Human Factor Analysis of Light Emitting Diode Technologies for Aerospace Suitability in Human Space Flight Applications

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Light emitting diodes (LED) are semiconductors that convert electrical energy into light and are used by commercial markets to replace traditional fluorescent and incandescent lighting technologies. Advantages of transitioning to LED technologies in spacecraft are reduced mass, reduced occupied volume, reduced power, improved color control, longer operating life, and lower cost associated with power consumption and disposal. Light emitting diode technologies remain a controversial technology in the aerospace industry, where there are no flight qualified sources and commercial manufacturers are the only source for procurement. An earlier phase of this research effort provided empirical evidence that selected commercial LEDs are capable of meeting NASA and DOD qualification and screening requirements. This paper addresses phase two of the research involving reliability for human factors in search of adverse effects, such as fatigue, eye strain, and headaches in astronauts. Reliability is defined as quality over time and the quality of cabin crew light is essential for long term missions where crew habitation relies solely on artificial light sources. In an effort to advance the technology readiness level (TRL) for human spacecraft lighting, a randomized block design was deployed for evaluating human factor effects using soft white light, emitted from LEDs and a general luminaire assembly (GLA) fluorescent representing current lighting on the International Space Station (ISS). There was no statistical evidence to support claims that the LED technology involved in this research caused fatigue, eye strain and/or headache in humans and that selected LED technologies may be considered for TRL advancement.

Nomenclature

α	= statistical significance level
AIAA	= american institute for aeronautics and astronautic
ANOVA	= analysis of variance
DOD	= department of defense
DOE	= design of experiments
F	= f-distribution used in statistical analysis of variance
GLA	= general luminaire assembly
H_0	= null hypothesis
H_1	= alternate hypothesis
IRB	= institutional review board
ISS	= international space station
LED	= light emitting diode
LUX	= luminous emittance using luminous flux per unit area of light
MIL	= military
P	= probability value of obtaining a statistical effect in hypothesis testing
Q	= research question
TRL	= technology readiness level

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I. Introduction

THE research problem for this study was a government and private aerospace industry problem involving use of unproven light emitting diodes (LEDs) as a suitable alternative to existing fluorescent lighting. Commercial space designers are required to manage space flight designs in accordance with parts selections made from qualified parts listings approved by DOD and NASA agencies for reliability and safety (Lindenmoyer & Stone, 2010). The problem addressed by this study was that LEDs remain an unproven technology in the aerospace industry, where commercial manufacturers are the only source for procurement and unanswered questions remain about effects on astronaut cognition and health. Aerospace engineers tasked with design and development activities of space flight hardware, and considering integration of LEDs, will be required to manage to the NASA technology readiness level system (TRL) (Yiyuan et al., 2011). A TRL 7 is achieved by successfully demonstrating that new technology suitably meets intended function while being subjected to simulated space flight environments (Mankins, 2009). The space environment was achieved through laboratory testing which was represented in this analysis.

Brainard et al. (2012) published literature investigating melatonin production in a space habitation by subjecting humans to LED's in a laboratory setting. However, scientific literature is void of in-depth analysis of LEDs involving effects on humans living inside a spacecraft habitat. Cohen et al. (2011) revealed that a robust LED system does no good to the user if the selected technology creates glare, resulting in unwanted eye strain and other effects which are undesirable for task lighting purposes when applied to a human user environment. This research study tested the suitability of commercial LEDs for reliability and human factors which may assist the commercial and government aerospace personnel with technology classification for human space flight applications in conjunction with design of experiment (DOE) statistical analysis methods for answering research questions about human factors. Research results will assist design engineers in making informed decisions about component selection in accordance with mission goals for safety, reliability, and compliance with human factor requirements.

II. Sample of Human Participants

Jackson (2012) stated collecting random samples from a larger population is often the only manageable and cost effective option for making statistical inference about an entire population. This study utilized subsets representing the larger population. Eighteen university students, recruited and randomly selected from student membership ranks of the American Institute for Aeronautics and Astronautics (AIAA), participated in this study at a Madison, Wisconsin test facility. Table 1 illustrates descriptive statistics for the human participants used in this study and supports the view that the Likert scale survey instrument provided independence among each non-astronaut participant for representing the U.S. astronaut population.

