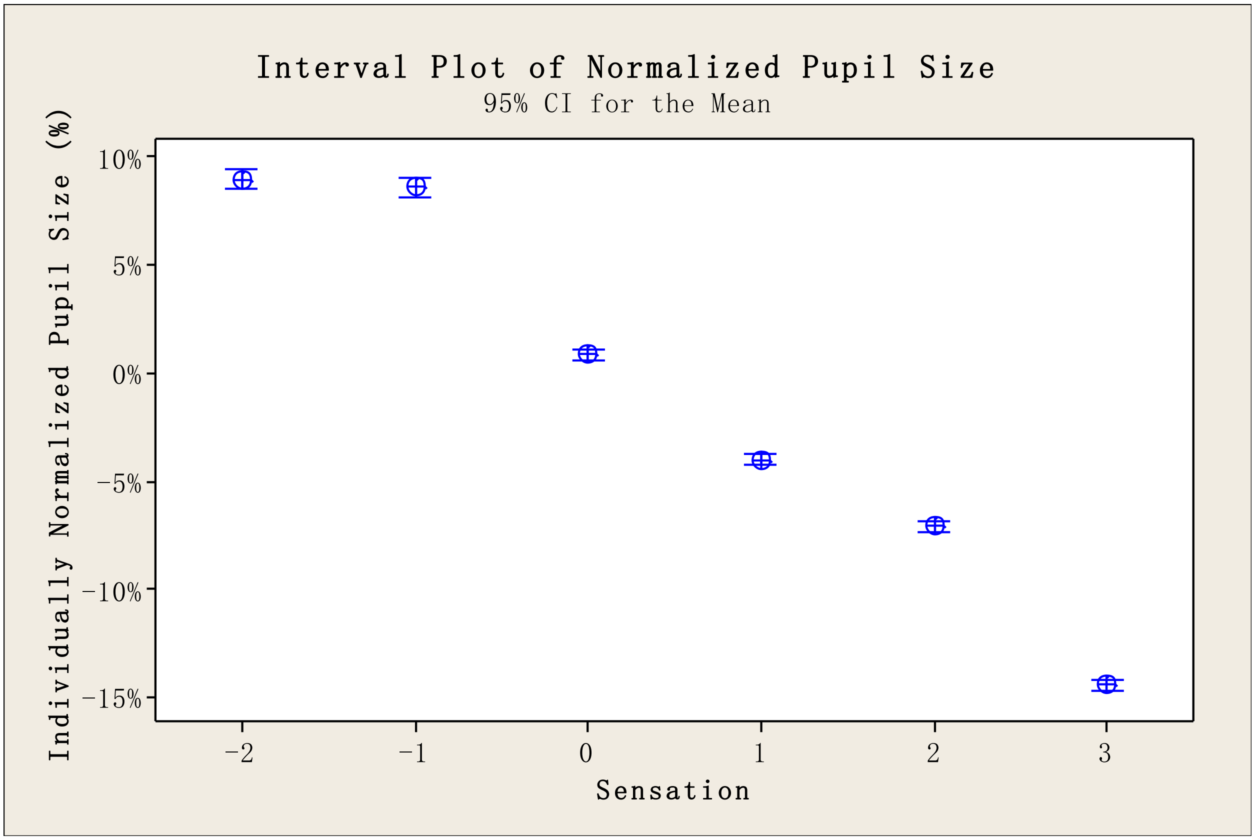


Figure 5.15 Interval plot of standardized pupil size per visual sensation to illuminance intensity (second round).

The pupil size patterns for visual sensations based on the combined data of all individuals are shown in Figure 5.14. Overall, the standardized pupil sizes decreased while the generated illuminance intensity was increasing. Figure 5.15 contains basically the same data as Figure 5.14, but it shows a 95% confidence interval for pupil sizes per visual sensation. Except sensation -2 and sensation -1, the interval lines are clearly differentiated from each other. There was no participant reporting sensation -3 ("very dark") in the second round.

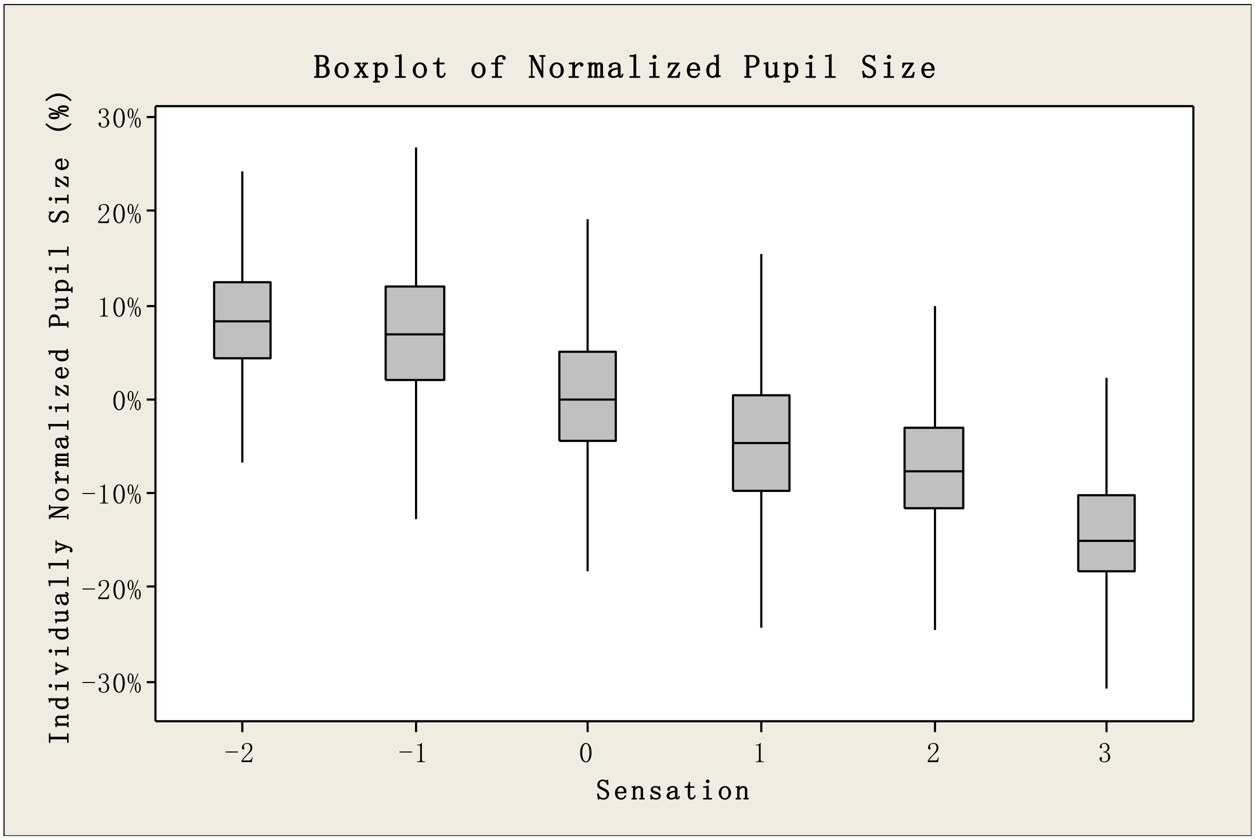


Figure 5.16 Boxplot of standardized pupil size per visual sensation to illuminance intensity (second round).

Table 5.6 One-way ANOVA test: Standardized Pupil Size versus Sensation

```
Source        DF  Adj SS   Adj MS  F-Value  P-Value
Sensation      5   112.5  22.4962  2708.71    0.000
Error      22673   188.3   0.0083
Total      22678   300.8

       S    R-sq  R-sq(adj)  R-sq(pred)
0.0911324  37.40%    37.38%     37.36%
```

```
Means

Sensation     N      Mean    StDev        95% CI
-2          970   0.08933  0.07080  ( 0.08359,  0.09506)
-1         2650   0.08595  0.11569  ( 0.08248,  0.08942)
0          5419   0.00821  0.09214  ( 0.00578,  0.01064)
1          5732  -0.04047  0.09528  (-0.04283, -0.03811)
2          4299  -0.07113  0.08346  (-0.07385, -0.06840)
3          3609  -0.14441  0.07450  (-0.14739, -0.14144)
```

```
Pooled StDev = 0.0911324
```

For comparisons in different physiological categories, same procedure was adopted as done in first round. The calculated pupil size change rate and other findings in different groupings will be explained in Section 5.4.

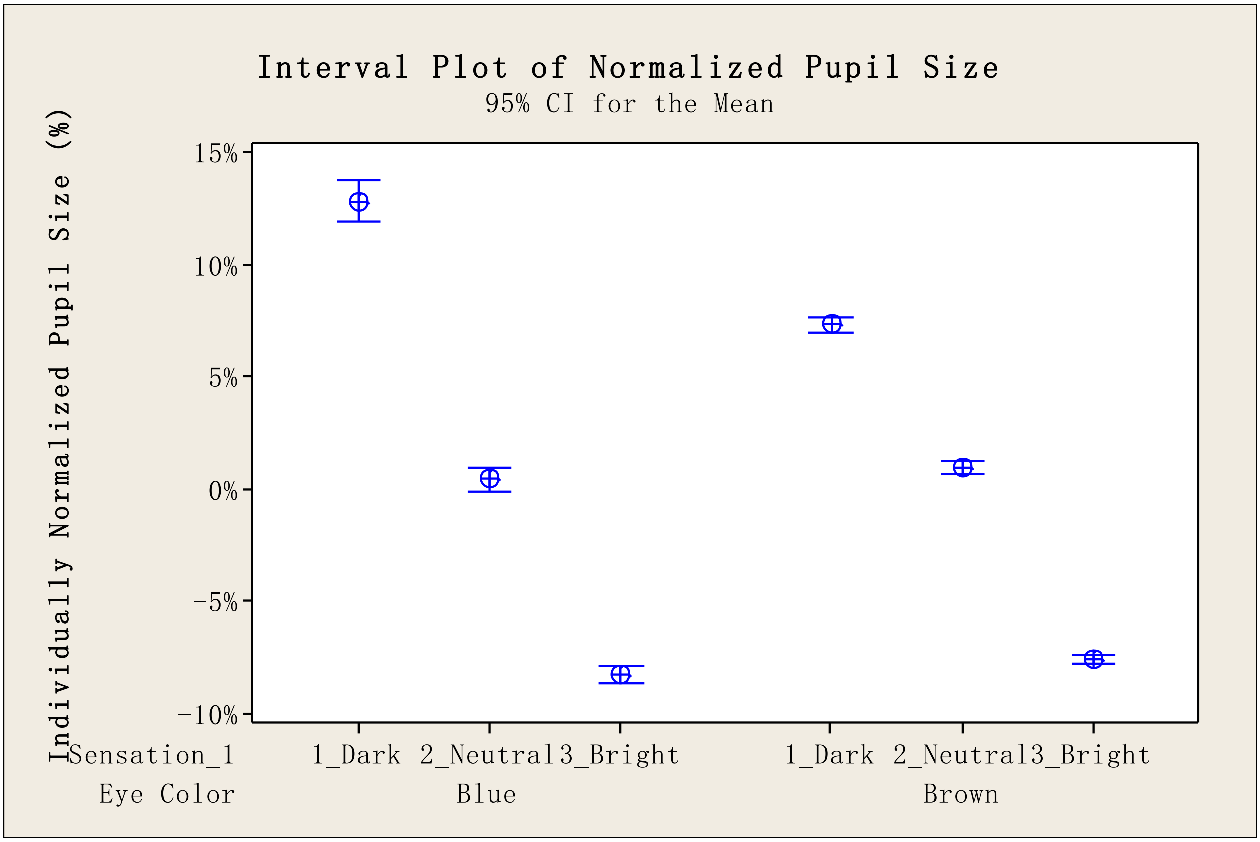


Figure 5.17 Interval plot of comparisons of overall standardized pupil size per visual sensation between eye color groups (second round).

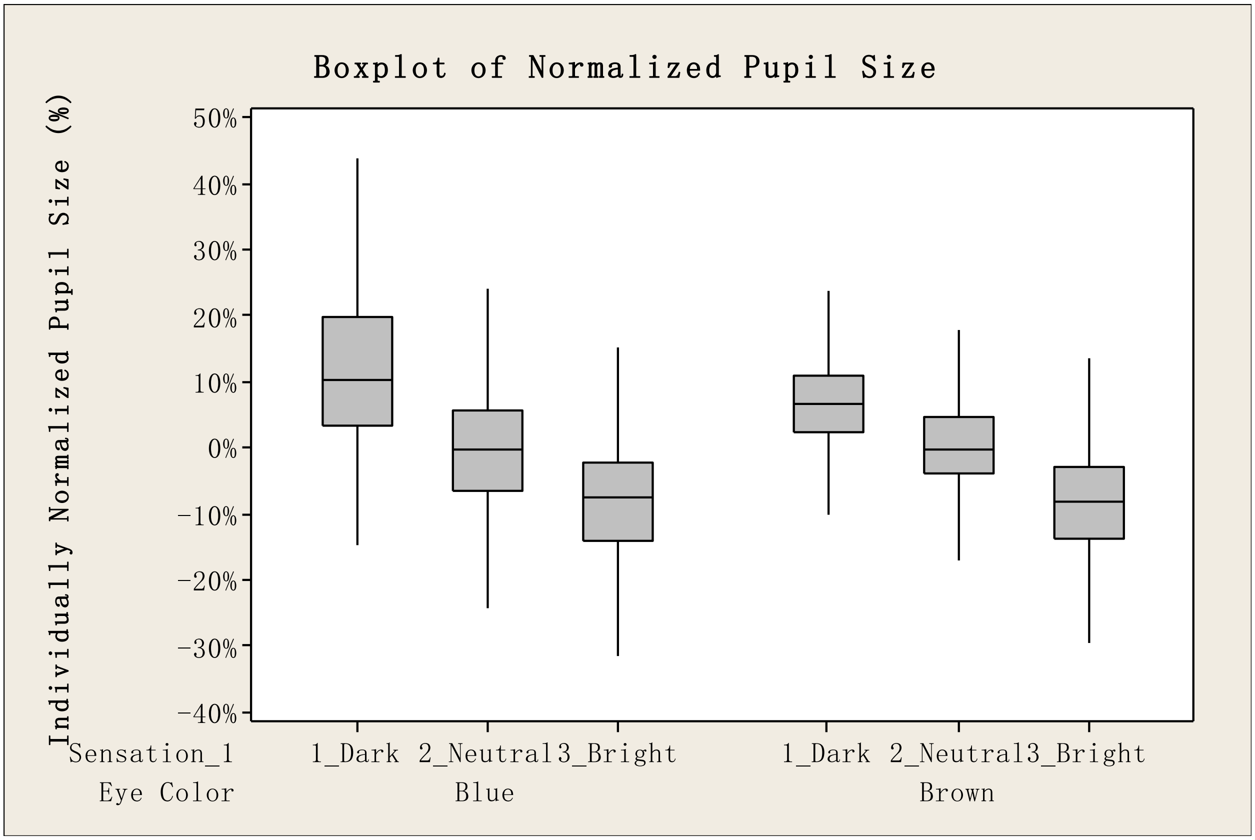


Figure 5.18 Boxplot of comparisons of overall standardized pupil size per visual sensation between eye color groups (second round).

