

Measurement of Temporal Summation of Visual Acuity With Use of Modified Tachistoscope

Kazushi Niwa and Takashi Tokoro

*Department of Ophthalmology, Tokyo Medical and Dental University,
School of Medicine, 1-5-45 Yushima, Bunkyo-ku, Tokyo 113, Japan*

Abstract: Visual acuity was measured in 18 normal eyes of 10 subjects ranging in age from 20 to 30 years, using a modified tachistoscope. We changed the exposure duration of the target (1–1000 msec) or background luminance (0.1–200 cd/m²). Visual acuity improved with increasing duration of exposure. At background luminance over 10 cd/m², critical duration time was approximately 500 msec. At low luminances below 10 cd/m², however, critical duration was prolonged. This tendency was also seen when pupil diameter was fixed at 3 mm using an artificial pupil. Visual acuity also could be determined as the product of background luminance and exposure duration. We concluded that these findings follow the Bloch-Bunsen-Roscoe law. **Jpn J Ophthalmol 1997;41:403–408** © 1997 Japanese Ophthalmological Society

Key Words: Critical duration time, exposure duration, tachistoscope.

Introduction

Visual acuity is defined as the spatial limit of visual discrimination, and is usually assessed with a high-contrast target, without limiting the duration of exposure. The ability to discriminate an object with a very short flash exposure (foveal visual acuity with a short exposure) and the ability to discriminate an object obscured against background (contrast visual acuity) are also important visual functions. Visual acuity with a short exposure has been measured for many years.^{1,2,3} Visual acuity is dependent on a duration of exposure up to about 500 msec; and the critical duration of visual acuity is thought to be about that period of time. Yamade et al.,⁴ and Baron et al.,⁵ demonstrated that critical duration time did not change when target luminance was altered. However, they determined the effect of a change in background luminance only at relatively high levels of luminance (80 cd/m² or more). In the present study, we have determined visual acuity with exposure dura-

tion ranging from 1 to 1000 msec at levels of background luminance ranging from 0.1 to 200 cd/m². We used a modified tachistoscope which we developed for this experiment.

Methods

Subjects consisted of 10 volunteers (18 eyes) with normal vision except for the presence of slight refractive errors (spherical equivalent power within 0.5 diopter). Their ages ranged from 20 to 30 years. All subjects were well informed about the experiment and gave their written consent to participate.

The tachistoscope used was a three-dimensional kinetic vision tester DA-2 that was developed by our group⁶ (Figure 1). Its basic optical system is shown in Figure 2. The internal target of the Badal system is controlled by a computer (PC9801 FA, NEC, Tokyo). The Badal target was physically situated 30 meters from the eye being tested. The stimulus-presentation unit in the instrument was designed to control duration of exposure, luminance, size, and orientation of the Landolt ring. The target was presented against a dark background (below 0.01 cd/m²). In general, the delay time for the response of the eye movement was about 200 msec after presentation of

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Address correspondence and reprint requests to: Kazushi NIWA, MD, Department of Ophthalmology, Tokyo Medical and Dental University, School of Medicine, 1-5-45 Yushima, Bunkyo-ku, Tokyo 113, Japan

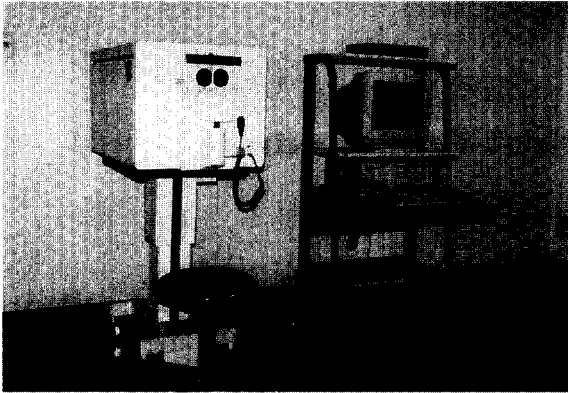


Figure 1. Three-dimensional kinetic vision tester DA-2.

the stimulus. When the site of target presentation can be predicted, as in the present experiment, it is thought that eye movement is directed in advance to the site where the target is to be presented.⁷ Therefore, we did not use a fixation mark in the present study. A black Landolt ring against a white background was used as the target. The size of the Landolt ring could be changed at intervals of 0.1, corresponding to a visual acuity of 0.1~1.6. The background luminance could be changed in eight steps (0.1, 0.3, 1.3, 10, 30, 100 and 200 cd/m²).