Table 1
Descriptive Statistics for Human Participants

Demographic Characteristics	n	%
Gender		
Female	4	.22
Male	14	.78
Ethnicity		
Asian	1	.05
African-American	1	.05
White/Caucasian	16	.99
Field of University Study		
Mechanical Engineering	6	.33
Bio Medical	4	.22
Aerospace Mechanics	6	.33
Mathematics	2	.11
Color Blindness Test		
Students Tested/Pass Rate	18	100.00
Age		
Maximum Age	45	
Minimum Age	18	
Average Age	22	

n = 18

The human subjects were comprised of 22.2% female and 77.7% male, which is in line with the current US astronaut population of approximately 20% female and 80% male (Johnson Space Center Houston). Formal data from NASA regarding astronaut ethnicity was unavailable from Johnson Space Center, Houston, Texas. In this study one Asian male and one African-American female are represented in the sample. The US astronaut population is comprised of men and women who typically have university degrees in engineering, biological and physical sciences, and mathematics. The human sample contained 66.4% individuals currently studying a mechanical or aerospace engineering field, 22.3% studying biomedical sciences, and 11.3% studying mathematics. Only one of the participants was pursuing a Master of Science degree and the remaining

17 students were pursuing Bachelor of Science degrees. The oldest participant was 45 years of age and the youngest was 18 with a mean age of 22.

A. Recruitment

Under NASA research grant WSGC2014 a stipend of $15 per hour was offered to qualified participants who volunteered and were willing to make their own travel arrangements to participate in scheduled testing. A pre-survey interview was conducted and a pseudolsochromatic plate Ishihara color blindness test administered to selected volunteers as a means for qualifying human subjects for participation, where all 16 color patterns must be identified to assure consistency over human subjects (Khokhar et al., 2011). Twenty eight students responded where 18 were selected based on gender and then ethnicity to align with demographic of US astronaut corps.

B. Ethical Awareness

Prior to collecting data, permission was obtained from the Northcentral University IRB where all ethical guidelines were followed when using human subjects as a means of evaluating human factor effects from LED lighting. Jackson (2012) stated that the ultimate responsibility of the researcher is to ensure the welfare and safety of all subjects. Each volunteer subject was required to sign a consent form confirming willingness to participate in the experiment. Participants were also guaranteed that all data will be kept confidential, anonymous, and free from personal information ever being linked in future presentations or studies. According to the classifications of ethics risk, as described by Jackson (2012), the study did not involve variables that fall outside activities that might be deemed abnormal to daily life or routine. Using criteria outlined by Jackson (2012) there was minimal risk involving psychological or physical stress on the human participant. As an ethical precaution, participants were assured that they were free to remove themselves from the experiment at any time during the study using their own free will. Participants were also assured that there was no deception, misrepresentation, or information released that could embarrass or cause harm to them or the organization they represent. Upon completion of each experimental trial participants were debriefed and asked if they experienced any ill effects such as claustrophobia, nausea, headache, or other unforeseen symptoms.

III. Research Questions and Hypotheses

A. Research Questions

The central research question was to what extent is commercially designed and manufactured light emitting diodes (LEDs) a suitable replacement for fluorescents in space flight applications, in conjunction with human factor effects? The goal of the investigation was to elicit data that will create new knowledge and improve the body of knowledge for spacecraft lighting phenomenon within the commercial and government aerospace industries. The following research questions were investigated, using appropriate statistical techniques to support this inquiry:

Q1. Does the light from the NASA general luminaire (GLA) International Space Station (ISS) fluorescent result in reported fatigue, eye strain and/or headache in humans, when study participants perform detailed tasks of reading and assembling mechanical parts for an extended period of two uninterrupted hours?

Q2. Does the light from the white LED result in reported fatigue, eye strain and/or headache in humans, when study participants perform detailed tasks of reading and assembling mechanical parts for an extended period of two uninterrupted hours?

