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The Effect of Daylight Illumination in Nursing Buildings on Reading Comfort of Elderly Persons

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Abstract: Reading is one of the popular activities among elderly persons. A reasonable level of daylight illumination can ensure the visual comfort of reading for elderly persons. State arousal level and subjective comfort report are important parameters reflecting the effect of daylight illumination on visual comfort of reading in elderly persons. In this study, daylight illumination measurements were conducted in a nursing institution of Shenyang, China. Moreover, the methods of electrodermal activity (EDA) physiological index measurement and questionnaire scoring were used to compare and analyze the state arousal level and visual comfort of elderly persons under different illumination conditions. The results show that when elderly persons were involved in their daily reading activity, the acceptable daylight illumination range was between 300 and 1000 lx. When the daylight illumination was between 600 and 800 lx, the state arousal level and visual comfort was high; when it was 700 lx, the state arousal level and visual comfort was the highest. Although 500 and 900 lx both indicated neutral illumination, the evaluations were more consistent at 500 lx than at 900 lx. At 300, 400, and 1000 lx, visual comfort was poor and the state arousal level was low. At 300 lx, visual comfort was the worst and the state arousal level was the lowest. This study provides a reliable reference for architects to design the daylight conditions of the living spaces of the elderly.

Keywords: state arousal level; visual comfort; daylight illumination; elderly persons; reading behavior

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1. Introduction

Globally, an increasing number of people are aging; consequently, the quality of life of elderly persons has become the focus of the international community. It is crucial to provide a comfortable lighting environment for elderly persons. Due to visual decline [1], special consideration should be given to the lighting design of their living spaces. Reading is among the most popular leisure activities among elderly persons [2–5]. However, with age, the ciliary muscle loses its ability to contract and the pupil size decreases, resulting in presbyopia [6]. There is insufficient light intake for narrow pupils. Hence, elderly persons often need higher illumination to make up for the decline in visual ability. Studies have shown that illumination considerably influences the reading ability of elderly persons with low vision [7]. As the world's population ages, many countries and institutions have studied the illumination standard of reading for elderly persons and recommended specific values and ranges. However, lighting design standards in different countries do not have an agreed illumination value required for reading. The Architectural Lighting Design Standard of China [8] stipulates that, typically, reading lighting in the bedroom should be 300 lx. American National Standards Institute (ANSI) lighting standards [9] stipulate that reading lighting in the bedroom is 750 lx. The Lighting Handbook of Japan [10] stipulates

that reading lighting in the bedroom is 600–1500 lx. Some scholars have conducted studies on the illumination preferred by seniors in terms of reading. Robert G. Davis conducted an experiment on the visual preference of elderly persons when reading under 1076, 107.6, and 10.76 illuminations. Results indicate that the favored illumination of elders was 1076 lx [11]. Zhang and Ma investigated the visual executive power and subjective comfort of elderly persons when reading under 50, 300, and 1000 lx. The results showed that elderly persons had the best visual executive power and relatively good subjective comfort when reading under 1000 lx [12]. The standards and research listed above were set or carried out under the assumption of artificial lighting. According to the living habits of the elderly persons, it is normal for them to read in daylight in front of windows. In the context of carbon peaking and carbon neutrality, it is also encouraged to make full use of daylight in daily activities. However, no detailed regulations apply to daylight illumination in the lighting design standards according to indoor activities of elderly persons in China, Japan, or the United States.

Illumination is a common parameter for evaluating the quality of daylight environment, and lighting evaluation methods such as DF, DA, and UDI all use illumination as the basic parameter. Illumination has an important supporting role for human visual function, and is not only the most important photometric indicator for elderly persons to complete reading tasks, but also one of the important indicators for evaluating the comfort and health associated with the lighting environment. Furthermore, elderly persons, as a special social group, have a certain dependence on daylight [13]. Physiologically, daylight can regulate the secretion of melatonin in their bodies and promote the absorption of calcium ions. Psychologically, daylight can reduce the risk of depression in elderly persons. Although they have different needs for daylight, they are highly satisfied with activities performed in a daylight environment [14]. As such, it is of great significance to focus on the impact of daylight illumination on the reading behavior of elderly persons in nursing buildings.

The main purpose of this study was to investigate daylight illumination of comfortable reading for elderly persons. "Comfort" is a state of relaxation and peace without physiological pressure, which is related to the overall state of a person. The full range of factors, both mental and physical, can be described as being involved in the state. Traditionally, subjective questionnaire surveys are commonly used in comfort-related research, such as human perceived comfort experience and comfort evaluation. This paper refers to the methods used in international research on emotions. Based on the view that "comfort" includes not only physical sensations, but also psychological factors [15], the combination of a physiological index measurement and a subjective questionnaire survey was used to analyze state arousal level and visual comfort in the reading of elderly persons. The effect of different levels of daylight illumination on reading by elderly persons was then explored.

2. Materials and Methods

2.1. Research Subjects

Elderly persons living in senior care institutions were the research subjects of this study. The enrolled subjects met the following requirements: self-care elderly people aged 60–89, graduated from primary school or above, with normal naked or corrected vision, no color blindness, cognitive impairment, or Alzheimer's disease, and reading behavior at least twice a week. A total of 30 seniors were enrolled, 15 men and 15 women.

2.2. Reading Materials

To reduce the impact of different reading materials, fonts, and other factors on the physiology and psychology of elderly persons, the length of each reading activity was controlled; also, the reading material was provided by our research group. The newspaper was selected as the experimental reading material (Figure 1). The background color of the newspaper was light gray and white. The font color was black, and font size was the 12 pt. for Han Chinese characters. Eight paragraphs from eight issues of the newspaper were randomly selected. The layout of each paragraph was the same with 100 words each.

The reading time of each paragraph was controlled at approximately 5 min, and each paragraph was in the same position of the newspaper. The content of the material was serial articles. Simple and understandable emotional stories were selected to eliminate personal preferences of elderly persons and reduce the impact of article content on their cognitive and emotional states.