Table 5.7 One-way ANOVA test: Standardized Pupil Size versus Sensation between Eye Colors

ANOVA for Blue

```
Analysis of Variance

Source        DF  Adj SS   Adj MS  F-Value
P-Value
Sensation_1    2   32.81  16.4074  1359.32
0.000
Error       5399   65.17   0.0121
Total       5401   97.98


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
0.109865  33.49%    33.47%     33.41%
```

ANOVA for Brown

```
Analysis of Variance

Source         DF  Adj SS   Adj MS  F-Value
P-Value
Sensation_1     2   57.48  28.7405  3421.08
0.000
Error       17274  145.12   0.0084
Total       17276  202.60


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.0916570  28.37%    28.36%     28.35%
```

```
Means

Sensation_1     N     Mean    StDev
95% CI
1_Dark        894   0.12850  0.14277
( 0.12130,  0.13570)
2_Neutral    1401   0.00422  0.09837
(-0.00153,  0.00997)
3_Bright     3107  -0.08329  0.10373
(-0.08715, -0.07942)

Pooled StDev = 0.109865
```

```
Means

Sensation_1      N      Mean     StDev
95% CI
1_Dark       2726    0.07320   0.08579
(  0.06976,   0.07664)
2_Neutral     4018    0.00960   0.08984
(  0.00677,   0.01244)
3_Bright     10533  -0.075968  0.093785
(-0.077719, -0.074218)

Pooled StDev = 0.0916570
```

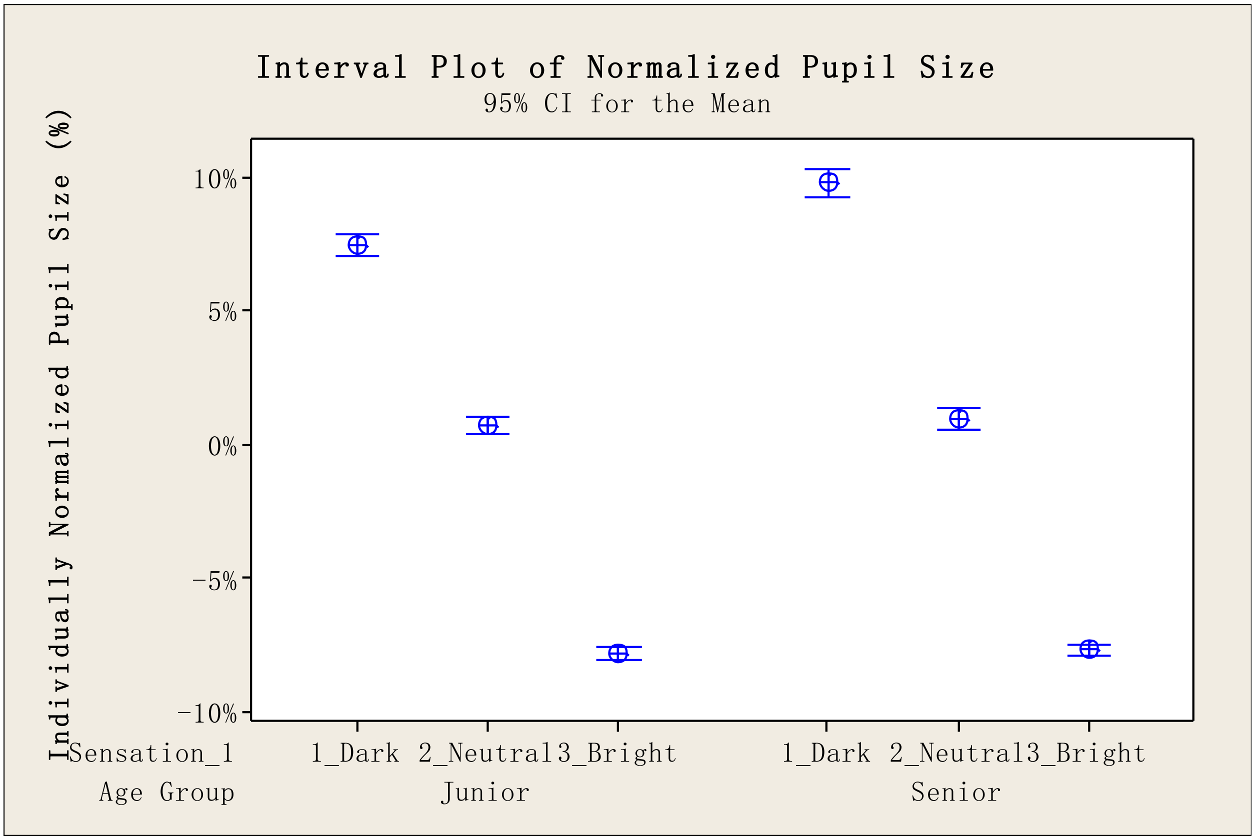


Figure 5.19 Interval plot of comparisons of overall standardized pupil size per visual sensation between age groups (second round).

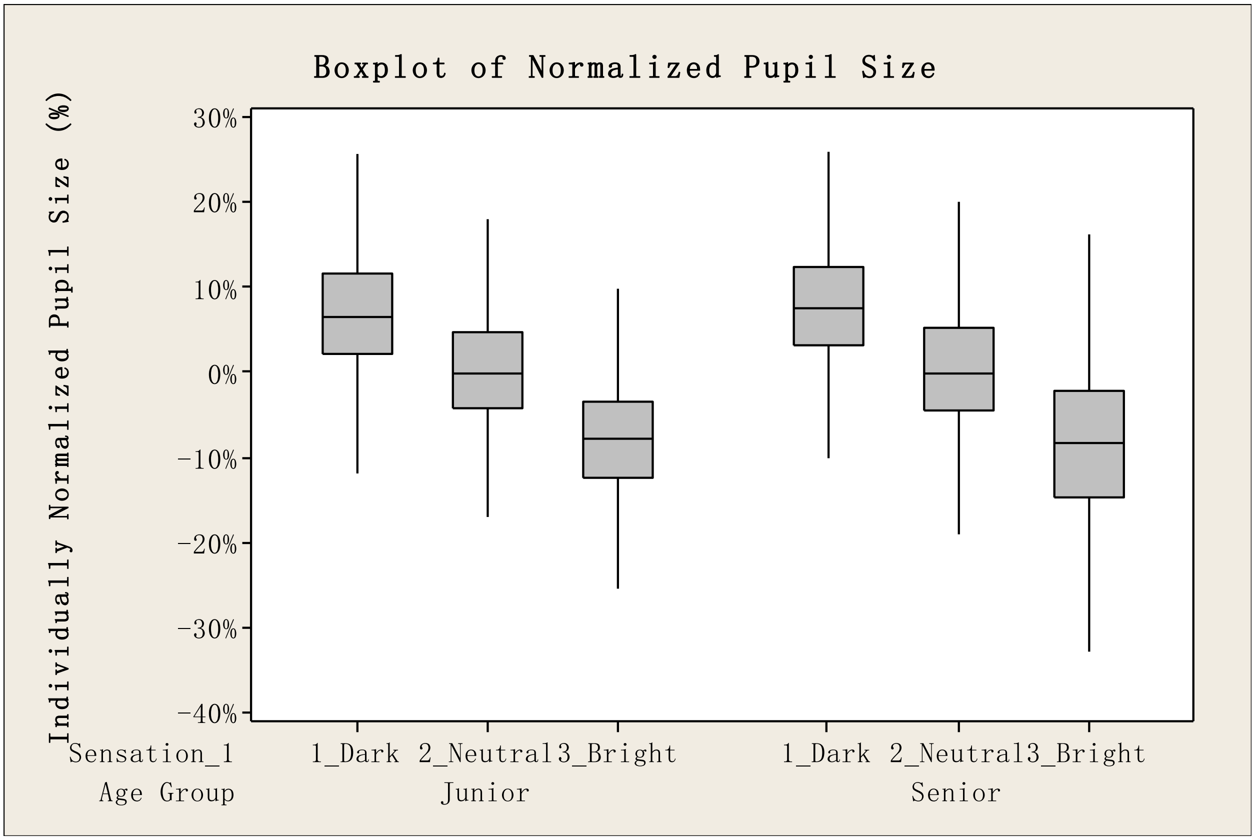


Figure 5.20 Boxplot of comparisons of overall standardized pupil size per visual sensation between age groups (second round)

Table 5.8 One-way ANOVA test: Standardized Pupil Size versus Sensation between Age Groups

ANOVA for Junior

```
Analysis of Variance

Source        DF  Adj SS   Adj MS  F-Value
P-Value
Sensation_1     2   32.84  16.4222  2231.37
0.000
Error       9054   66.63   0.0074
Total       9056   99.48


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.0857886  33.02%     33.00%      32.97%
```

```
Means
```

ANOVA for Senior

```
Analysis of Variance

Source         DF  Adj SS   Adj MS  F-Value
P-Value
Sensation_1      2   55.47  27.7341  2598.44
0.000
Error       13619  145.36   0.0107
Total       13621  200.83


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
0.103312  27.62%     27.61%      27.58%
```

```
Means
```

```
Sensation_1     N      Mean    StDev
95% CI
1_Dark       1677   0.07429  0.08151
( 0.07018,  0.07839)
2_Neutral    2651   0.00699  0.08186
( 0.00373,  0.01026)
3_Bright     4729  -0.07863  0.08935
(-0.08107, -0.07618)

Pooled StDev = 0.0857886
```

```
Sensation_1     N      Mean    StDev
95% CI
1_Dark       1943   0.09771  0.12155
( 0.09311,  0.10230)
2_Neutral    2768   0.00938  0.10102
( 0.00553,  0.01323)
3_Bright     8911  -0.07711  0.09963
(-0.07925, -0.07496)

Pooled StDev = 0.103312
```

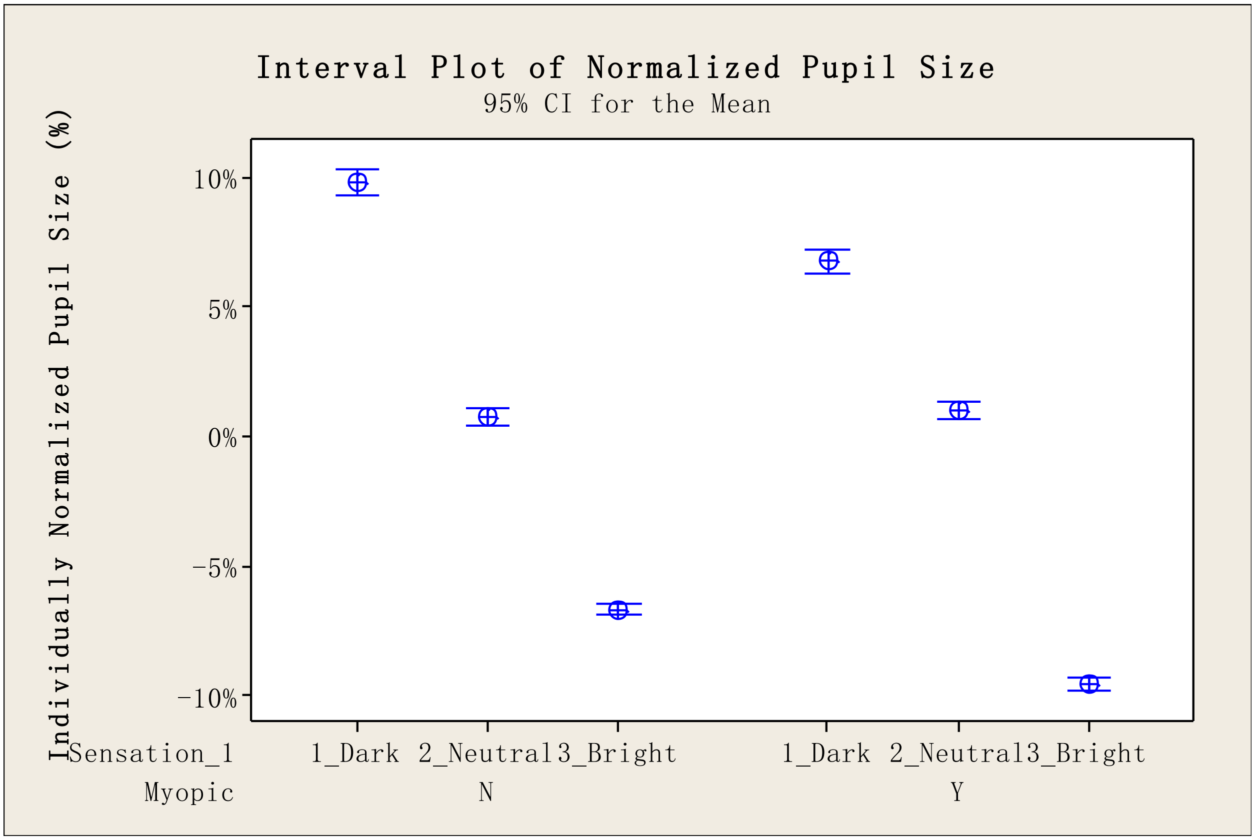


Figure 5.21 Interval plot of comparisons of overall standardized pupil size per visual sensation between myopic groups (second round).