Q3. Does the light from the blue LED result in reported fatigue, eye strain and/or headache in humans, when study participants perform detailed tasks of reading and assembling mechanical parts for an extended period of two uninterrupted hours?

B. Hypotheses

$H1_o$. There is no statistically significant reported fatigue, eye strain and/or headache in humans from the GLA fluorescent, when study participants perform detailed tasks of reading and assembling mechanical parts for an extended period of two uninterrupted hours.

$H1_a$. There is statistically significant reported fatigue, eye strain and/or headache in humans from the GLA fluorescent, when study participants perform detailed tasks of reading and assembling mechanical parts for an extended period of two uninterrupted hours.

$H2_o$. There is no statistically significant reported fatigue, eye strain and/or headache in humans from a white LED, when study participants perform detailed tasks of reading and assembling mechanical parts for an extended period of two uninterrupted hours.

H2$_a$. There is statistically significant reported fatigue, eye strain and/or headache in humans from a white LED, when study participants perform detailed tasks of reading and assembling mechanical parts for an extended period of two uninterrupted hours.

H3$_o$. There is no statistically significant reported fatigue, eye strain and/or headache in humans from blue LED light, when study participants perform detailed tasks of reading and assembling mechanical parts for an extended period of two uninterrupted hours.

H3$_a$. There is statistically significant reported fatigue, eye strain and/or headache in humans from blue LED light, when study participants perform detailed tasks of reading and assembling mechanical parts for an extended period of two uninterrupted hours.

IV. Experimental Design

Human factors testing consisted of 54 treatments for the purpose of detecting experimental variation where each participant was exposed to experimental settings assigned over each block of three variables. The randomized block experimental design was based on the Analysis of Variance (ANOVA) math model. A total of 18 male and female participants were required to participate in a total of 54 treatments in accordance with the designated randomized block experimental design.

Montgomery (2013) stated that the randomized block experimental design can be used to investigate one factor or variable of primary interest and other controlled variables can be considered nuisance factors when conducting ANOVA. According to Hassan et al. (2012), the number of subjects being tested has the potential for producing significantly different readings and selected factors might differ slightly. Factors that consist of rigid hardware that can be placed into a test scenario and removed for replacement by another test factor can be considered a nuisance factor and be blocked accordingly. Since the three designated light fixtures are factors for testing against all combinations of subjects, the randomized block design was suitable for randomly testing each light fixture, or block, with each subject. Table 2 illustrates a randomized block design containing randomized numbers in each cell to show an example of varied run order. Experimental blocks are A, B, and C where each human subject was exposed to each factor at some point in the experiment.

Table 2

Completely Randomized Block Design Showing Random Order of Participants and Factors

Human	Factor Setting		
Subject	A	B	C
a	1	3	6
b	4	2	9
c	7	8	5

The design was replicated six times using three different human subjects during each experimental replication. To assure research validity and reliability, each human subject was exposed to each factor on different test appointments to remove bias from potential fatigue, boredom, and other unintended influences caused by continuous exposure to the designated test environment.

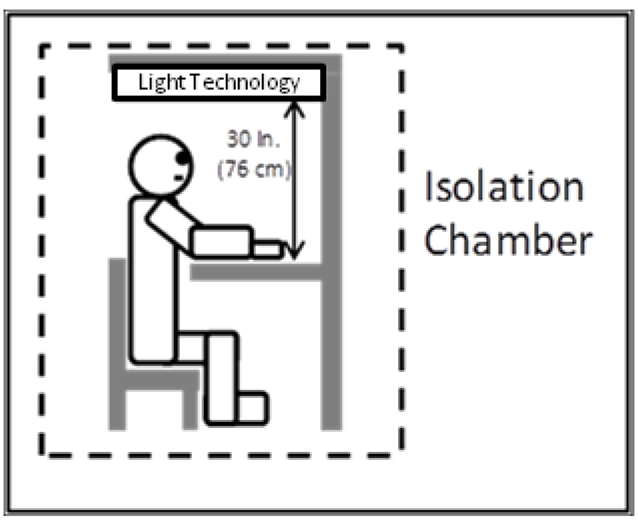

Figure 1. Quality of light test environment for human subjects.

