EXPERIMENTAL STUDY ON WALKING SPEED IN ESCAPE ROUTE CONSIDERING LUMINOUS CONDITION, SMOKE DENSITY AND EVACUEE’S VISUAL ACUITY

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ABSTRACT

Travel speed measurements to clarify the effect of visibility on evacuee’s performance were conducted. Visual ability is an independent variable. The two age groups (30 young and 30 aged) are subjected to visual acuity tests, prior to the travel experiment. Eight levels of floor illuminance, complete or incomplete adaptation conditions and luminous conditions with or without smoke were set. The travel speed of the younger group is faster than that of the aged group regardless of illuminance level and smoke density, but the age difference of travel speed can be treated by visual acuity. In this report, a calculation model to predict travel speed by luminous environment (incorporating illuminance level, adaptation condition, and smoke density) and evacuee’s visual acuity was conducted. This model helps predict the performance of evacuees such as the adaptation process after sudden blackouts or travel speed under fire smoke.

KEYWORDS: Evacuation, Travel speed, Visual acuity, Illuminance, Adaptation, Smoke density

INTRODUCTION

When a serious fire breaks out causing power failure or smoke in large area, deterioration of visibility is expected. This deterioration of visibility may significantly influence the evacuation behavior of evacuees, potentially resulting in serious human hazards, like the fire in the subway in Taegu, Korea. This report studies the relationship among visual conditions, human visual ability and travel speed in fire smoke based on the following experiment.

Lowered visibility in escape routes in emergency situations in urban areas can induce human damage resulting from difficulty in expeditious evacuation. Simmons[1] and Jaschinski[2] studied the relations between luminous quantities and travel speed of evacuees. However, due to several points left unexplored by their studies, direct application of the findings to concrete design of evacuation routes may cause some problems.

1. From their correlation between illuminance on floor surface and travel speed, it is not clear at which illuminance value travel speed reaches its maximum.
2. From their correlation between illuminance on floor surface and travel speed for different age groups, it is not clear if the difference of visual acuity between the groups is involved in the result.
3. Effect of light adaptation on the travel speed under circumstances with sudden change of illuminance in the course of evacuation was not investigated.

In order to resolve their problems, the visibility and travel speed for different luminous conditions and visual acuities of subjects were studied in this paper. Travel speed measurements were conducted to clarify the effect of visibility on evacuee’s performance.

METHODS

Experimental Apparatus

The experimental space (1.77 $_{\text{Height}}$ × 1.77 $_{\text{Wide}}$ × 27.78 $_{\text{Length}}$ m) is divided into three sections; adapting space (Length 5.58 m), travel space (18.48 m) and evaluation space (3.72 m). Fig. 1 shows the cross-section view of the experimental space. Daylight is shut off by walls and shading curtain, and the reflectance ratio of all the wall surfaces is 0.427.

Fluorescent lights of 20 W are installed at the corner of the ceiling and sidewall with 3.6 m interval, securing evenly distributed illuminance around the center of the floor. The lights of the adapting space and travel space are connected to respective dimmers, allowing control of the floor illuminance level of each space separately from 0.03[lx] to 300[lx].

Infrared sensors are located on the sidewall with 3.0 m interval to measure when a subject crosses the sensors. For the visual task, cubic blocks (dimension 0.1 m or 0.05 m, reflectance ratio 0.36, luminance contrast with the floor 0.16) are randomly put on the floor.

Subjects are first exposed to the illuminance of the adapting space for 2.5 minutes, then they enter the travel space, negotiate the blocks until they reach the evaluation space, where they answer the questionnaire on visibility, ease to walk, and anxiety while walking.

