Intellectual productivity under task ambient lighting

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A subjective experiment was conducted to evaluate intellectual productivity in three lighting conditions: (a) conventional ambient lighting, (b) task ambient lighting with normal colour temperature (5000 K), and (c) task ambient lighting with high colour temperature (6200 K). In the experiment, cognitive tasks were given to 24 participants. The concentration time ratio, which is a quantitative and objective evaluation index of the degree of concentration, was measured. The results showed that the average concentration time ratio under the task ambient lighting with high colour temperature was 72.5% which was 5.0% points higher than that under the conventional ambient lighting. It is believed that intellectual work can be performed better when the concentration time ratio is high

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1. Introduction

Task ambient lighting can reduce energy consumption by combining a low uniform lighting system and a local lighting system instead of conventional uniform lighting systems while maintaining the light levels around working spaces. Previous studies[1,2] have revealed that task ambient lighting is also effective in increasing worker satisfaction and productivity. However, evaluations in previous studies were based mainly on questionnaires (subjective evaluation) and/or simulated office tasks, which might be greatly affected by a learning effect[3].

The present study examined two forms of task ambient lightings in comparison to conventional ambient lighting using the concentration time ratio (CTR), which is a quantitative and objective evaluation index proposed in one of the authors' previous studies[4]. The CTR represents the ratio of the time spent truly concentrating on a task over the total time spent for completing the task rather than the amount of the achievement (e.g. the number of processed tasks per minute). Therefore, it is difficult for CTR to be affected by the learning effect, which means that it is possible to distinguish the performance change induced by the environmental change from that induced by a learning effect. Furthermore, it is expected that intellectual work can be performed better when the concentration time ratio is high. Therefore, intellectual productivity can be measured indirectly by CTR. Here, intellectual productivity is defined as the amount of intellectual output during a certain period of time, which is producible by knowledge processing rather than by a simple response or muscular labour.

The contribution of this paper is to demonstrate the improvement of workers' intellectual productivity by introducing task ambient lighting, quantitatively and objectively. This has been difficult, heretofore, because no means have been available to measure intellectual productivity objectively in a quantitative manner with the learning effect cancelled.

2. Evaluating intellectual productivity

As Ramírez[5] noted, "*there are no universally accepted methods to measure knowledge worker productivity, or even generally accepted categories*". Among various classifications, the classification by Ilgen[6] and Wyon[7] is more or less accepted universally[8-11]. Ilgen[6] classified evaluation methods of productivity into three categories; physiological, objective, and subjective. Wyon[7] further classified objective and subjective methods into six categories: (1) Simulated work (subject performs a realistic but artificial task), (2) Diagnostic tests (subject performs a test procedure unlike any real task), (3) Embedded tasks (outcome metric derived from part of an existing task), (4) Existing measures (existing outcome metrics are made available), (5) Absenteeism (new or existing records of sick leave are used), and (6) Self-estimates (subjects report their own perceived level of efficiency). All evaluation methods have their respective benefits and shortcomings.

2.1 Physiological method

The physiological method measures one or more of the subjects' physiological indices such as heart rate[12], electrodermal activity[13], and cerebral blood flow[14]. This method is based on an assumption that the physiological measures have some relation to nervous system activity. Although this method can measure phenomena objectively, sensors such as a heart rate monitor, electrodes, or near-infrared spectroscopy must be prepared, which might restrict subjects' movement. Furthermore, some sensors require constant vigilance by experimenters during the measurement. It is also problematic that physiological responses are sensitively affected by many factors simultaneously. For instance, heart rate is affected not only by environmental factors such as temperature[15] but also by subject’s personal characteristics[16]. Therefore, as Jin noted[11], "*an extremely stable and well controlled experimental environment is required in order to obtain reliable data*".

2.2 Simulated work

When using the simulated work method, specially designed tasks are performed. The task performance (e.g. number of performed tasks) is measured. Typically, text typing[17-23], arithmetical calculation (addition and/or multiplication)[17-19], proof-reading tasks[17,20-22,24], summary extraction etc.[23] have been used. To evaluate intellectual productivity, especially for the work in an office, it is necessary that the simulated task resemble actual office work, which means that the task must become rather complex. However, complex tasks tend to be affected by a learning effect. A longer practice session is necessary for complex tasks to reach saturation compared to simple tasks[25,26]. Therefore, it is necessary to cancel the learning effect to evaluate slight effects induced by environmental change. A possible method to cancel the learning effect is to design the experiment in a manner in which participants are divided into multiple groups. Each group is presented to different conditions in a different order. However, the speed of learning varies from person to person[27,28]. Therefore, the number of participants must be large to obtain statistically significant result. Another possible method is using the learning curve to compensate the learning effect. However, a long-term experiment is necessary to deduce and compensate the learning effect[29].

2.3 Diagnostic tests

Several kinds of diagnostic tests have been designed to measure specific abilities or disorders. Some of them are the SPES test[30], the Continuous Performance Test[31], and the Dynamic Visual Acuity Test[32]. The SPES test is a computerized psychological test battery that consists of several simple performance tests such as simple reaction time, choice reaction time, and colour word vigilance[30]. The Continuous Performance Test is a computerized neuropsychological test that consists of visual and auditory tests to assess attention-related problems[31]. The Dynamic Visual Acuity Test is a test that measures eye gaze stabilization during head movement[32]. The diagnostic test was used to measure the influence of environmental change[33]. However the tests fundamentally consist of simple primitive tasks intended to be used to measure specific abilities or disorders and are much different from real office work as its definition represents. No report in the literature describes a study showing the association between diagnostic test performance and intellectual productivity.