Disadvantages to conducting a laboratory survey are cost and time, and due to these limitations sample sizes may be considered small (Langer et al., 2011). This sample size is greater than the sample used in the Brainard et al. (2012) study which was increased with the intention of improving internal and external validity. Figure 1 illustrates the experimental configuration, using human subjects placed in a standardized test chamber free from distractions, for the purpose of conducting experimental runs in accordance with the randomized block design settings.

Figure 3 illustrates the three lighting conditions administered in the quality of light survey where the same human subjects were exposed to the three factors for two hours each. Measuring design effects for human factors was executed by subjecting volunteer participants to two hours of uninterrupted exposure to either GLA fluorescent or LED light sources. The test conditions were randomized and human subjects were asked to perform a task that involved reading, color discernment, and LEGO model assembly. Upon completion of the test duration the test subject was asked to fill out a survey about their experience using the Likert scale illustrated in Figure 2. Likert scale results were analyzed for the purpose of answering the three research questions previously discussed.

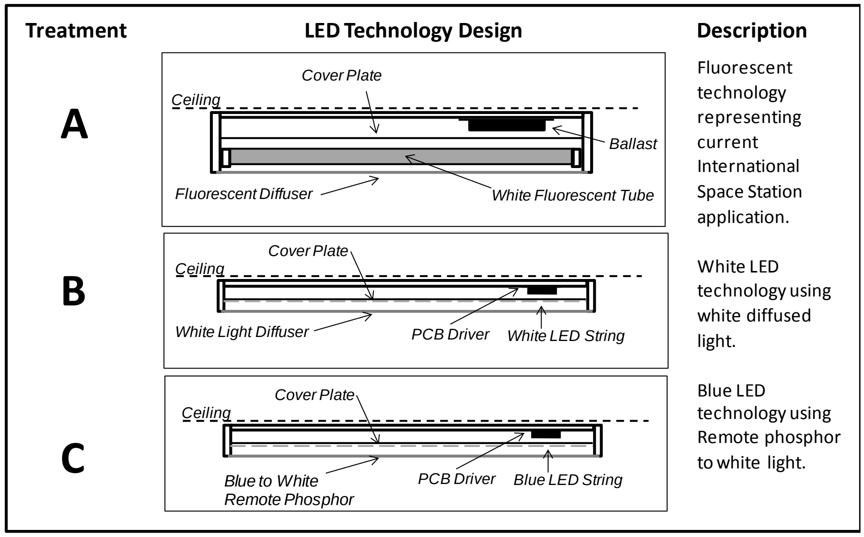

Figure 3. Schematic of light fixtures representing experimental factors.

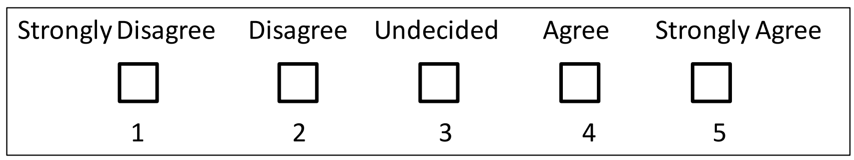

Figure 2. Likert scale for response to quality of light survey questions.

V. Research Assumptions, Limitations, and Delimitations

A. Assumptions

A statistical assumption was that proper DOE controls were incorporated into each experiment that provide random selection of samples, replicated enough times to provide a high degree of data accuracy, reliability and avoidance of bias. It was assumed that the human subject sample size and use of the Likert scale survey instrument provided independence among each non-astronaut participant for representing the U.S. astronaut population. It was also assumed that participants answered the lighting survey questions accurately and honestly.