Visual acuity was measured under monocular conditions following complete correction of refractive error and in room luminance of about 30 lux. After the pupil was dilated by 0.4% tropicamide, an artifi-

cial pupil 3 mm in diameter was used to avoid effects of the pupil size on retinal illuminance for the right eyes of two of the subjects (in these cases, the retinal illuminance corresponded to 0.71, 2.1, 7.1, 21, 71, 210, 710 and 1400 trolands). Data were collected after the subject had adapted to the level of ambient light for at least 1 minute.

Measurements were done rapidly. The duration of exposure was set in seven steps (1, 3, 10, 30, 100, 300 and 1000 msec). An electronic shutter made of lead zirconate and lead titanate modified with lanthanum oxide (Shimon, Tokyo) opened to present the target at each predetermined period. The rise-and-fall time was less than 0.1 msec. The visual acuity at each exposure time was determined by the up-and-down method. The threshold of detection varies according to the orientation, even with the same width of the gap.⁸ Therefore, only two directions (right and left) were used for the orientation of the Landolt ring. The test was done with ascending gap sizes. The subject was instructed to state the orientation of each target or to say "blank" when no gap could be seen. When the subject failed to indicate the orientation correctly or responded as "blank," the size of the gap was increased. When the subject gave a correct answer, five or more measurements were obtained by changing the orientation of the Landolt ring for each gap size and each exposure duration time. If the percentage of correct responses was below 60%, the gap size was increased by one step. When the subject correctly identified the orientation in more than

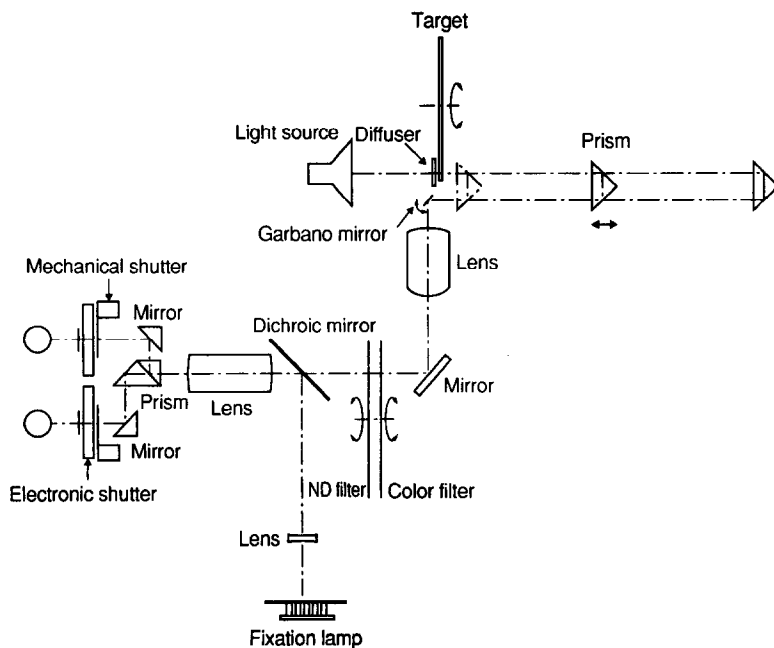


Figure 2. Schematic layout of the three-dimensional kinetic vision tester DA-2.

60% of the tests, measurements were done with a gap size of one step down.

The minimum gap size for which the orientation was correctly identified in 60% or more of the tests was taken as the visual acuity for that duration of exposure. In addition, each subject was instructed to press the response switch when he (or she) recognized the actual position of the target presented at the visual acuity obtained with a duration exposure of 1000 msec. When the response was correct, the visual acuity and the response time were recorded. Visual acuity was also measured without any limitation in the duration of exposure. Because it required more than 1 hour to complete the measurements of each eye, subjects were allowed to have a rest between tests if they wished.

Results

The results of average visual acuity versus the duration of exposure obtained at different background luminances are shown in Figure 3. The visual acuity measured without limitation in exposure time was the same as the value obtained with an exposure duration of 1000 msec for any background luminance. For each different background luminance, a regression line was obtained with the least squares method by plotting the exposure duration (msec) in logarithmic scales versus the visual acuity. The intersection of the regression line and the visual acuity obtained without limitation in exposure time indicates the critical duration time (Figure 4).

