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Empirical Evaluation of Optimal User-Centered LED Lighting Environments in Residential Bathrooms

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Abstract

This user-centered research aims to empirically evaluate color temperature (K) and illuminance (lx) of residential bathroom lightings to determine the most optimal lighting conditions for productive task performance as well as for satisfying users' emotional needs. Using 3 LED lighting fixtures, 4 types of lighting contexts were investigated; main lighting, task lighting, shower lighting, and bath lighting. Two lightings were installed parallel to the vertical edges of the main bathroom mirror to be used as main and task lighting, while another fixture was installed above the bathtub to be used for shower and bathing. For each lighting context, subjects (N = 54) were instructed to perform a few tasks during which time the users were exposed to different lighting conditions with color temperature ranging from 2700 K ~ 6500 K and illuminance ranging from 100 lx ~ 700 lx. Upon completing the given tasks, subjects were asked to evaluate the lighting conditions and their applicability for performing the given tasks. Based on the user evaluations, the most optimal lighting conditions for the different lighting scenarios are as follow: 1) 3500 K ~ 4300 K and 150 lx for main lighting, 2) 3500 K ~ 4300 K and 500 lx ~ 700 lx for task lighting, and 3) 2700 K ~ 3500 K and 100 lx ~ 150 lx for shower/bath lighting. These results can be used to adjust the lighting standards suggested by KS, as well as be utilized by both engineers and designers in designing new types of user-centered bathroom lightings.

Key words: Emotional Design, Lighting Design, User-Centered Lighting, LED

1. Introduction

As society experiences economic and social development, living standards improve and people demand a higher quality of life. With this progression, the concept of bathrooms is also gradually transforming into a space full of vitality. In this regard, many researches have been conducted to explore and fulfill the new consumer needs with emphasis on bathroom architecture and interior design. In one study, the Korean people's bathroom activities as well as thoughts and emotional responses to current bathroom situations were surveyed (Lee and Kim, 2010). Based on the findings, a basic design guideline for creating a healthy bathroom

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space that incorporates modern lifestyles was proposed. Another study investigates the importance and benefits of color in bathrooms, particularly for the elderly (Kang and Lee, 2009). The use of different colors can stimulate different feelings of temperature, and therefore produce various physiological and psychological reactions.

Together with social development, there have also been tremendous scientific advancements in LED lighting technology. A popular trend observed today is the replacement of traditional fluorescent with LEDs. The easy controllability to alter color temperature and illuminance of LEDs gives users the creative freedom to illuminate a room to best suit their needs. Hence, lighting design can be used as one of the main elements that contribute to inaugurating a user-centered bathroom environment for high quality living.

For the concern of safety, the lighting association of Korea (KS) offers standards for illuminance (lx) in bathrooms. However, actual bathroom lighting measurements in Korean homes indicated that illuminance levels are typically below their suggested values (Lee and Choi, 2005). Moreover, the KS does not provide any color temperature suggestions for bathroom lighting, nor has there been any empirical research regarding LEDs in relation to user-centered bathroom environments. Hence, this study aims to conduct a user-centered evaluation on color temperature and illuminance of residential bathroom lightings using LEDs to derive best lighting conditions for different bathroom scenarios.

2. Purpose of Study

The purpose of this study is to empirically evaluate bathroom lightings and find the most optimal lighting conditions in terms of color temperature (K) and illuminance (lx). The selected lighting conditions should not only improve user task performance but also satisfy users' emotional needs by providing a sense of comfort under different user context and activities. The results of this research can be used by both engineers and designers in developing smart lighting systems for bathrooms as well as for other environments that share similar user behaviors and activities.

3. Experiment 1: Psychological Evaluation of Bathroom Tasks

3.1. Objective of Experiment

Prior to conducting the main experiment on determining the most optimal lightings for different bathroom activities, it was first necessary to conduct a preliminary study to derive various bathroom scenarios in which the different lighting conditions could be evaluated. The purpose of Experiment 1 was to group bathroom activities based on their arousal level and to derive specific bathroom scenarios that need different lighting conditions from those groupings.

3.2. Participants

24 subjects (12 males and 12 females) were recruited to participate in Experiment I. The average age of subjects was 22.8 with a standard deviation of ±3.05. To concentration on activities and user behaviors of conventional Korean residential (apartment) bathrooms, all the subjects were Korean.