B. Limitations

This research contained a number of limitations. The first limitation was that astronaut candidates in the United States are typically between the ages of 26 and 46 with the average age of the 46 person astronaut cadre being approximately 35 years (Johnson Space Center Houston). Volunteers selected from the American Institute of Aeronautics and Astronautics did not represent the average age of 35 where the perception of light quality could be influenced by younger aged participants under the age of 26. Mitigation for differences in user perception of light were compliance with visual requirements of the pseudolsochromatic plate Ishihara color blindness test as described by Khokhar et al. (2011). A second limitation was that the use of the Likert scale presented limitations in that wording of questions could have been interpreted differently by each participant introducing bias when recording a human experience into numerical form (Chowdhury et al., 2009). Additionally, each human subject was exposed to each factor and depending on order of light exposure, bias from potential fatigue, boredom, and other unintended influences could have been introduced into the Likert scale measurement of research data. Jackson (2012) warned of the subject effect where human participants threaten internal validity by consciously or unconsciously affecting results by introducing their own expectations. A third limitation was that human subjects, used to research effects of LED lights, involved convenience sampling. Jackson (2012) stated that convenience sampling is a technique that can be used where the researcher seeks volunteers from an identified group or location such as a professional, or student organization and draws conclusions about an entire population based on sampled results. Therefore, focusing the research on volunteers from the AIAA was a subset of the population expected to provide valuable data about an astronauts experience under selected lighting conditions.

C. Delimitations

Two delimitations were instituted for the study. The first delimitation was that convenience sampling was used to test LED effects on human subjects inside an isolation chamber providing participants with a quiet, climate controlled test environment free of distractions as an earth based representation of a spacecraft interior. The second delimitation was controlling the study using design of experiment techniques (randomization, replication, and assignment of factor settings) for reliability, validity, analysis and double checking of data.

VI. Evaluation of Results

The null hypothesis was tested according to the following hypothesis statements:

$\mathbf{H_o}$: $\mu_{1(\text{GLA fluorescent})} = \mu_{2\ (\text{White LED})} = \mu_{3\ (\text{Blue LED})}$, and
$\mathbf{H_1}$: $\mu_i \neq \mu_k$ for at least one pair of i, j, k.

Figure 4. Earth based capsule for human factors lighting experimentation.

Each participant was randomly exposed to three experimental lighting conditions inside an earth based mockup space capsule (see Figure 4). This human factor testing required a one-way evaluation of three means comparing the between-subjects effects on one independent variable, measured by participant Likert scores.

Light fixtures were verified immediately prior to each experimental trial to meet the NASA task lighting requirement of 538 Lux (+50 and –100), using a calibrated light meter (NASA Human Integration Design Handbook, 2010). Upon completion of the three factor randomized block design of experiment, Likert scale data were inputted into MINITAB 16 statistical software for the purpose of dividing the variation observed in experimental data and analyzing for statistical significance. The magnitude of difference from each data source was compared to the distribution to determine if a particular variable contained variation significant enough to conclude that there is a difference in the data (Aoki & Takemura, 2009). A quality of light questionnaire was administered at the conclusion of each two hour test period where ANOVA tables and *p*-values were calculated for each question on the questionnaire.

P-value calculations are summarized in Table 3 and when a $p < .05$ was observed, it revealed that a particular Likert question was statistically significant (Montgomery, 2013). Table 3 illustrates a summary of the analysis of the post-human factors 7-item survey, where analysis revealed items 2 and 7 were statistically significant yielding *p*-values of < .05.

Table 3
Analysis of Variance P-Value Value Summary of Survey Items

No.	Post Test 7-Item Scale	*P*-Value
1	I was able to see colors with this light.	0.53400
2	The color of the light was white.	0.0380*
3	The light quality was suitable for reading.	0.49200
4	The light fixture did not emit unpleasant noise.	0.43600
5	I did not experience eye strain as a result of the light.	0.34900
6	The light did not cause a headache and/or fatigue.	0.56600
7	I could use this light as my sole source of lighting.	0.000**

Note. * $p < .05$; ** $p < .001$.

A. Evaluation of Research Questions

The purpose of this research was to seek information about eye strain, fatigue, and headaches. Therefore, Table 4 illustrates the ANOVA results for survey items 5 on eye strain where all three experimental factors, light fixtures that emitted artificial white light (GLA fluorescent for baseline, and nuisance factors white LEDs, and blue LEDs), were found to contain a main effect that is not statistically significant as denoted by the *p*-value of 0.349. The degrees of freedom (DF), sum of squares (SS), and the mean square (MS) have been included in the ANOVA table illustrations as supplemental information where the main values of interest are *F* and *P*.