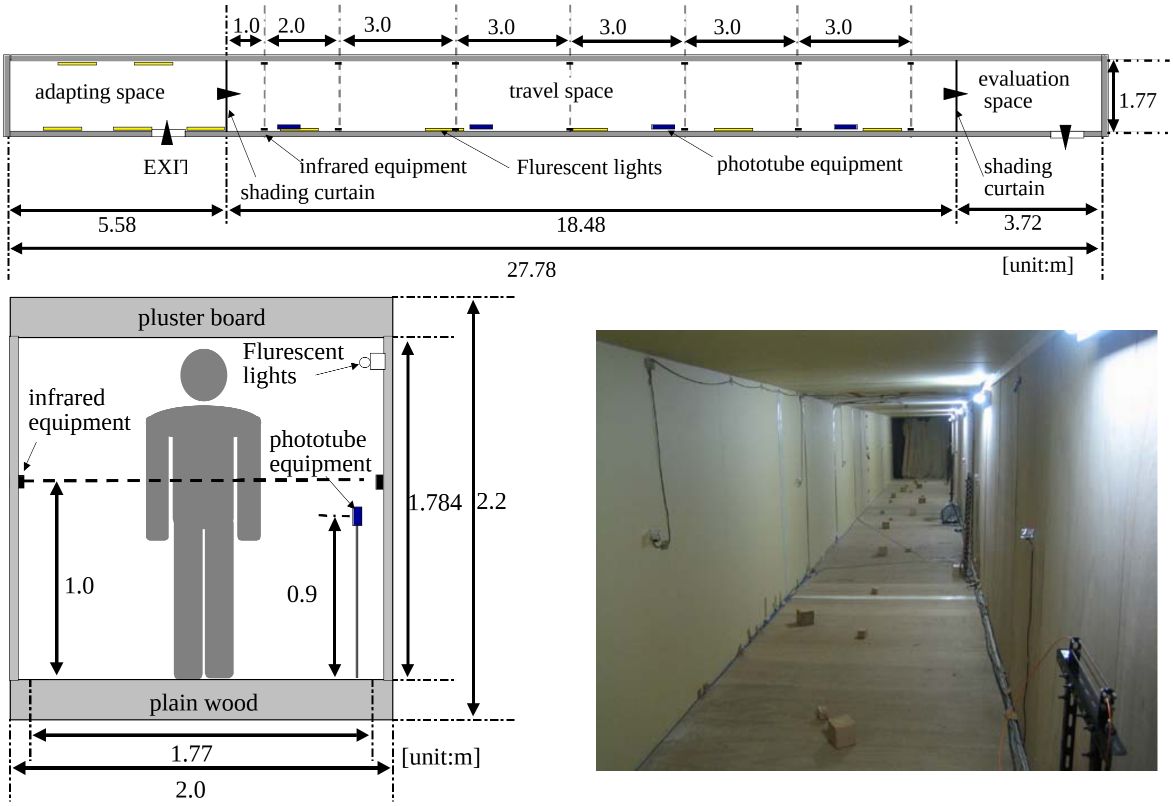


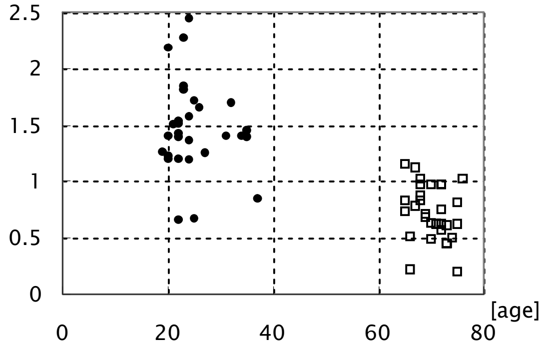
FIGURE 1. Experimental space

Subjects

Visual ability is an independent variable. Two age groups (young and aged) are subjected to visual acuity tests, prior to the travel experiment. Subjects consist of 30 youths and 30 seniors. A test chart of

Landolt Ring is used for visual acuity. In order to measure visual acuity under the same illuminance levels of travel space, the subjects adapt to each illuminance level for 2.5 minutes in a measurement room. The wall reflectance of the measurement room is 0.93, and luminous distribution over the test chart is almost even. The distance of the test chart from a subject is 1.5 m. The reflectance of the test chart is 0.70, and the contrast between background and Landolt Ring is 0.94. Each subject answers the gap direction of Landolt Ring, and his visual acuity under each illuminance level was determined by 80% of the correct answer ratio of 8 gap direction tested.

Fig. 2 shows the maximum visual acuity at 1000[lx]. There are obvious differences in the maximum visual acuity between the young and aged groups. The visual acuity of the aged group is about one half of that of the young group.