Table 1 shows the average slope of regression lines and the average critical duration time in logarithmic scales at different background luminances.

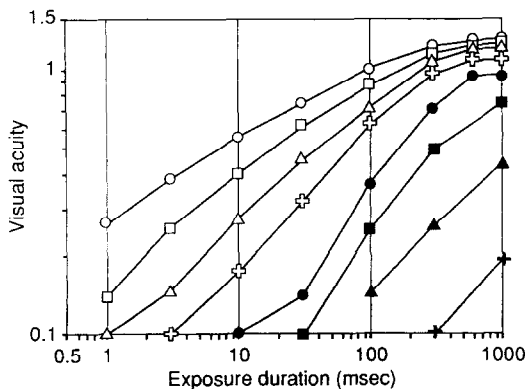


Figure 3. Average visual acuity plotted as function of exposure duration on log-log coordinates in 18 subjects at various levels of background luminance. ○, at background luminance of 200 cd/m²; □, 100; △, 30; open cross, 10; ●, 3; ■, 1; ▲, 0.3; and closed cross, 0.1.

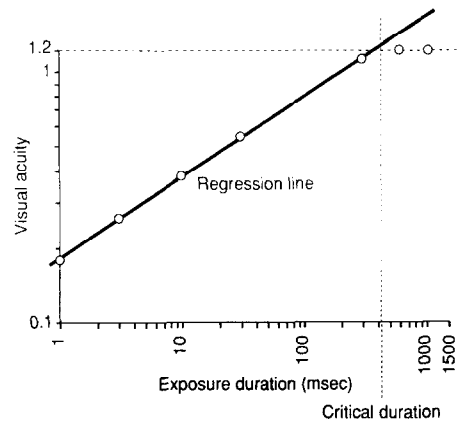


Figure 4. Maximum time over which temporal summation of visual acuity can occur is termed "critical duration."

The Wilcoxon rank-sum test was used in statistical analysis, and a level of $P < 0.05$ was defined as statistically significant. Comparisons were made between slopes at adjoining background luminances, for example, the slope at 200 cd/m² and that at 100 cd/m². The regression line showed a sharp slope in the range of 200~3 cd/m² with a decrease in background luminance ($P < 0.01$). At background luminance of 1 cd/m² and 0.3 cd/m², however, no significant difference was seen in the slope of the regression lines. At background luminance of 0.1 cd/m², most of the subjects could barely discriminate the 0.1 target at an exposure duration of 300 msec. Thus, no regression line could be obtained because the number of plots was too small. At background luminances ranging from 10 to 200 cd/m², the critical duration time was not changed by the alternation of target luminance. However, the critical duration time was prolonged with background luminance lower than 10 cd/m².

Table 1. Average Slope of Regression Lines and Average Critical Duration Time in 18 Subjects at Various Levels of Background Luminance

Background Luminance (cd/m ²)	Slope	Exposure Duration (log msec)	Critical Duration (msec)
200	0.23 ± 0.041	2.708 ± 0.056	510
100	0.31 ± 0.050**	2.739 ± 0.106	548
30	0.37 ± 0.034**	2.740 ± 0.056	550
10	0.43 ± 0.066**	2.753 ± 0.073	566
3	0.54 ± 0.089**	2.838 ± 0.025	689**
1	0.54 ± 0.099	2.889 ± 0.058	774*
0.3	0.48 ± 0.13	2.958 ± 0.052	973**
0.1	—	—	—

* $P < 0.05$.

** $P < 0.01$.

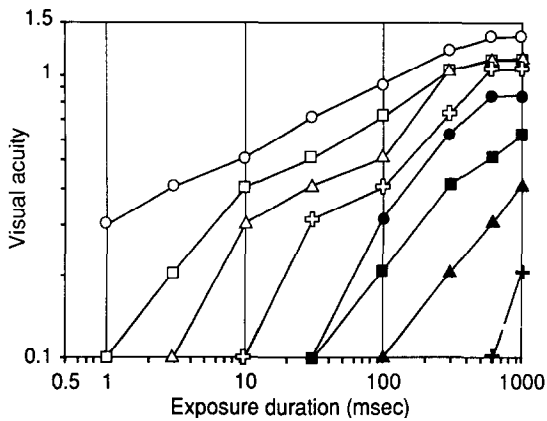


Figure 5. Average visual acuity plotted as function of exposure duration on log-log coordinates in representative visually normal 20-year-old woman at various levels of background luminance. ○, at background luminance of 200 cd/m²; □, 100; △, 30; open cross, 10; ●, 3; ■, 1; ▲, 0.3; and closed cross, 0.1.