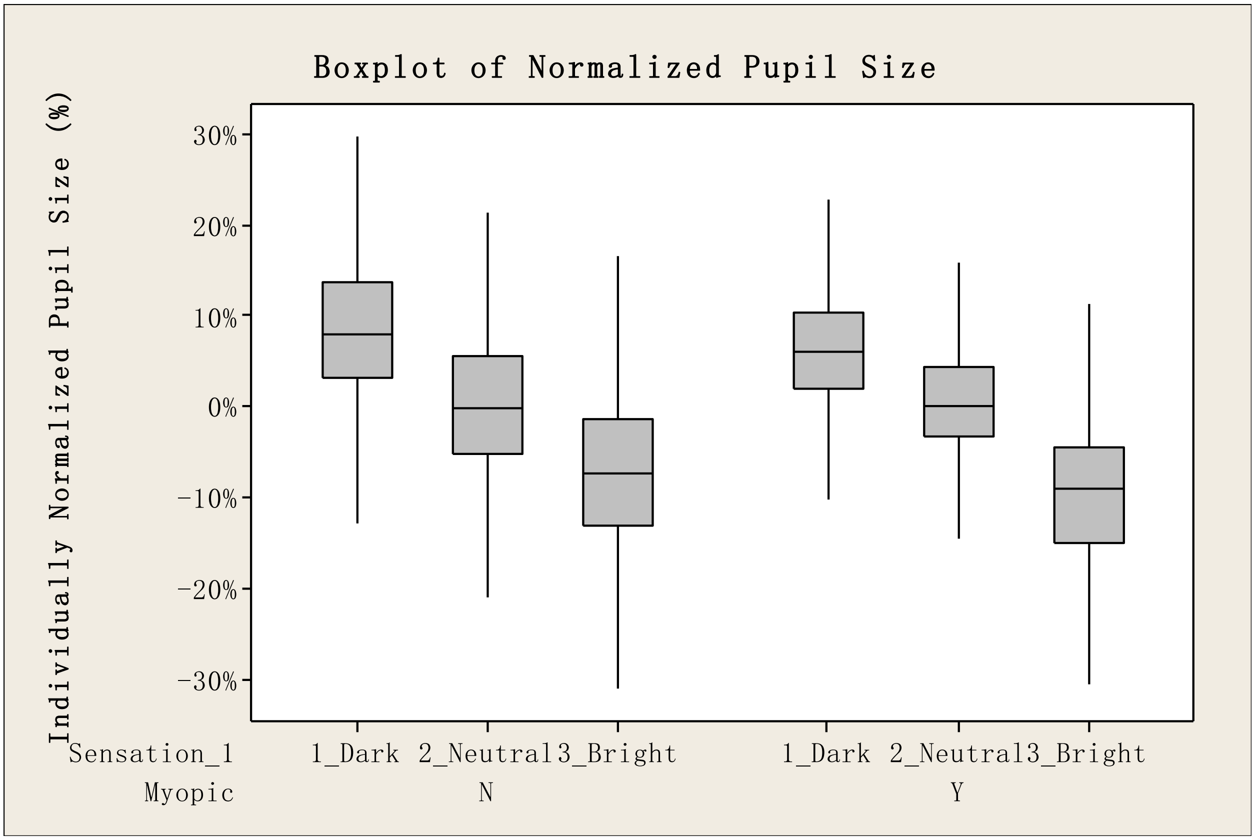


Figure 5.22 Boxplot of comparisons of overall standardized pupil size per visual sensation between myopic groups (second round)

Table 5.9 One-way ANOVA test: Standardized Pupil Size versus Sensation between Myopic Groups

ANOVA for N

```
Analysis of Variance

Source         DF  Adj SS   Adj MS  F-Value
P-Value
Sensation_1     2   53.96  26.9776  2533.83
0.000
Error       14489  154.26   0.0106
Total       14491  208.22


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
0.103184  25.91%     25.90%      25.88%
```

ANOVA for Y

```
Analysis of Variance

Source        DF  Adj SS   Adj MS  F-Value
P-Value
Sensation_1    2   35.09  17.5462  2616.56
0.000
Error       8184   54.88   0.0067
Total       8186   89.97


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.0818890  39.00%     38.99%      38.96%
```

```
Means

Sensation_1     N      Mean    StDev
95% CI
1_Dark      2311   0.09793  0.11547
( 0.09372,  0.10213)
2_Neutral    3518   0.00719  0.10053
( 0.00378,  0.01060)
3_Bright     8663  -0.06724  0.10075
(-0.06941, -0.06507)

Pooled StDev = 0.103184
```

```
Means

Sensation_1     N      Mean    StDev
95% CI
1_Dark      1309   0.06732  0.08171
( 0.06288,  0.07175)
2_Neutral    1901   0.01010  0.07416
( 0.00642,  0.01378)
3_Bright     4977  -0.09573  0.08470
(-0.09800, -0.09345)

Pooled StDev = 0.0818890
```

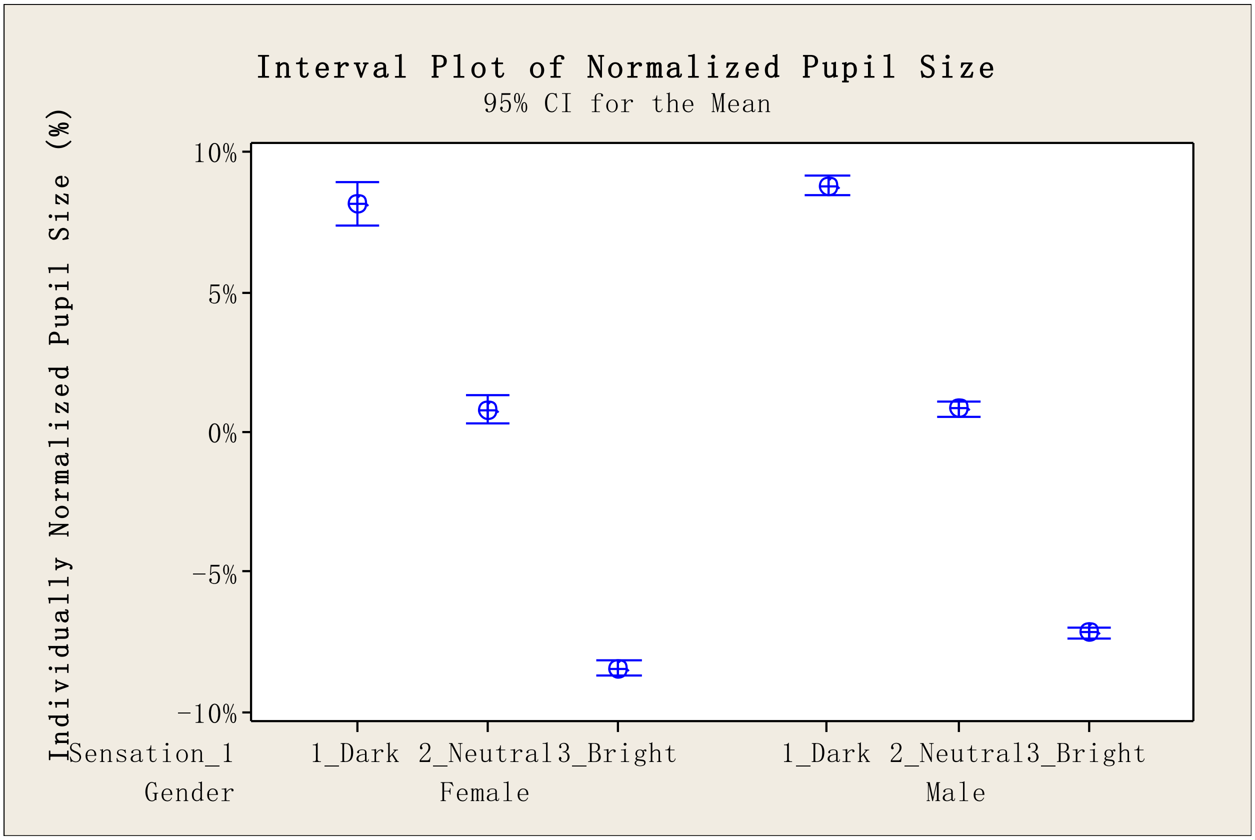


Figure 5.23 Interval plot of comparisons of overall standardized pupil size per visual sensation between gender groups (second round).

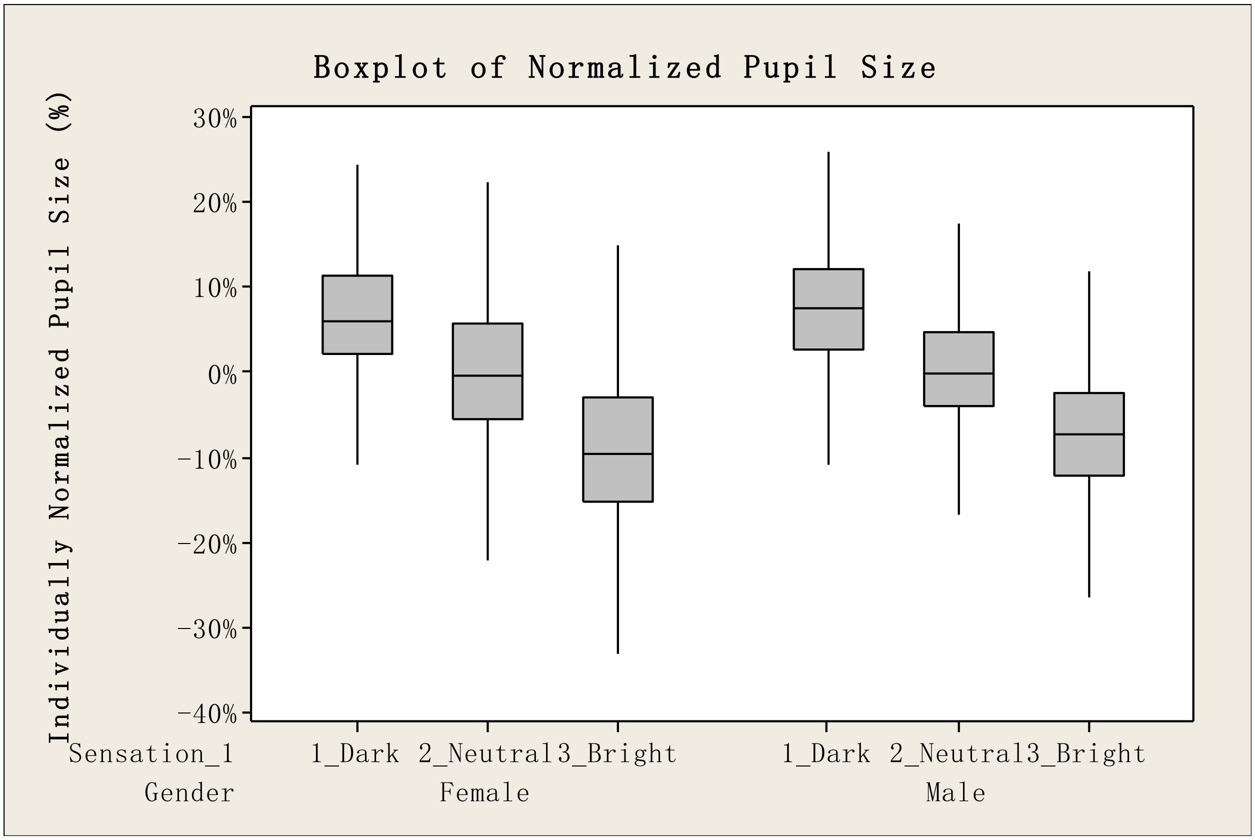


Figure 5.24 Boxplot of comparisons of overall standardized pupil size per visual sensation between gender groups (second round)

Table 5.10 One-way ANOVA test: Standardized Pupil Size versus Sensation between Gender Groups

ANOVA for Female

```
Analysis of Variance

Source        DF  Adj SS   Adj MS  F-Value
P-Value
Sensation_1    2   27.75  13.8759  1253.97
0.000
Error       8758   96.91   0.0111
Total       8760  124.66


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
0.105193  22.26%     22.24%      22.20%
```

ANOVA for Male

```
Analysis of Variance

Source         DF  Adj SS   Adj MS  F-Value
P-Value
Sensation_1     2   56.00  28.0006  3387.08
0.000
Error       13915  115.03   0.0083
Total       13917  171.03


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.0909223  32.74%     32.73%      32.71%
```

```
Means

Sensation_1    N     Mean   StDev
95% CI
1_Dark       828   0.08167  0.11801
( 0.07450,  0.08883)
2_Neutral   1805   0.00810  0.10854
( 0.00324,  0.01295)
3_Bright    6128  -0.08453  0.10232
(-0.08716, -0.08189)

Pooled StDev = 0.105193
```

```
Means

Sensation_1    N     Mean   StDev
95% CI
1_Dark      2792   0.08840  0.10153
( 0.08502,  0.09177)
2_Neutral   3614   0.00827  0.08277
( 0.00530,  0.01123)
3_Bright    7512  -0.07201  0.09050
(-0.07407, -0.06996)

Pooled StDev = 0.0909223
```

5.3 – Third Round

Similarly, the same analysis method and procedure was adopted for round three. Boxplots for the purpose of illustrating quartile distributions of data and interval plots for the purpose of illustrating estimated mean value with 95% confidence interval for whole data set, and each categorized groupings were displayed.

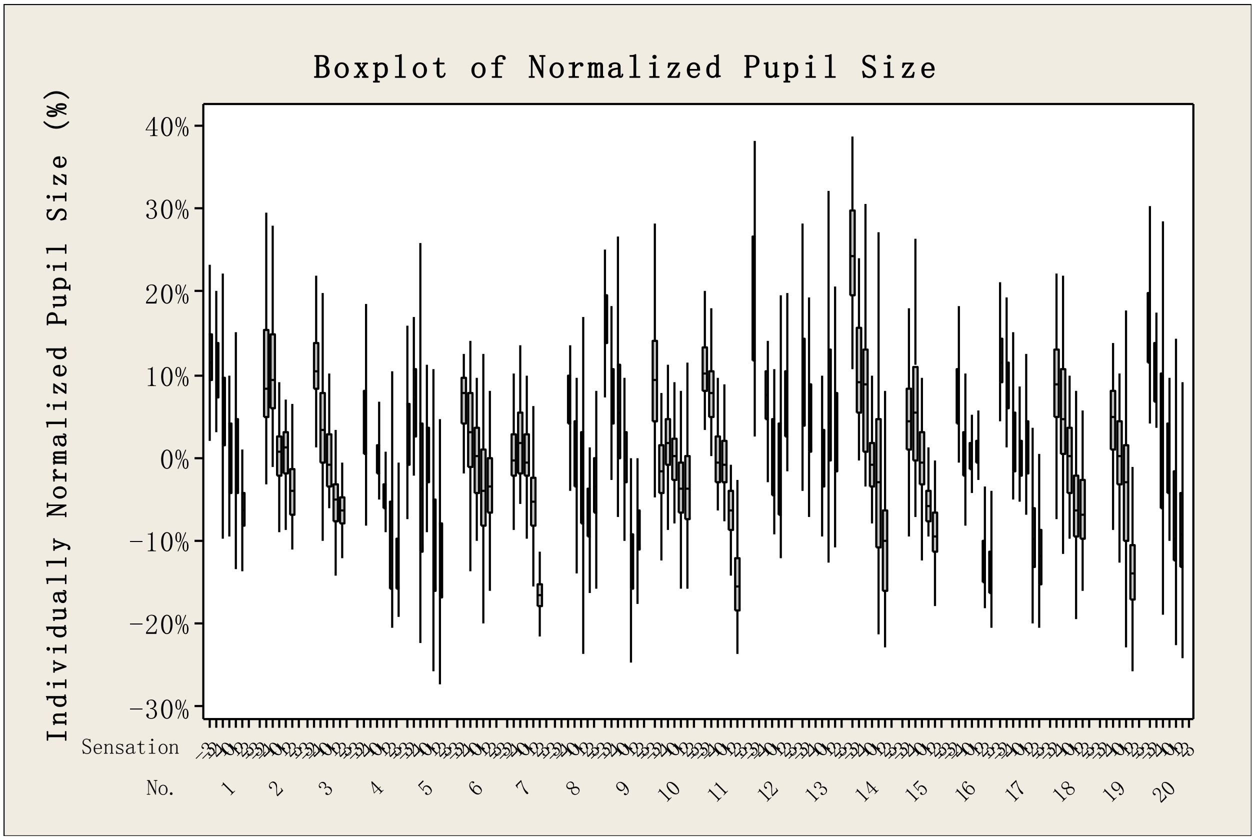


Figure 5.25 Standardized pupil size distribution in each subject’s test (“No.” indicates a subject ID).