	Young	Aged
age	24.9±5.1	70.2±3.3
visaul acuity	1.48±0.40	0.72±0.24

average±standard deviation

FIGURE 2. Visual acuity at 1000 [lx] and age of subjects

Relationship between Background Luminance and Visual Acuity

Visual ability is enhanced with higher illuminance (or luminance). Fig. 3 shows the relations between visual acuity and background luminance of Landolt Ring tests for age groups (calculated by average scores and standard deviation of each illuminance). The luminous level on the surface of Landolt Ring test chart was controlled by an illuminance meter, so the background luminance of test chart from the surface illuminance and the reflectance of test chart were calculated using the following equation [1].

$$L = \frac{E \times \rho}{\pi} \qquad [1]$$

where the background luminance of Landolt Ring test chart is L[cd/m^2], the surface illuminance of test chart is E[lx], and the reflectance of test chart is ρ [-]. In this experiment, ρ is 0.70.

In Fig. 3, positive correlations are confirmed between visual acuity and background luminance, and the aged subjects' visual acuity is consistently about one half of that of the young subjects. Therefore, representing visibility under light conditions by visual acuity means considering individual differences.

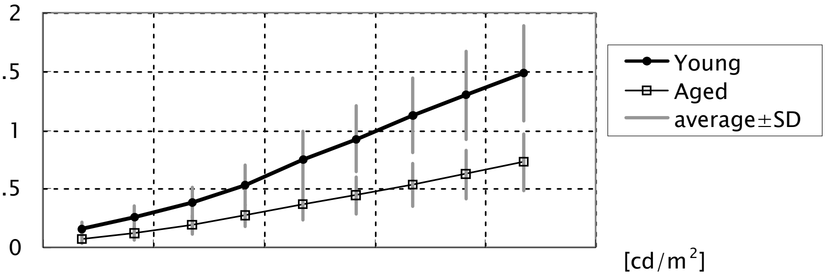


FIGURE 3. Relationship between illuminance and visual acuity

Lighting Conditions

Table 1 shows the luminous conditions in this series of experiment. Eight levels of floor illuminance of the travel space were set: 0.03, 0.1, 0.3, 1, 3, 10, 30, and 100 [lx]. Two types of adaptation were tested: complete adaptation and incomplete adaptation. The illuminance difference between the adapting space and travel space is treated as the ratio of the illuminance of adapting space to that of the travel space i.e. “the illuminance ratio, $RE_{adaptation}$”. The illuminance ratio is expressed as equation [2]. The illuminance ratio is set from 1 to 10000, and if the illuminance ratio is equivalent to 1, it means that the adaptation condition is complete.

$$RE_{adaptation} = \frac{E_a}{E_t} \qquad [2]$$

where the illuminance on the floor level of adapting space is E_a[lx], and the illuminance on the floor level of travel space is E_t[lx].

TABLE 1. Luminous conditions in this experiment

Adaptation		complete	incomplete adaptation			
$RE_{adaptation}$		1	10	100	1000	10000
Floor Illuminance	0.03[lx]	●	●	●	●	●
	0.1	●	●	●	●	
	0.3	●	●	●	●	
	1	●	●			
	3	●				
	10	●				
	30	●				
	100	●		(●Experiment Condition)		

RELATIONS AMONG ILLUMINANCE, TRAVEL SPEED AND VISUAL ACUITY UNDER COMPLETE ADAPTATION

Relationship between Illuminance and Travel Speed

The relation between travel distance and speed in travel space (18 m) for an aged subject is shown as an example in Fig. 4. No remarkable change of speed with travel distance is seen here, but the speed tends to increase with the level of floor illuminance.

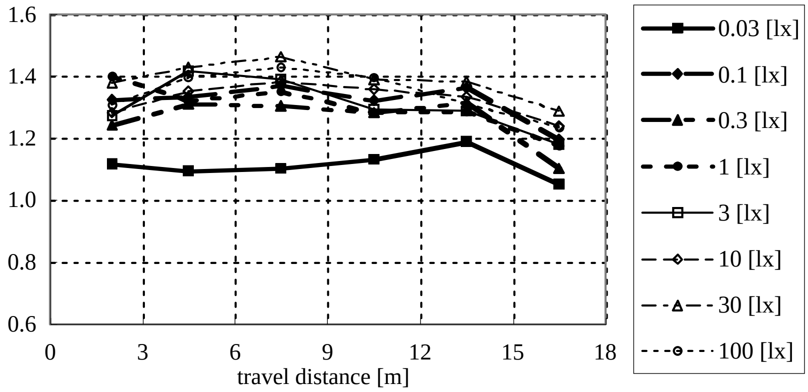


FIGURE 4. Relationship between travel distance and travel speed
(the data of an aged subject who is 65 years old and her visual acuity at 1000[lx] is 0.73)