Table 4
Analysis of Variance for Research Questions 1-3 for Eye Strain

Dependent Variable: Item 5 Eye Strain					
Source	DF	SS	MS	F	P
Light Fixture	2	1.037	0.519	1.07	0.349
Error	51	24.611	0.483		
Total	53	25.648			

Note. p >.05.

The *F*-distribution at α = .05 was also used to verify that an *F*-ratio of 1.07 is not significant at 2 degrees of freedom, where F_{Calc} 1.07 < $F_{Crit\ (2,51)}$ 3.15 from the *F*-distribution table in Montgomery (2013) . Thus p 0.349 > .05 and a low value *F*-ratio of 1.07 revealed that there is not sufficient evidence to support a difference between the three independent variables for eyestrain and the null hypothesis cannot be rejected. There is no statistically significant reported fatigue, eye strain and/or headache in humans from the GLA fluorescent, when study participants perform detailed tasks of reading and assembling mechanical parts for an extended period of two uninterrupted hours.

Similarly, Table 5 illustrates the ANOVA results for survey item 6 about headache and fatigue were found to contain a main effect that is not statistically significant as denoted by the *p*-value of 0.566.

Table 5
Analysis of Variance for Research Question 1-3 Headache and or Fatigue

Dependent Variable: Item 7 Headache and or Fatigue					
Source	DF	SS	MS	F	P
Light Fixture	2	0.704	0.352	0.58	0.566
Error	51	31.167	0.611		
Total	53	31.870			

Note. p >.05.

The *F*-distribution at α = .05 was also used to verify that an *F*-ratio of 0.58 is not significant at 2 degrees of freedom, where F_{Calc} 0.58 < $F_{Crit\ (2,51)}$ 3.15 from the *F*-distribution table in Montgomery (2013) . Thus p 0.566 > .05 and a low value *F*-ratio of 0.58 revealed that there is not sufficient evidence to support a difference between the three independent variables (GLA fluorescent, blue LED, and white LED) for fatigue and/or headache and the null hypothesis cannot be rejected. There is no statistically significant reported fatigue, eye strain and/or headache in humans from the GLA fluorescent, when study participants perform detailed tasks of reading and assembling mechanical parts for an extended period of two uninterrupted hours.

B. Evaluation of Other Significant Findings

The previously illustrated Table 3 contains significant *p*-values for Likert survey items 2 and 7. While these two survey items fall outside of the research questions, they provide additional insight to future consideration of LED's in human spaceflight. The one-way ANOVA illustrated in Table 6 reveals a p 0.038 < .05 for item 2*: the artificial light emitted was perceived as white*. Additionally, the one-way ANOVA illustrated in Table 7 reveals a p

0.000 < .05 was found for item 7: *participant could use a particular light source as the sole source for his/her lighting needs.*

Table 6
Analysis of Variance for Survey Item Two

Source	DF	SS	MS	F	P
Light Fixture	2	3.197	1.598	3.48	0.038*
Error	51	23.423	0.459		
Total	53	26.620			

Note. * $p < .05$.

Table 7
Analysis of Variance for Survey Item Seven

Source	DF	SS	MS	F	P
Light Fixture	2	15.148	7.574	13.32	0.000**
Error	51	29.000	0.569		
Total	53	44.148			

Note. ** $p < .001$.

The results contained in the ANOVA tables above indicate that for each of the two statistically significant survey items (Table 6 and Table 7), at least one of the factor sample means is significantly different from the others. However, the ANOVA evaluation does not reveal where the statistical significance resides. A Tukey's post hoc test was administered to compare each data set for the studied factors to determine which light fixture settings differ significantly from the other (Jackson, 2012; Montgomery, 2013). Tukey's post hoc methodology for the two statistically significant questions (acceptance alpha or α of < .05) involved paired comparisons among the sample means for each experimental factor. Table 8 illustrates the post hoc grouping information for survey item 2, revealing that the LEDs were perceived significantly different by the participants than the fluorescent light currently used on the ISS.