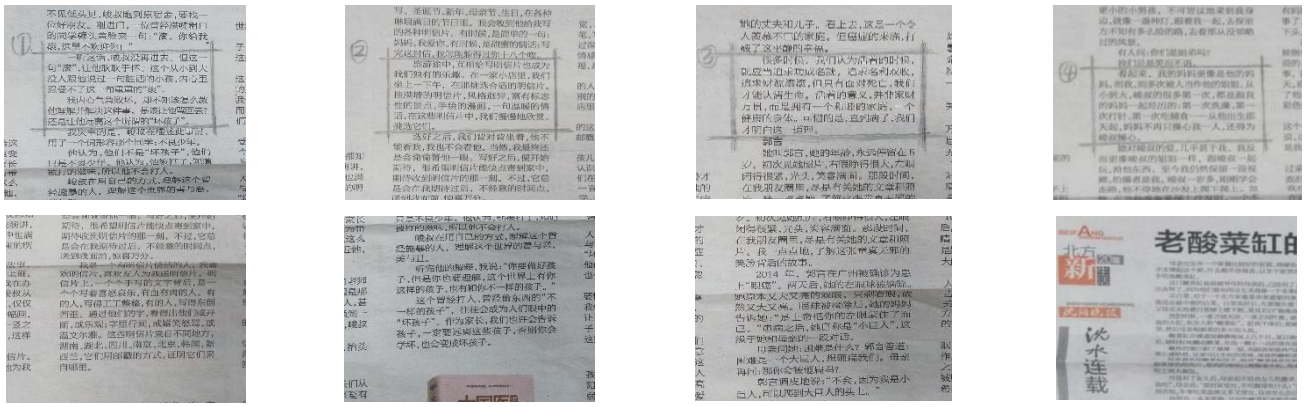

Figure 1. Reading materials.

2.3. Daylight Illumination Measurement

This study was based on the residential building of an elderly care institution in Dongling District, Shenyang, China. The building was established in 2014, with four floors and 12 households on each floor (Figure 2). All dormitories are single rooms, with a size of 3.6 × 6 m. These dorms include bedrooms, a leisure area, and independent bathrooms. The walls and ceilings in the room are painted white, and the floor is made of brown wood. The window in the room has a size of 2 × 1.8 m and is a height of 1 m from the ground, and faces south.

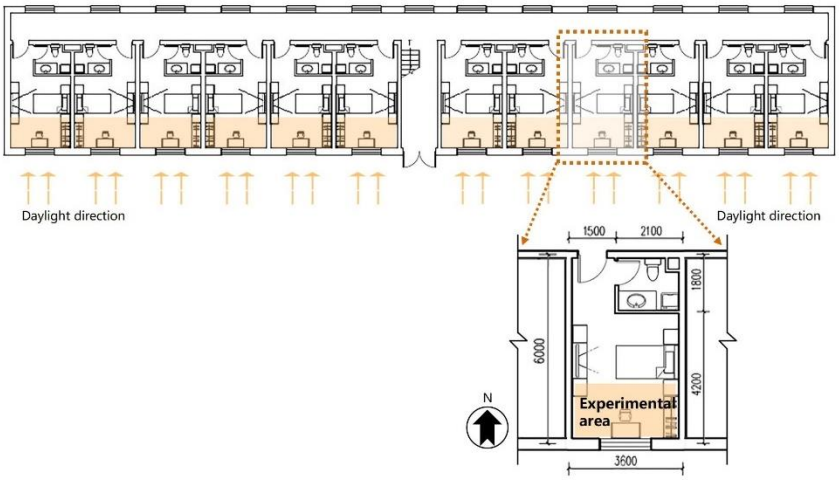

Figure 2. Floor orientation and room layout.

The elderly persons read experimental materials on the desk under the window. The desk is 0.75 m high, and the chair is 0.42 m high. After a survey of 30 elderly persons, their one-day activities were summarized in Table 1, and experimental time was finally determined. The illumination was measured between 8:00 and 10:00 every morning. Combined with the Architectural Lighting Design Standard of China, the illumination range of the experiment was set as 300–1000 lx. Prior to the start of the experiment, the elderly persons were free to change the illumination using the curtains. A TES-1330A illumination meter (TES Electrical Electronic Corp.) was used to measure the illumination before the elderly persons started reading. Electrodermal activity (EDA) data were received in real time using a laptop placed on the table at the rear left of the subject (Figure 3).

Table 1. The general situation of nursing homes.

Timetable	5:00–6:00	6:00–8:00	8:00–10:00	10:00–12:00	12:00–14:00	14:00–16:00	16:00–18:00	18:00–21:00	21:00–05:00
Bed room	B	I	A		K		L, E	D	K
Dining room		L		L					
Chess room			J			H			
Reading room									
Outdoor	F					G		N	
Foyer				M					

Types of activity: A. Reading books and newspapers; B. Getting up; C. Using computer; D. Watching TV; E. Doing housework; F. Fitness; G. Walking; H. Playing mahjong; I. Raising flowers; J. Play chess; K. Sleeping; L. Eating; M. Chatting; N. Dancing P. Others.

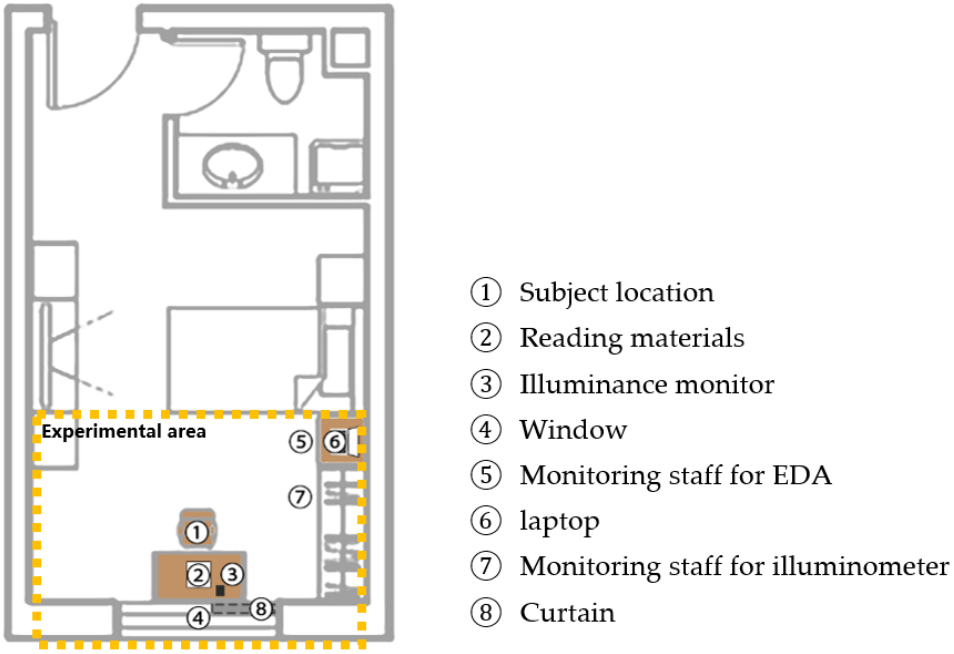

Figure 3. Experimental area plan.