Fig. 5 shows the relations between travel speed and floor illuminance for two age groups calculated by average scores and standard deviation of each illuminance level regardless of travel distance. At 1 [lx] of floor illuminance and lower, the average speed of young subjects is higher than senior subjects, which supports the findings of the existing studies by Simmons[1] and Jaschinski[2]. If the floor illuminance is higher than 3 [lx], the travel speed is constant regardless of age groups.

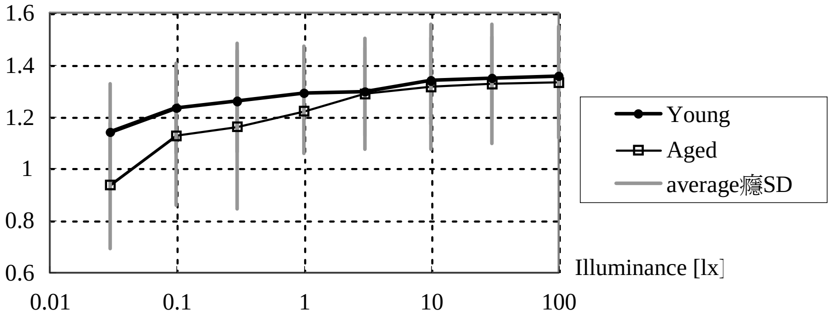


FIGURE 5. Relationship between illuminance and travel speed

Relationship between Travel Speed and Visual Acuity

The relations between visual acuity and travel speed by age groups are shown in Fig. 6. The visual acuity under each floor illuminance level is calculated using the results in Fig. 2. The floor luminance can be calculated from the floor illuminance and the reflectance of floor ($\rho = 0.36$) by equation [1]. The data of visual acuity under each floor illuminance is quoted from the same luminance level in Fig. 2. Therefore, Fig. 6 shows combined results of Fig. 2 and Fig. 5.

In Fig. 6, the age difference is not seen, which implies that travel speed is held by visual acuity regardless of age.

From the relationship shown in Fig. 6, the travel speed under complete adaptation v_o[m/s] can be correlated with visual acuity (VA) as expressed by equation [3] ($R^2 = 0.91$). Hence, if visual acuity under the light conditions of a disaster situation can be predicted, the performance (travel speed) of evacuees can also be predicted by this equation.

$$\begin{cases} v_o = 0.146 \times \log_e(VA) + 1.499 & (\mathrm{VA} < 0.3) \\ v_o = 1.323 & (\mathrm{VA} \geq 0.3) \end{cases} \qquad [3]$$

where VA is visual acuity, and v_o[m/s] is the travel speed under complete adaptation.

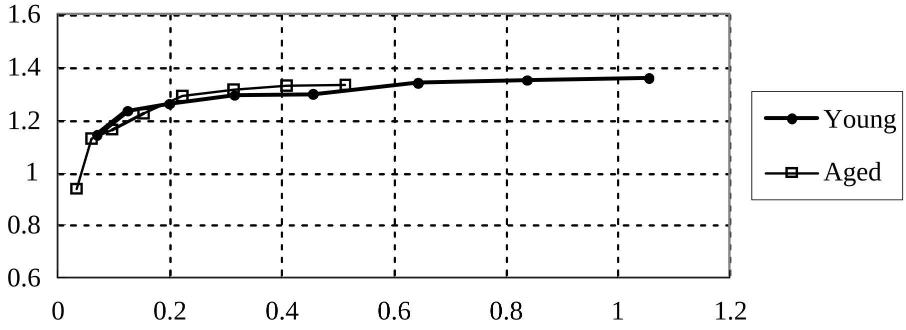


FIGURE 6. Relationship between travel speed and visual acuity

TRAVEL SPEED UNDER INCOMPLETE ADAPTATION

Relationship between travel speed and illuminance change

An example of relations between travel distance and speed under incomplete adaptation is shown in Fig. 7. When the illuminance at the adaptation space and at the travel space is significantly different, the travel speed increases to the level of complete adaptation's speed as subjects travel farther. On the other hand, when illuminance difference is small, little change is seen according to the travel distance.