Table 8
Tukey's Post Hoc for Survey Item Two

Factors-Light Fixture	N	Mean	Std. Deviation	Grouping	
Blue LED	18	4.6511	0.8704	A	
White LED	18	4.1811	0.6727	A	B
GLA fluorescent	18	4.0987	0.4095		B

Note: Means that do not share a letter are significantly different.

Additionally, Table 9 illustrates the post hoc grouping information for survey item seven, revealing that both the remote phosphor blue LED and the diffused white light LED are perceived significantly different by participants than the fluorescent light currently used on the ISS.

Table 9
Tukey's Post Hoc for Survey Item Seven

Factors-Light Fixture	N	Mean	Std. Deviation	Grouping
Blue LED	18	4.3889	0.8024	A
White LED	18	3.9444	0.9003	A
GLA fluorescent	18	3.1111	0.5016	B

Note: Means that do not share a letter are significantly different.

These two items of interest yielded statistically significant results from the randomized block design one-way ANOVA. Each human participant in this study was exposed to three different light fixture experimental factor settings (GLA fluorescent, white LED, blue LED) and was then asked which light fixture emitted artificial light perceived as white light, which resulted in a significant finding of p 0.038 < 0.05. A Tukey's post hoc analysis revealed that participants deemed the blue LEDs as providing the most white light (mean = 4.65), followed by the white LEDS (mean = 4.18) , with the GLA fluorescent light perceived as providing the least white light (mean = 4.099). Likewise, analysis of Likert responses to the question about whether a participant could use a particular light source as their sole source of artificial habitat lighting was also significant at p 0.000 < 0.05. Further analysis using a Tukey's post hoc method revealed that the blue LEDs using remote phosphor (mean = 4.389) were preferred over white LEDS (mean = 3.944), with the least deemed useable as a sole source of artificial light being the GLA fluorescent (mean = 3.111).

VII. Summary

Research question one involved studying the quality of light from a GLA fluorescent light fixture to learn if it causes fatigue, eye strain and/or headache in humans, when study participants performed detailed tasks of reading and assembling mechanical parts for an extended period of two uninterrupted hours. Using a randomized block experimental design, an insignificant effect was revealed resulting in failure to reject the null hypothesis. There was no statistical evidence within the human sample indicating that the GLA fluorescent light caused fatigue, eye strain and/or headache, when study participants perform detailed tasks of reading and assembling mechanical parts for an extended period of two uninterrupted hours. Cohen et al. (2011) discussed humans as perceiving fluorescent and incandescent artificial lighting sources as more pleasant than LEDs. These results support claims by Cohen et al. (2011) and agree with my assumption that the GLA fluorescent currently being used on the ISS was a suitable baseline variable for the randomized block design.

Research question two involved studying the quality of light from white LEDs. There was insufficient evidence to support a claim that the study's white LEDs caused fatigue, eye strain and/or headaches in humans, when study participants performed detailed tasks that involved reading and assembling for an extended period of two uninterrupted hours. Failure to reject the null hypothesis was supported by the theory advanced by Chen and Kwok (2011) that LED wavelengths could be stabilized using a top-emitting cover diffusing light beams to reduce glare and retinal stress on humans.

Research question three evaluated the third and final variable evaluating artificial white light created from blue LEDs passing through a remote-phosphor plate. An insignificant effect failed to reject the null hypothesis. There was no statistical evidence within the human sample that this particular LED light design caused fatigue, eye strain and/or headaches in humans performing detailed tasks of reading and assembling mechanical parts for an extended period of two uninterrupted hours. This result support claims made by Dal Lago et al. (2012) and Meneghini et al. (2009) that phosphor materials deposited onto LED substrates, once tested, can mitigate against the warnings published by Cohen et al. (2011) about LEDs emitting improper light waveforms causing glare or dangerously strong beams of light causing negative human factor effects. Dal Lago et al. (2012) published literature concluding that the use of remote phosphor in LEDs improved extraction of light efficiency, a reduction in phosphor operating temperature when compared to the LED encapsulated method, and that diffusion of blue light (to white light) from the remote phosphor is an improvement to the human user. Statistical evidence examined in this study supports the view that blue LEDs, using remote phosphor, does not produce adverse effects and were perceived by the human participants as the most desirable for selection as a sole lighting source of artificial habitat lighting.

