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Research Article

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Research on Light-Dark Adaptation of Human Vision in Tunnel Portals

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ABSTRACT

To study the characteristics of light and dark adaptation in tunnel portal sections and to determine the influencing factors of light-dark vision adaptation, basic tunnel lighting and linear design data are obtained. In this paper, we use a light-shielded tent to simulate the dark environment of a tunnel in experiments, observe the driver recognition time of target objects during the light-dark adaptation process, and analyze the light-dark adaptation time of human vision. Based on a large number of experimental data, we examined the relationship between age, gender, illuminance and light and dark adaptation times and established a model of the relationship between age, illuminance and light and dark adaptation times. The experimental results revealed that the dark adaptation time is generally longer than the light adaptation time. The dark adaptation time is positively related to age and basically exhibits a cubic relationship. There is no significant correlation between the light adaptation time and age, but the overall trend is that the light adaptation time gradually increases with increasing age. There is no correlation between gender and light and dark adaptation times, but there is a notable correlation between the light and dark adaptation times and illuminance. When the illuminance ranges from 11000-13000 lux, the light and dark adaptation times are the longest.

Please note: Vision, tunnel portal, tunnel entrance section, tunnel exit section, light adaptation, dark adaptation, adaptation time

1. INTRODUCTION

Tunnel entrance and exit sections are transition sections in the vehicle operating environment. When driving from the natural light environment of a highway into the artificial light environment of a tunnel entrance section or when exiting from the artificial light environment of a tunnel exit section, the natural light environment of the highway produces different light environmental differences. When this difference is stark, it can lead to a visual lag in drivers and cause short-term visual impairment. This is often called the black hole or white hole effect [1]. This affects driver recognition of vehicles or obstacles ahead, driving stability, and safety and comfort, which can easily lead to an increased stress on drivers, operational errors, and traffic accidents.

Research on the visual characteristics in tunnel entrance and exit sections has been a topic of considerable interest in the field of tunnel engineering. Domestic and foreign scholars have conducted extensive research in this field, but few meaningful results have been obtained.

In the study of driver visual characteristics in tunnel entrance and exit sections, Narisada K. used eye tracker records to establish an index of gaze characteristics to describe eye movement attributes [2]. Zwahlen H. T. et al. used an onboard video eye movement recording system to record various eye movement data of drivers at tunnel entrances and analyzed the visual parameters of the gaze and saccade characteristics [3]. Masha Maltz et al. studied the eye movement characteristics in the visual search process of drivers [4]. David Crundal et al. examined the average gaze duration, number of gaze points, and other related eye movement characteristics of drivers based on observation of the visual search process of drivers in different road scenes [5], [6]. It established a model of the relationship between the driver adaptation time and road brightness based on the adaptation time from when a driver notices the reaction target until its outline is discerned [7]. Y. Liu et al. adopted the heart rate change rate index to evaluate the impact of tunnel lighting on drivers and established a relationship model between the heart rate change rate and influencing factors [8]. Z. Du et al. proposed the maximum transient speed of the pupil area (MTPA) as an indicator of the visual load in response to visual shocks in light and dark adaptation [9], [10]. Y. Hu et al. implemented a point-point brightness meter to measure the brightness at the entrance and exit of a tunnel and used the equivalent light curtain brightness to calculate the

adaptive brightness at each location [11]. In addition, a mathematical model of the relationship between the brightness levels at the tunnel entrance and outside the tunnel was established [12]. J. Hu et al. calculated the threshold value of the brightness difference in the entrance section of a tunnel at night at different design speeds [13]. F. Huang found that when entering a tunnel, an excessively high illuminance transition rate tends to increase the driver visual load and psychological tension [14]. Mehri et al. compared the safety lighting level at a tunnel entrance with the De Boer scale and found that the black hole effect would cause the eyes of a driver to not readily adapt to brightness level changes at the tunnel entrance, thereby increasing the risk of traffic accidents along this section [15]. Y. Chen et al. reported that the dark adaptation position of the driver of a large truck is closer to the door, and there is a higher visual load when driving along a tunnel entrance section, while the driving safety is poor [16], [17], [18], [19]. Zhao, En Zhong, et al. analyzed the influence of LED color rendering on dark adaptation of human eyes at tunnel entrance [20]. L. Dong et al. revealed that light-emitting diodes (LEDs) with correlated color temperatures (CCTs) ranging from 4000–4500 K are preferable for tunnel entrance lighting [21]. G. Zhi, et al. evaluated the safety of illuminance transition at highway tunnel portals on basis of visual load [22]. N. Zhou et al. simulated human visual perception under nighttime illuminance [23].

In the study of the relationship between human visual characteristics and age, previous results [24] demonstrate that human visual characteristics degenerate with age and the ability to adjust the eye lens, pupil agility, visual sensitivity and speed and total amount of dark and light adaptation all decrease. The final effect of age on vision is visual acuity deterioration. The highest visual acuity occurs at an age ranging from 14 to 20 years. After an age of 30 years, visual acuity gradually decreases. Beyond the age of 60 years, visual acuity is only 1/3 ~ 1/4 of that at an age of 20 years.

In a dynamic road traffic system consisting of people, cars, roads and different environments, more than 80% of road, traffic and environmental information during driving is obtained by drivers through vision [25]. According to the aforementioned studies, the light and dark changes in a tunnel portal affect human visual performance [26]. However, quantitative evaluation of the light and dark adaptation characteristics of drivers is uncommon in China and abroad.

In this paper, we used a light-shielded tent to simulate the dark environment of a tunnel and measure the adaptation time of a driver at different illuminances through actual measurements. Then, we analyzed the light and dark adaptation characteristics of the driver upon entering and exiting the tunnel.

2. EXPERIMENTAL SCHEME

2.1 Experimental elements

In the experiments, a light-shielded tent was used to simulate the dark environment of a tunnel. The experimental site was located in an open campus grassland. In addition, to simulate the noise environment of a tunnel portal, the noise was controlled at 50-55 dB [27].

To ensure that the illuminance at the simulated tunnel entrance or exit changed significantly, the experiments were conducted on a sunny day, from 9:30-19:30.

2.2 Observers

Observers, who had been driving for longer than 1 year were chosen for the experiments, including 5 age groups, namely, 21–30, 31–40, 41–50, 51–60 and 61–70 years. Across the different age groups, male and female drivers were distributed as equally as possible. All observers had normal vision or a normal corrected vision. None of the observers suffered from night or color blindness or other conditions affecting night vision performance. All observers were well rested and exhibited normal reactions, and alcohol consumption and medication usage were prohibited during the experimental period.

To ensure accuracy of the experimental parameters, it is necessary to adopt a certain sample size. Taking the measured adaptation time as an accuracy parameter, the minimum measured sample size is:

$$N \geq \left(\frac{\sigma K}{E} \right)^2 \quad (1)$$

where

N is the sample size;

σ is the overall standard deviation, and a value of 1 s is adopted in this paper;

K indicates the confidence level, and when a confidence level of 95% is considered, $K = 1.96$; and

E is the allowable error, which is 0.15 s in this paper.

Based on **Equation (1)**, $N \geq 171$ is obtained. In this study, 237 observers were chosen. The observers is shown in **Fig. 1**.

2.3 Experimental setup

1. Light-shielded tent: The dark environment inside a tunnel was simulated with the tent, with a height of 3.0 m, length of 8.0 m and width of 4.0 m. The illuminance ranged from 40 ~ 520 lux in the light-shielded tent. The light-shielded tent is shown in **Fig. 2(a)**.

2. Digital illuminance meter: The ambient illuminance was measured with a TES-1339, and the measurement illuminance range was 0.0 ~ 990000 lux, while the resolution was 0.01 lux. The measurement accuracy was $\pm 3\%$. It is shown in **Fig. 2(b)**

3. Camera: The adaptation time of the observers was recorded upon entering and leaving the simulated tunnel in the experiments. It is shown in **Fig. 2(c)**.

4. Test board and card: The test board was 1.2 m high. There are 20 test cards, including simple Chinese characters and animal images, with the size of 0.15 * 0.15m. The distance between the eyes and the test card was 60-80 cm, which allowed the graphic elements to be identified.

5. Car: A noisy environment was simulated.

2.4 Experimental procedure

Step 1. Ambient illuminance measurement

The illuminance was measured at 2 m from the entrance side, at the center of the tunnel, and at 2 m from the exit side of the simulated tunnel.

Step 2. Dark adaptation time measurement

The observers were notified in advance of the experimental route. First, observers walked into the tunnel from 2 m outside the simulated tunnel and approached the center of the tunnel, at which point they identified the objects on the test card. A camera recorded the time from entering the tunnel to identifying the objects.

Step 3. Light adaptation time measurement

The observers remained in the tent for 3 minutes, walked out of the tent, and identified the objects on the test card. Another camera recorded the time from exiting the tunnel to reading the object names.

Experimental procedure is shown in **Fig. 3**.

2.5 Experimental design

Experiment 1: A total of 237 observers entered the site randomly for testing, ensuring that the time and personnel were random.

Experiment 2: To exclude the effects of age, gender, individual differences and other factors on the adaptation time, 4 females and males in the age groups of 21-30, 31-40, and 41-50 years were randomly selected, for a total of 24 observers. The experiment was repeated at different illuminances, and measurements were recorded every 20-30 minutes.

2.6 Experimental error control

To ensure data validity, each experiment was repeated 3 times, and the average data of these three experiments were considered the characteristic visual data of the observers.