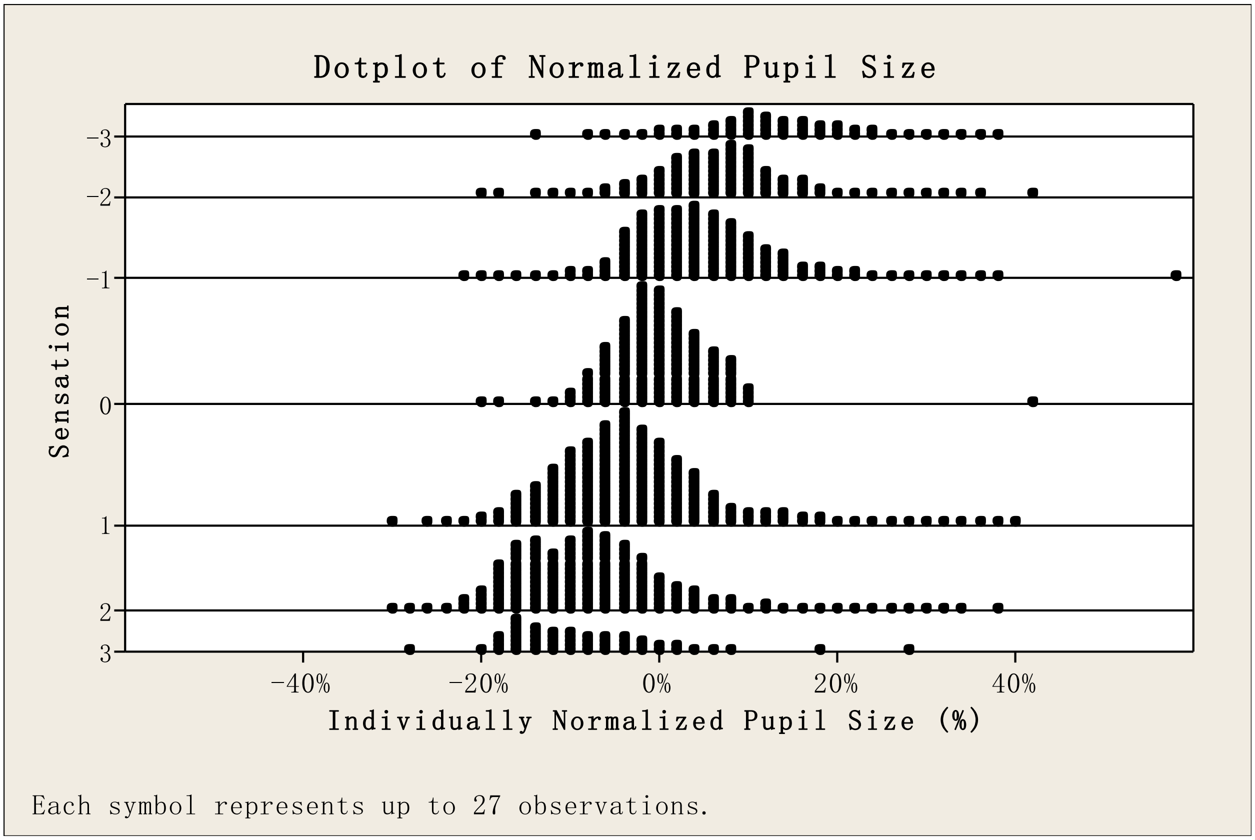


Figure 5.26 Overall standardized pupil size distribution per visual sensation to illuminance intensity (third round).

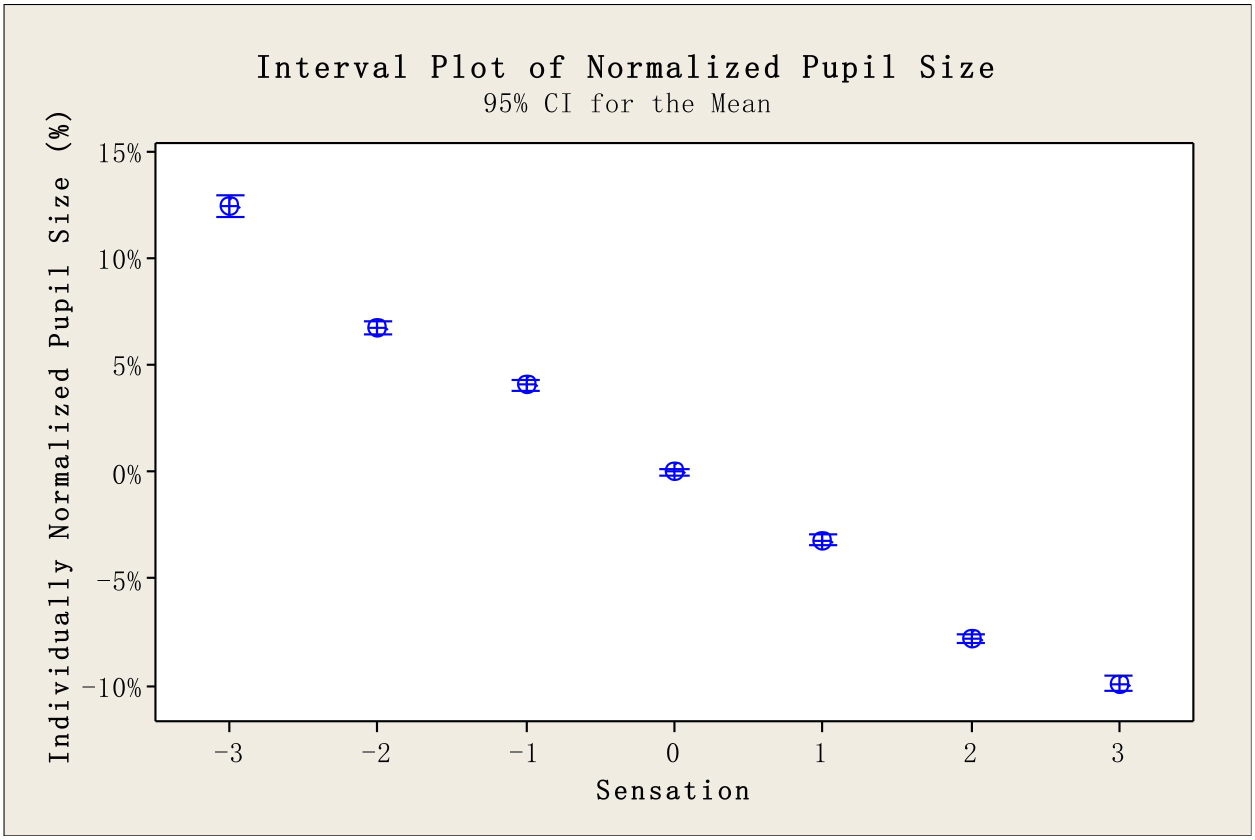


Figure 5.27 Interval plot of standardized pupil size per visual sensation to illuminance intensity (third round).

The pupil size patterns for visual sensations based on the combined data of all individuals are shown in Figure 5.26. Overall, the standardized pupil sizes decreased while the generated illuminance intensity was increasing. Figure 5.27 contains basically the same data as Figure 5.26, but it shows a 95% confidence interval for pupil sizes per visual sensation. The interval lines are clearly differentiated from each other among all sensation levels. Larger pupil size change was observed in “dark” zones than in “bright” zones.

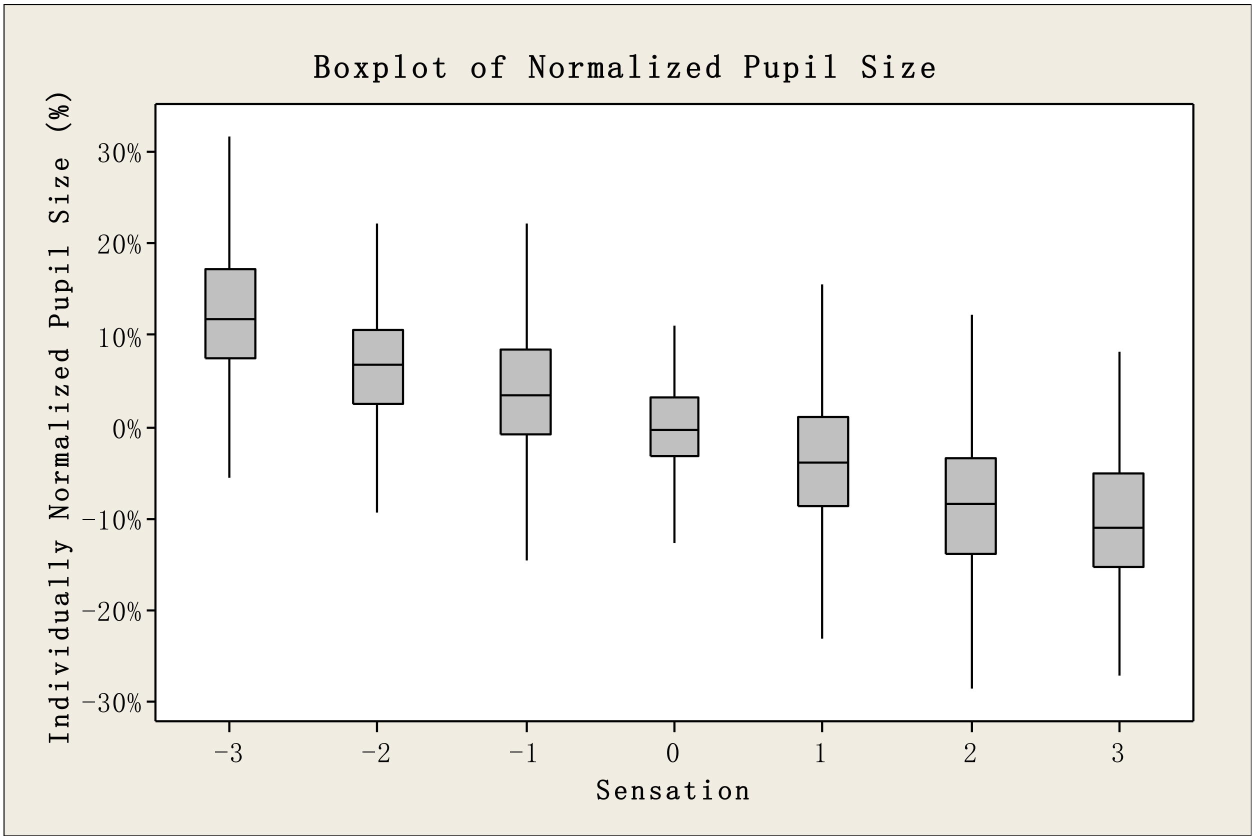


Figure 5.28 Boxplot of standardized pupil size per visual sensation to illuminance intensity (third round).

Table 5.11 One-way ANOVA test: Standardized Pupil Size versus Sensation

```
Analysis of Variance

Source       DF  Adj SS   Adj MS  F-Value  P-Value
Sensation     6   76.18  12.6965  2310.34    0.000
Error     22453  123.39   0.0055
Total     22459  199.57


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.0741316  38.17%     38.16%      38.13%
```

```
Means

Sensation     N      Mean    StDev         95% CI
-3         1063   0.12529   0.08196  (  0.12084,  0.12975)
-2         2218   0.06768   0.06654  (  0.06460,  0.07077)
```

```
-1        3807   0.04079   0.07623  (  0.03844,  0.04315)
0         4156  0.000000  0.047034  (-0.002254, 0.002254)
1         5580  -0.03203   0.08503  ( -0.03397, -0.03008)
2         4448  -0.07849   0.08215  ( -0.08067, -0.07631)
3         1188  -0.09961   0.06347  ( -0.10383, -0.09539)

Pooled StDev = 0.0741316
```

For comparisons in different physiological categories, same procedure was adopted as done in first round. The calculated pupil size change rate and other findings in different groupings will be explained in Section 5.4.