2.4 Embedded tasks

It is sometimes possible to evaluate productivity by deriving outcomes from a part of an existing task or by embedding a similar task into existing procedures for which outcomes can be measured quantitatively. For instance, Wyon *et al* evaluated the effects of negative ionization by embedding measureable driving-related tasks, such as responding to an alert, into a regular driving task[34]. Wargocki *et al* embedded exercises such as reading or mathematics into normal school work to evaluate the effect of air temperature and ventilation rate in the classroom[35]. Embedded tasks are acceptable for workers because they can conduct the tasks in the same way as their ordinary work. However, similarly to existing measures described later, the number of relevant works is limited.

2.5 Existing measures

In some cases, productivity can be evaluated directly using existing measures. For instance, Fisk *et al* evaluated worker performance using the number of processed calls at a call center[36]. Mas *et al* evaluated worker productivity using the check-out speed of cashiers and investigated how workers influence each other[37]. In this way, productivity can be evaluated quantitatively and objectively using existing measures but only in some cases. Quantitative measures are not always available. Applicable works are few.

2.6 Absenteeism

Absenteeism is a rate or period of absence from work or other regular duty[38,39]. Because absenteeism is a habitual pattern of absence, the measurement is usually conducted over a long period such as months or a year[40,41]. Therefore, absenteeism is not an adequate measure to be applied to a comparison of tentative environments, which are available during limited time periods.

2.7 Self-estimates

Self-estimates or Subjective Productivity Measurement (SPM) is a measurement approach that collects information related to productivity through a questionnaire or an interview[42]. The self-estimates are widely applicable in various works. The results can be analyzed quantitatively and qualitatively. The self-estimate method assumes that the workers can estimate their own productivity properly. However, as Hacker *et al* noted[43], "*people are generally inaccurate in predicting their performance*". Moreover, as Seppanen commented[44], self-estimates may be influenced by subjects' expectations or biases. For instance, Clausen *et al* reported that self-evaluated performance improvements of simple proofreading and addition tasks induced by reducing dissatisfaction about the environment is much greater than actual improvements[45]. Therefore, experiments must be designed carefully to omit biases and expectations, which are difficult to omit if environments are changed drastically because the apparent environmental change makes it easy for subjects to notice the objectives of experiments.

3. Quantitative evaluation by concentration time ratio

3.1 Cognitive state transition model

The Concentration Time Ratio (CTR) is calculated from the answering times to a receipt classification task (see Section 3.2). When performing a task that contains problems of equal difficulty, the answering times must be fundamentally equal. However, the actual histogram of the answering times has a wide distribution, as shown in Figure 1. One possible cause of the distribution is a phenomenon called blocking, defined by Bills[46] as "*a pause in the responses equivalent to the time of two or more average responses*". The phenomenon was explained by Bills as "*periods, experienced by mental workers, when they seem unable to respond, and cannot, even by an effort, continue until a short time has elapsed*." This unavoidable pause is expected to shape the wide distribution of answering times around the mode even if the tasks have equal difficulty. Then, we assume that workers perform a task while switching between at least two kinds of states: working state and short-term rest state. In the working state, they assign their cognitive resources for a certain period to proceed with the task. In the short-term rest state, they unconsciously stopped the task for a short time. Here, we assume that one problem can be completed when a worker stays at the working state a certain number of times. However, it is known that the distribution of response times for a simple cognitive task can be fitted well with one of the ex-Gaussian, inverse-Gaussian, log-normal or

Gamma distributions[47]. Moreover, when the probabilities of the state transitions between the working state and the short-term rest state are assumed to be a fixed value, the model can be regarded as a two-state Markov model. The probability distribution of a two-state Markov model can be expressed using a lognormal distribution. Therefore, it would be reasonable to assume that the left part of the distribution originates from the transition between the working state and the short-term rest state. However, the existence of the right long tail of the distribution, which appears more clearly when a higher level of the cognitive task is conducted for a longer time, cannot be explained by the two-state transition model alone. We therefore infer the existence of another state: long-term rest state. In the long-term rest state, subjects consciously stop the task to take a break or think about other things rather than continue the task for a long period. Summarizing the above, we assume that the workers perform cognitive tasks while switching between a working state, a short-term rest state, and a long-term rest state as shown in Figure 2. The validity of this three-state transition model was confirmed experimentally in our previous study[48]. That study confirmed that simulated answering times based on the three-state transition model matched the actual results of answering times for receipt classification task well.