3. RESULTS AND ANALYSIS

3.1. Comparative analysis of the light and dark adaptation times

Using **Experiment 1** data, we compared and analyzed the durations of the light and dark adaptation times.

Let the dark adaptation time be T_D and the light adaptation time be T_L , and the difference between the dark and light adaptation times is ΔT ; then, $\Delta T = T_D - T_L$. **Fig. 4** shows that there were 19 cases with $\Delta T < 0$ and 219 cases with $\Delta T > 0$.

Fig. 5 shows the relationship between the adaptation time difference and illuminance. Clearly, the dark adaptation time is longer than the bright adaptation time under all illuminance conditions.

Fig. 6 reveals the relationship between the adaptation time difference and age. Clearly, the dark adaptation time is longer than the light adaptation time at all ages.

Fig. 7 shows that as the age increases, the difference between the light and dark adaptation times increases. The difference between the dark and light adaptation times is basically less than 3.0 s, and most of the differences are concentrated between 0.2 and 1.4 s.

3.2 Characteristics of light and dark adaptation based on age

Based on **Experiment 1** data, we analyzed the light and dark adaptation times at the different ages. To reduce the effect of illuminance on the correlation between the adaptation time and age, we selected the data at an illuminance ranging from 500-8000 lux for a total of 20 effective samples, as shown in **Figs. 8 and 9**.

1. Correlation analysis between the adaptation time and age

We conducted correlation analysis between the dark and light adaptation times and age. The Spearman correlation coefficient is denoted as R_s in Table 1.

(1) The dark adaptation R_s value is 0.805, and the P value is below the theoretical significance level of 0.01, indicating that the dark adaptation time exhibited a significant positive correlation with the age.

(2) The light adaptation R_s value is 0.079, which indicated that there was no significant correlation between the light adaptation time and age.

2. Establishing the relationship between the dark adaptation time and age

Let age be denoted as a , and regression analysis is performed to obtain **Equation (2)**:

$$T_D = 2.819 \times 10^{-5} a^3 - 0.003 a^2 + 0.092 a + 0.226 \quad (2)$$

Fig. 10 shows the obtained model fitting result of the relationship between the age and dark adaptation time.

To validate the model, we performed a correlation test on the model, as summarized in **Table 2**.

Table 2 indicates that $R^2 = 0.743$, which implies that the degree of fitting of the cubic function model is acceptable.

The model was further tested with t and F tests, and the results are listed in **Tables 3 and 4**, respectively.

Tables 3 and 4 indicate that the significance value $P \leq 0.001$, demonstrating that there is a significant cubic function relationship between the age and dark adaptation time.

Our results revealed the following:

(1) The dark adaptation time and age basically exhibited a cubic correlation, i.e., the dark adaptation time generally increased with increasing age.

(2) **Equation (2)** attained statistical significance.

(3) The dark adaptation time was basically shorter than 4.0 s, and most values were concentrated between 1.2 and 2.4 s.

3) Analysis of the relationship between the light adaptation time and age

Fig. 11 shows the scatter diagram of the light adaptation time with the age.

Fig. 11 shows the following:

(1) There were large individual differences in the light adaptation time, and there was no clear correlation with the age, but the overall trend was a gradual increase with increasing age.

(2) The light adaptation time was basically shorter than 2.0 s, and most light adaptation times ranged from 0.7 to 1.5 s.

3.3 Characteristics of light and dark adaptation based on gender

According to **Experiment 1** data, we analyzed the effect of gender on the light and dark adaptation times. To eliminate the influences of age and illuminance on the analysis results, data on observers older than 55 years old and obtained at an illuminance exceeding 12000 lux were excluded. The adjusted effective data contained 192 groups.

Figs. 12, 13, 14 and 15 show the relationships between gender and dark and light adaptation times. Clearly, the adaptation time remained basically the same regardless of gender at the different ages and illuminances. Therefore, it can be considered that there is no correlation between gender and light and dark adaptation times.

3.4. Characteristics of light and dark adaptation based on Illuminance

Using **Experiment 2** data, we analyzed the influence of illuminance on the characteristics of light and dark adaptation responses. In the experimental sample data, the effects of age, gender and other factors on the adaptation time were eliminated, and the effective sample data consisted of 176 groups.

1. Analysis of the relationship between the adaptation time and illuminance

In this paper, box charts were adopted to evaluate the adaptation time at the different illuminances. The statistics at each illuminance level included 5 characteristic metrics of the sample lower boundary, 25th quantile, 75th quantile, sample upper boundary and average value.

As shown in **Fig. 16**, the dark adaptation time increased with increasing illuminance and reached a maximum value at 11000-12000 lux. When the illuminance exceeded 11000-12000 lux, the dark adaptation time gradually decreased with increasing illuminance, but the downward trend was slower than the upward trend, and the average value finally stabilized at approximately 1.5 s.

Fig. 17 reveals that the light adaptation time increased with increasing illuminance and reached a maximum value at 12000-13000 lux. When the illuminance was higher than 12000-13000 lux, the light adaptation time gradually decreased with increasing illuminance, but the downward trend was slower than the upward trend, and the average value finally stabilized at approximately 0.9 s.

2. Establishing the relationship between the adaptation time and illuminance

Based on the average adaptation time at each illuminance level in the **Experiment 2** data, we analyzed the relationship between the average adaptation time and illuminance and determined the illuminance-average adaptation time relation via fitting, as shown in **Fig. 18**.

Equations (3) and **(4)** were obtained by establishing the relationships between the average adaptation times and illuminance.

$$T_1=1.03\times 10^{-13}l^3-7.81\times 10^{-9}l^2+1.44\times 10^{-4}l+1.09 \quad (3)$$

$$T_2=3.74\times 10^{-14}l^3-3.77\times 10^{-9}l^2+7.91\times 10^{-5}l+0.63 \quad (4)$$

where

T_1 : Average dark adaptation time;

T_2 : Average light adaptation time;

l : Illuminance.

To validate the model, we performed correlation analysis and *F tests* on **Equations (3)** and **(4)**, and the results are summarized in **Tables 5** and **6**, respectively.

Table 5 indicates that $R^2>0.8$, which implies that the degree of model fitting is acceptable.

Table 6 indicate that the significance value $P\leq 0.001$, demonstrating that there is a significant cube function relationship between the adaptation time and Illuminance.

In summary, we have obtained the following:

(1) **Fig. 18** shows that at the same illuminance, the dark adaptation time is longer than the light adaptation time, which is consistent with the previous analysis results.

(2) Illuminance directly affects the dark and light adaptation times, and they basically have cubic relations.

(3) **Equations (3)** and **(4)** attain statistical significance.

VI. CONCLUSION AND FUTURE WORK

In this paper, we analyzed the relationships between the light and dark adaptation times and age, gender, and illuminance in simulation experiments and studied the visual light and dark response characteristics of drivers at tunnel entrances. The following conclusions can be drawn:

1. After a driver enters or exits a tunnel, a certain vision adaptation time is required.

2. Under all illuminance conditions, the dark adaptation time is longer than the light adaptation time, indicating that the visual discomfort for drivers caused by the tunnel entrance is more severe than that caused by the tunnel exit, i.e., the black hole effect is more dangerous than the white hole effect. With increasing age, the difference between the light and dark adaptation times increases.

3. There is a notable positive correlation between the dark adaptation time and age, namely, with increasing driver age, the dark adaptation time increases. The light adaptation time is not notably correlated with the age.

4. Under the different age and illuminance conditions, the adaptation time remains basically the same regardless of gender. It can be concluded that there is no correlation between gender and light and dark adaptation times.

5. The dark adaptation time is highly correlated with the illuminance. The light and dark adaptation times increase with increasing illuminance, reaching maximum values at 12000-13000 lux and 11000-12000 lux, respectively. When the illuminance continues to increase, the adaptation time gradually decreases with increasing illuminance, but the downward trend is slower than the upward trend.

Our ultimate goal is to digitize the light and dark vision response characteristics of drivers in tunnels, such as the adaptation time in tunnel portals in different directions, to provide a broader theoretical basis for tunnel portal linear and lighting design.

Therefore, in future work, we will expand our research. First, the number of samples across different age groups will be increased, and the sample data accuracy will be improved. Second, the difference in illuminance will be widened, and the laws of light and dark vision adaptation characteristics will be studied for larger illuminance differences. Third, the appropriate test scheme for a tunnel mouth will be established.

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Ethical Statements

All subjects gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Shaanxi Jiaotong hospital Research Ethics Committee (No: 200401).

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Author Contributions: Conceptualization, C.L.; Methodology, C.L; Validation, C.L.; Formal Analysis, C.L. and W.Q.; Investigation, C.L. and W.Q.; Resources, C.L.; Data Curation, C.L.; Writing—Original Draft Preparation, C.L.; Writing—Review and Editing, C.L. and W.Q.; Funding Acquisition, C.L.

Conflicts of Interest: The authors declare no conflict of interest.