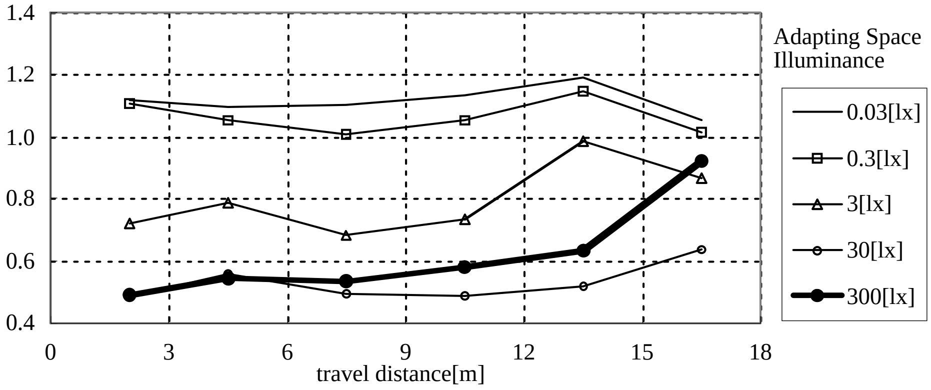


FIGURE 7. Relations between travel distance and speed under incomplete condition
(the data at travel space 0.03[lx] of an aged subject who is 65 years old and her visual acuity at 1000[lx] is 0.73)

The illuminance difference between the adapting space and travel space is treated as the ratio of the illuminance of the adapting space to that of the travel space i.e. "the illuminance ratio, $RE_{adaptation}$". The illuminance ratio is expressed as equation [2]. The illuminance ratio is set from 1 to 10000 (see Table 1).

Moreover, the ratio of travel speed ($Rv_{adaptation}$) regarding the effect of adaptation is defined by equation [4].

$$Rv_{adaptation} = \frac{v_i}{v_o} \qquad [4]$$

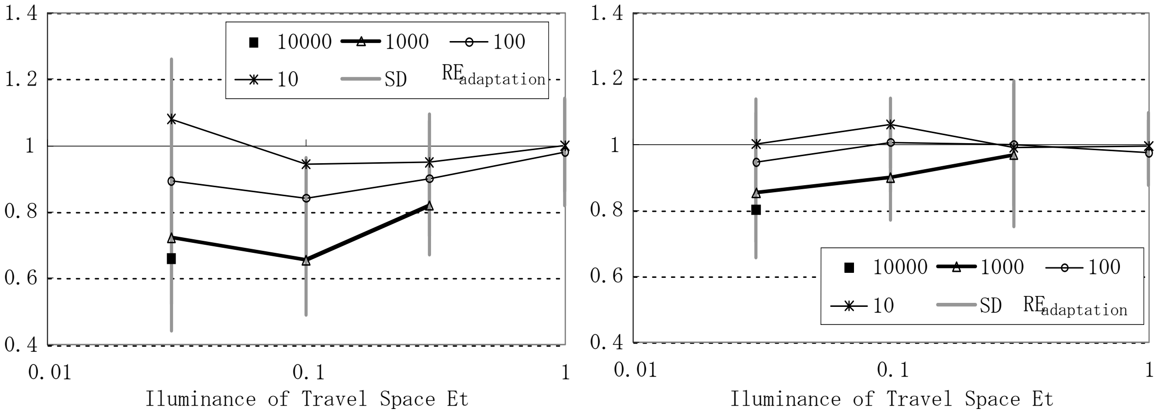
where v_o[m/s] is the travel speed under complete adaptation, and v_i[m/s] is the travel speed under incomplete adaptation.

The relations among the illuminance of travel space E_t[lx], the illuminance ratio $RE_{adaptation}$, and the ratio of travel speed $Rv_{adaptation}$ are shown in Fig. 8 by age groups (calculated by average scores and standard deviation of each experimental condition). E_t is lower and $RE_{adaptation}$ is greater, $Rv_{adaptation}$ tends to decrease. The aged group shows this tendency more prominently.