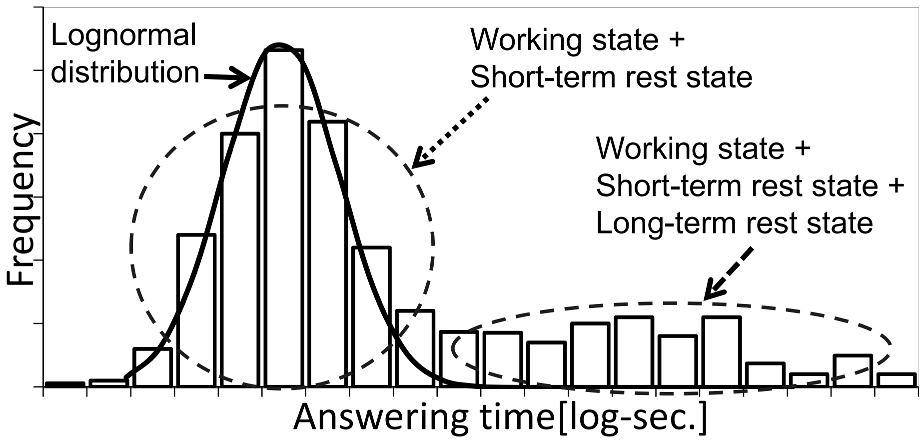

Figure 1. Histogram of answering times and a lognormal distribution.

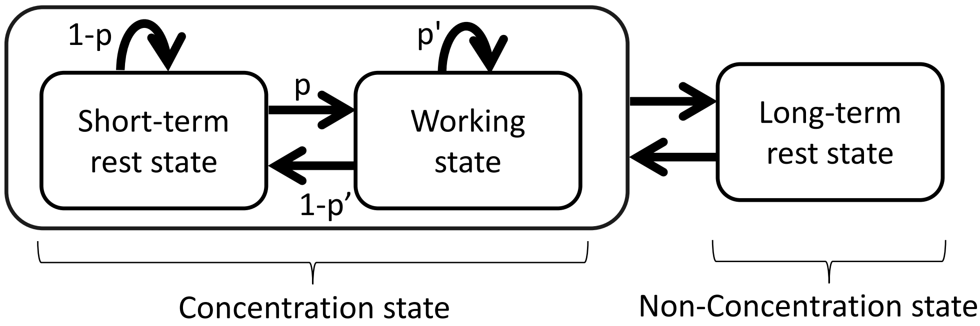

Figure 2. The work state model.

Considering that concentration is a work state in which cognitive resources are assigned to the target task, it can be assumed that the working state and the short-term rest state are concentrating states, whereas the long-term rest state is a non-concentrating state. The right distribution of the histogram includes not only the working state and the short-term rest state, but also the long-term rest state, whereas the left distribution of the histogram expresses the sum of the working state and the short-term rest state. Therefore, it can be inferred that the distribution of the concentrated state can be approximated as the following lognormal distribution (Figure 1).

$$\mathrm{f(t)} = \frac{1}{\sqrt{2\pi}\sigma t} \exp\left[-\frac{(\ln(t)-\mu)^2}{2\sigma^2}\right] \quad (1)$$

Here, t, exp(μ) and σ denote the answering time for one problem, the median, and the standard deviation of the lognormal distribution, respectively. The lognormal distribution is a two-parameter distribution for which the logarithm is normally distributed. Figure 3 depicts how parameters μ and σ affect the distribution. Intuitively speaking, μ and σ are relatively related to the median and width of the distribution, but they are different from a normal distribution. Values which represent the distribution's character cannot be expressed using the simple variables of equation (1). For example, the lognormal distribution's average $\bar{f}$ and median $\tilde{f}$ are calculated respectively using equations (2) and (3).

$$\bar{f} = \exp(\mu + \frac{\sigma^2}{2}) \quad (2)$$

$$\tilde{f} = \exp(\mu) \quad (3)$$

By fitting equation (1) to the left distribution of the histogram, μ and σ can be estimated assuming that the near left end of the distribution includes only the answering times of problems for which the worker answered without staying in the long-term rest state. Therefore, if a lognormal distribution is fitted to the near left end of the distribution, then the goodness of the fit will be extremely high. Consequently, the lognormal distribution is fitted according to the steps below[48]:

Step 1. Sort the answering times in ascending order.

Step 2. Compute a cumulative distribution curve of the sorted answering times and normalize the curve so that the maximum of the curve is 1.0, thereby making it easy to compare the answering time distribution and lognormal function.

Step 3. Fit a normalized cumulative function of lognormal form to the cumulative distribution curve computed in the Step 2 using the least squares method, then calculate the correlation coefficient between the function and the curve.

Step 4. Remove the first (longest) answering time from the sorted answering times.

Step 5. Repeat from Step 2 to Step 4 until the remaining number of answering times reaches the threshold τ chosen in advance.

Step 6. Obtain μ and σ of the fitted lognormal function when the correlation coefficient calculated in Step 3 is the largest.

The threshold τ used at the Step 5 should be chosen according to the time duration allocated to one task set. For this study, we set the threshold to 20, which will be the minimum number of answered problems when it is regarded that the worker tackles the task seriously even if they are extremely exhausted.