3.3. Method

In order to achieve the two objectives, Experiment I investigated the arousal levels of different activities in a bathroom. During the experiment, users were given a list of 12 common bathroom activities, which were carefully selected from previous research that examines daily actions in residential spaces (Lee and Hong, 2010). The list of the activities is provided in Table 1.

Table 1. 12 bathroom activities selected for arousal level evaluation.

Urination	Bowel movement	Bathing
Message	Reading	Hand washing Laundry
Shower	Use of Bidet	Sauna
Sink Activities (washing face, hands, brushing teeth, etc.)	Styling hair	Applying makeup and/or shaving

The subjects were instructed to position the activities across an arousal scale based on a 7 point Likert system by recollecting the levels of alertness and focus that they experienced while performing the given activities in their bathrooms. For example, if a high level of focus was required in styling hair, then this activity would be positioned at the right end of the arousal scale, with a score of 7 or 6.

3.4. Bathroom Task Results

The positioning of activities on the arousal scale indicated that the bathroom activities could be clustered into 3 main groups; general activities, task activities, and bathing. These activities can be distributed in three different bathroom areas; main area, sink area, and tub area, respectively. Shower was initially included in the general activities category. However, because of the difference in bathroom area (shower occupies the tub area, whereas general activities typically occupy the main area), shower was removed to stand as its own activity group. Moreover, shower was not combined with bathing, despite both activities occupying the tub area for the reason that showering is a daily task, whereas bathing is generally considered an occasional leisure activity. Hence, a total of 4 main bathroom lighting scenarios − main lighting, task lighting, shower lighting and bath lighting − were extracted for evaluation in Experiment 2.

4. Experiment 2: Empirical Evaluation of Bathroom Lightings

4.1. Objective of Experiment

The objective of Experiment 2 is to derive the most optimal lighting condition for each of the 4 bathroom lighting scenarios (main lighting, task lighting, shower lighting, and bath lighting) derived from Experiment 1.

4.2. Participants

A total of 54 subjects (26 males and 28 females) were recruited for Experiment 2. The average age of the subjects was 21.98 and a standard deviation of ±3.17. All subjects had no vision deficiencies.

4.3. Method

4.3.1. Experimental Setup

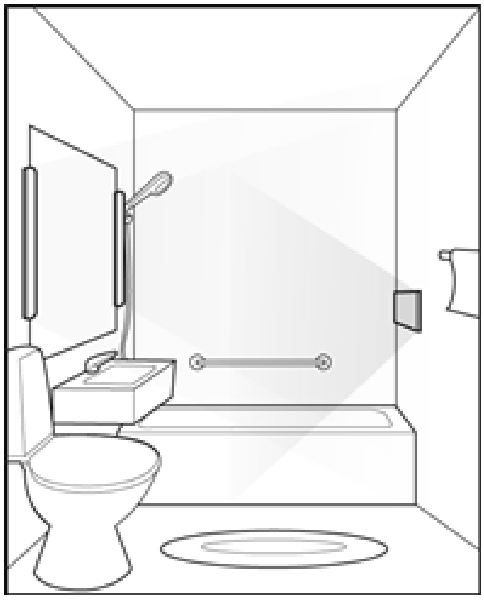

Figure 1. Experimental setup of bathroom: Two lighting fixtures by the bathroom mirror for main and task lighting, and one fixture above the bathtub for shower and bath lighting.

The experiment was conducted in a residence hotel bathroom (240cm x 124cm x 212cm) that resembles a conventional Korean apartment bathroom. A total of three lighting fixtures were installed; two lighting fixtures mounted parallel to the vertical edges of the main bathroom mirror to be used as main and task lighting, and one lighting fixture mounted above the bathtub to be used as shower and bath lighting (Figure 1). There were no windows in the bathroom, and the original lighting mounted on the center of the ceiling was turned off during all periods of experimentation.

4.3.2. Lighting Variables

Each lighting fixture was programmed to illuminate variations of color temperature and illuminace based on the KS standards and lighting recommendations from user-centering lighting research (Fernandez, 2012). Table 2 shows the range of lighting variables used for each bathroom scenario.