The final illumination value was determined using the mean value of the illumination at the midpoint of each side of the reading material and the intersection of the diagonal (Figure 4). To reduce the fluctuation in daylight illumination, reading material with fewer words was first chosen in order to minimize the reading duration. Based on the experience during the pre-experiment, the elderly persons are not sensitive to changes in illumination within 50 lx. Thus, when the experiment was carried out, the illumination meter was placed close to the top of the reading material, and data that did not change beyond 50 lx throughout were adopted. A staff member stood at the left rear of the elderly persons and observed the illuminance meter's value on the table throughout the process to control the illumination change during the experiment (Figure 3) in order to avoid the problem of glare or uneven illumination during the experiment, which may have caused discomfort to the elderly persons. Before the experiment, the elderly persons could slightly adjust the position of the curtain, chair, and reading materials according to the actual situation (Figure 5). At the end of the experiment, elderly persons were asked if they encountered glare or excessive fluctuations in their visual field brightness. Data collected when this occurred were eliminated. The measurements were performed over 20 weeks from September 2017 to March 2018, and 217 valid data points were obtained.

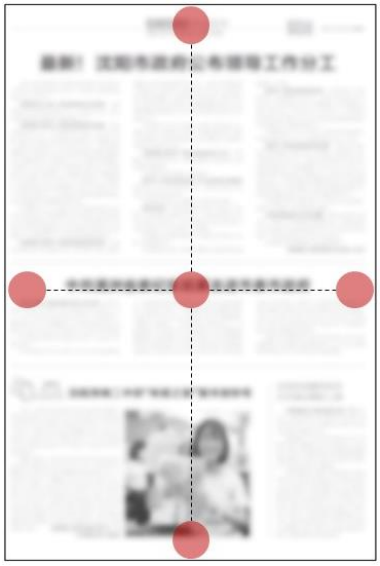

Figure 4. The selected points of the illumination value.

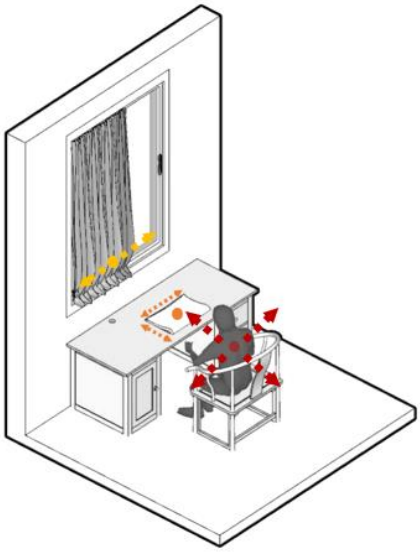

Figure 5. Adjustable position.

2.4. Visual Comfort Level Measurement

2.4.1. Measurement of Skin Conductance

When an individual engages in cognitive activities or is exposed to particular emotional stimuli, areas of the brain such as the anterior cingulate gyrus and the amygdala act, resulting in a sympathetic nervous system reaction [16]. The more excited the sympathetic nervous system becomes, the more stimulated the sweat glands become. In addition, the sweat glands secrete sweat to the skin surface through pores in the skin. When a balance between positive and negative ions in the secretion occurs, the skin conductance (SC) changes. Changes in SC thus indicate the activity level of specific areas of the brain during reading tasks, notably crucial cognitive and emotional activities. According to research, the neural systems of emotion and cognition are closely interwoven, and both positive and negative emotions play a role in learning and remembering [17]. Thus, it can be seen that the shift in SC indicates the state arousal level of the elderly persons during reading. However, it is possible that a well-lit environment facilitates the arousal or that the arousal compensates for the annoyance produced by a poor light environment. This was investigated further with the subjective questionnaire. The mean of the time-domain characteristics of the SC can reflect the average level of electrodermal activity in the statistical period [18]. The

greater the absolute value of the mean change rate in different periods, the higher the state arousal degree.

An electrodermal activity (EDA) wireless physiological sensor (KingFar International Inc. Beijing, China) was used to collect and monitor the data of the SC indicators. Data storage and analysis were performed with a human–machine environment synchronization experimental platform (Ergo LAB). During reading, the elderly persons needed to wear the EDA wireless physiological sensor on the palm via an electrode so that the original physiological signal could be collected and transmitted to the Ergo LAB experimental platform in real time (Figure 6). The experimental platform has built-in filtering methods such as Smooth, Guass, and Hann, which can extract SC index data from the collected original signal and analyze the mean of SC time-domain characteristics in the corresponding time window.



(**a**) (**b**) (**c**) (**d**)

Figure 6. Instruments. (**a**) Human–machine environment synchronization experiment platform. (**b**) EDA modules. (**c**) Physiological sensing kit. (**d**) Wearing instruments.

2.4.2. Subjective Questionnaire

This research established two evaluation methods: a subjective comfort questionnaire and electrodermal activity measurement. The questionnaire was designed for the subjective visual comfort of elderly persons when reading at different illumination levels. The question was "What is your visual comfort level when reading at this illumination level?". The 5-point Likert scale method was adopted, in which five evaluation scales, from very uncomfortable to very comfortable, were used (Figure 7). There is no academic consensus on the concept of "visual comfort", and there are two widely used methods of evaluating visual comfort: One of them is the "no annoyance method", which states that no discomfort is considered comfortable. In other words, no physiological pain or irritation is considered to be visual comfort. Another is the "well-being method", which is based on subjective happiness and satisfaction [19]. In this study, "visual comfort" was defined as a state in which the reading task could be accomplished without physical or psychological stress by combining these two ways.