When they concentrate on the task, the expected time of the $f(t)$ distribution is an average answering time. Therefore, the average answering time $\overline{\mathrm{CT}}$ in the concentration state is calculated using equation (4).

$$\overline{\mathrm{CT}} = \exp(\mu + \frac{\sigma^2}{2}) \quad (4)$$

The total time used for the concentration state can be expressed as $\mathrm{N} \cdot \overline{\mathrm{CT}}$, where N is the number of problems they answered when performing the task. Therefore, the concentration time ratio CTR is calculated using equation (5), where the total task performing time is T_{Total}.

$$\mathrm{CTR} = \frac{N \cdot \overline{CT}}{T_{Total}} \quad (5)$$

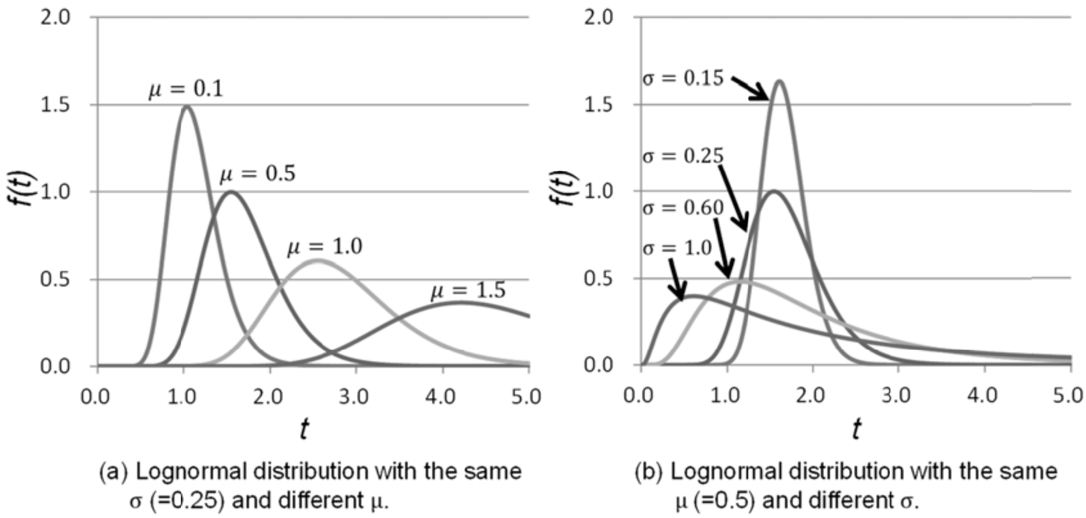

Figure 3. Lognormal distributions with one varying parameter.

Because task performance (answering speed) is improved by repeating the problem solving by learning, it is difficult to evaluate intellectual productivity by task performance alone. The CTR, however, is unaffected by learning because it only expresses the time ratio of the concentration state in the total task performing time, which will not be affected much by learning.

3.2 Cognitive task used for measuring CTR

To measure CTR, it is necessary to present a number of problems to participants and measure the answering time used for each problem. For this purpose, a receipt classification task was prepared[4]. The receipt classification task was designed according to the following requirements:

1. The problems can be processed continuously at the participant's own pace.
2. The problems should have equal difficulty.
3. The strategy used to solve the problems will not change during the evaluation.
4. The problems are solvable by a rule-based response to imitate actual office work rather than by a simple response.

Figure 4 shows the receipt classification task prepared for measuring the CTR. The participant was asked to classify receipts printed on paper into one of 27 categories by the day when the receipt was printed: "1st - 10th", "11th - 20th", and "21st - 31st", the type of trader by which the receipt was printed: "Retail", "Restaurant", and "Transport" and the amount of money: 0 - 5000 Yen, 5001 - 50,000 Yen, and more than 50,001 Yen. Each participant was required to answer the proper category by pressing one of 27 buttons on an iPad display. The answering time of each problem is measured as the time interval between the button presses on the iPad, and sent to a server computer where the answering times are recorded. The answering time therefore includes not only the time necessary to classify the receipt but also the time necessary to turn the papers.

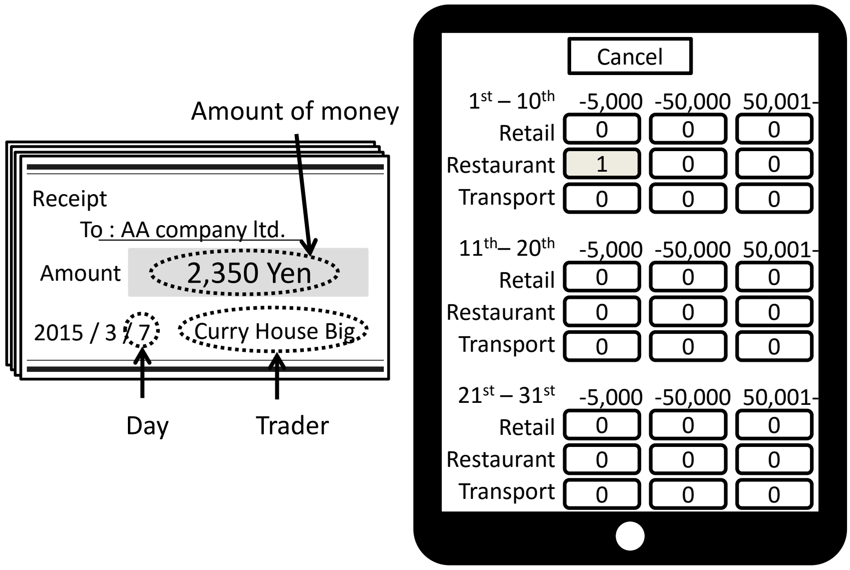

Figure 4. Receipts classified by participants (left) and the interface to be used to input the classified results (right).