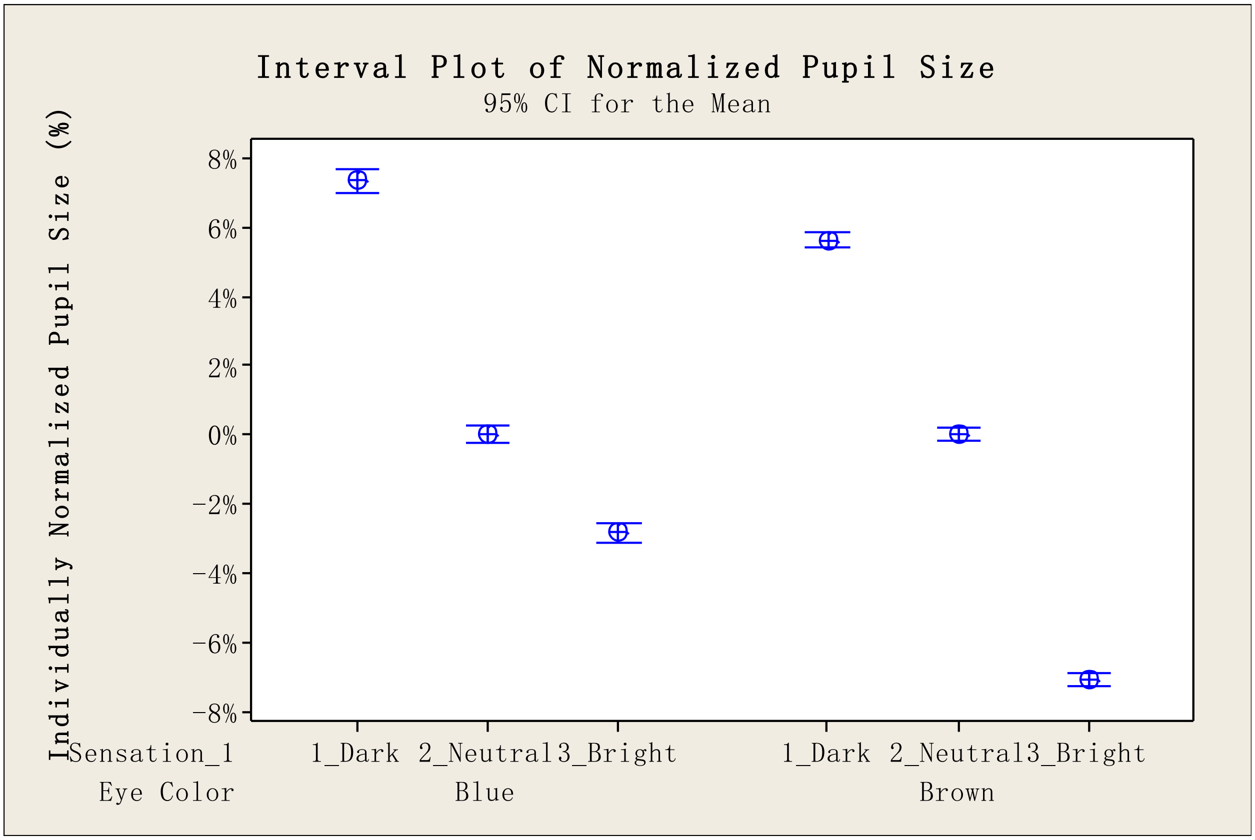


Figure 5.29 Interval plot of comparisons of overall standardized pupil size per visual sensation between eye color groups (third round).

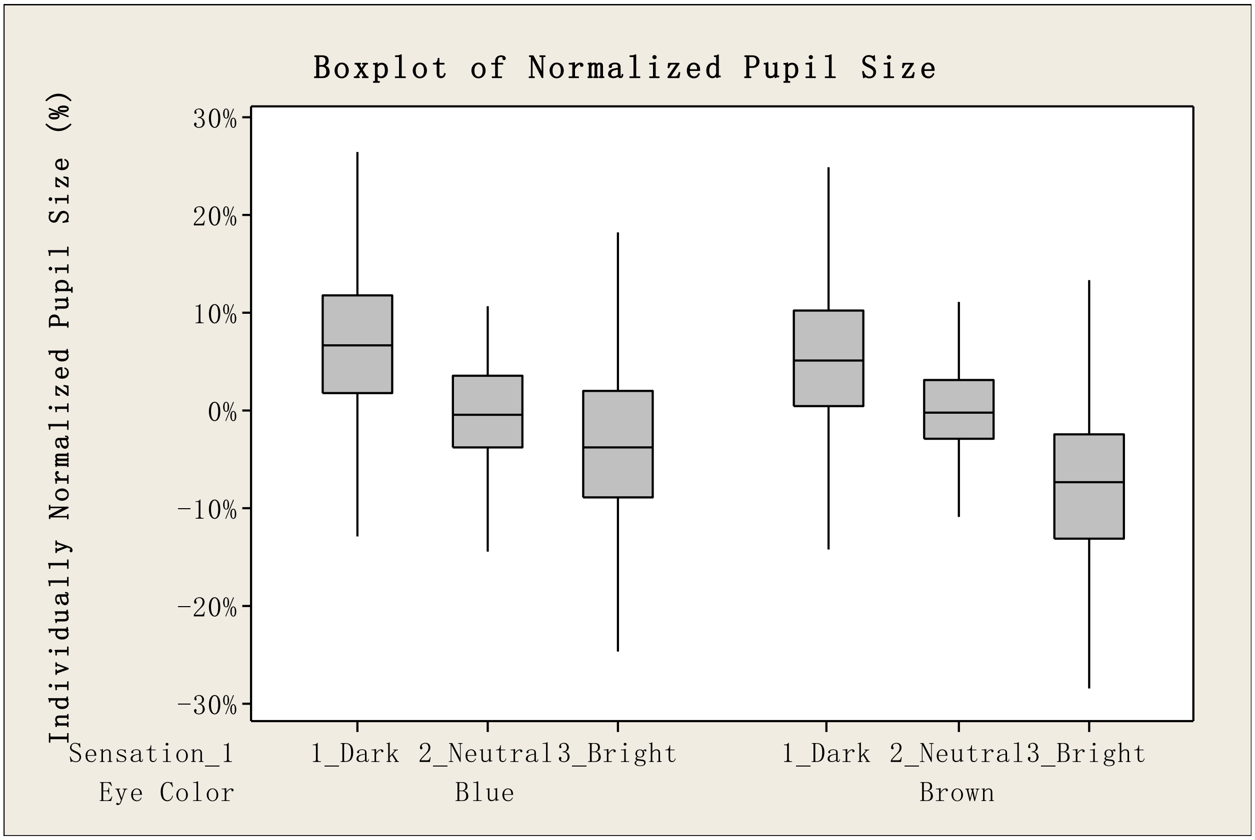


Figure 5.30 Boxplot of comparisons of overall standardized pupil size per visual sensation between eye color groups (third round).

Table 5.12 One-way ANOVA test: Standardized Pupil Size versus Sensation between Eye Colors

ANOVA for Blue	ANOVA for Brown
Analysis of Variance Source DF Adj SS Adj MS F-Value	Analysis of Variance Source DF Adj SS Adj MS F-Value

```
P-Value
Sensation_1     2   15.20  7.60241  1143.19
0.000
Error        7616   50.65  0.00665
Total        7618   65.85


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.0815486  23.09%     23.07%      23.04%
```

```
P-Value
Sensation_1      2   47.87  23.9372  4354.97
0.000
Error        14838   81.56   0.0055
Total        14840  129.43


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.0741385  36.99%     36.98%      36.97%
```

```
Means

Sensation_1     N      Mean    StDev
95% CI
1_Dark       2438   0.07320  0.08189
( 0.06996,  0.07644)
2_Neutral    1606   0.00000  0.04931
(-0.00399,  0.00399)
3_Bright     3575  -0.02853  0.09223
(-0.03120, -0.02586)

Pooled StDev = 0.0815486
```

```
Means

Sensation_1     N      Mean     StDev
95% CI
1_Dark       4650    0.05595   0.07801
(  0.05381,   0.05808)
2_Neutral    2550   0.000000  0.045551
(-0.002878,  0.002878)
3_Bright     7641  -0.071219  0.079244
(-0.072881, -0.069556)

Pooled StDev = 0.0741385
```

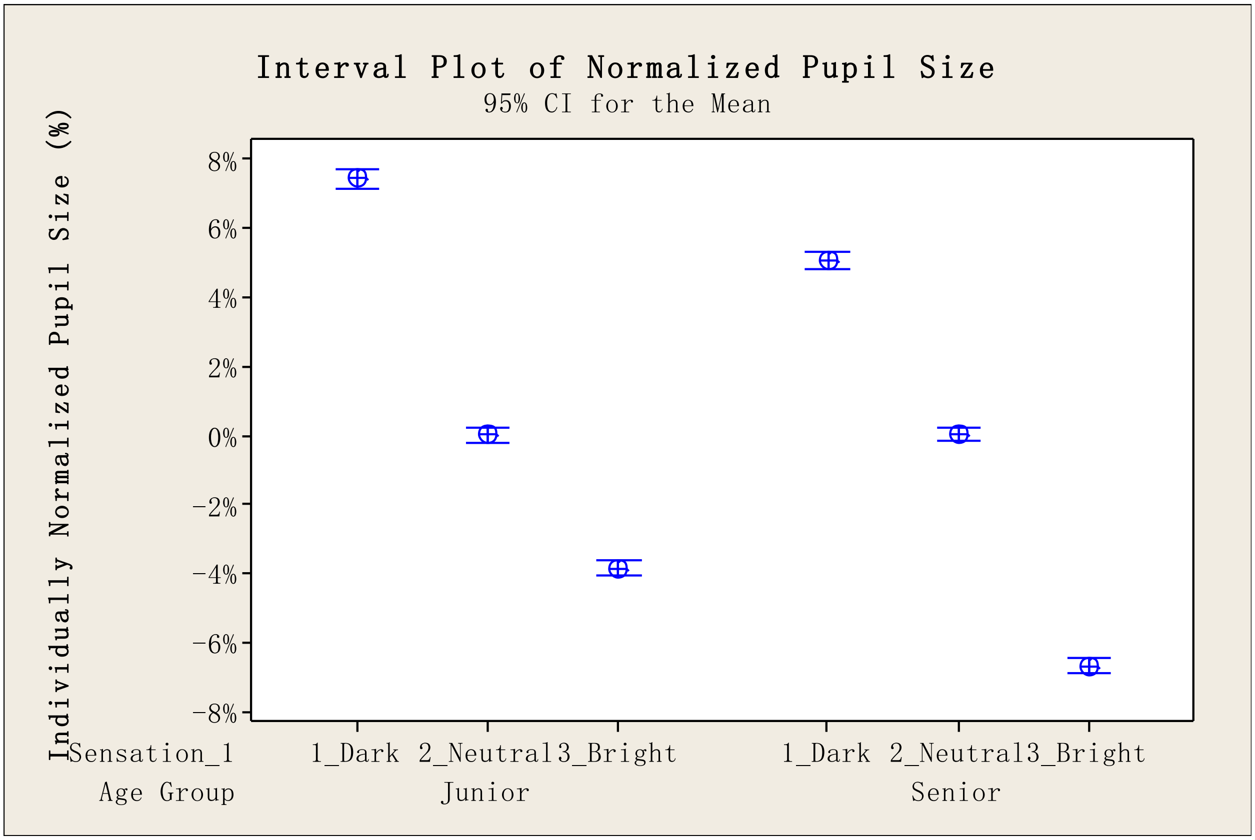


Figure 5.31 Interval plot of comparisons of overall standardized pupil size per visual sensation between age groups (third round).

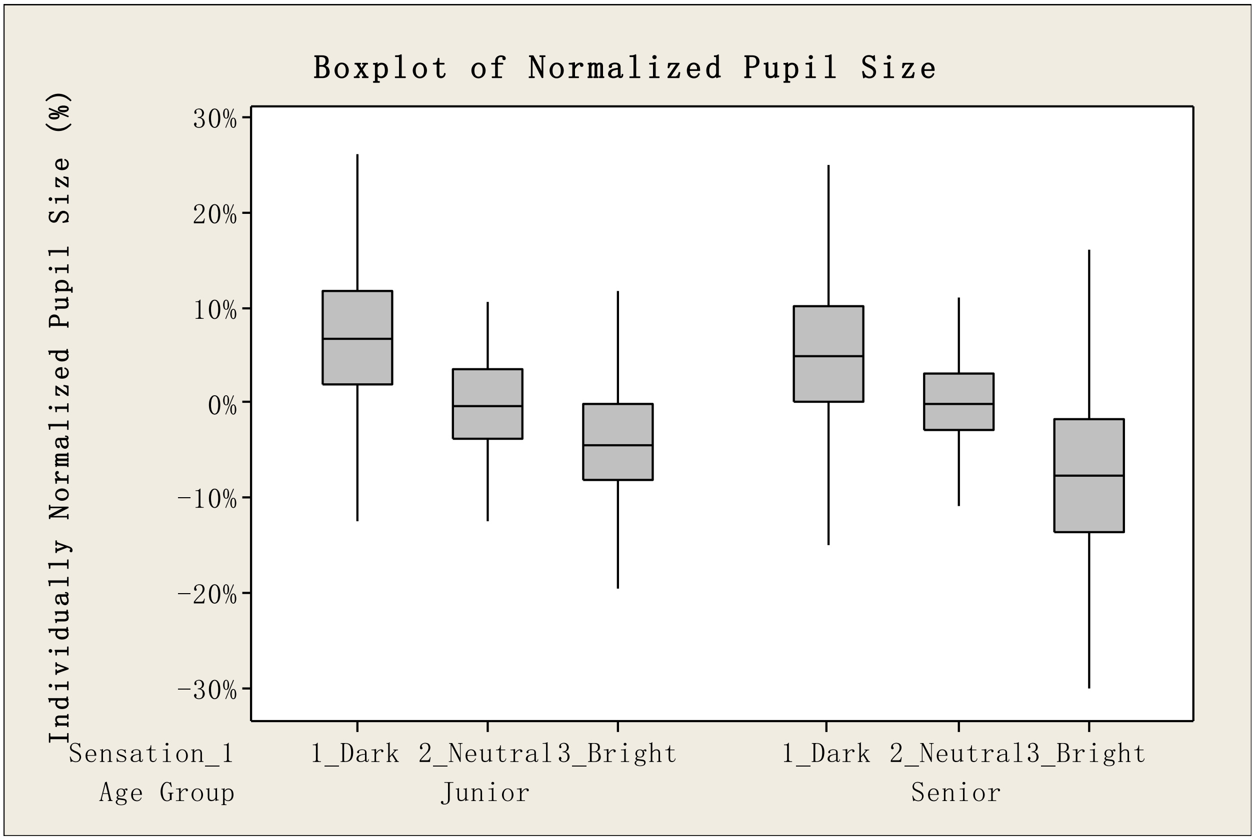


Figure 5.32 Boxplot of comparisons of overall standardized pupil size per visual sensation between age groups (third round)

Table 5.13 One-way ANOVA test: Standardized Pupil Size versus Sensation between Age Groups

ANOVA for Senior	ANOVA for Junior
Analysis of Variance Source DF Adj SS Adj MS F-Value	Analysis of Variance Source DF Adj SS Adj MS F-Value

```
P-Value
Sensation_1     2   36.16  18.0823  2729.78
0.000
Error       13453   89.11   0.0066
Total       13455  125.28


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0813884  28.87%     28.86%      28.84%
```

```
P-Value
Sensation_1    2   22.73  11.3673  2272.26
0.000
Error       9001   45.03   0.0050
Total       9003   67.76


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0707293  33.55%     33.54%      33.51%
```

```
Means

Sensation_1     N      Mean     StDev
95% CI
1_Dark       3757   0.05082   0.07795
(  0.04822,  0.05342)
2_Neutral    2192  0.000000  0.045067
(-0.003407, 0.003407)
3_Bright     7507  -0.06700   0.09077
( -0.06884, -0.06516)

Pooled StDev = 0.0813884
```

```
Means

Sensation_1    N     Mean    StDev
95% CI
1_Dark      3331   0.07435  0.07999
( 0.07195,  0.07675)
2_Neutral   1964   0.00000  0.04915
(-0.00313,  0.00313)
3_Bright    3709  -0.03862  0.07154
(-0.04089, -0.03634)

Pooled StDev = 0.0707293
```