Figures

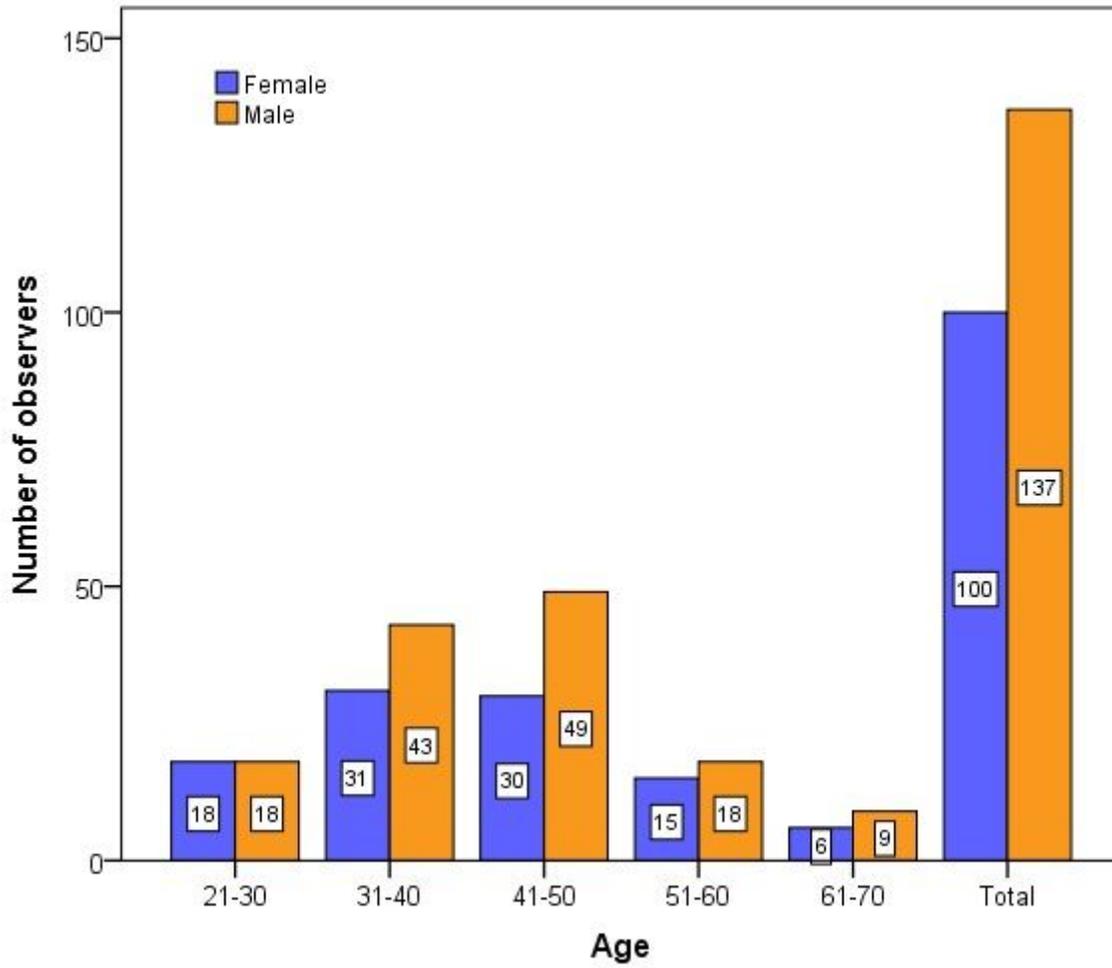


Figure 1

Composition of the observers



(a)



(b)



(c)