4. Method

The lighting conditions examined were conventional ceiling lighting (Ambient), a combination of conventional ceiling lighting and task lighting with normal correlated colour temperature (Normal-Task Ambient (TA)), and that with high correlated colour temperature (High- Task Ambient (TA)), as shown in Tables 1 and 2. The correlated colour temperature of the task lighting in the High-TA condition is higher than that in the Normal-TA condition, which aims at the effect of awakening[49,50]. Although the illuminance of all the conditions is 750 lux on the desk, the energy consumption of the Normal-TA and High-TA conditions is only 59% of that of the Ambient condition. Furthermore, it is expected that the workers can concentrate better on their tasks in the Task Ambient conditions because the room area except for the desk is dark, as shown in Figure 5, thereby eliminating the surrounding visual noise.

Figure 5. The desktop in the High-Task Ambient condition.

Figure 6 shows the experimental procedure. The experiment was conducted for four consecutive days: Monday-Thursday. The first day was mainly for the introductory explanation, the practice of the receipt classification, and the dummy task. As the dummy task, the participants were asked to conduct a word classification task, which is a task to classify words printed on paper into one of 27 categories by the sort of character, the first vowel, and meaning. The word classification task is not adequate to be used for measuring CTRs because the difficulty varies according to the knowledge of the participants. The task was therefore used as the dummy task in the experiment. Each day was divided into four sets: one set was conducted in the morning; three sets were conducted in the afternoon. Lunch rest was allocated between SET1 and SET2. 10 minute rests were also allocated between SET2 and SET3, and SET3 and SET4. SET1, SET2, and SET3 were composed of the receipt classification task (30 minutes), 3 minutes rest, and a dummy task (30 minutes) performed to avoid boring the participants with the receipt classification task. The CTRs were calculated for the receipt classification task of SET1, SET2, and SET3. Questionnaire responses were given (the results are not presented in this paper) and the critical flicker frequency was measured using the Flicker Test before and after the SET1, before and after the SET2, and after the SET3. The participants also performed SET4 (receipt classification task) for 10 minutes to avoid the terminal effect.

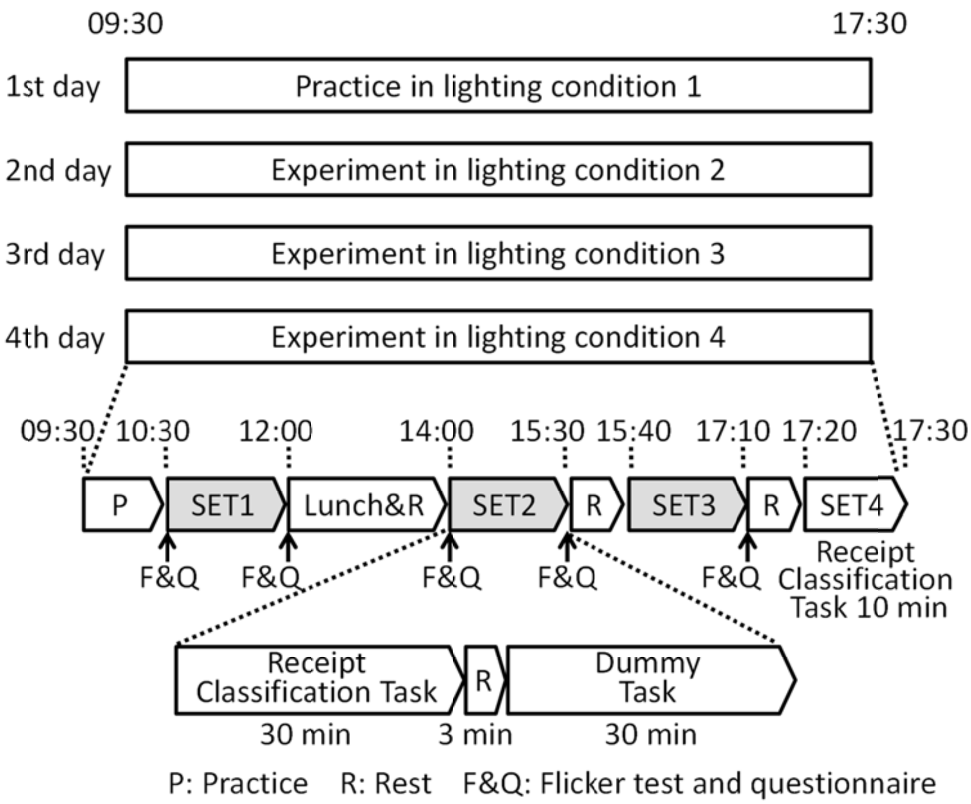

Figure 6. Experimental procedure.

In this experiment, 12 men and 12 women aged 30-53 years participated. None was colour-blind. They were divided into six groups (four participants in each group). The order of the lighting condition was counterbalanced to eliminate the order effect of the lighting conditions, as shown in Table 3. The participants were told the following: "*Please keep pace so that you can continue the work from 9 a.m. to 7 p.m. at the same speed. Perform the work as accurately as possible*." Participants were also instructed not to ingest any caffeine such as tea or coffee during the experiment. The beverage (water) and lunch were served during the experiment. The experiment was conducted from 29 July through 5 September in 2013 in an experimental room at Kyoto University (with a floor area of 55 m^2). Figure 7 depicts the experimental room in the Ambient condition. To simulate an office environment, some books were placed in front of each participant and posters to simulate bookshelves were pasted on the partitions. All windows in the room were shaded. The room temperature was set to 26±1°C. Humidity was set to

70±10%. The CO_2 concentration was kept to less than 800 ppm. The noise level was kept to less than 55 dB.