Figures 5 and 6 show the relationship between the exposure duration time and visual acuity in a 20-year-old woman under two conditions: with natural and with artificial pupils. Her natural pupil diameter was 5.5 mm at room luminance of 30 lux: the apparent pupil size was not monitored during the experiment. The slope of the regression lines and the critical duration times at different background luminances in this subject as measured with natural pupils and with artificial pupils are shown in Tables 2 and 3, respectively. No difference was seen in the critical duration time between the natural and artificial pupils at background luminances over 10 cd/m². However, at

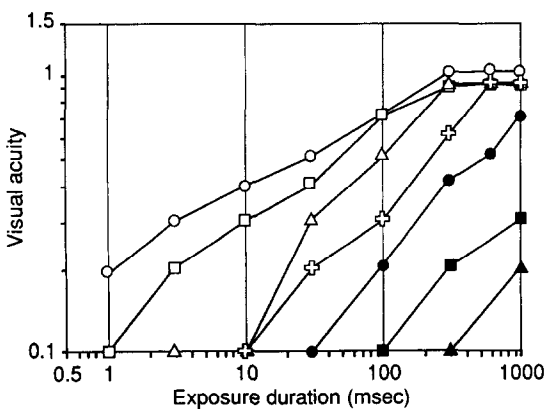


Figure 6. Average visual acuity is plotted as function of exposure duration on log-log coordinates in representative visually normal 20-year-old woman with artificial pupils at various levels of retinal illuminance. ○, at retinal illuminance of 1400 troland; □, 710; △, 210; open cross, 71; ●, 21; ■, 7.1; ▲, 2.1; and closed cross, 0.71.

Table 2. Average Slope of Regression Lines and Average Critical Duration Time in Representative Visually Normal Observer (20-year-old Woman) With Natural Pupils at Various Levels of Background Luminance

Background Luminance (cd/m ²)	Slope	Critical Duration (msec)
200	0.23	562
100	0.34	479
30	0.39	575
10	0.50	617
3	0.61	646
1	0.57	774
0.3	0.48	956
0.1	0.60	790

luminances below 3 cd/m², the regression lines with artificial pupils were less steep than those with natural pupils, and the critical duration time was prolonged. Figure 7 shows the relationship between exposure time and retinal illuminance required to obtain a particular visual acuity. For visual acuity below 0.7, the coefficient of the regression line was approximately minus one. This means that the visual acuity could be determined as the product of the exposure duration and retinal illuminance.

Discussion

The spatial limit of visual discrimination at a short exposure time has been measured by many researchers.^{1,2,3} Although some differences are seen according to experimental conditions, visual acuity is dependent on the exposure duration up to about 500 msec. The critical duration time of visual acuity is thought to be about 500 msec. Recently, Kono et al⁹

Table 3. Average Slope of Regression Lines and Average Critical Duration Time in Representative Visually Normal Observer (20-year-old Woman) With Artificial Pupils at Various Levels of Background Luminance

Retinal Illuminance (troland)	Slope	Critical Duration (msec)
1400	0.24	524
710	0.32	447
210	0.44	537
71	0.50	759
21	0.56	954
7.1	0.48	891
2.1	0.31	1412
0.71	—	—

determined that with exposure duration ranging from 60 to 1000 msec, the critical duration time of visual acuity averaged 620 msec. In the present experiments, the critical duration time approximated 500 msec at background luminances ranging from 10 to 200 cd/m². This value is in agreement with previous reports.^{1,2,3,9} Yamade and colleagues⁴ reported that diminishing the luminance or presence of glaring light reduced the visual acuity with limited exposure time but did not alter the critical duration time. They compared the critical duration time of visual acuity at background luminance of 85.75 cd/m² and 686 cd/m². In the present study, the levels of background luminance were reduced further, and the critical duration time tended to be prolonged below 10 cd/m².