Figure 2

Experimental setup

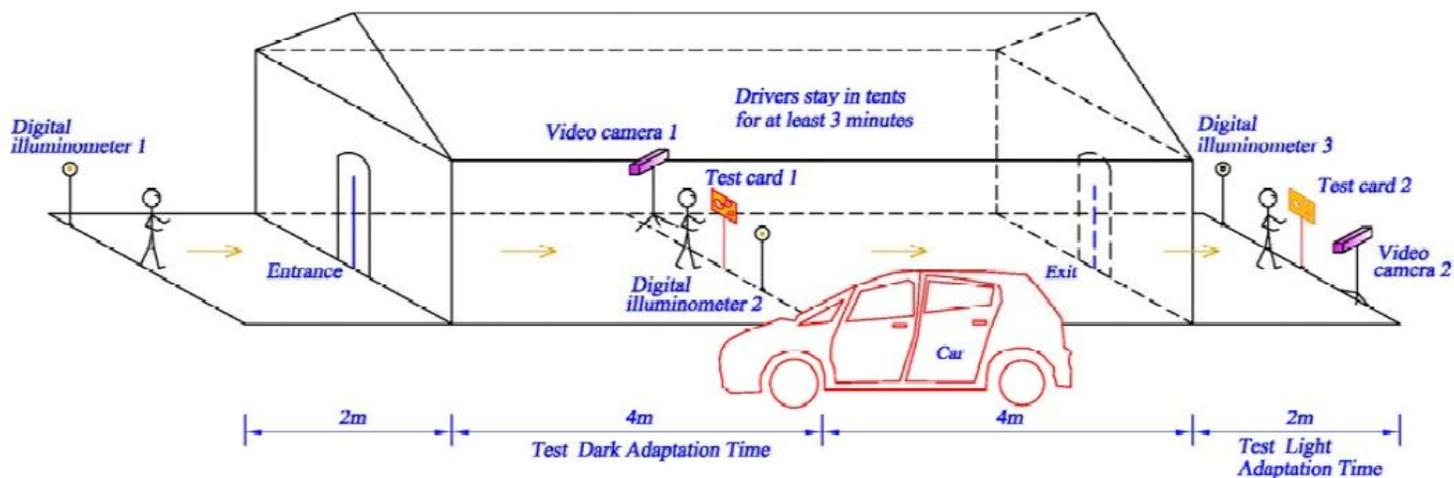


Figure 3

Schematic of the experiment

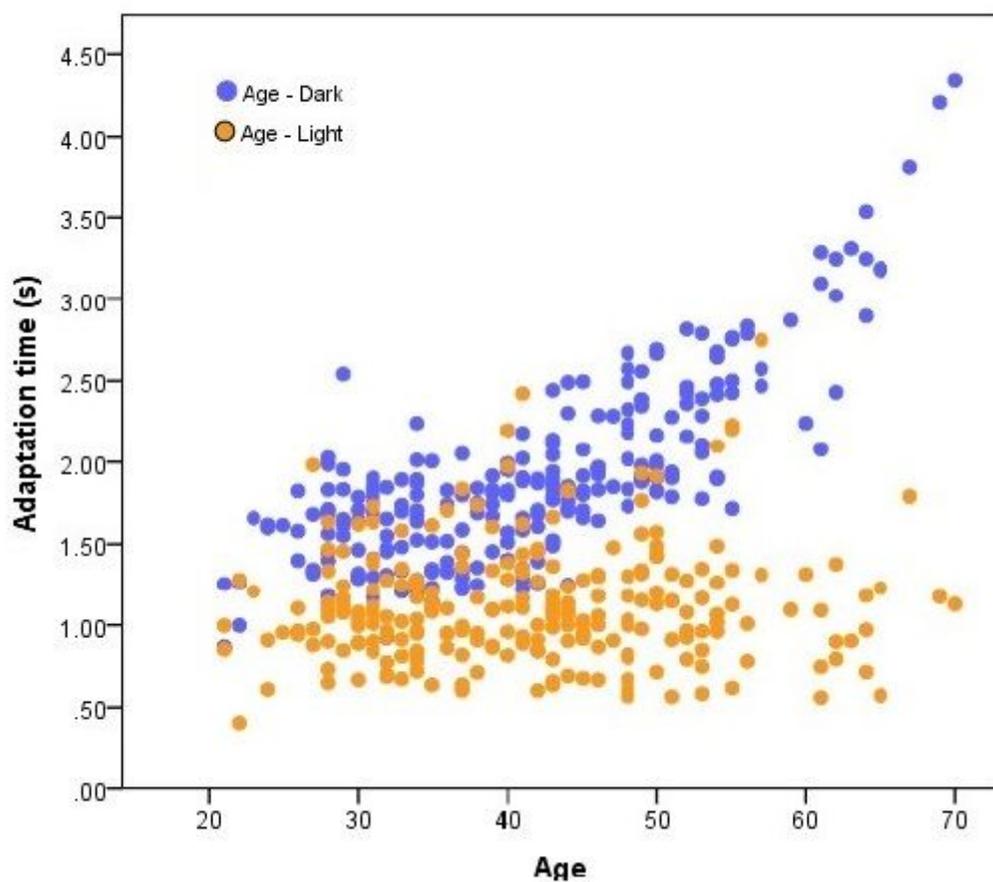


Figure 4

Measured light and dark adaptation time distributions

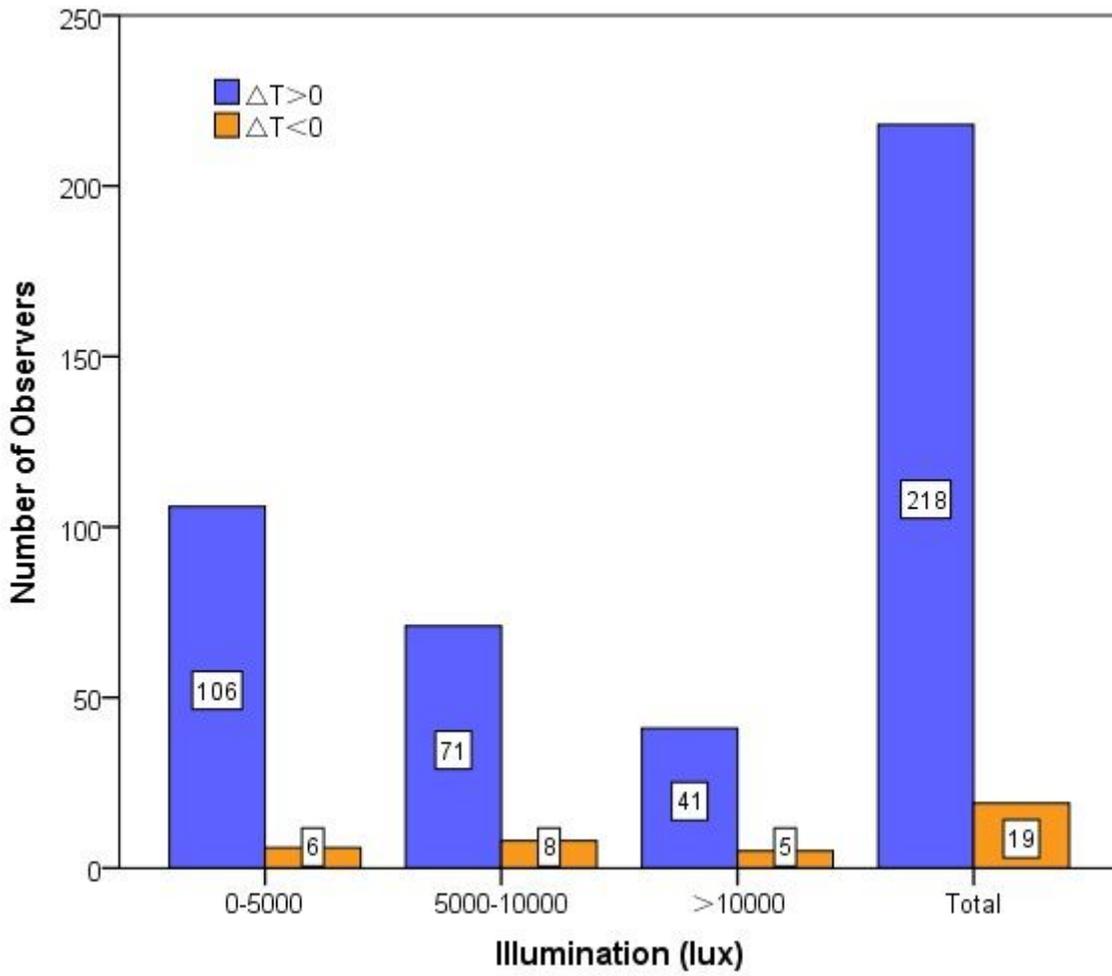


Figure 5

Relationship between the adaptation time difference and illuminance

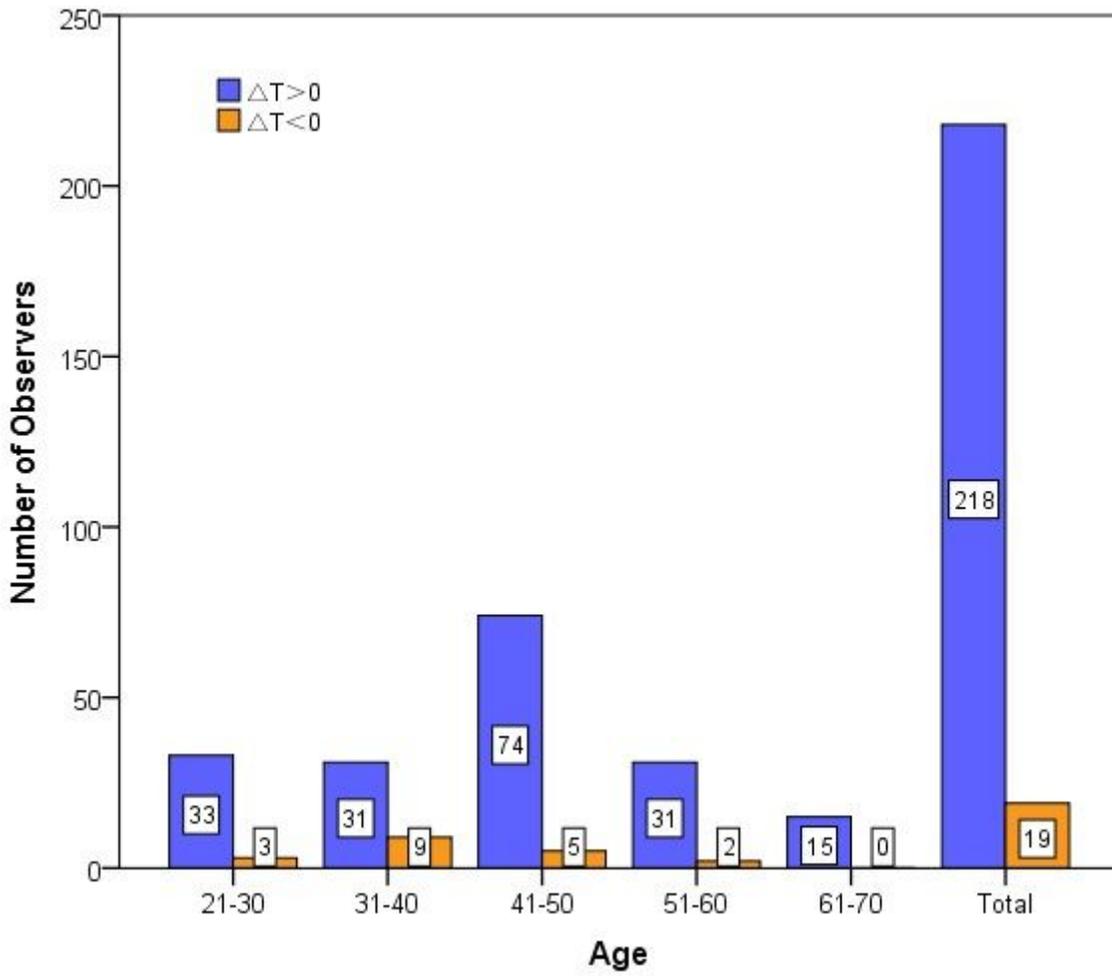


Figure 6