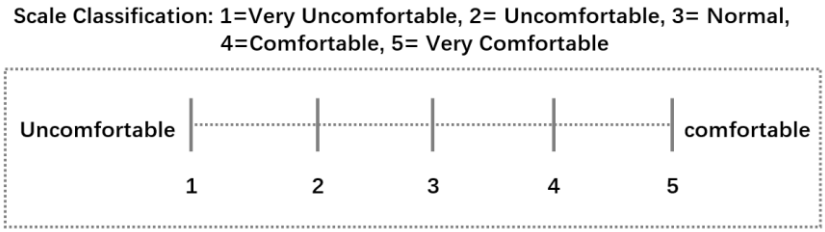

Figure 7. Subjective psychological evaluation scale.

At the end of reading, the persons enrolled in this study were asked whether they had fully seen and understood the reading materials. The data from the cases when they could not fully see and understand the reading materials were excluded. All respondents were informed of the purpose of the study and how the data would be used before filling out the questionnaire. According to the requirements of local legislation and institutions, this study did not require ethical review and approval. A total of 240 questionnaires were distributed, and 217 valid questionnaires were returned, with a recovery rate of 90%.

Q: What is your visual comfort level when reading at this illumination level?

2.5. Experimental Process

Before the experiment, the physiological signal baseline of the elderly persons was collected for 5 min in a daylight environment with approximately 300 lx illumination and uniform light. The mean value of the SC time-domain characteristics during this period was considered the baseline value. The collection site was on a chair next to a desk in the elderly person's own bedroom. The posture was a natural sitting posture, and the ambient illumination was adjusted using the curtains. The baseline only needed to be collected once, and there was no need to repeat it before every illumination.

After the baseline was determined, the participants could adjust their comfortable reading posture by themselves or adjust the illumination of the surrounding daylight by adjusting the curtains. After 3–5 min adjustment time, reading could start. The illumination value was randomly set in each experiment, in order to reduce the impact of the previous illumination value on the elderly persons; time was also left for them to make adjustments after each change in illumination. Throughout the reading process, the elderly persons wore physiological sensors. Ergo LAB human-machine experimental software marked the physiological data in real time at the beginning and end of reading. The recording stopped after the elderly persons finished their reading. Subsequently, the elderly persons began to complete the subjective questionnaire. The staff asked the elderly persons whether they experienced any discomfort such as glare during reading, and whether they fully saw and understood the content of the reading materials. The entire measurement process is illustrated in the figure below (Figure 8).

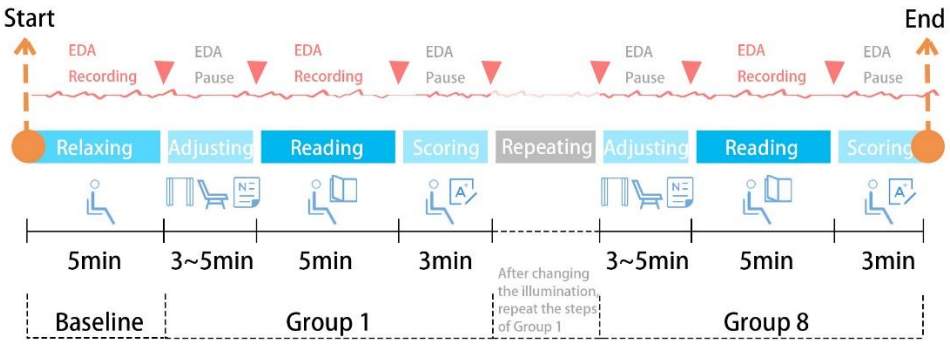

Figure 8. Experimental process.

3. Results

3.1. Daylight Illumination Measurement Results

A total of 217 illumination data points ranging from 300 to 1000 lx were used; this is the daylight illumination range that is acceptable for the elderly person to read. The questionnaire data and physiological data measured under different illumination levels were grouped according to the distribution of illumination data. The illumination difference corresponding to each group of data did not exceed 100 lx. Eight groups were recognized, i.e., "300 lx," "400 lx," "500 lx," "600 lx," "700 lx," "800 lx," "900 lx," and "1000 lx," with 25 to 30 valid data points under each group (Table 2).

Table 2. Illumination data summary.

Data Summary	
Illumination range	300–1000 lx
The total number of data	217
The number of data group	8
The number of valid data under each group	25–30

3.2. Influence of Daylight Illumination on Visual Comfort

3.2.1. Data Preprocessing

Analysis of Covariance

The level of basic electrodermal activity is related to personality characteristics. Individuals who have a higher basic electrodermal activity tend to be more introverted, nervous, and emotionally unstable. In contrast, individuals with a lower basic level are found to be more cheerful and outgoing, and have a more balanced mentality and better psychological adaptation. The time-domain mean of SC of each elderly person under different illumination was plotted on a scatterplot. According to this scatterplot (Figure 9), although the change in the electrodermal activity level of each elderly person was relatively small under different illumination conditions, a large difference in its values between different subjects was observed. This difference may originate from different physiques and cannot be artificially controlled. Covariance analysis was used to explore whether the individual's basic electrodermal activity level would affect the analysis of the SC time-domain characteristic mean under different illumination levels, and to clarify whether the SC time-domain mean values measured by different subjects could be directly compared.

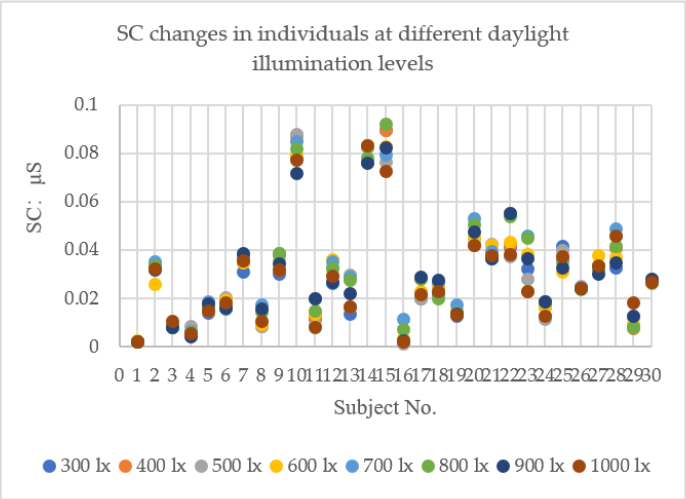

Figure 9. SC changes in individuals at different daylight illumination levels.