Figure 7. Experimental environment (Ambient condition).

5. Results and discussion

Of 24 participants, three participants were omitted from analyses because results showed that one participant in Group 5 misunderstood the rules for classifying receipts. The results of one participant in Group 2 could not be fitted with the lognormal distribution stably. In addition, it was found by conversation with the experimenter that one participant in Group 6 noticed the experiment objective and tried to produce better performance in the Task Ambient condition intentionally.

Figure 8 shows the distributions of answering times (bar chart) and fitted log-normal distributions (dotted line) of Subject 12 in Group 3 on Wednesday (Ambient condition) and on Tuesday (High-TA condition). These are typical distributions of the answering times. The minimum correlation coefficient among all SETs except for the omitted three participants was 0.98, which shows a high goodness of fit.

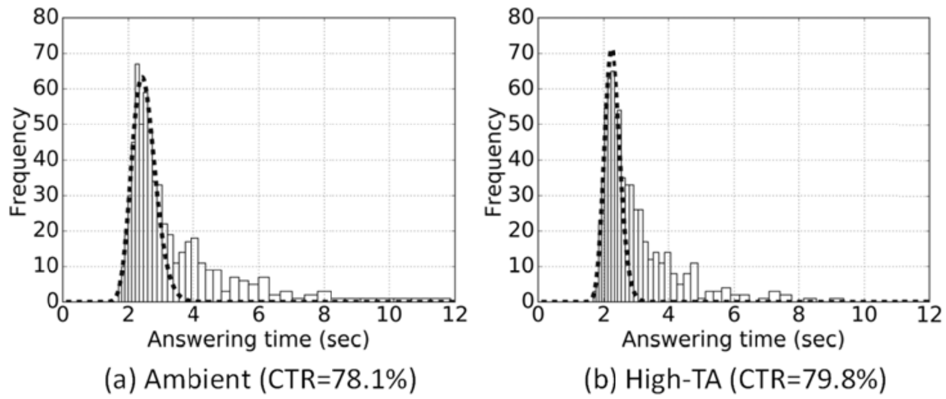

Figure 8. Answering time distribution for one subject (bar chart) and fitted lognormal function (dotted line) in (a) Ambient condition and (b) High-Task Ambient condition.

Figure 9(a) presents the task performance (number of answers per minute) of the receipt classification task for the first day and fourth day. The distribution normality was confirmed using Kolmogorov-Smirnov tests. As the figure shows, the one-tailed paired t-test revealed a statistically significant difference caused by the learning effect ($p < 0.001$). The change of productivity by the change of the lighting condition is indistinguishable from the change by the learning effect. Figure 9(b) presents the CTR for first day and fourth day. The same analysis as that shown in Figure 9(a) was done for the CTR, but no statistically significant difference was found between the results for first day and fourth day. The effect size of the performance and CTR were calculated using Cohen's d. The results were 0.712 and 0.139, respectively, for performance and CTR. We interpret an effect size of 0.712 as a large effect, and the effect size of 0.139 as a small effect, which means that the CTR was unaffected by a learning effect. The CTR for first day and fourth day does not change much, although the performance for the fourth day is higher than that for the first day, which implies that the time spent concentrating for each problem decreases as the participants become familiar with the task, and the procedure to produce the task is optimized.

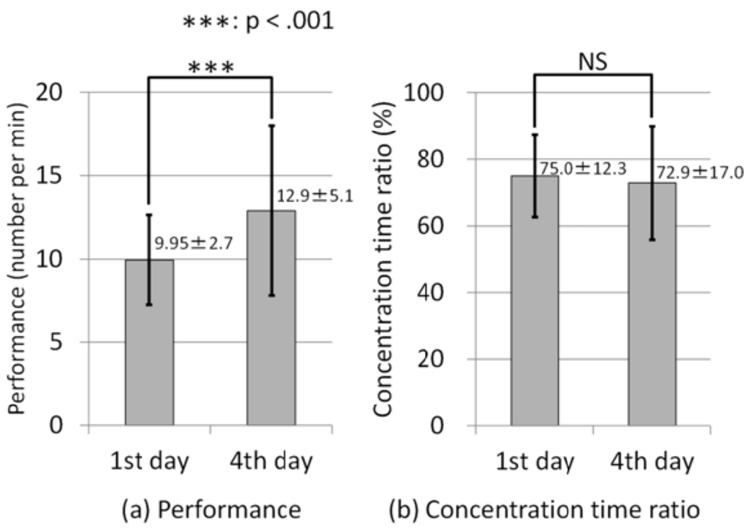

Figure 9. Mean scores and standard deviations for performance and concentration time ratio of receipt classification task for the first day and the fourth day.