Relationship between the adaptation time difference and age

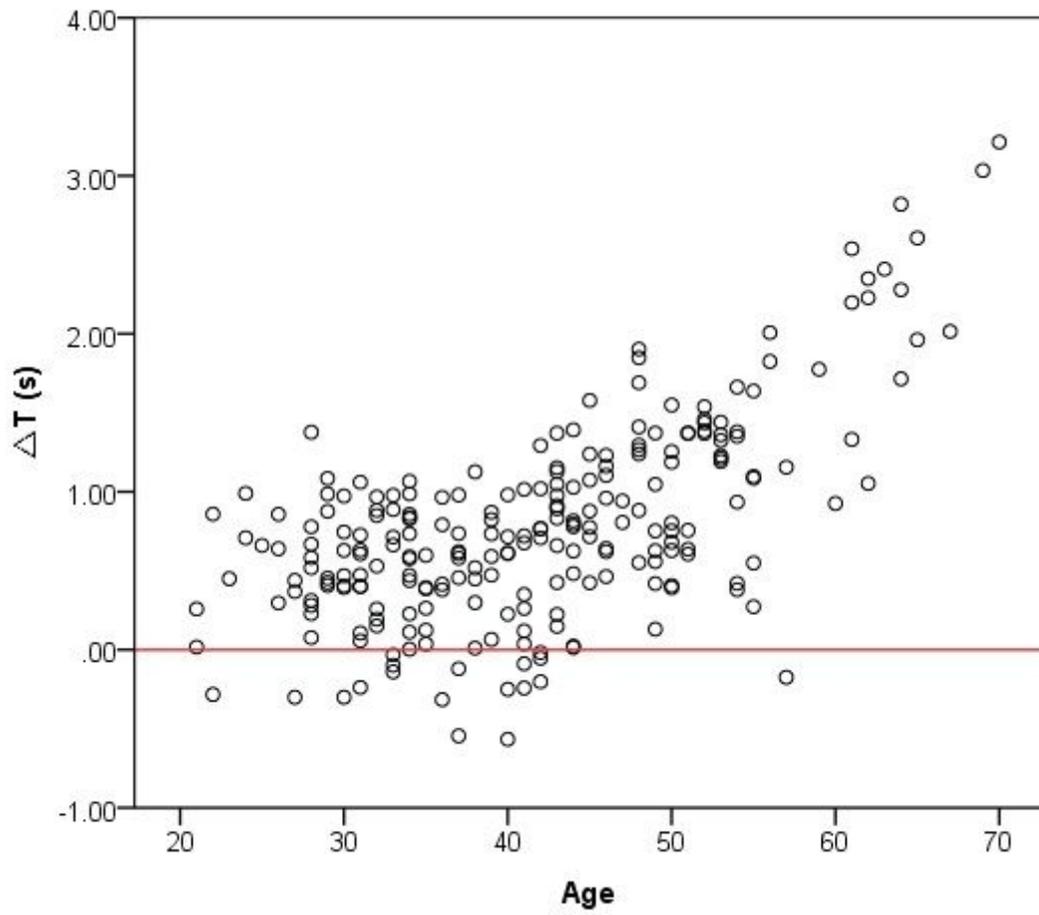


Figure 7

Measured adaptation time difference distribution

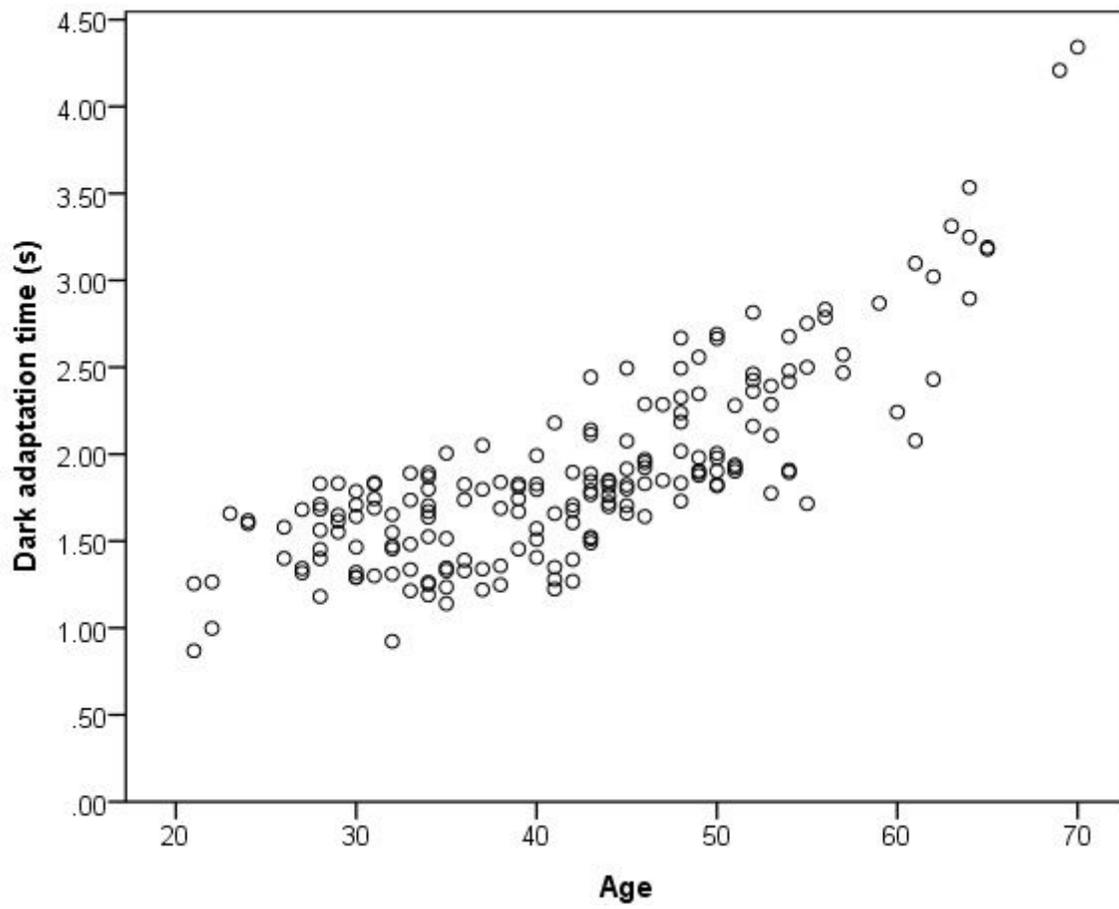


Figure 8

Relationship between the dark adaptation time and age (500-8000 lux)

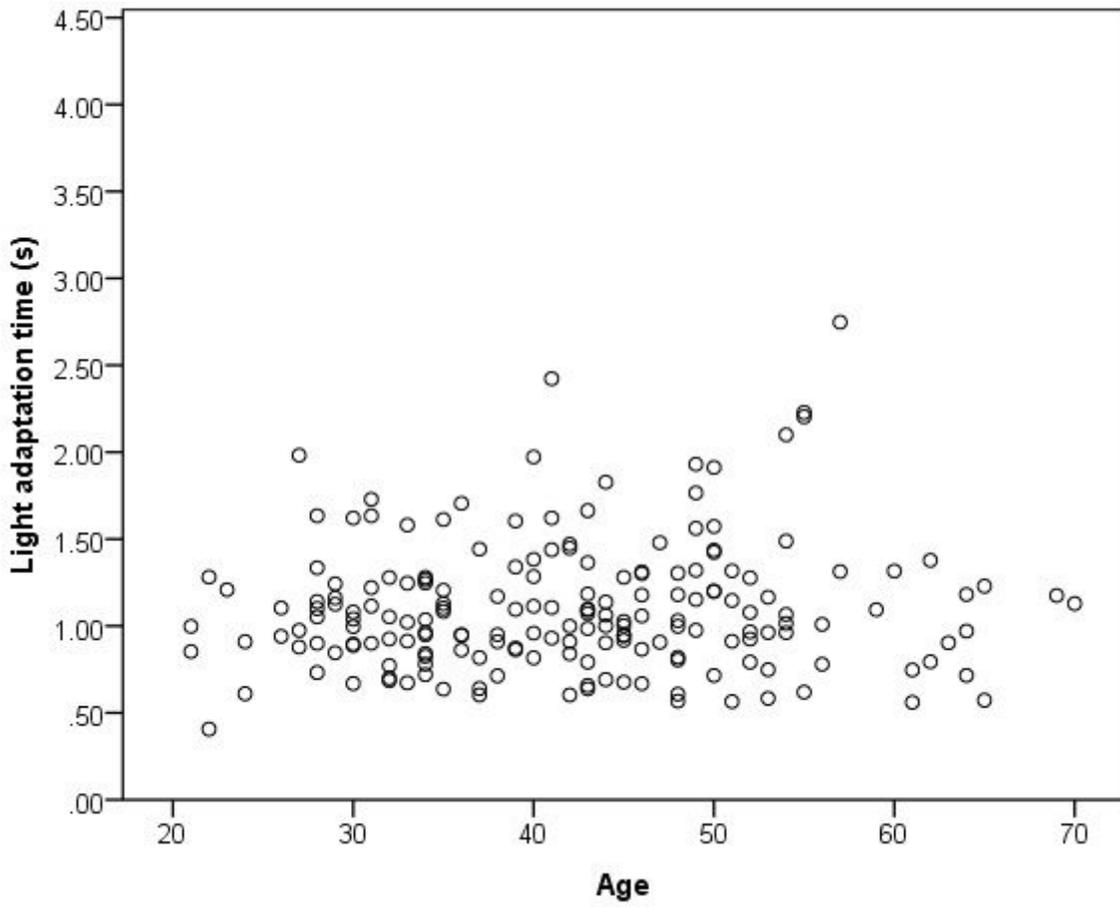


Figure 9

Relationship between the light adaptation time and age (500-8000 lux)