In this study, the SC time-domain characteristic mean values (hereinafter referred to as the baseline value) of the elderly persons during the baseline period was the covariate. The illumination was the independent variable, and the SC time-domain characteristic mean (hereinafter referred to as the SC mean value) under different illumination was the dependent variable. The statistical results of covariance are shown in the table below. The between-subjects effects test shows the baseline value of covariate p (Sig.) = 0.000 < 0.01 (Table 3). Hence, it can be considered that an interactive relationship existed between the SC mean value of the dependent variable and the baseline value of the covariate, indicating that a person's initial electrodermal activity level did affect the electrodermal activity level under different illumination conditions.

Table 3. Between-subjects effects test.

Dependent Variable: SC Time-Domain Mean Values					
Source	**Type III Sum of Squares**	**Degrees of Freedom**	**Mean Square**	**F**	***p* (Sig.)**
Modified model	1033.506 [a]	8	129.188	525.045	0.000
Intercept Distance	9.049	1	9.049	36.775	0.000
Baseline	1028.447	1	1028.447	4179.796	0.000
Illumination	5.060	7	0.723	2.938	0.006
error	56.838	231	0.246		
Total	3256.463	240			
Total after correction	1090.344	239			

[a.] $R^2 = 0.948$ (After adjustment $R^2 = 0.946$).

After deducting the effect of covariate baseline on the experiment, p (Sig.) had a value of 0.006 < 0.05 (Table 4), showing that the illumination of the independent variable still had a significant effect on the SC mean value of the dependent variable.

Table 4. Univariate tests.

Dependent Variable: SC Time-Domain Mean Values					
	Sum of Squares	**Degrees Of Freedom**	**Mean Square**	**F**	***p* (Sig.)**
Contrast	5.060	7	0.723	2.938	0.006
error	56.838	231	0.246		

SC Time-Domain Mean Value Normalization

To eliminate the influence of each elderly person's initial electrodermal activity level, it was necessary to perform data normalization. The specific operation of normalization involves subtracting the SC mean value of an elderly person's reading under different illumination conditions from the baseline value, and dividing the result by the baseline value. The change rate Δk obtained is the normalized result. The Δk value indicates the state arousal level. A high Δk indicates high state arousal, whereas a low value indicates low state arousal. The equation below shows the normalization process, where Δk denotes the normalized change rate of the SC. $\overline{X}_{emotion}$ refers to the SC mean value under a certain illumination, and $\overline{x}_{calm}$ represents the baseline value. The formula is as follows [20]:

$$\Delta k = \frac{\overline{X}_{emotion} - \overline{x}_{calm}}{\overline{x}_{calm}}$$

3.2.2. State Arousal

Correlation Analysis

The variance homogeneity analysis of Δk data revealed a significance $p = 0.000 < 0.05$; thus, it was impossible to use the parametric test. Therefore, the nonparametric Kaplan–Meier (KM) analysis was performed to test the difference between each group of data. The obtained significance was $p = 0.006 < 0.05$, indicating a significant difference. As such, the data could be further analyzed. The illumination and Δk values did not satisfy the normal distribution; thus, Spearman correlation analysis was performed. The results show that the correlation coefficient was 0.108 > 0.01 (Table 5), revealing a significant correlation.

Table 5. Spearman correlation coefficient of illumination and Δk.

			Illuminance	**Δk**
Spearman Rho	Illumination	Correlation coefficient	1.000	0.108
		Significance (2-tailed)	-	0.097
		Number of cases	217	240
	Δk	Correlation coefficient	0.108	1.000
		Significance (2-talied)	0.097	-
		Number of cases	217	240

Cumulative Analysis

First, analysis of variance (ANOVA) was performed on Δk under each group of illumination to test whether there was significant difference in state arousal under different illumination conditions. A variance homogeneity test revealed that p (Sig.) = 0.460 > 0.05; thus, ANOVA could be continued. The results are shown in the table below. p (Sig.) = 0 < 0.01 indicated a significant difference in state arousal under different illumination conditions (Table 6).

Table 6. ANOVA analysis results.

	Δk				
	Sum of Squares	**Degrees of Freedom**	**Mean Square**	**F**	***p* (Sig.)**
Between groups	51.523	7	7.360	6.203	0.000
Within group	242.047	204	1.187		
total	293.570	211			

The Δk value can indicate the arousal degree. The greater the value, the greater the arousal, whereas the smaller the value, the smaller the arousal degree. By accumulating the Δk value under each group of illuminations, the trend of arousal under different illumination conditions can be determined (Figure 10). For 600–900 lx, the state arousal degree was the largest. Under other illumination values, the state arousal degree was small (Table 7). However, the positive or negative state of each group remained unknown. Thus, further analysis in combination with the results of subjective questionnaire was required.