Relationship between Travel Speed and Visual Acuity under Incomplete Adaptation

The difference seen in Fig. 8 can be explained by visual acuity. The ratios of travel speed under different floor illuminance versus visual acuity are plotted in Fig. 9. The visual acuity under each floor illuminance level is calculated using the results in Fig. 2. The floor luminance can be calculated from the floor illuminance and the reflectance of floor ($\rho = 0.36$) by equation [1], and the data of visual acuity under each floor illuminance is quoted from the same luminance level in Fig. 2. Therefore, Fig. 9 shows combined results of Fig. 2 and Fig. 8.

Under the condition that the illuminance ratio is equivalent to 10 (i.e., the illuminance of adapting space is 10 times that of travel space), the ratio of travel speed ($Rv_{adaptation}$) under complete adaptation is equivalent to nearly 1. Regression equations in Fig. 9 are established when the illuminance ratio ($RE_{adaptation}$) is more than 100.



(a) Aged group (b) Young group

FIGURE 8. Relationship between travel speed and illuminance change

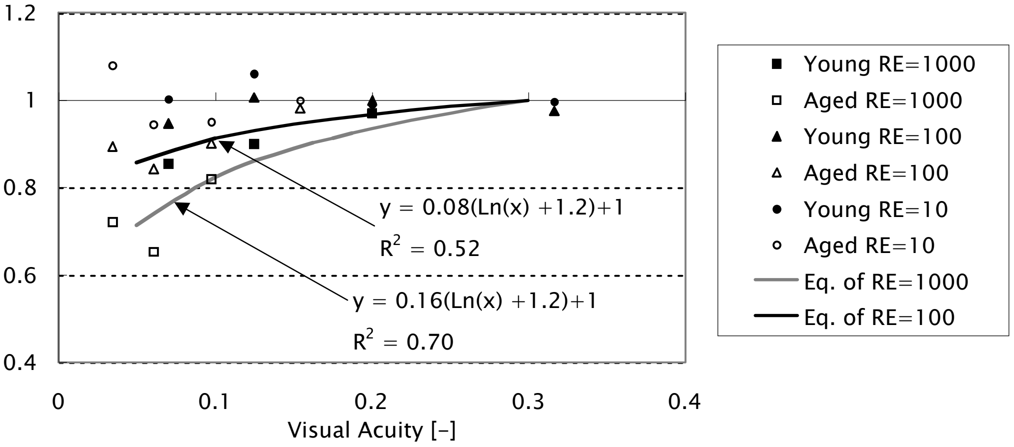


FIGURE 9. Relationship between the ratio of travel speed and visual acuity under incomplete adaptation

The regression relations between visual acuity and v_i[m/s] in Fig. 9 are given by equation [5] including equations [2] and [4]. Combining equation [5] with equation [3] can calculate the travel speed under incomplete adaptation conditions.

$$\left[\begin{array}{l} \textit{If}\ \mathrm{VA} < 0.3, \\ \begin{cases} \dfrac{v_i}{v_o} = \left(\log_{10}\dfrac{E_a}{E_t} - 1\right) \times 0.08\{\log_e(VA) + 1.2\} + 1 & (\dfrac{E_a}{E_t} > 10) \\ \dfrac{v_i}{v_o} = 1 & (\dfrac{E_a}{E_t} \leq 10) \end{cases} \\ \textit{and if}\ (\mathrm{VA} \geq 0.3), \\ \begin{cases} \dfrac{v_i}{v_o} = 1 \end{cases} \end{array}\right] \qquad [5]$$

where E_a and E_t are the illuminance of adapting space and travel space[lx], v_o and v_i are the travel speeds under complete and incomplete adaptations[m/s], and VA is visual acuity, respectively.

TRAVEL SPEED IN SMOKE

Because of the high likelihood that evacuees in a fire may have to travel in smoke, it is necessary to predict how smoke influences evacuees' performance. A smoke generator that can optionally adjust the discharge rate of white smoke in the experiment was used. The smoke discharged is diffused uniformly enough in the travel space using a fan. Except smoke, other fundamental experiment conditions (experiment space, subjects, experiment process and so on) are the same. Subjects are also unchanged except that one young subject is excluded because of personal reasons.