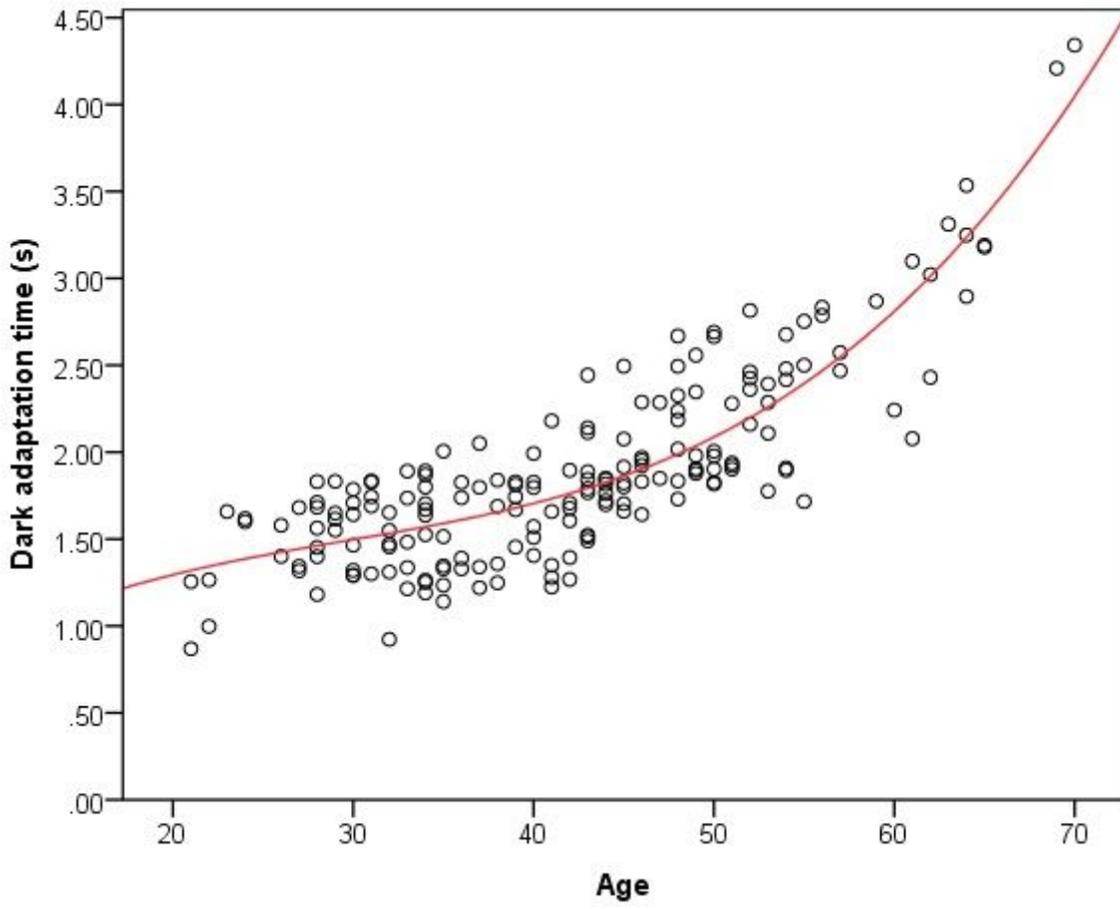


Figure 10

Regression curve of the dark adaptation time and age

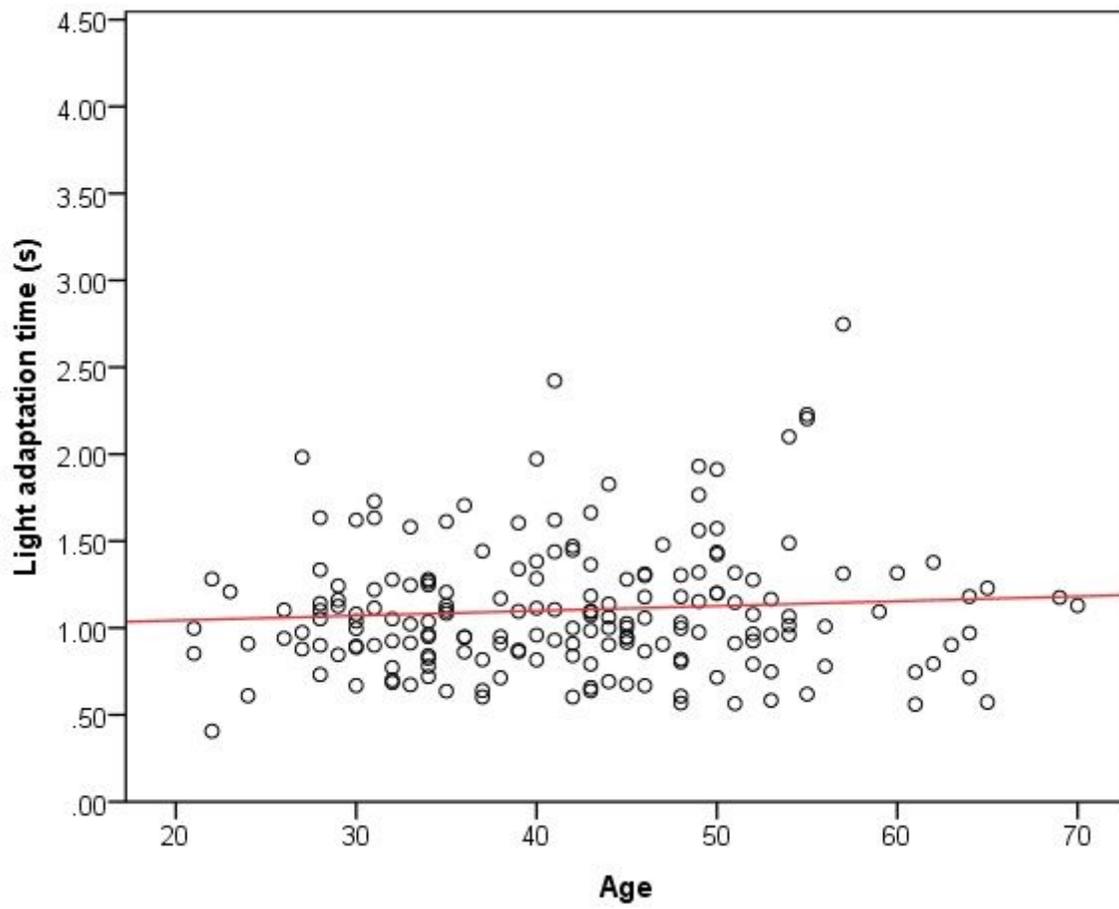


Figure 11

Relationship between the light adaptation time and age Figure 12.