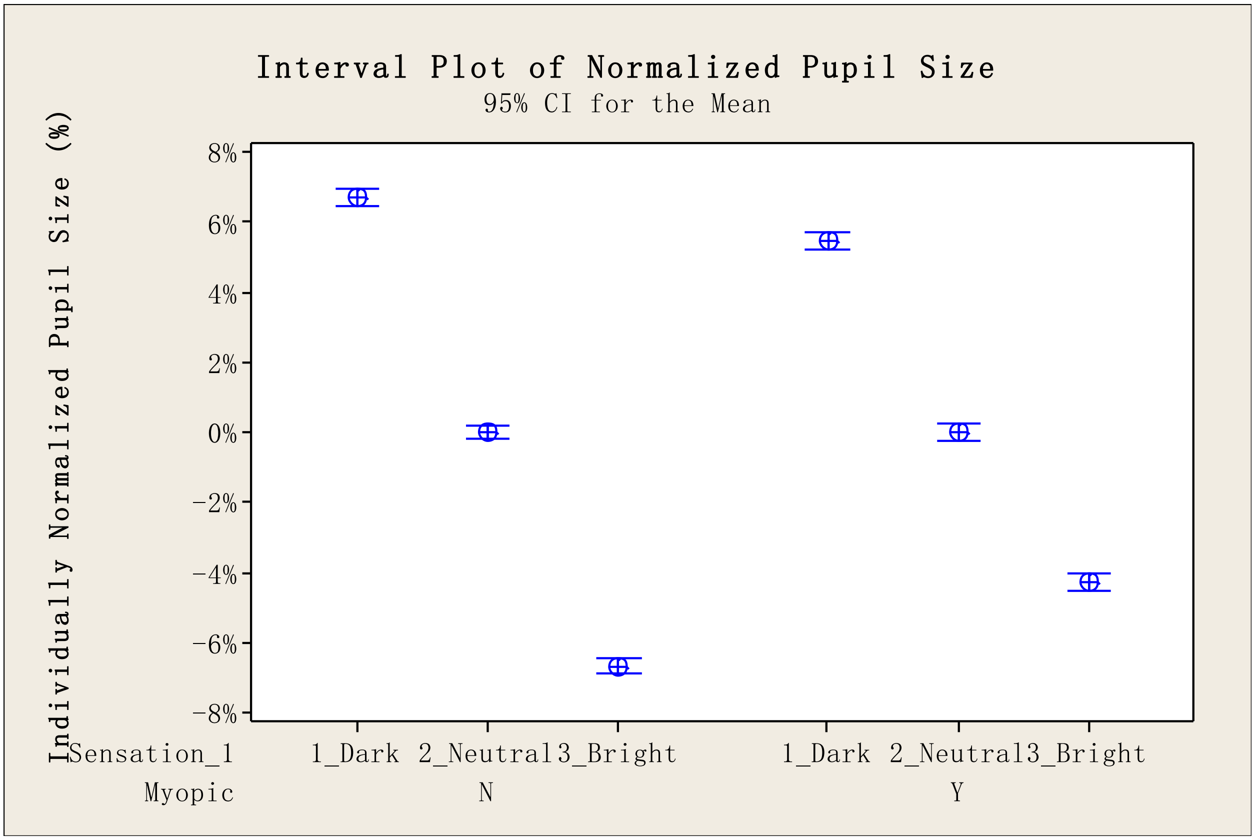


Figure 5.33 Interval plot of comparisons of overall standardized pupil size per visual sensation between myopic groups (third round).

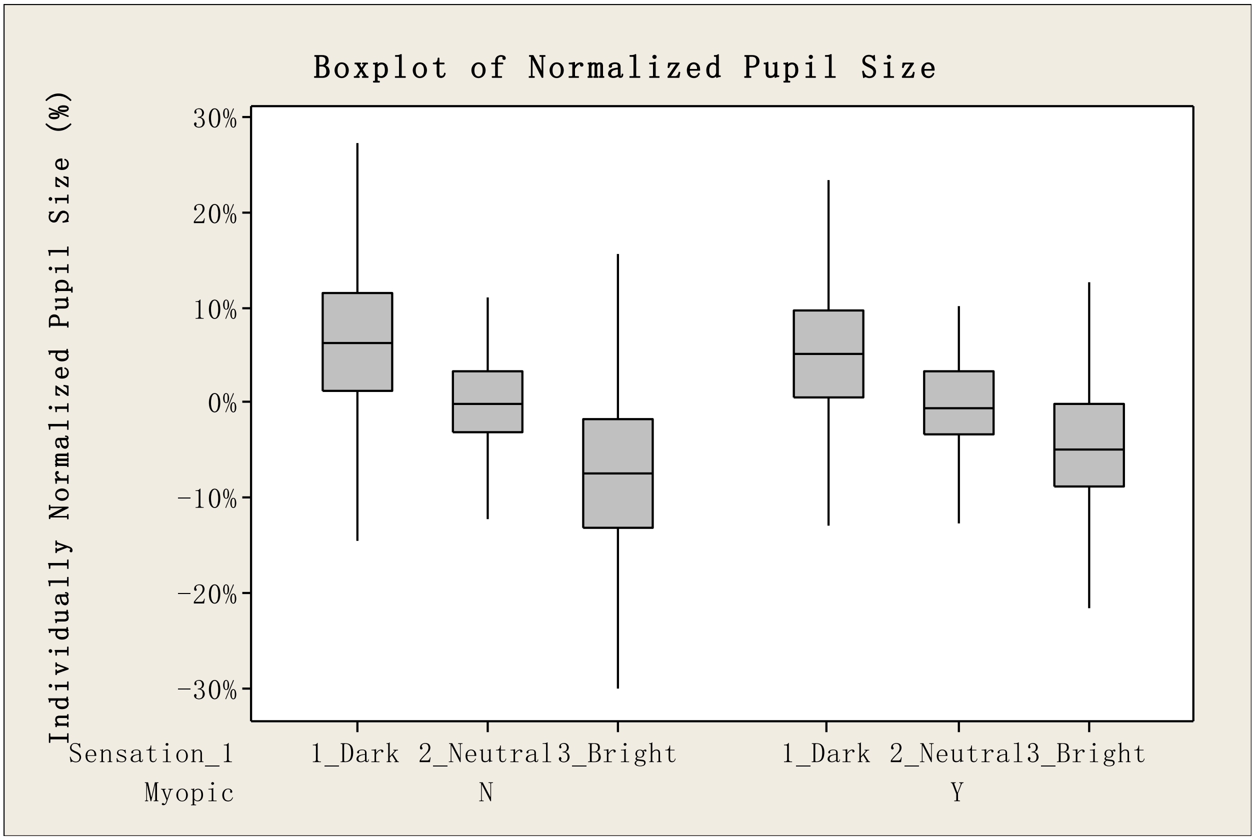


Figure 5.34 Boxplot of comparisons of overall standardized pupil size per visual sensation between myopic groups (third round)

Table 5.14 One-way ANOVA test: Standardized Pupil Size versus Sensation between Myopic Groups

ANOVA for N

```
Analysis of Variance

Source         DF  Adj SS   Adj MS  F-Value
P-Value
Sensation_1      2   46.44  23.2207  3602.80
0.000
Error       13374   86.20   0.0064
Total       13376  132.64


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.0802820  35.01%     35.00%      34.99%
```

ANOVA for Y

```
Analysis of Variance

Source        DF  Adj SS   Adj MS  F-Value
P-Value
Sensation_1    2   17.15  8.57710  1585.26
0.000
Error       9080   49.13  0.00541
Total       9082   66.28


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.0735564  25.88%     25.86%      25.84%
```

```
Means

Sensation_1     N      Mean     StDev
95% CI
1_Dark      4080   0.06706   0.08533
(  0.06460,  0.06952)
2_Neutral    2487  0.000000  0.046864
(-0.003155, 0.003155)
3_Bright     6810  -0.06702   0.08658
( -0.06893, -0.06512)

Pooled StDev = 0.0802820
```

```
Means

Sensation_1     N      Mean    StDev
95% CI
1_Dark      3008   0.05485  0.07098
( 0.05222,  0.05748)
2_Neutral    1669  -0.00000  0.04730
(-0.00353,  0.00353)
3_Bright     4406  -0.04306  0.08286
(-0.04524, -0.04089)

Pooled StDev = 0.0735564
```

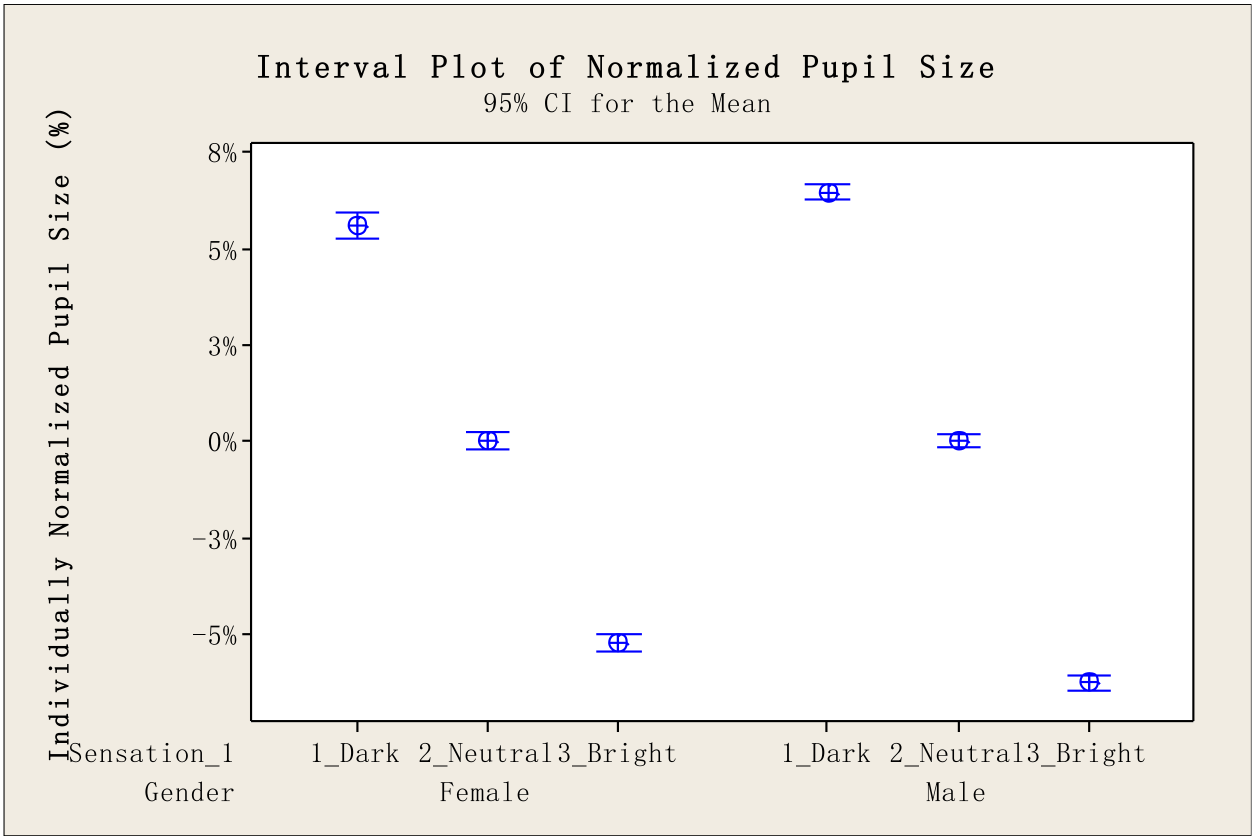


Figure 5.35 Interval plot of comparisons of overall standardized pupil size per visual sensation between gender groups (third round).

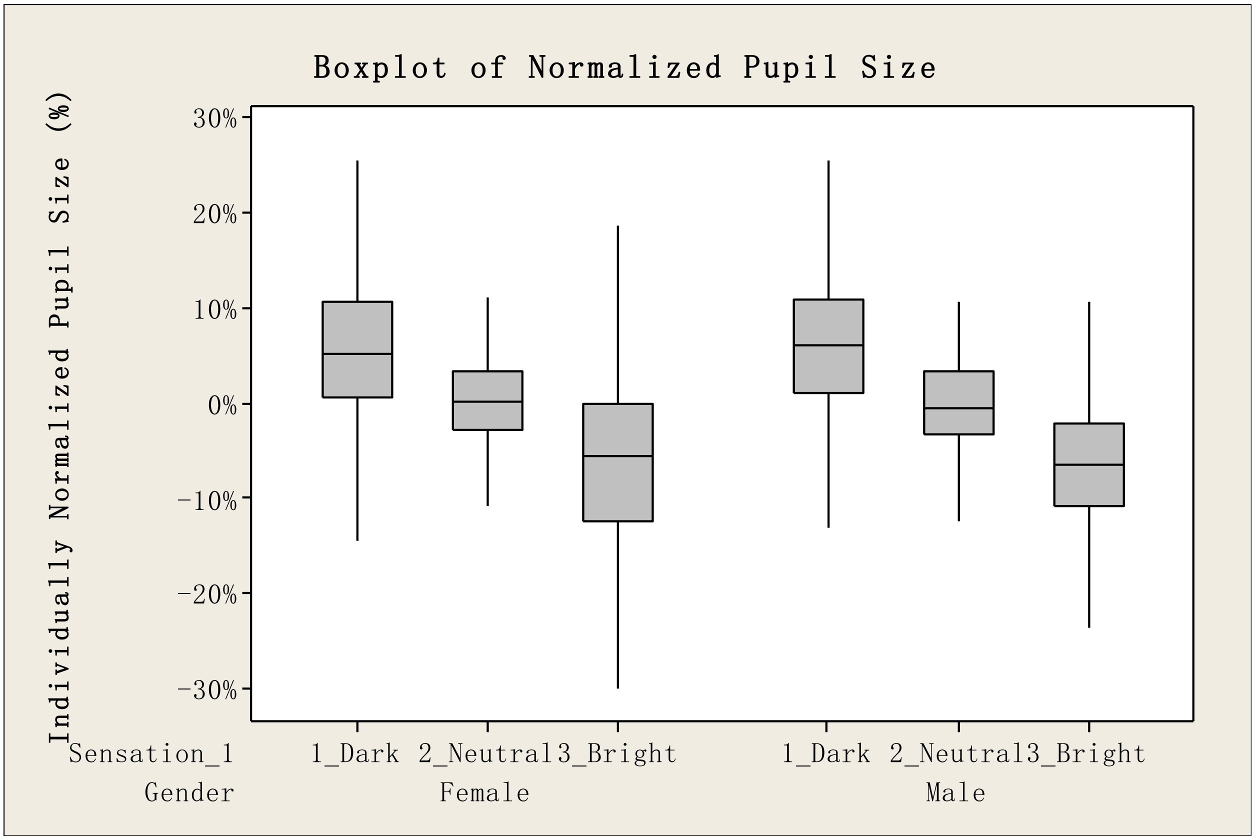


Figure 5.36 Boxplot of comparisons of overall standardized pupil size per visual sensation between gender groups (third round)