Fig. 10 shows the smoke density under each illuminance condition calculated by average scores and standard deviation. Control of the smoke density was extremely hard, therefore the smoke density was different depending on the experiment date even if the floor illuminance in the travel space is the same (0.2~1.8[1/m]). The average density of the whole experiment is 0.68[l/m].

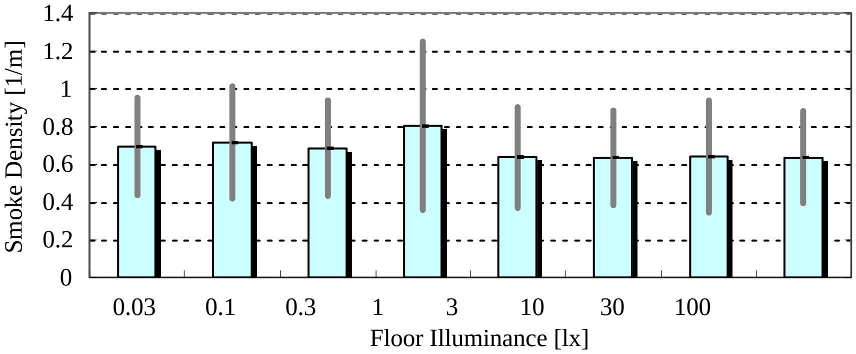


FIGURE 10. Fluctuation of smoke density under each illuminance conditions

Effects of Smoke on the Relationship between Illuminance and Travel Speed

Fig. 11 shows the relations between floor illuminance and travel speed in smoke for the two age groups (calculated by average scores and standard deviation of each illuminance). In Fig. 5, there is little difference between the travel speed of the young and aged group, and both travel speeds are constant under the illuminance condition 3[lx] or more. However, under the conditions more than 3[lx] in smoke, the travel speeds of both groups increase as illuminance increases. The travel speed of the young group is consistently higher than that of the aged group.

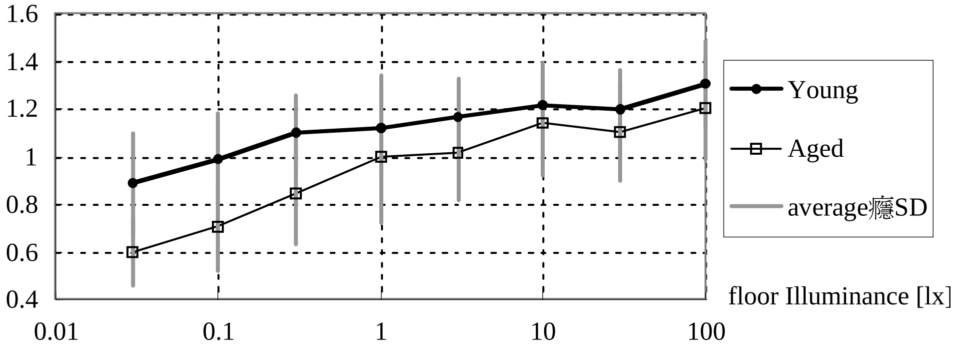


FIGURE 11. Relationship between illuminance and travel speed in smoke

Even under the same illuminance conditions, subjects walk more slowly with smoke than without. Therefore, the ratio of travel speed in smoke (Rv_{smoke}) regarding the effect of smoke is defined by equation [6].

$$Rv_{smoke} = \frac{v_s}{v_o} \qquad [6]$$

where v_o[m/s] is the travel speed under complete adaptation without smoke, and v_s[m/s] is the travel speed under complete adaptation in smoke.

The difference seen in Fig. 11 can be explained by visual acuity as well. The relations between the ratio of travel speed in smoke (Rv_{smoke}) and visual acuity by age groups are shown in Fig. 12. The visual acuity under each floor illuminance level is calculated using the results in Fig. 2. The floor luminance can be calculated from the floor illuminance and the reflectance of floor ($\rho = 0.36$) by equation [1], and the data of visual acuity under each floor illuminance is quoted from the same luminance level in Fig. 2. Therefore, Fig. 12 shows combined results of Fig. 2 and Fig. 11.

The age difference is not seen, which implies that the effect of smoke on travel speed can be explained by visual acuity regardless of age.