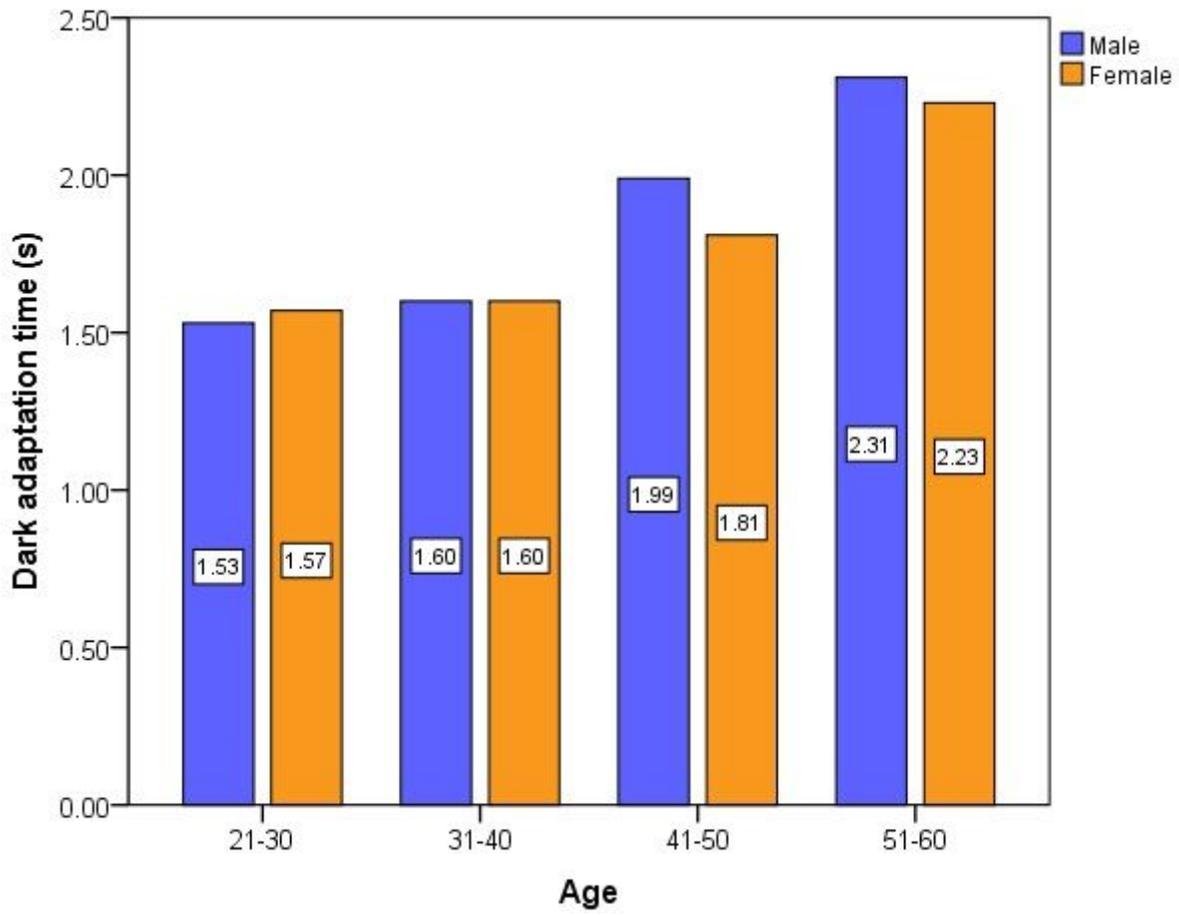


Figure 12

Relationship between gender and dark adaptation time by age

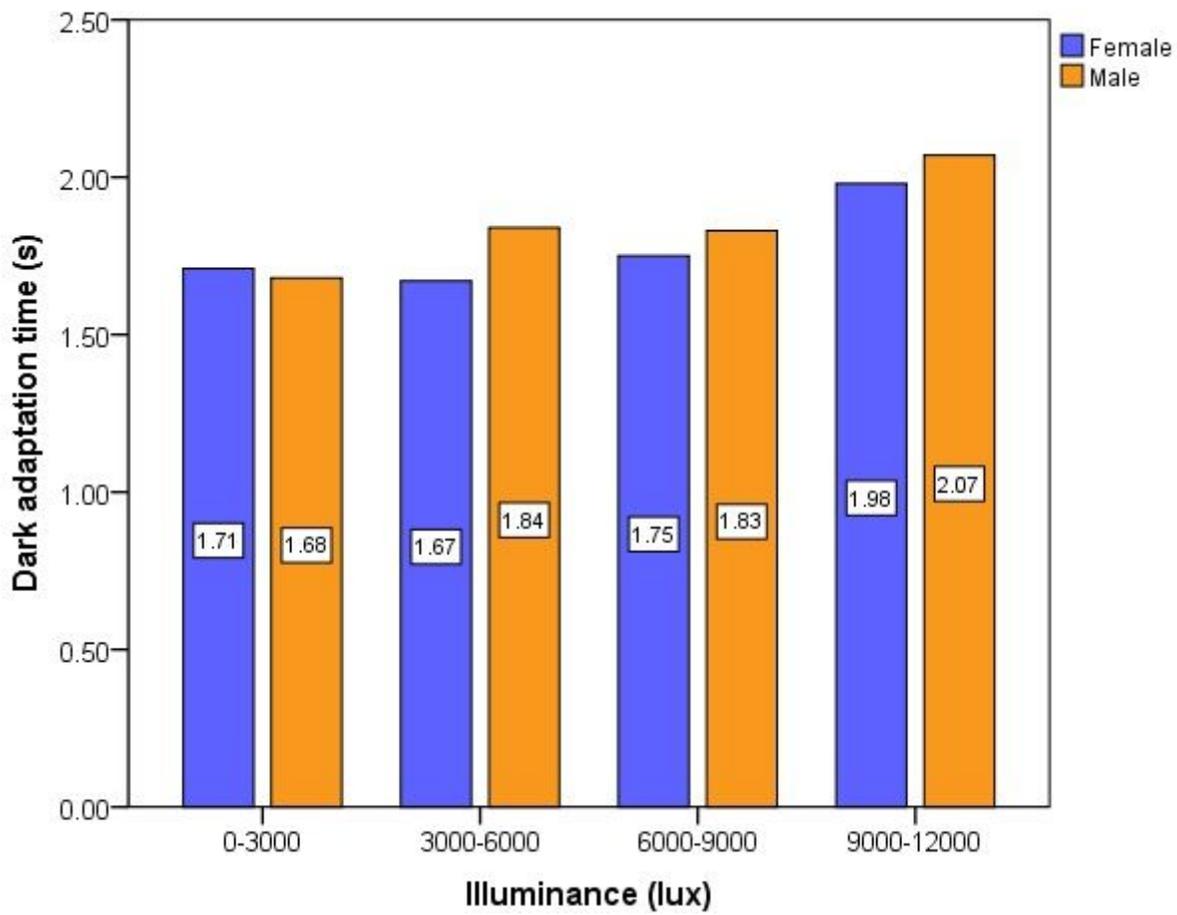


Figure 13

Relationship between gender and dark adaptation time by Illuminance

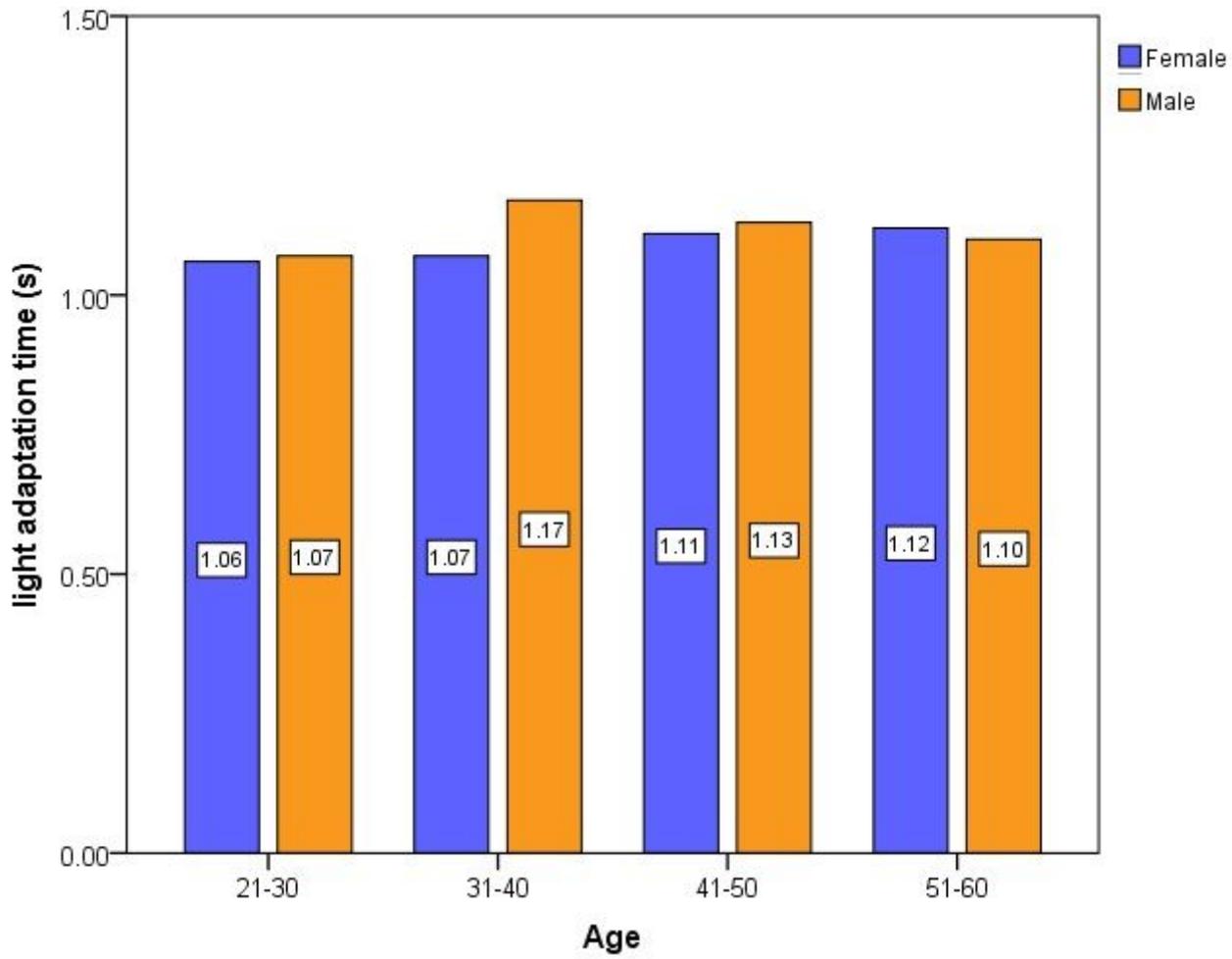


Figure 14

Relationship between gender and light adaptation time by age

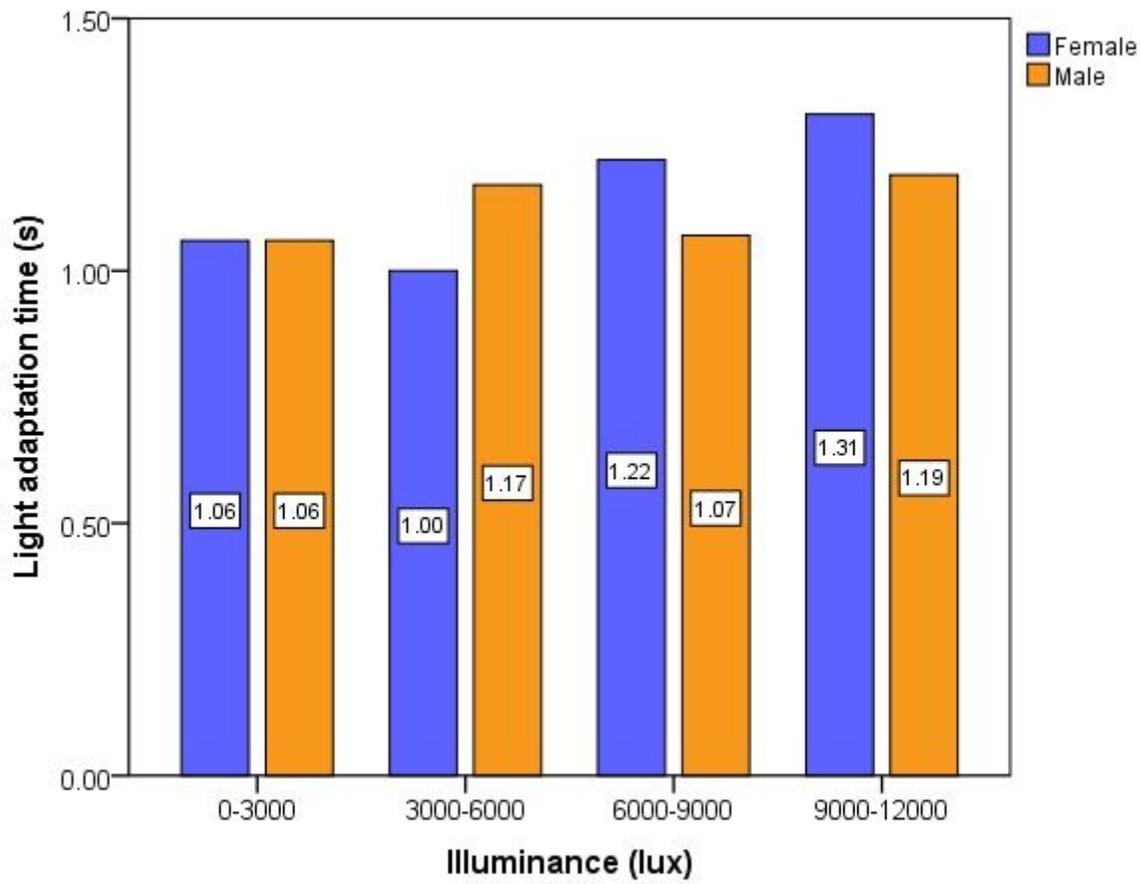


Figure 15