Figures 10 and 11 respectively show CTRs in the three lighting conditions and the performance (mean answering time), respectively. No statistically significant difference was found in the mean answering times among three lighting conditions using one-way repeated measures ANOVA (Figure 11). CTR in the Normal-TA condition did not pass a Kolmogorov-Smirnov test ($p < 0.05$) that was applied to confirm the distribution normality. The Normal-TA condition was therefore omitted from the following statistical analysis. Improved concentration is expected in the High-TA conditions compared to the Ambient condition because the focused TA lighting will be able to reduce the cocktail party effect of vision. The cocktail party effect for hearing is a well-known phenomenon by which a person can recognize personally meaningful words from a conversation by filtering out other noise, or in which we notice personally meaningful words even if we do not devote attention intentionally to the conversation[51]. This ability is explained by assuming that we always spend some cognitive resources unconsciously to events occurring around us[52]. Shapiro *et al* reported that the cocktail party effect can be extended to vision[53]. They showed that our names can be recognized even when they are presented to unattended visual stimuli. This fact implies that cognitive resources will be allocated to a great degree when we see many objects. They will affect our consumption of cognitive resources. By contrast, when we see only a few objects, more cognitive resources can be allocated to the target task and will increase the concentration time ratio for the target task. Therefore, the one-tailed paired t-test was used for the comparison of the High-TA condition and the Ambient condition. The results showed that the CTR in the High-TA condition was 5.0% points higher than that of Ambient condition with a statistically significant difference ($p < 0.01$).

No parametric statistically significant difference was shown between the Normal-TA and High-TA, but the average of CTR in the High-TA condition is larger than that in the Normal-TA condition (1.6% points). These results are in line with previous studies in which more primitive tasks were used to evaluate the participants' performance.

Regarding the task ambient lighting, Newsham *et al* showed that task lighting improves performance of the text typing task in which participants retype passages from printed originals to the computer, and a vigilance task in which participants simply respond to events as soon as possible[2]. Veitch *et al* also reported that when task lighting is employed with direct and indirect lighting, speed may increase for the proofreading task in which participants find different characters by comparing lines that include upper case letters, lower case letters, and numbers[54].

However, Boyce *et al* reported that illuminance distribution does not affect performance directly for the vision test (participants report whether they can see targets drawn on computer screen with various contrast, or net), vigilance test (participants respond to a random prompt as soon as possible), and cognitive judgements (participants rate accuracy of a passage summary)[55]. A possible reason that the effect of illuminance distribution variance was small in the Boyce *et al* experiment is that the illuminance distribution variance between workspace and surrounding was smaller than that in our experiment. Participants were able to control the illuminance of lighting in the Boyce *et al* experiment but were unable to control it in our experiment.

Regarding colour temperature, Lehrl *et al* showed that blue light improves performance on simple reading aloud task compared to normal light[56]. Lockley *et al* showed that blue light significantly reduce subjective sleepless rating, auditory reaction time, and attentional failures[57]. Deguchi *et al* demonstrated that high colour temperature light (7500 K) activates a contingent negative variation (CNV), one of the features of the electroencephalogram which represents subject's expectation of a stimulus occurrence, than lower colour temperature light (3,000 K)[49]. Mills *et al* demonstrated that high colour temperature light (17,000 K) significantly improve self-reported ability to concentrate[50]. A possible reason that the effect of colour temperature variation is smaller in our experiment than in previous studies is that the colour temperature of High-task Ambient condition in our experiment is lower than that of the previous study.

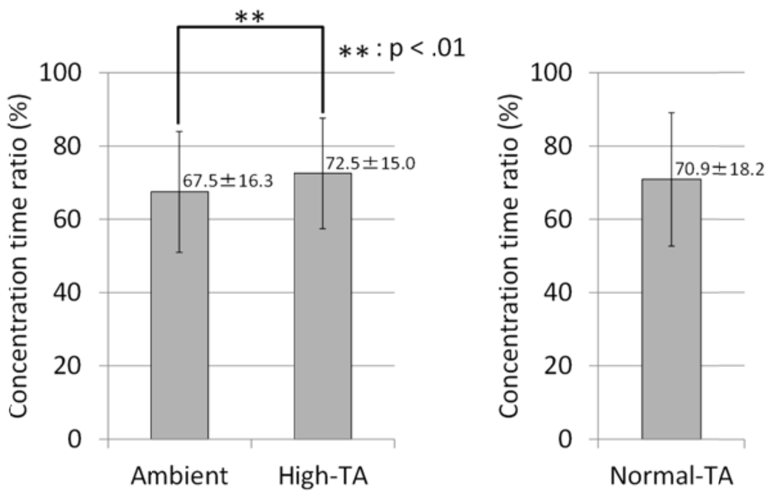

Figure 10. Mean scores and standard deviations for the concentration time ratio of receipt classification task in three lighting conditions.

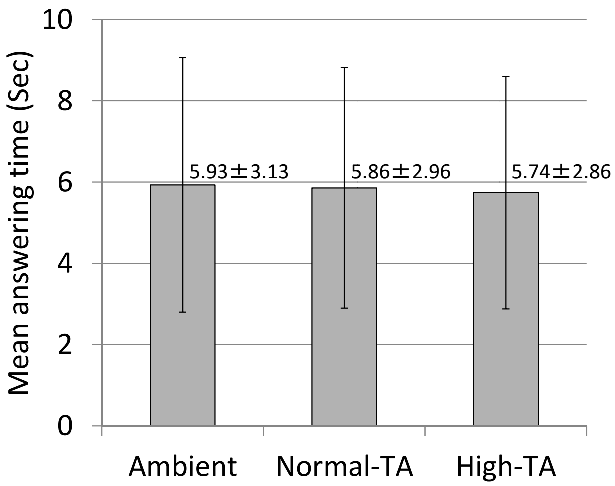

Figure 11. Mean and standard deviations for the answering times of the receipt classification task in three lighting conditions. (CTR in the Normal-TA condition did not pass the distribution normality test (Kolmogorov-Smirnov test).