Table 5.15 One-way ANOVA test: Standardized Pupil Size versus Sensation between Gender Groups

ANOVA for Female

```
Analysis of Variance

Source         DF  Adj SS   Adj MS  F-Value
P-Value
Sensation_1     2   20.51  10.2548  1409.30
0.000
Error        9753   70.97   0.0073
Total        9755   91.48


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.0853028  22.42%     22.40%      22.38%
```

ANOVA for Male

```
Analysis of Variance

Source         DF  Adj SS   Adj MS  F-Value
P-Value
Sensation_1     2   41.39  20.6967  3999.77
0.000
Error       12701   65.72   0.0052
Total       12703  107.11


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.0719337  38.64%     38.63%      38.62%
```

```
Means

Sensation_1    N     Mean    StDev
95% CI
1_Dark      2411   0.05607  0.08461
( 0.05266,  0.05947)
2_Neutral    1650   0.00000  0.04693
(-0.00412,  0.00412)
3_Bright     5695  -0.05246  0.09379
(-0.05468, -0.05025)

Pooled StDev = 0.0853028
```

```
Means

Sensation_1    N      Mean     StDev
95% CI
1_Dark      4677    0.06488   0.07701
(  0.06281,  0.06694)
2_Neutral    2506  -0.000000  0.047110
(-0.002817, 0.002817)
3_Bright     5521   -0.06292   0.07665
( -0.06482, -0.06103)

Pooled StDev = 0.0719337
```

5.4 – Discussions between different rounds

Sections 5.1, 5.2 and 5.3 mainly discussed pupil size change per visual sensation under different lighting settings as well as comparisons between categorized groupings of human subjects according to physiological features. Checking consistency of previous comparisons in different experiment rounds and discuss other potential findings, especially difference between experiment rounds, is also very important.

5.4.1- Checking Consistency of Previous Observations

By comparing overall standardized pupil size distribution of first round (Figure 5.2, Figure 5.3), second round (Figure 5.14, Figure 5.15) and third round (Figure 5.26, Figure 5.27), the pupil size patterns for visual sensations based on the combined data of all individuals follow similar trend among different rounds, which is, the standardized pupil sizes decreased while the generated illuminance intensity was increasing. And the mean value per sensation is mostly clearly differentiated from each other. Furthermore, the interval of each sensation is relatively small which indicates the potential use as baseline for each sensation under those lighting conditions.

By grouping human subjects into different categories based on their physiological features, a better understanding of those physiological characters could be achieved. Through comparisons between eye colors among all three rounds (Figure 5.5, Figure 5.18 and Figure 5.31), it can be concluded that the eye color has effect on pupil size change. Subjects with brown eye color had less pupil size change when reported dark sensations. While, subjects with blue eye color has consistent large pupil size change in dark sensation than in bright sensation.

In comparisons between age groups among all three rounds (Figure 5.7, Figure 5.20 and Figure 5.33), a consistent result was not found. There is larger pupil size change in the junior group in the first round, larger pupil size change in the senior group in the second group and similar pupil size pattern but different distribution in the third round. Therefore, age doesn’t seem to have effect on pupil size change. A possible reason for this observation could be restrictions on the samples or the standard of division to the group. 25 may not be the right choice for division. And there were less samples in >25 group. A larger range of age should be achieved and would be more precise.

Through comparisons between myopic and non-myopic groups among all three rounds (Figure 5.9, Figure 5.22 and Figure 5.35), consistent effect of myopia on pupil size has been observed. Myopic subjects have less pupil size change than the non-myopic group, especially when in dark environment. It can be easily understood because myopic subjects have less ability in controlling their pupils.

In the end, comparisons between gender groups among all three rounds (Figure 5.11, Figure 5.24 and Figure 5.37) don’t indicate any significant effect of gender on pupil size. This is consistent with background research mentioned in Chapter 2.

5.4.2- Findings Observed from Comparisons between Experiment Rounds

The settings of three rounds differentiated in light color temperature and task types. It is also important to discuss whether color temperature and task types have any effect on pupil size. Comparisons between first round and second round, second round and third round were done separately to test the effect of color temperature (Figure 5.37) and task type (Figure 5.38).

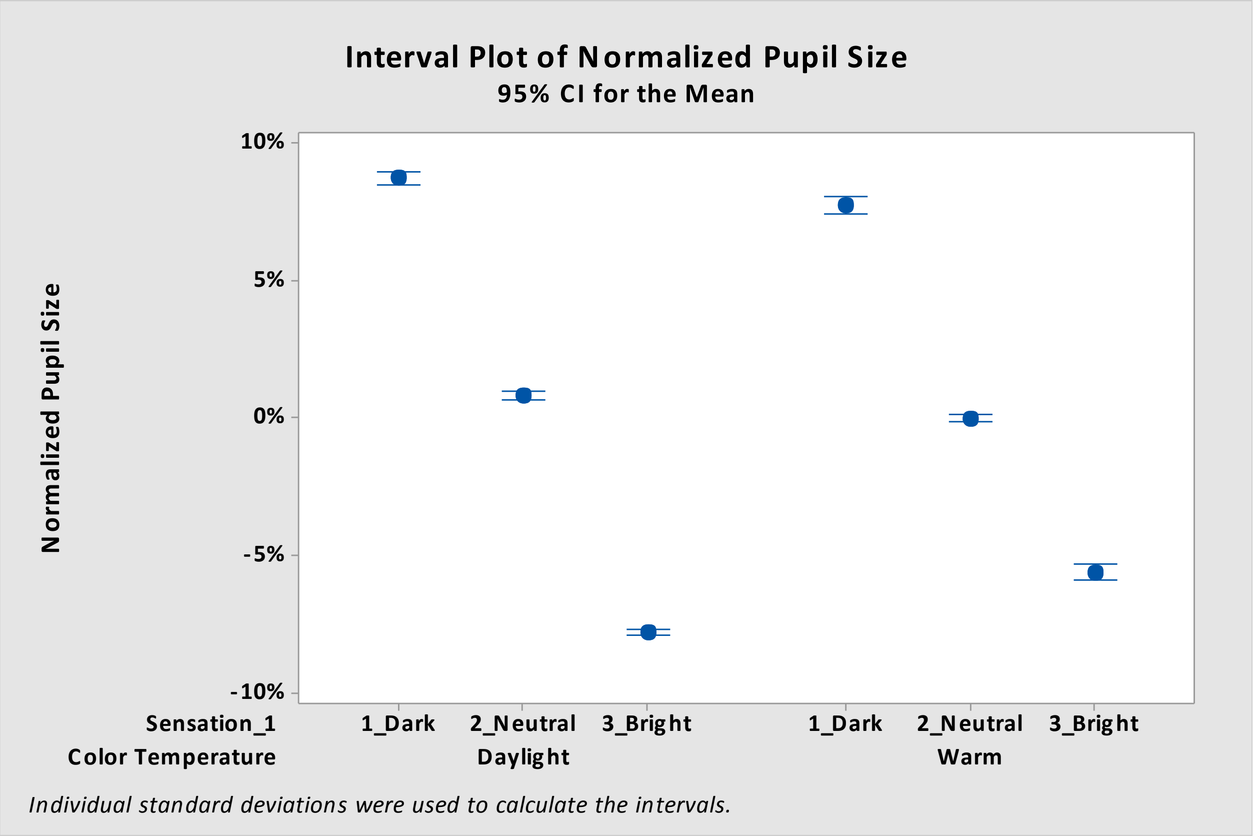


Figure 5.37 Interval plot of comparisons of overall standardized pupil size per visual sensation between color temperatures.

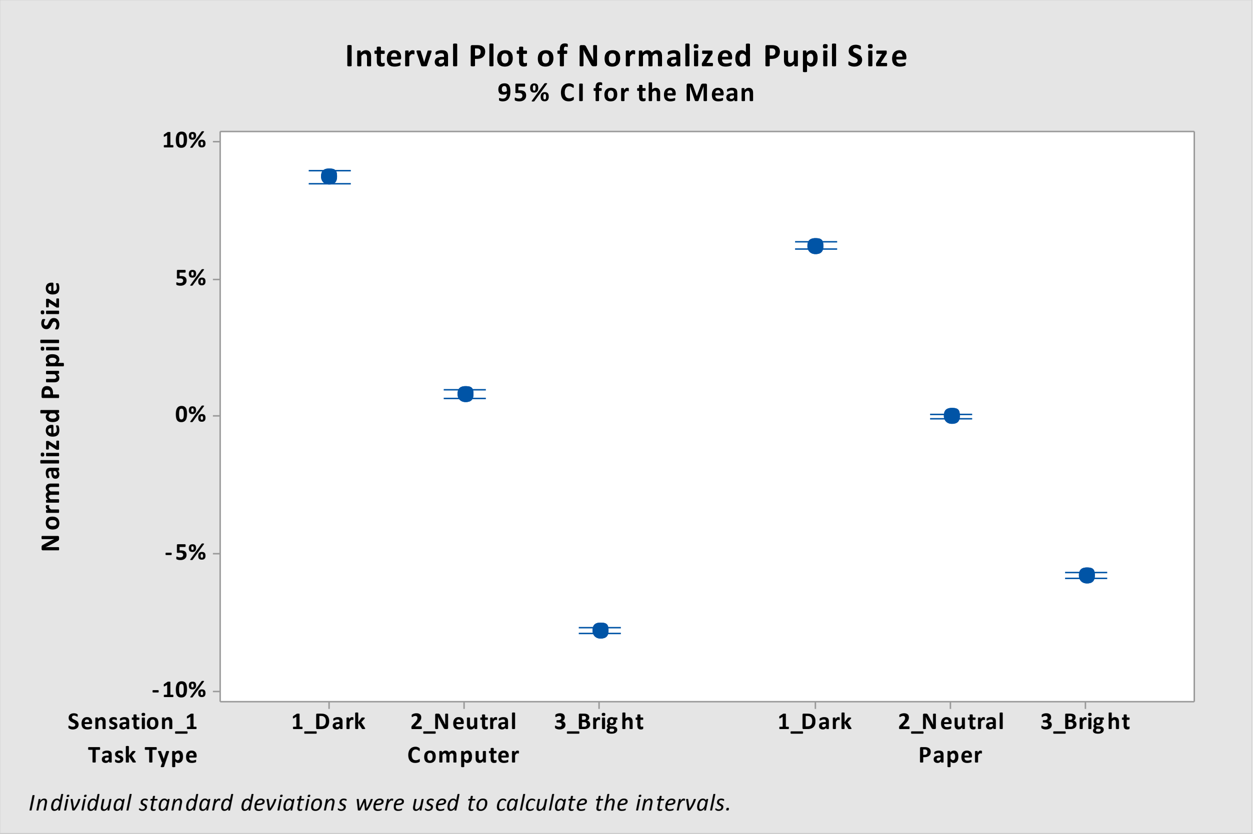


Figure 5.38 Interval plot of comparisons of overall standardized pupil size per visual sensation between task types.

Daylight seems to cause larger pupil size change than warm color temperature. A computer-based task seems to cause a larger pupil size change than a paper-based task as well.

5.5 – Summary

After doing comparisons between different rounds, it is clear that categorized human subjects share similar pupil size responses to different lighting conditions. There are also some particular features in each group as well. Then, a summary of each round is shown in column figures for a better graphical display (Figure 5.39, Figure 5.40 and Figure 5.41).

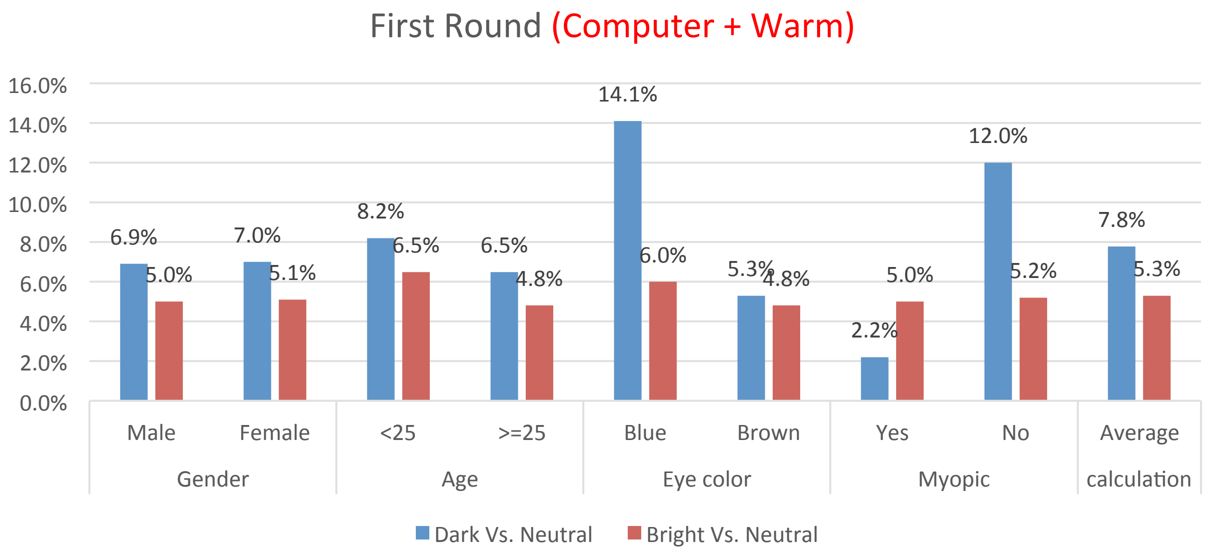


Figure 5.39 Summary of average pupil size change in each category of first round.