The latent period for the accommodation response is approximately 360 msec, and the interval from the start to the end of accommodation is about 640 msec.¹⁰ The latent period for pupillary reaction is 200~500 msec, and the interval from start to finish of contraction is usually 260~300 msec.^{11,12} Thus, there is an interval of about 1000 msec from the time when a visual stimulus initiated until the completion of the accommodation response. For the completion of the pupillary reaction, an interval of 460~800 msec is required. The critical duration of visual acuity, about 500 msec, is consistent with the time required for completion of the pupillary reaction. Therefore, effects of the visual optical factor on the critical duration cannot be excluded. However, Baron and co-workers⁵ reported that the critical duration time did not change when the effect of pupillary or accommodative factors was suppressed by use of 0.5% cyclopentolate eye drops and an artificial pupil. Thus, central neural elements beyond the retina constitute the chief factor affecting the temporal summation of visual acuity. In the present study, the temporal summation of visual acuity of two eyes with artificial pupils was determined with unchanged pupil size. At a background luminance over 10 cd/m², there was no difference in the critical duration time as compared with the value for natural pupils. At levels of luminance below 3 cd/m², however, the regression lines for the results with artificial pupils had less steep slopes compared to those with natural pupils, and there was a prolongation of the critical duration time. This is because the visual acuity with artificial pupils was less than that with natural pupils when the exposure duration exceeded 300 msec. Although the apparent pupil size was not monitored during the experiment, Campbell et al¹³ reported that the visual acuity is best with pupil diameters over 4 mm at a luminance below 3 cd/m². We postu-

lated that there was a difference in visual acuity after completion of the pupillary reaction because of low retinal illuminance when using a 3-mm artificial pupil.

The temporal summation of physiologic excitation to luminance is well known. During a limited period of time, light perception depends on the product of luminance and time (Bloch law), similar to the compensatory relationship between the iris diaphragm and the exposure duration in photography. The Bunsen-Roscoe law of photochemistry is an analogue of the Bloch law. Essentially, the Bloch-Bunsen-Roscoe law is not applied to the perception of form (resolution task) but to the perception of light (detection task). Temporal summation also occurs in discrimination of forms, and is similar to that for threshold luminance.^{2,14} According to Baron et al⁵ when visual acuity is plotted on a time-luminance reciprocity, a less steep slope is obtained than would be expected from the Bloch-Bunsen-Roscoe law for threshold luminance. In the present experiment, the findings for visual acuity up to 0.7 followed the Bloch-Bunsen-Roscoe law (complete temporal summation), as can be seen in Figure 7. However, it is considered that the Bloch-Bunsen-Roscoe law is not applied to the findings at visual acuity of 0.9 or 1.0 for two reasons. Firstly, incomplete temporal summation occurs in high levels of visual acuity or temporal summation does not occur.¹⁵ Secondly, as the difference in the width of the gap in the Landolt ring corresponding to the difference of 0.1 for decimal notation becomes relatively smaller in high level of visual acuity, visual acuity shows too large variations even though complete temporal summation occurs.

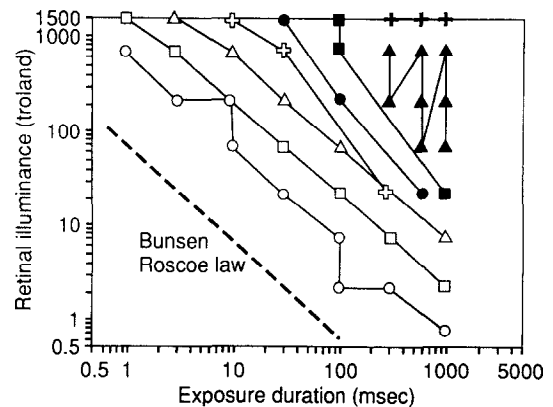


Figure 7. Relationship of exposure duration (msec) and retinal illuminance (trolands) required to obtain a particular visual acuity in representative visually normal 20-year-old woman. Dashed line indicates trend of Bunsen-Roscoe law. ○, visual acuity of 0.1; □, 0.2; △, 0.3; open cross, 0.4; ●, 0.5; ■, 0.7; ▲, 0.9; and closed cross, 1.0.

We plan to use this tachistoscope to assess eye strain in people who work using visual display terminals (VDT); a prolongation of the critical duration time is expected despite good visual acuity in fatigue condition. We intend to further improve this instrument by adding 2 or 3 steps in exposure time, in the range from 300 to 1000 msec, and by setting the steps of visual acuity to obtain the log visual acuity at equal intervals, as defined in the Draft International Standard of the International Organization for Standardization.¹⁶

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