Relationship between gender and light adaptation time by Illuminance

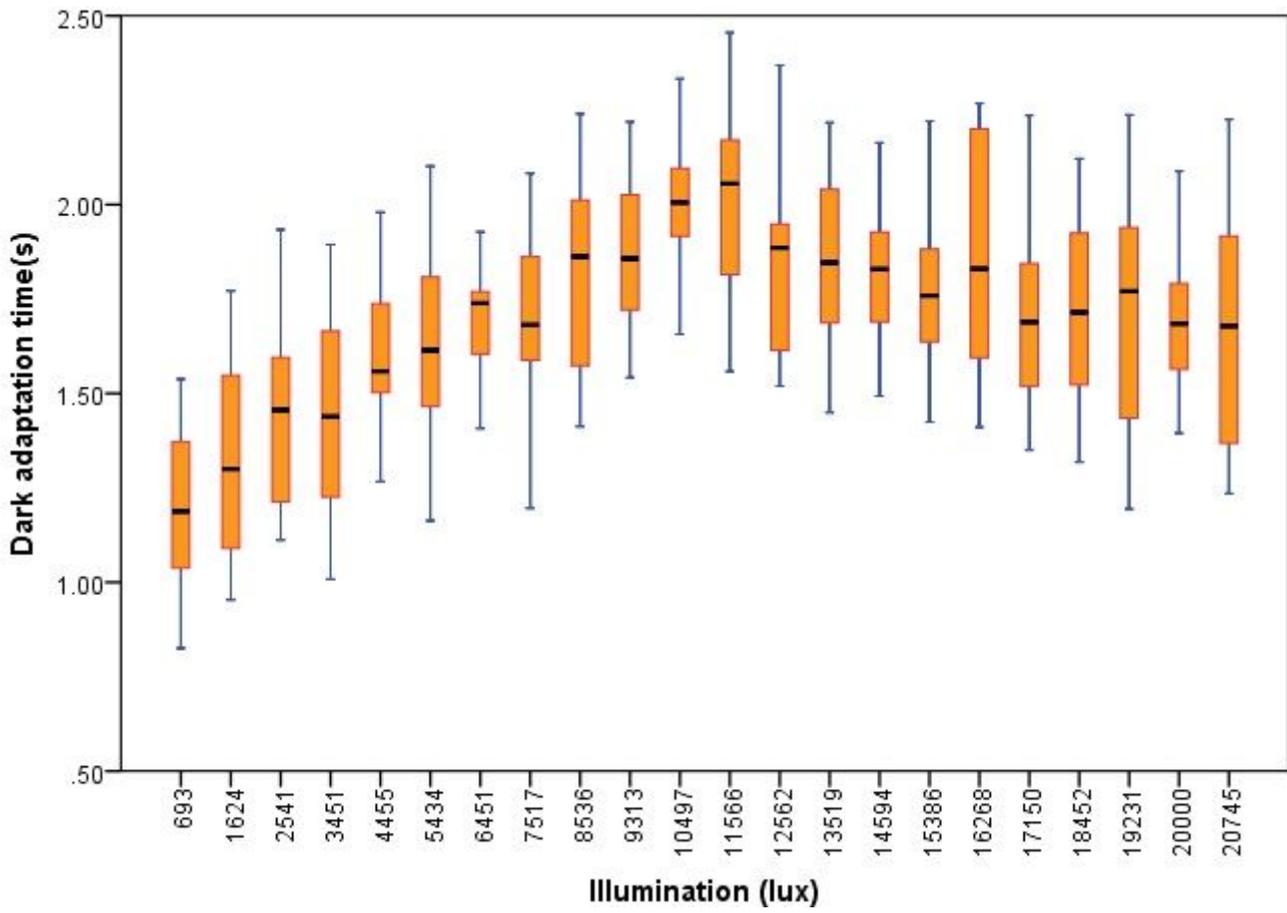


Figure 16

Relationship between the dark adaptation time and illuminance

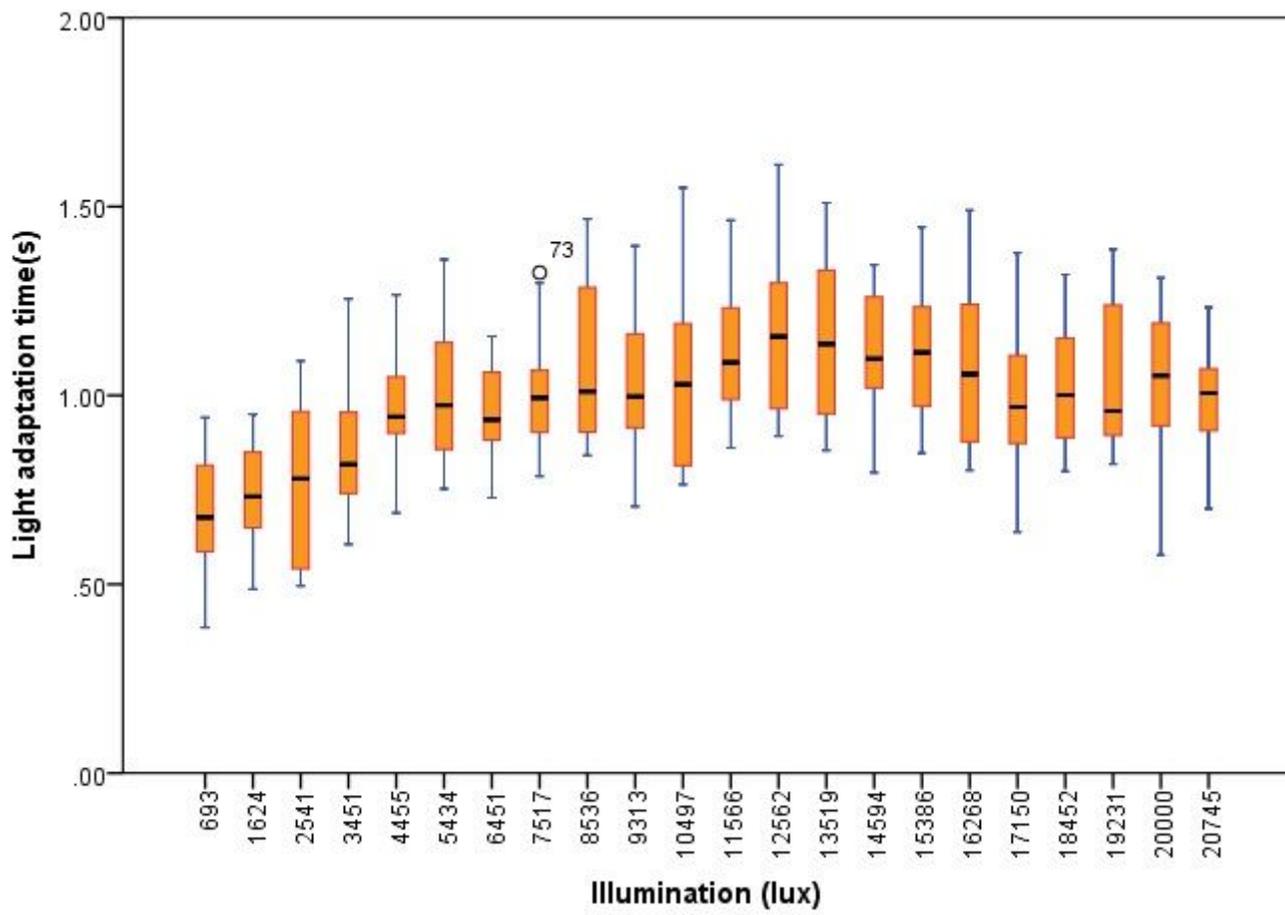


Figure 17

Relationship between the light adaptation time and illuminance

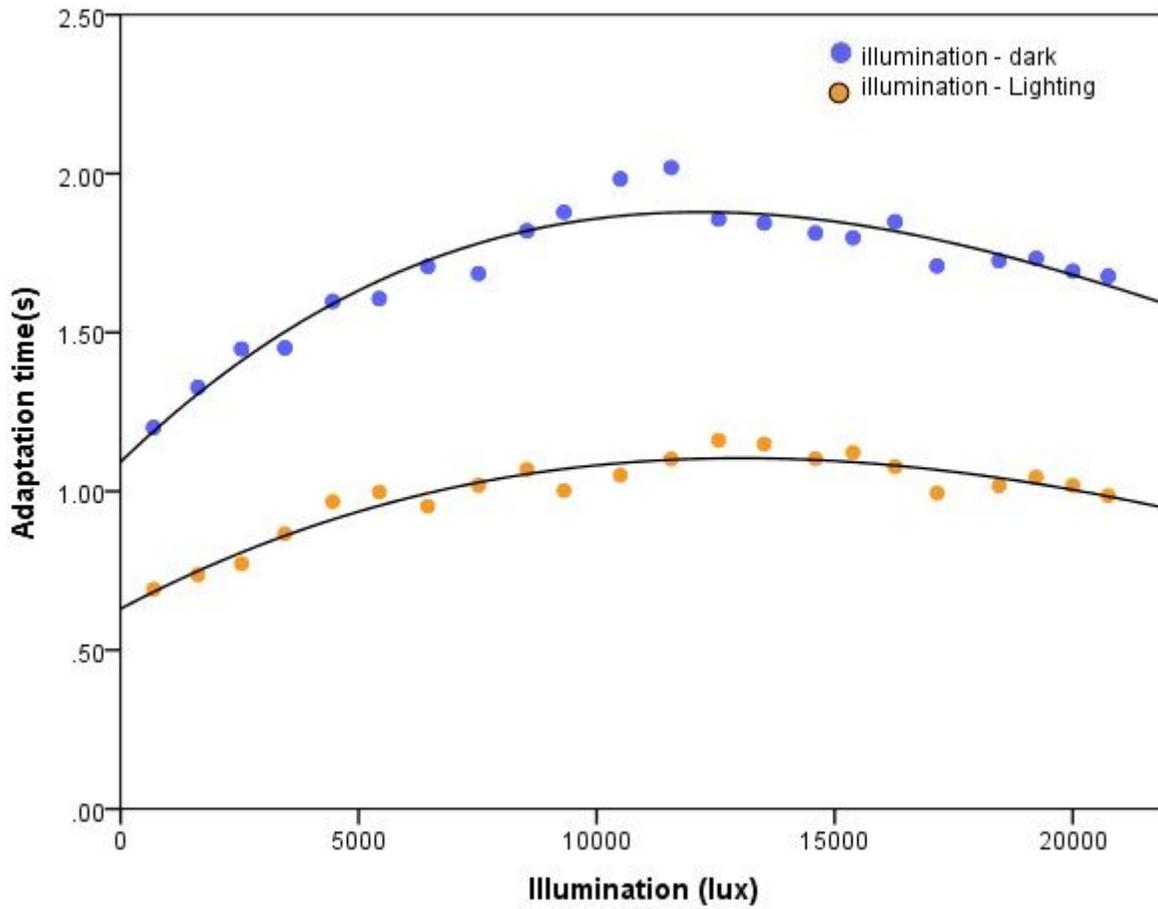


Figure 18

Adaptation time and illuminance models

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Tables.pdf](#)