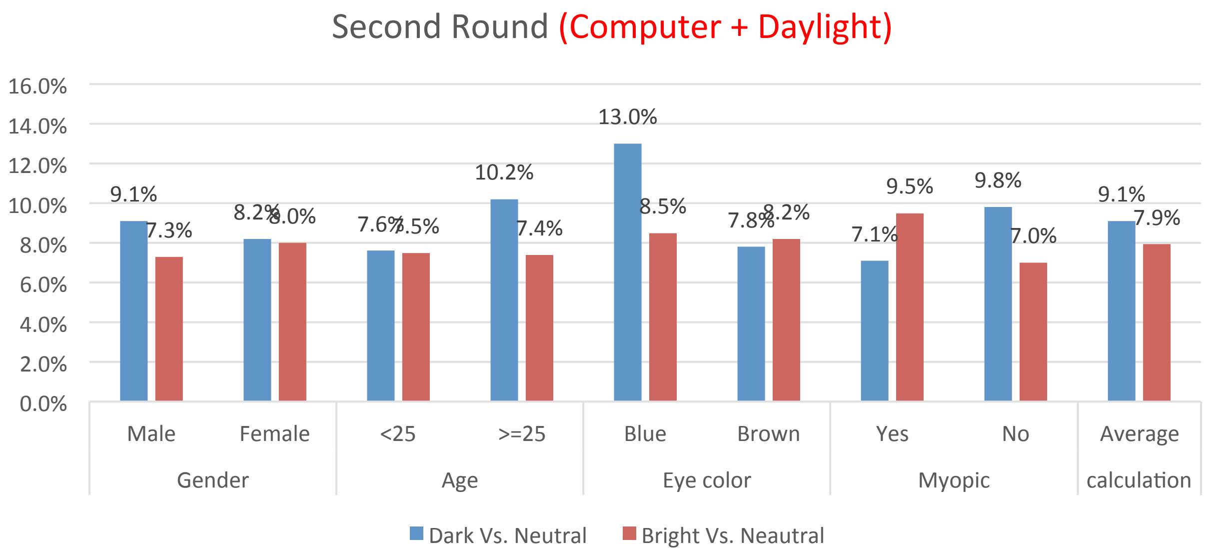


Figure 5.40 Summary of average pupil size change in each category of second round.

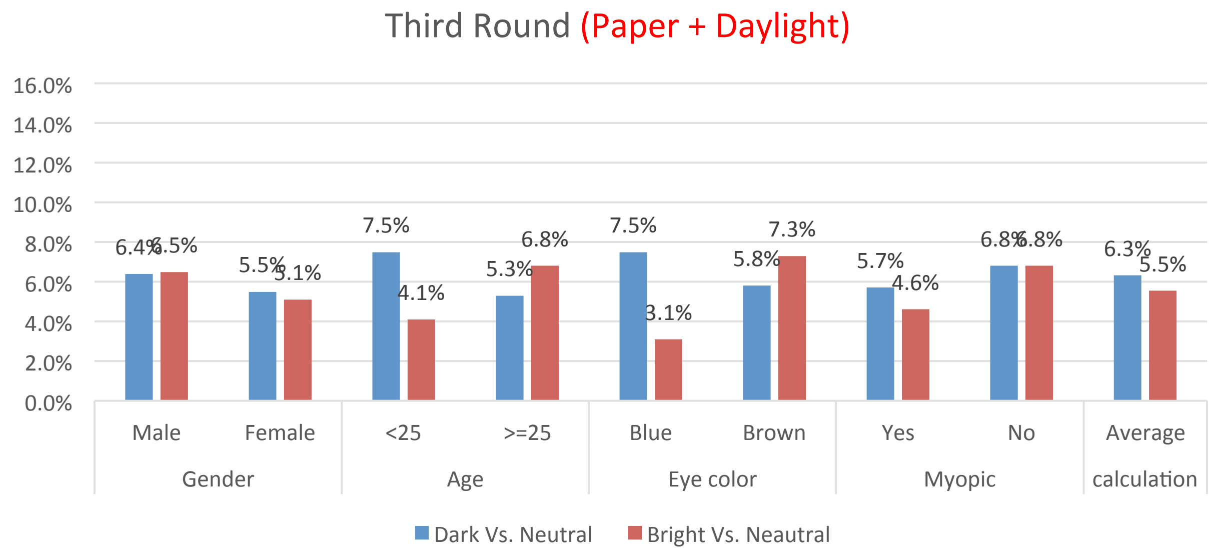


Figure 5.41 Summary of average pupil size change in each category of third round.

With collected pupil size, pupil size calculations of human subjects groups based on physiological divisions under different lighting conditions were conducted. All calculated results could be used as reference in future lighting control.

Chapter 6: Conclusions of Study

The study was aiming at figuring out the potential use of pupil size for future office lighting control. For the purpose of testing the relationship between pupil size and lighting condition and excavating other potential effects, conducting human subject experiment was chosen as method for the study. USC School of Architecture provided a chamber, and experimental devices were installed based on the experiment design and requirements.

Three rounds of experiment were finished, and 20 volunteers participated in each round. There was only one participant per experiment to be tested. Each experiment lasted on an average of 1 hour and 20 minutes. During the experiment, participant was required to finish a certain type of work (computer-based or paper-based) under different lighting conditions, and visual responses to the lighting conditions were collected through questionnaire and pupil size. Lighting parametric data were also monitored and stored automatically during the tests.

The relationship between pupil size and lighting condition was subjected to statistical analysis. Differences among physiological groups of human subjects were also summarized as important findings.

6.1 – Illuminance, Sensations and Pupil Size

Illuminance, sensation, and pupil size were selected as three significantly important parameters consequently representing lighting condition, subjective feeling/judgment ,and objective physiological response. Ten levels of illuminance ranging from 50 lux to 1400 lux with 150 lux interval were created for each human subject involved experiment as an indicator. A 7-point scale questionnaire was adopted to collect participant’s sensation per illuminance level. Through the entire experiment, the pupilometer worn by the participant was monitoring and collecting pupil size parametric data. By combining all those data, relationships among illuminance, sensations, and pupil size could be analyzed and concluded. The potential use of pupil size was also validated.

Preferred illuminance range differentiates significantly per visual sensation, and for each sensation there is a corresponding illuminance range. Since average luminance and illuminance have a linear regression relation with each other, for each sensation, there is also a corresponding average luminance range. Sensations could reflect participants' preference both objectively and subjectively.

Standardized pupil size distribution has significant difference per visual sensation, which is consistent through all three rounds of experiment. There is at least about 4% difference in pupil size between visual sensations. It is certain that pupil size can be considered as an indicator of preferred lighting conditions, which demonstrates the potential use of pupil size for lighting control.

6.2 – Further Conclusions based on Physiological Features of Human Subjects

Based on the previous study and research purpose, age, gender, ethnicity, eye color and myopic or non-myopic were chosen as physiological features and were collected from participants' questionnaires. Restrictions had also be adopted to reduce effect on human subjects' behaviors due to other factors, which included food and drink prohibition during experiment, etc.

There were two groups in each category for the further analysis. The study was also trying to balance number of people in each group to minimize the effect due to large difference in sample size of each group in the category. Finally, among all three rounds of experiment, except eye color category, all other categories have achieved 40%/60% distribution between two groups which mostly satisfied study expectations. By applying classifications to pupil size data of human subjects, more findings were concluded:

Comparisons of overall standardized pupil size per visual sensation between eye colors, age groups, myopic groups as well as gender groups, present the differentiated standardized pupil size distribution due to the physiological features of human subjects.

Eye color and myopia have a significant effect on pupil size change. Subjects with brown eye color have an average of 4.2% less pupil size change compared with subjects with blue eye color; myopic group has an average of 4.5% less pupil size than non-myopic group. However, age and gender don't indicate any consistent effect on pupil size, since average pupil size difference between two age groups in three rounds are 3.4%, -2.5% and -0.5%; average pupil size difference between gender groups in there rounds are very limited, which are -0.2%, 0.2% and 2.3%. A previous study (Winn et al. 1994) indicated that gender doesn't have effect on pupil size. It is validated in this study.

6.3 – Color Temperature and Task Type

As mentioned in Chapter 3 and Chapter 4, color temperature and task type are two other important factors studied in this research. Therefore, three rounds of experiment were conducted separately with different lighting fixtures and other device installed: warm color temperature + computer-based task, daylight color temperature + computer-based task, and daylight color temperature + paper-based task. By conducting comparisons between these three groups, effect of color temperature and task type was observed:

About 2.5% larger pupil size change has been observed in daylight group than in warm group, and 2.7% larger in computer-based task group than in paper-based group.

6.4 – Potential Use of Findings

With the findings of pupil size, automatic lighting control based on pupil size may be possible. Current devices, such as a pupilometer, smartphone or even Google glass (Google glass is a smart-control device developed by Google, which is like goggle with very tiny glass for display and a highly integrated projector installed, by using Google glass, it is very easy to take pictures searching for information, just like using a smartphone) , make it possible for convenient and in-time tracking and monitoring. When a tracking device identifies pupil size, judgment based on the human physiological features and collected dataset will analyze and calculate out if current lighting condition is appropriate, too light, or two dark for the specific subject. Then, a control signal indicating the optimal amount of change to the lighting device will be sent. As a result, lighting is adjusted. The conceptual controlling strategy is shown in Figure 6.1.

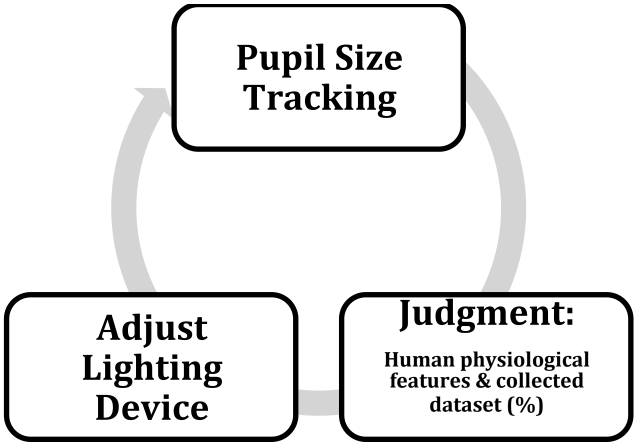


Figure 6.1 Conceptual strategy for automatic lighting controlling

This strategy could be adopted for both individual lighting control and group lighting control. Or even, it provides idea for office lighting, layout design. By adopting this strategy, it is believed that large amount of electricity could be saved for office lighting, then a more efficient, environmental friendly working environment could be achieved.

Chapter 7: Future Work

Human factors, lighting parameters, and hardware and software combination could be improved. There are also limitations when conducting this research, which could be paid more attention to or solved in the future.

7.1 – Possible Improvements on Participants

Although the sample size (20 participants in each round) in this research is believed enough for an efficient analysis, a larger sample size is always better to accessing more precise and stable results for a human subject involved research. The bigger sample size could result in a more reliable statistical result with narrower confidence interval range, which is more useful for the future automatic control logic generation for the lighting.

Meanwhile, a better variety of participants should be also achieved and balanced in the experiment. Each physiological featured group is best to be divided equally to reduce the potential negative effect due to the different sample size in the compared groups. As the study was conducted on the campus, most participants involved in the experiment are graduate and undergraduate students which similar age. A better age group division should include more middle-aged people and old people as well. More people with blue eye color should be recruited to balance the eye color category. A detailed consideration on myopia should also be studied as different glasses degree could also behave differently.

7.2 – Possible Improvements on Lighting Parameters

Illuminance was used as a major parameter representing the lighting condition. It also served as a reference when creating different lighting conditions. Although luminance was calculated and discussed as well, a deeper research on luminance and other lighting parameters should be conducted in the future.

The relationship between illuminance and average luminance was discussed and a regression was generated based on the collected. However, there is a range of luminance for the workstation at each illuminance level. And distribution of luminance in the captured view from fisheye lance varies a lot. In this case, not only average luminance value should be considered, the minimum, maximum and distribution of luminance in the view should also be analyzed to reach a deeper understanding of luminance effect on pupil size and visual sensations. In addition, other parameters such as contrast ratio, light spectrum may also be included in the future study.

Daylight could also be introduced into this study since another major component in office lighting design is combining daylight with artificial lighting. In this way, a better and more efficient office lighting design could be achieved in the future by integrating automatic control for both artificial lighting and daylight. This strategy will also have an effect on the façade design and office layout.

7.3 – Possible Improvements on Hardware and Software

A lot investment has been put into this study for sensors, device, and software. There are more than 40 LED lamps, there are two computers for monitoring and conducting task purposes. And there is precious pupilometer tracking pupil size. But it still could be improved.

In the beginning of this study, there were blinking problems of light source due to the unstable power supply in the chamber, especially when it was at low illuminance levels, which caused negative effect on participant’s response to the satisfaction level. Although the problem was minimized a lot by replacing the manual dimmer, it still has occasional blinking when other big machine on the basement level, such as elevator, was in use. THe power supply could be fixed or a better dimmer or self-designed and made dimmer could be used to fully satisfy experiment requirement.

Sometimes, there were complains from participants about the glare problems that caused by the reflective glass on the pupilometer from light source. A temporary solution, which used a cap or a small paperboard to cover top of pupilometer, was introduced. But it blocked some view above the pupilometer, which is not serious but unfavorable in the experiment. It might be problem of the location of LED lamps, the distance of LED lamps to participant's head is relatively smaller than traditional office. Therefore, a better design of the light source should be considered.

The light source used in the chamber was LED lamps, which are different from lighting fixtures used in the current offices. Replacing LED lamps could not only achieve a better office-like environment but also may solve glare problems.

Currently, there are too many devices on the table, which may be some distractions for the participant. Two laptops were used and one was for pupilometer and the other was for illuminance meters. And each laptop has software installed for collecting data purpose. If those two data collection programs could be combined, there would be easier to monitor and collection. The combined data would also be more sufficient since it saved a large amount of time for preliminary data packaging and preparation. The combined program only requires one computer and saves space in the chamber as a result. In addition, it could also integrate dimming control in the program so as to be more accessible to different lighting conditions.

7.4 – Strategy Development

A calculated pupil size change based on different conditions was summarized in this study. But detailed control strategy and formula based on the collected database should be worked in the future. Some validation research should be conducted for the strategy to ensure its proficiency.

With a detailed control strategy and formula, software could be programmed and developed for controlling lighting devices or even other self-designed physical applications. However, real testing of all those software and physical applications is very necessary. Commissioning in a real project would be the most valuable. Both short term and long term periods commissioning are highly recommended.

As mentioned in the Chapter 6, the strategy is not restricted to the office lighting control. It could also be developed for other purposes but with further related research. Pupil size based control strategy is believed to have broader use in the industry. More related research are highly recommended and valued.

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