Table 2. Color temperature (K) and illuminance (lx) range for the 4 types of bathroom lightings.

Main Lighting		Task Lighting	
CT (K)	Illuminance (lx)	CT (K)	Illuminance (lx)
2700 3500 4300 5200	50 100 150	2700 3500 4300 5200	300 500 700
Shower Lighting		**Bath Lighting**	
CT (K)	Illuminance (lx)	CT (K)	Illuminance (lx)
2700 3500 4300 5200	100 150 200	2700 3500 4300 5200	50 100 150

4.3.3 Experimental Task

To assess the most optimal main bathroom lighting, subjects were first required to evaluate 4 color temperature options (2700 K, 3500 K, 4300 K, and 5200 K) prior to entering the bathroom. The evaluation was done while subjects stood in front of the bathroom door with all other lightings turned off. However, to maintain a certain level of natural lighting, the curtains of the room were left opened. The approximate color temperature and illuminance just outside the bathroom door in ranged from 3343 K to 5543 K and 1.11 lx to 9.50 lx depending on the time of day.

After seeing all the options, subjects were asked to select the most optimal color temperature for main lighting. After having selected a color temperature, the subjects entered the bathroom with the door closed. The experiment communicated with the subject and controlled the lighting settings using a wireless controller outside the bathroom. Next, subjects were asked to perform and act out a series of tasks. Under the main lighting scenario, subjects were instructed to perform general bathroom activities such as washing hands and sitting on the toilet seat. The subjects were exposed to three levels of illuminance for the color temperature they selected prior to entering the bathroom and were asked to select the most optimal illuminance level for completing those tasks. Similar, processes were executed for the other three scenarios. Subjects first selected the most optimal color temperature, then the most optimal illuminance while acting out the given tasks for each scenario to determine the best combination of the two lighting parameters. For shower and bath lighting, subjects imagined themselves taking a shower and bath. The main lighting which the subjects selected earlier was turned on during the evaluation of shower and bath lightings. This was because the function of the tub luminaire was focused more towards mood and/or task lighting, rather than ambient lighting. For task lighting, tedious activities that require lots of concentration such as applying makeup, styling one's hair, shaving (for men) were asked to be imitated by the subjects. The order in which the bathroom lighting scenarios were evaluated was as follows; main lighting, shower lighting, bath lighting, and task lighting, respectively. The flow of the

Figure 2. Experimental flow: 1) main lighting, 2) shower lighting, 3) bath lighting, 4) task lighting.

experimental process is illustrated in Figure 2.

4.4. Experimental Results

The results of a One-way Anova test indicated that there was a significant difference between the average preferred levels of color temperature among the four bathroom lighting scenarios ($F(3, 212) = 15.98$, $p<0.05$). A significant difference was also found between preferred illuminance levels among the four scenarios.

However, because color temperature and illuminance were set as nominal dependent variables in the user evaluation, the mean value of color temperature and illuminance is not an accurate representation of the most optimal lighting conditions in the different bathroom lighting scenarios. Hence, further statistically analysis using the Chi-Square Test was conducted.

Table 3. Frequency count for most preferred (optimal) color temperature and illuminance.

Lighting	CCT Count	Illuminance Count
Main	2700 K = 8 **3500 K = 22** **4300 K = 16** 5200 K = 8	50 lx = 0 100 lx = 8 **150 lx = 46**
Shower	**2700 K = 21** **3500 K = 16** 4300 K = 12 5200 K = 5	**100 lx = 16** **150 lx = 22** **200 lx = 16**
Bath	**2700 K = 32** **3500 K = 16** 4300 K = 5 5200 K = 1	**50 lx = 16** **100 lx = 27** 150 lx = 11
Task	2700 K = 6 **3500 K = 16** **4300 K = 23** 5200 K = 9	300 lx = 7 **500 lx = 22** **700 lx = 25**

With the exception of shower lighting illuminance, there were significant differences between frequency count of most preferred color temperature and illuminance levels for all four bathroom lighting scenarios. The most optimal ranges for color temperature and illuminance based on the statistically analysis for the user-centered evaluation are shown in Table 4.