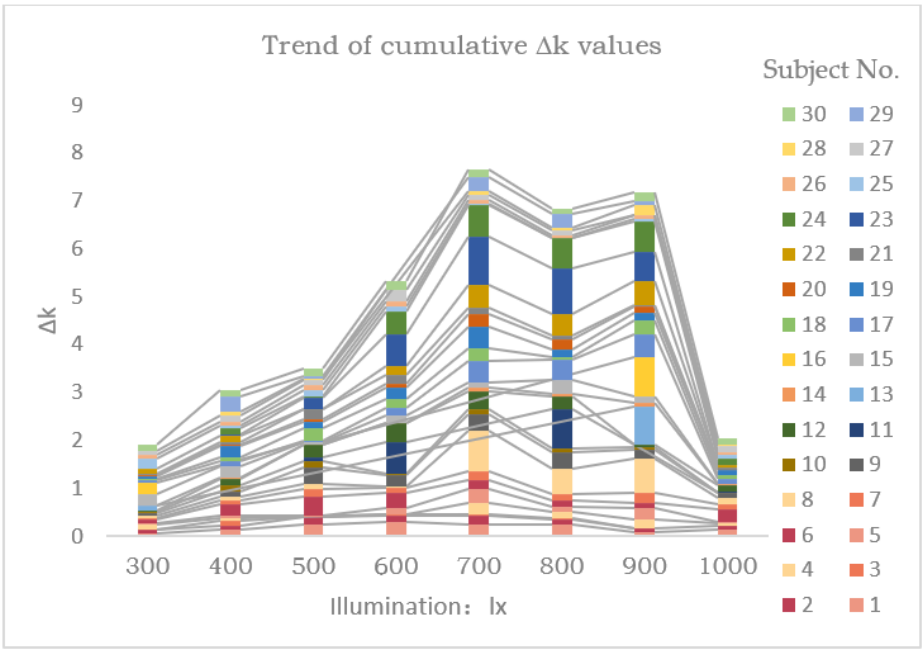

Figure 10. Trend of cumulative Δk value.

Table 7. Cumulative Δk value result.

Illumination (lx)	300	400	500	600	700	800	900	1000
Cumulative Δk	1.93	3.06	3.51	5.34	7.66	6.85	7.18	2.04

3.2.3. Visual Comfort

Correlation Analysis

The score data of visual comfort questionnaire were analyzed by variance homogeneity, and the significance was p = 0.387 > 0.05. Hence, one-way ANOVA was performed, and the significance determined was p = 0.000 < 0.05, indicating a significant difference; thus,

in-depth analysis could be conducted. The illumination value and comfort score did not meet the normal distribution; therefore, the Spearman correlation analysis was performed. The results show that the correlation coefficient was 0.312 > 0.01, revealing a significant correlation (Table 8).

Table 8. Spearman correlation coefficient of illumination and visual comfort score.

			Questionnaire Score	Illuminance
Spearman Rho	Questionnaire score	Correlation coefficient	1.000	0.312
		Significance (2-tailed)	-	0.000
		Number of cases	240	240
	Illumination	Correlation coefficient	0.312	1.000
		Significance (2-tailed)	0.000	-
		Number of cases	240	240

Descriptive Analysis

The scores of visual comfort questionnaire of each group were counted, and the proportion of "Very Uncomfortable", "Uncomfortable", "Normal", "Comfortable", and "Very Comfortable" in each group was counted. From the questionnaire scores, it was found that (Figure 11):

1. When the illumination was 300 and 400 lx, the proportion of "Comfortable" and "Very Uncomfortable" below 3 points was very high, reaching 96.66% and 63.33%, respectively. At 500 lx, the proportion of "Normal" had the highest proportion, reaching 63.33%.
2. At 600 and 700 lx, the proportion of "Comfortable" and "Very Comfortable" more than 3 points was very high, accounting for 93.33% and 86.67%, respectively. At 800 lx, the proportion over 3 points still exceeded half, accounting for 56.67%. The proportion of "Normal" of 3 points also reached 40%, and the proportion of less than 3 points was only 3.33%.
3. At 900 lx, the proportion of "Uncomfortable" and "Very Uncomfortable" below 3 points was 30%. The largest proportion is 3 points for "Normal"., accounting for 46.67%. At 1000 lx, the proportion of "Uncomfortable" and "Very Uncomfortable" below 3 points was 40%, close to the proportion of "Normal" (46.67%).

Based on the above situation, it can be preliminarily concluded that 300 and 400 lx resulted in negative visual perception for most elderly persons, who were unable to read without physical or psychological stress. With the increase in illumination, the visual perception tended to be positive at 500 lx. At 600 and 700 lx, positive feedback was obtained from most elderly persons, and their feelings were biased towards comfort. When the illumination was 800 lx, the opinions began to diverge. Although the number of elderly persons who had normal feelings increased, more elderly persons felt comfort. At 900 lx, the number of elderly persons who considered they had normal feelings were in the majority, at nearly half. At 1000 lx, the number of the elderly persons who considered they had normal feelings was similar to that who were uncomfortable, but a small proportion of elderly persons felt comfortable.

By averaging the visual comfort scores under each group of illumination values, the general trend of visual comfort could be obtained (Table 9). The range of discomfort fell within 0–3 points. From the average value, 300, 400, and 1000 lx can be considered as negative discomfort in the range of less than 3 points. The scores under 900 and 500 lx were close to 3 points, which can be judged as normal. The scores under 600, 700, and 800 lx were in the range of more than 3 points, which can be considered as positive comfort.