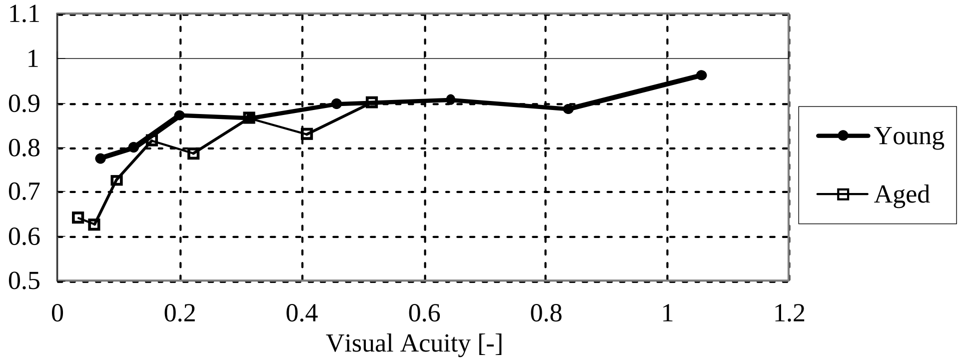


FIGURE 12. Relationship between visual acuity and ratio of travel speed in smoke

Relations between the ratio of travel speed in smoke (Rv_{smoke}) and visual acuity is shown in equation [7] ($R^2 = 0.83$) including equation [6]. Equation [3] and equation [5] show convergence with $VA \geqq 0.3$, but equation [7] suggests smoke affects travel speed at higher levels of visual ability.

$$\frac{v_s}{v_o} = 0.087 \times \log_e(VA) + 0.9507 \qquad [7]$$

where v_o and v_s are the travel speeds under complete adaptations without and with smoke [m/s], and VA is visual acuity, respectively.

Equation [7] is applicable to smoke density Cs = 0.68[1/m]. Higher density of smoke leads to lower visibility, so the ratio of travel speed in smoke is predicted to decrease. Also, when smoke density is zero (Cs = 0), v_s equals v_o, so the ratio of travel speed in smoke is equivalent to 1. With that condition in mind, incorporating Cs variable into equation [7], equation [8] is constructed.

$$\frac{v_s}{v_o} = 0.128\{\log_e(VA) - 0.567\} \times Cs + 1 \qquad [8]$$

where v_o and v_s are the travel speeds under complete adaptations without and with smoke [m/s], Cs is smoke density [1/m], and VA is visual acuity, respectively.

In this experiment, variance of smoke density is greatest when young subjects are tested with floor illuminance of 1[lx]. Fig. 13 shows relations between 29 young subjects' individual ratio of travel speed in smoke (Rv_{smoke}) and smoke density (Cs). Under this condition their average visual acuity is 0.32 and correlation coefficient of the regression line is $R^2=0.55$, therefore the validity of the equation is confirmed.

Combining equation [3] and equation [8] can successfully predict the travel speed of evacuees through space with smoke.

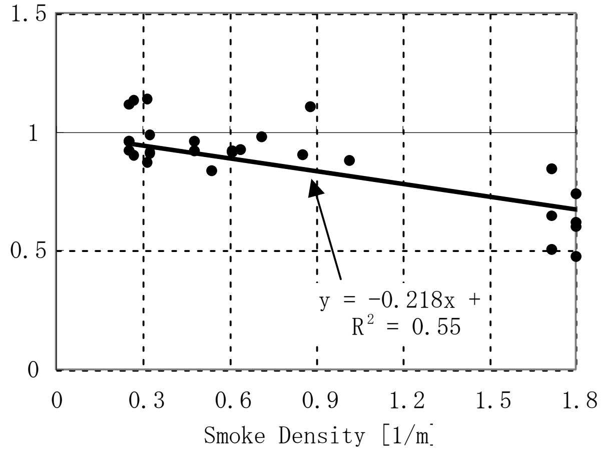


FIGURE 13. Relations between smoke density and the ratio of travel speed in smoke
(Visual acuity of young subjects is 0.32)

CONCLUSIONS

Performance of Evacuees is predictable by the visibility conditions such as luminous environment and evacuee's visual acuity. This paper constructs a calculation model to predict travel speed by luminous environment (complete or incomplete adaptation, and smoke density) and evacuee's visual acuity. This model helps predict the performance of evacuees such as adaptation process after sudden blackout or travel speed under fire smoke.

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