Figure 12 shows the critical flicker frequency in each lighting condition, which was analyzed with a one-way repeated measures ANOVA. The data for one group (4 participants) was missing because of measurement failure. The results showed that the critical flicker frequency significantly differed over time ($F(4, 16) = 7.03$, $p < 0.001$) only in the Ambient condition. A *post-hoc* Bonferroni t-test for the Ambient condition revealed statistically significant differences between before and after SET1 ($p < 0.05$), and before SET1 and the others except after SET1 ($p < 0.01$). Therefore, the fatigue of cerebral neocortex was found only in the Ambient condition. This result is also explainable by the fact that the Task Ambient lighting can reduce the cocktail party effect of vision so that the unconscious processing was reduced.

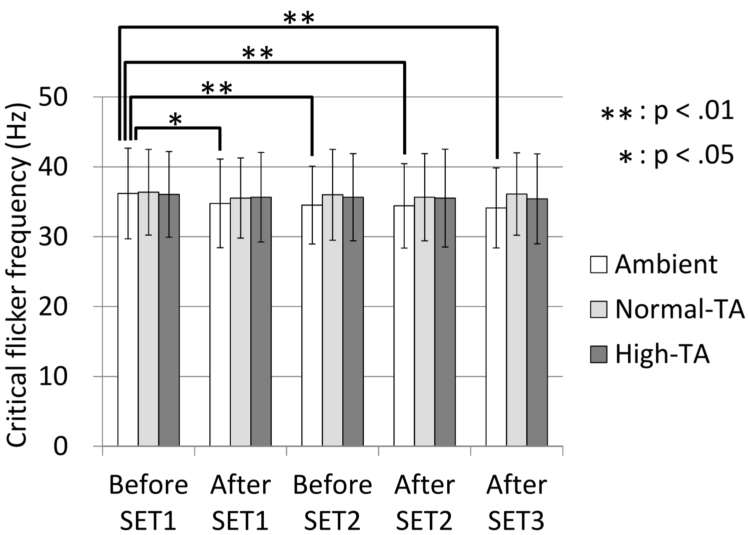

Figure 12. Mean scores and standard deviations for the critical flicker frequency in the three lighting conditions.

6. Conclusions

Three lighting systems were evaluated quantitatively and objectively using the CTR proposed in the authors' previous study[4]. The evaluation results showed that the task ambient lighting system with high colour temperature (6,200 K) provides better performance than the ambient lighting system by 5.0% points of the CTR, although no statistically significant difference was found between the task ambient lighting systems with different correlated colour temperatures. For future work, further studies will be conducted to verify the results of the evaluations obtained in this study by conducting similar evaluation experiments in an actual office.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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Figure captions

Figure 1. Histogram of answering times and a lognormal distribution.

Figure 2. The work state model.

Figure 3. Lognormal distributions with one varying parameter.

Figure 4. Receipts classified by participants (left) and the interface to be used to input the classified results (right).

Figure 5. The desktop in the High-Task Ambient condition

Figure 6. Experimental procedure

Figure 7. Experimental environment (Ambient condition)

Figure 8. Answering time distribution for one subject (bar chart) and fitted lognormal function (dotted line) in (a) Ambient condition and (b) High-Task Ambient condition.

Figure 9. Mean scores and standard deviations for performance and concentration time ratio of receipt classification task for the first day and the fourth day.

Figure 10. Mean scores and standard deviations for the concentration time ratio of receipt classification task in three lighting conditions. (CTR in the Normal-TA condition did not pass the distribution normality test (Kolmogorov-Smirnov test).

Figure 11. Mean and standard deviations for the answering times of the receipt classification task in three lighting conditions.

Figure 12. Mean scores and standard deviations for the critical flicker frequency in the three lighting conditions.

Table 1. Lighting conditions.

	Illuminance (Ceiling / Task light)	Colour temperature (Ceiling / Task light)
Ambient	750 lux / 0 lux	5000 K / N/A
Normal-TA	300 lux / 450 lux	5000 K / 5000 K
High-TA	300 lux / 450 lux	5000 K / 6200 K

Table 2. Light source used in the experiment.

	Ceiling light	Task light (5,000K)	Task light (6,200K)
Vender	Panasonic Corp.	Panasonic Corp.	Panasonic Corp.
Model number	FHF 32EX-N-H	SQ-LD500-W	SQ-LD500-W (modified)
Lamp type	Fluorescent	LED	LED
Colour rendering index	Ra84	Ra90	Ra90
Control gear / Brightness control	HF electronic ballast	Duty cycle control	Duty cycle control
Frequency of electric supply	60 Hz	60 Hz	60 Hz

Table 3. Order of the lighting conditions for each group.

	Monday (1st day)	Tuesday (2nd day)	Wednesday (3rd day)	Thursday (4th day)
Group 1	High-TA	Ambient	Normal-TA	High-TA
Group 2	Normal-TA	Ambient	High-TA	Normal-TA
Group 3	High-TA	Normal-TA	Ambient	High-TA
Group 4	Normal-TA	High-TA	Ambient	Normal-TA
Group 5	Ambient	Normal-TA	High-TA	Ambient
Group 6	Ambient	High-TA	Normal-TA	Ambient