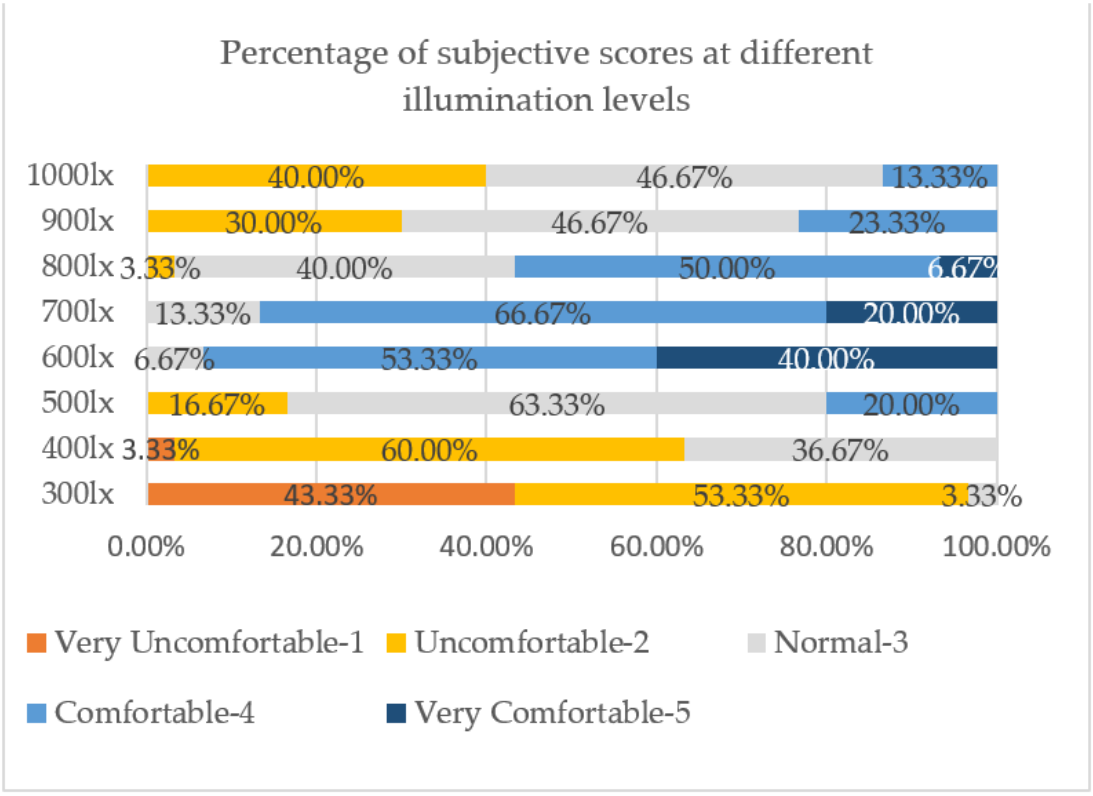

Figure 11. Percentage of subjective scores at different illumination levels.

Table 9. Average value of the visual comfort score.

Illuminatio (lx)	300	400	500	600	700	800	900	1000
Average score	1.6	2.36	3.04	4.36	4.07	3.6	2.9	2.69

3.3. Daylight Illumination Threshold Analysis

The average score of the visual comfort questionnaire of each group was compared with the accumulated Δk value. The comparison diagram is show in Figure 12.

Δk indicates state arousal level, and the visual comfort score indicates the trend of "Comfort" (>3 points), "Normal" (3.1> n > 2.9), and "Uncomfortable" (<3 points), which can be further divided into detail according to the level of 1–5 points (Table 10). According to the results of the subjective questionnaire, at 300–400 lx, the subjective visual comfort score was below 3, indicating discomfort. State arousal was also low, making it harder for the elderly persons to engage. When the illumination was increased to 500 lx, the situation improved, and most of the elderly persons were able to complete the reading task more easily. At the same time, the elderly persons' states of arousal rose during this procedure. At 600 lx, the subjective visual comfort score reached a maximum of 4.36 points, which was classified as "Very comfortable." This indicated that the elderly persons could read without feeling stressed, and their arousal level had improved slightly. When the light level was increased to 700 and 800 lx, the subjective comfort score decreased, but both scores were greater than 3 and still fell into the "comfort" category. At these illumination levels, the elderly persons were under greater pressure to complete the reading task than at 600 lx. Their state arousal was higher, which was a positive outcome. At 900 lx, the subjective visual comfort score remained at 3, despite the fact that state arousal remained high. Subjective visual comfort fell below a score of 3 at 1000 lx, and was classified as "uncomfortable", with a considerable decline in state arousal.

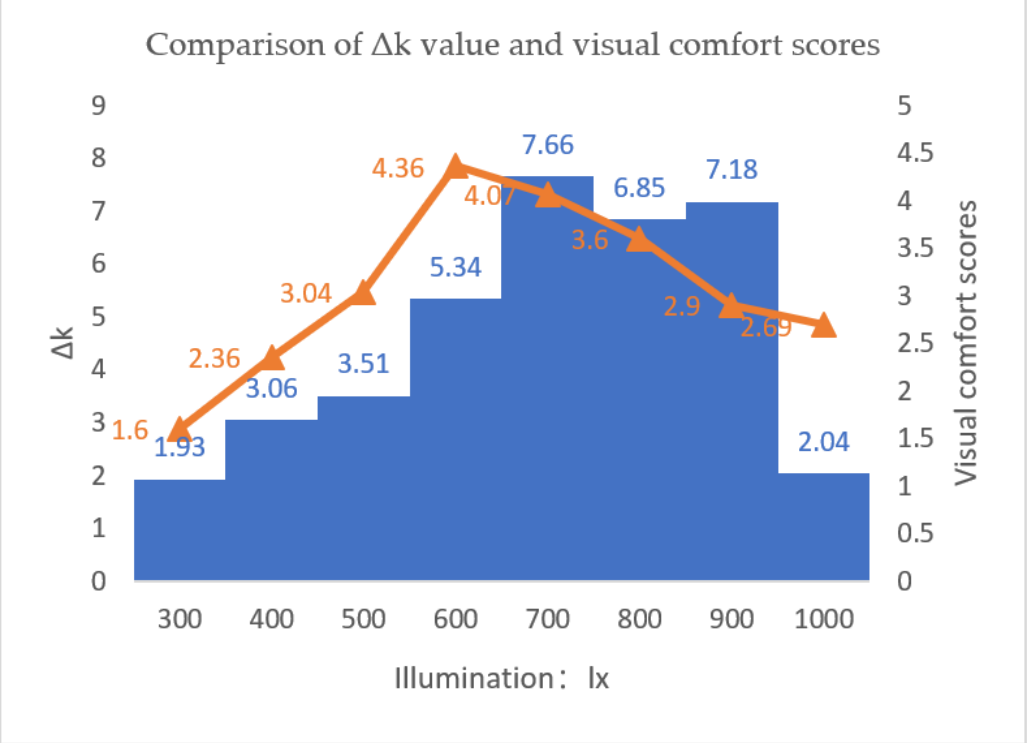

Figure 12. Comparison diagram of Δk and visual comfort scores.

Table 10. Ranking of scores of the visual comfort questionnaire.

Trend of Visual Feeling	Uncomfortable (n < 3 Points)			Normal (3.1 > n > 2.9)		Comfortable (n > 3 Points)		
Illumination (lx)	300	400	1000	900	500	800	600	700
Scores of visual comfort (n)	1.6	2.36	2.69	2.9	3.04	3.6	4.36	4.07
ArousalLevel (Δk)	1.93	3.06	2.04	7.18	3.51	6.85	5.34	7.66

4. Discussion

Based on the analysis of the experimental data, a trend can be noticed. When daylight illumination was set at 300–500 lx, subjective visual comfort scores rose in tandem with state arousal, showing that the elderly persons were gradually becoming more active and engaged. At an illumination level of 600–800 lx, the subjective visual comfort score dropped from its maximum point but remained in the "comfort" category, while state arousal levels continued to rise. Based on the elderly persons' subjective assessments, when the illumination was between 600 and 800 lx, the condition of state arousal was positive. It can be seen that physiological and psychological activity improved the elderly person's subjective perception. The levels of both 700 and the 600 lx had a subjective visual comfort score of 4 or more; 700 lx may be preferable since it resulted in a higher level of state arousal.