Many of the reasons for which subjects chose 3500K or 4300K for the color temperature of main lighting were related to emotional factors, such as appearing “warm”, “clean”, “fresh” and “comfortable”. Moreover, for the bathing scenario, 68.52% of the subjects preferred the main lighting to be turned on with the tub lighting. Subjects claimed that without the main lighting, the atmosphere was too dark with a sense of “depression” and “tension” rather than generating an enjoyable and relaxing atmosphere.

Table 4. Most optimal color temperature (K) and illuminance(lx) ranges for the 4 bathroom lighting scenarios.

Lighting Type	Color Temperature	Illuminance
Main	**3500 K (< 4300 K)** **(χ^2 = 10.30, df = 3, p<0.05)**	**150 lx** (χ^2 = 26.74, df = 1, p<0.05)
Shower	**2700 K (<3500 K)** (χ^2 = 10.15, df = 3, p<0.05)	**150 lx (>100 lx, <200 lx)** (χ^2 = 1.33, df = 2, p = 0. 51)
Bath	**2700 K (<3500 K)** (χ^2 = 42.74, df = 3, p<0.05)	**100 lx (> 50 lx)** (χ^2 = 7.44, df = 2, p<0. 05)
Task	**4300 K (>3500 K)** (χ^2 = 12.82, df = 3, p<0.05)	**700 lx (> 500 lx)** (χ^2 = 10.33, df = 2, p<0. 05)

5. General Discussion

Based on the results of the study, significant lighting conditions for traditional Korean apartment bathrooms were extracted. It was interesting to note, however, that shower lighting and bath lighting, despite their differences in arousal lighting from Experiment 1, showed similar tendencies in color temperature and illuminance preference. Therefore, for the actual implementation of the suggested lighting environment, it would be appropriate to use fixed tub lighting to 3500 K ~ 4300 K and 100 lx ~ 150 lx. However, instead of placing the tub lighting where it was positioned in this experiment, it would be more appropriate to install it near the ceiling. This type of positioning can help satisfy the conditions for shower lighting as well as provide the lower illuminance that users favor while bathing, during which a sense of coziness is often a primary concern.

This experiment focused on lighting for residential type bathrooms. However, the improvements in qualities of living not only affect private lives, but people's expectations of the general public as well. The bathroom structures are not only changing in private areas, but in public areas simultaneously. Hence, further research can be conducted on a larger scale, by investigating most optimal user-centered lightings in public bathrooms.

Moreover, bathrooms are not the only residential space where the users experience a wide range of arousal levels. Using similar methods to this study, further investigations can be carried out to evaluate user-centered lightings in other residential spaces. The collection of such results can help compose a complete user-centered lighting guideline for homes.

Lastly, these results can be compared to the current KS bathroom lighting standards (Table 5). For main lighting, the illuminance values are consistent at 150 lx. However, for task lighting, the difference was considerably large. KS suggests an illuminance level ranging in between 150 lx to 300 lx. The result from this experiment, on the other hand, suggests that the optimal illuminance for task lighting should be much higher at 700 lx. Moreover, the KS system does not provide any guidelines regarding bath and shower lighting. Hence, it is recommended that these results be used for the revision of the KS lighting standards to better suit new user needs, both functional and emotional.

Table 5. Comparison of optimal illuminance levels between KS lighting standards and results of current experiment.

Lighting Type	KS Illuminance (lx)	Illuminance from Experiment (lx)
Main	60-100-150	150
Shower	---	150 (> 100, < 200)
Bath	---	100 (> 50)
Task	150-200-300	700 (> 500)

6. Conclusion

Bathrooms are no just a place for nature's calling, but a living space where people perform varies daily activities that range greatly in arousal levels and requires various conditional needs. Lighting design can be an effective way to improve qualities of living in such spaces bathrooms, by providing users with productive environments in performing those various tasks and fulfilling users' psychological and emotional needs. This study conducted a user-centered evaluation of different bathroom lighting conditions to determine the most optimal luminaire settings for 4 types of bathroom lighting scenarios. The most optimal color temperature and illuminance are: 3500 K ~ 4300 K and 150 lx for main lighting, 2700 K ~ 3500 K and 100 lx ~ 150 lx for shower and bath lighting, and 3500 K ~ 4300 K and 500 lx ~ 700 lx for task lighting. The results of these studies can be used as guidelines for both designers and architectures in designing future bathrooms that satisfy both physiological and psychological user needs.

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