VIII. Future Research

This study revealed that there were no significant findings for eyestrain, headache, and/or fatigue in humans when human subjects were exposed to GLA fluorescents, and white and blue LEDs (see Figure 5). However, this analysis may provide considerations for future human spacecraft with the intent of strengthening the body of knowledge on lighting applications for space travel and contribute to systems theory as it supports spacecraft design and flight operations.

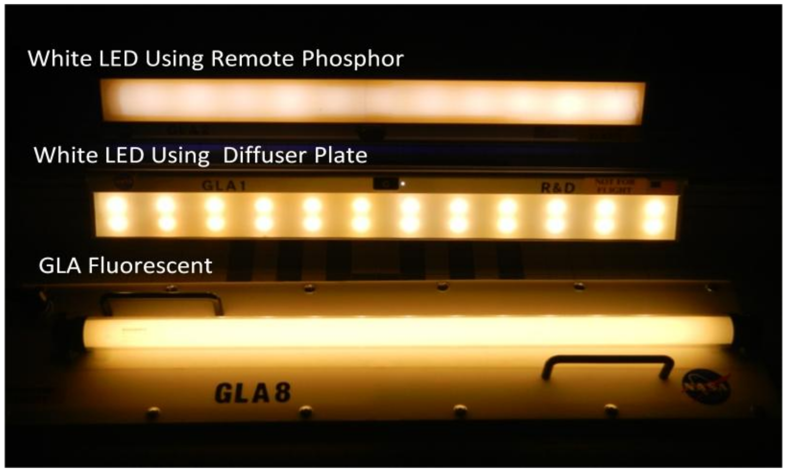

Figure 5. Lighting Fixtures Representing Experimental Factors.

Blue LEDs were selected as most desired technology that could be used as a sole source of habitat lighting. The findings from this study revealed that LED technology is a viable choice, when considering high reliability and human factors, however more research is warranted. Future research should include further testing of blue LEDs. Recommendations include using the basis of this study for replication, but attempt to reduce the research limitations discussed herein. Future research should include further testing of blue LEDs. Recommendations include using the basis of this study for replication, but reduce study limitations by: 1) testing human subject's exposure to LEDs in a simulated space habitat environment for several days, and 2) installing and testing LEDs in space modules being built for human spaceflight. Literature published by Tavana and Marbini (2011) should be considered, who emphasized that quality of light is critical to astronaut health in that light levels and sleep cycles and that artificial lighting systems should be used to maintain a circadian rhythm cycle. Additionally, Litaker et al. (2013) stressed that measuring design effects for human factors requires personal interaction between the test environment and human subjects and when earth-based human factors are evaluated multiple-day missions need to be simulated inside an earth-based crew cabin representing the habitable environment of spacecraft life. Future research examining effects of LED light on humans may want to examine how the factors discussed in this study impact humans over an extended period of time representing on-orbit space life that goes beyond the two hour periods used in this study.

IX. Conclusion

This study utilized a randomized block experimental design followed by ANOVA techniques to evaluate experimental factors: (a) GLA fluorescent, (b) LED diffused white light, and (c) LED blue light using remote phosphor. Research questions 1-3 were established to evaluate whether LED light is capable of providing comfortable ambient light free of fatigue, eye strain and/or headache in astronauts (Meras et al., 2011). Human factor effects were tested using 18 human participants to test human factor effects from two types of LED lighting technology against the existing NASA approved fluorescent used on the ISS. Experimental evidence revealed no statistically significant effects for eye strain and/or headache or fatigue where the null hypothesis was not rejected across the three research questions. This technical document has been written in support of advancing TRL and as evidence that LED fixtures used in this study successfully met requirements for astronaut spacecraft lighting needs, per *NASA Human Integration Design Handbook (2010)* where the requirement for task lighting is 538 Lux (+50 and –100).

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