However, this did not necessarily apply to the 900 and 500 lx levels, which were both rated 3 out of 5 as "normal." According to the proportion of subjective visual comfort scores, more than half of the elderly persons assessed 500 lx as "normal." At 900 lx, several subjects experienced trouble adjusting the uniformity of light in their field of view, and more glare cases were reported. Some subjects also reported preferring the higher illumination of 900 lx, which helped them see more clearly. As a result, high state arousal can be both a positive and a negative outcome. In terms of consistency of evaluation, the 500 lx level is superior to that of 900 lx.

5. Conclusions

It can be seen from the experimental data that the peak of subjective visual comfort score appeared at 600 lx, and the peak of state arousal level appeared at 700 lx. The reason for this peak gap can be analyzed from the changes of the two indicators. When the daylight illumination was low (300 lx), as the illumination increased, the elderly persons invested more energy, and the visual comfort also improved. However, when the illumination was increased to 800 lx, the elderly persons felt a certain pressure when reading, and the increase in state arousal then offset a part of this pressure. When the illumination was higher than 1000 lx, the elderly persons appeared to have low state arousal, and the visual comfort was also greatly reduced.

Within the context of this experiment, the most comfortable illumination range for the elderly persons to read in daylight was 600–800 lx, and 700 lx was optimal. This level was higher than the illumination of 300 lx recommended for reading under artificial lighting in the Architectural Lighting Design Standard of China. This showed that, due to the dependence of the elderly persons on daylight, their demand for daylight illumination was higher than that under constant artificial lighting. This conclusion was also confirmed by a study in UK, in which individuals tolerated significantly higher levels of daylight illumination than CIBSE's typical artificial lighting recommendations unless there was glare or direct sunlight [21].

The main conclusions can be summarized as follows:

1. At daylight illumination of 300–500 lx, subjective visual comfort rose, in addition to state arousal, a process in which the elderly persons became progressively more engaged.
2. At daylight illumination of 600–800 lx, subjective comfort decreased from its highest point, but remained in the "comfort" category, while state arousal continued to increase.
3. At daylight illumination of 800 lx, the active state of the elderly compensated for some of the stress caused by the light environment.
4. At daylight illumination of 900 lx, although the subjective visual comfort rating was close to "normal", the comments were polarized and it was difficult to determine whether the increase in state arousal was due to positive or negative factors.
5. When the lighting was dim, the elderly persons had low state arousal and found it harder to engage in reading tasks. As the degree of illumination rose, so did the arousal level, and the body state of the elderly gradually became more active. When the illumination level exceeded a specific threshold, however, the arousal level dropped dramatically.
6. The most comfortable reading illumination level for the elderly persons was between 600 and 800 lx, with 700 lx providing the best performance. The ranking of the visual comfort levels of the daily illuminance values under reading behavior is shown in Figure 13.



Figure 13. Schematic of illumination value and comfort level.

This experiment was chosen to take place in Shenyang, a city in China's harsh cold area, which is located at high latitudes. Long winters, low solar azimuths, and short daylight hours characterize cities in high latitudes. The elderly persons who live here are restricted to indoors and prefer the more daylight is brought indoors because they are psychologically closer to it. However, in cities located at low latitudes with high levels of daylight radiation (e.g., Guangdong), the issues to consider are quite different. On sunny days, low latitudes are characterized by intense daylight radiation, whereas cloudy

situations result in insufficient daylight hours. Although it is critical to bring in as much daylight as possible, too much direct light may generate glare and diminish the comfort of the light environment. The elderly persons in various climatic zones may have different adaptations to daylight, and additional research in various regions is needed.

In this research, extraneous light environment indicators such as glare [22] and illumination uniformity [23] were controlled for, although these two indications are also crucial for evaluating the quality of the light environment. At the same time, the primary purpose of the light environment indicators is to inform the architects' lighting design strategy. The physiology, psychology, and behavior of the elderly persons are affected by design considerations such as building orientation, room sizes, window sizes and parameters, frames and position, types of glazing, transmission characteristics of glazing, cleanliness of glazing, and interior room surfaces [24,25]. The comfort of the daylight environment is a systematic "human-behavior-environment" problem, which is better suited to multifactorial research with the use of appropriate algorithms. Before that, however, experiments are needed to clarify the specific relationships between the different factors. The best design strategy based on daylight performance indicators may be discovered using enough experimental sample data and a multi-objective algorithm [26].

6. Limitation

First, the set illumination range was 300–1000 lx in the experiments. This was based on the recommended value of reading illumination under artificial lighting in the Architectural Lighting Design Standard of China and the pre-judgment of the actual situation in the pre-experiment. However, there were also cases where it exceeded 1000 lx or was less than 300 lx in the experiments. Since elderly persons with normal vision and reading habits were selected in this experiment, only in certain cases did elderly persons with low sensitivity to light believe that illumination higher than 1000 lx was more comfortable, or those with relatively better vision and high tolerance of daylight illumination considered that daylight below 300 lx was acceptable. It can be seen that the acceptance of daylight illumination was also different for the elderly persons with different physiological and psychological states. This research focused on a certain category of elderly persons and was not representative of a broad group of elderly persons. In addition, this experiment set the time from 8:00–10:00 in the morning according to the reading habits of the elderly persons. Table 1 summarizes the activities of the elderly persons in one day, among which watching TV, playing cards, playing chess, eating, and chatting were the activities enjoyed by the elderly in other periods; these activities were also not covered in this research. Finally, the site selected for this article was a rectangular room facing south, which was relatively simple. The daylight features of other rooms were different from those facing the south direction and would behave differently over time. In addition, there were complex geometries, which needed to be specifically analyzed according to the movement tracking of the elderly persons' activities. These questions all need to be further explored in the future.

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