# Effect of glare on simple reaction time

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We systematized the study of the effect of glare on reaction time (RT), for visual conditions similar to the ones found during night driving: Mesopic range of adaptation (0.14 cd/m$^2$), glare levels of the order of those produced by car headlights ($E_G$=15, 60 lx), suprathreshold luminance contrasts, and a variety of spatial frequencies covering the selected range of visibility (1, 2, 4, and 8 c/deg). We found that for the no-glare situation, RT increases with decreasing contrast and increasing spatial frequency, which agrees with previous findings. When data are plotted as a function of the inverse of contrast, RT varies linearly, with $k$—the RT-contrast factor of Pieron's law—representing the slope of the lines. The effect of glare on RT is an increase in the slope of these lines. This effect is different for each spatial frequency, which cannot be accounted for in the classic approach considering that glare can be replaced by a single veiling luminance. We show that the effect of glare on RT must be modeled by an equivalent glare luminance that depends on spatial frequency. © 2008 Optical Society of America

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## 1. INTRODUCTION

When a bright light is present in the field of view, visibility is dramatically reduced. This effect has been modeled by adding a veiling luminance to the image that imitates the masking effect produced by the scattering of light in the ocular media [1]. Equation (1) shows the classic Stiles–Holladay disability glare formula,

$$Lv = 10E_G/\theta^2, \quad 1° < \theta < 30°, \tag{1}$$

where $Lv$ is the veiling luminance expressed in candelas per square meter (cd/m$^2$), $E_G$ is the illuminance produced by the glare source on the eyes in lux, and $\theta$ is the angle between the line of sight and the line of the glare source in degrees. Recently, CIE Report Number 146 [2] established a general equation to quantify the effect of glare by considering different ranges of angles, ocular pigmentation, and age influence.

Recent papers have reported results that cannot account for the veiling luminance model. Barraza and Colombo [3] showed that transient glare produces an increment of the lower threshold of motion of high contrast gratings presented right after the glare onset. They also showed that this effect disappears after 500 ms [4]. Colombo *et al.* [5] found that a transient glare source (500 ms) reduces the perceived brightness of mesopic patches displayed on dark surrounds. The latest studies have analyzed the dynamic of this brightness reduction [6] and have shown that, in certain situations, there is lightness constancy under transient glare conditions, which is not predicted by the veiling luminance model either [7]. All of these studies used high contrast stimuli for their experiments and were based on tasks different from the threshold contrast estimation used in the classic literature regarding glare (for a review see [8]).

The aim of this work was to evaluate the influence of glare on suprathreshold visual performance by measuring simple reaction times (RTs) in detection tasks with and without glare, and considering similar conditions to the ones found in night driving. RT is defined as the minimum time required for a subject to detect a stimulus after its presentation. Multiple studies used RT to explore the visual system. Some of them come from the field of lighting and proposed a model of relative visual performance including retinal illuminance, contrast, and size as parameters [9,10]. On the other hand, several authors approached the study of visual mechanisms by measuring the RT of sinusoidal gratings for a wide range of spatial frequency, contrast [11–15], and adaptation luminance [16,17].

These studies showed that RT is systematically shortened when luminance and contrast are increased. Interestingly, RT increases linearly when it is plotted against the inverse of contrast [16], making the slope of these lines a parameter that can be used to characterize how rapid RT changes in a particular condition. These lines also depend on spatial frequency; the higher the spatial frequency the steeper the line. This makes the slope less dependent on luminance for high spatial frequencies than for low ones, because the baseline for high spatial frequency is much steeper than the one for low spatial frequency [15,16].

In this context, the study of the effects of glare on RT becomes interesting not only because of the relevance of glare in tasks such as driving at night, but because RT can help to elucidate whether the visual impairment due to glare is just an effect of scattering or whether there is some other component related to visual mechanisms. It is well-known that a glare source increases the adaptation luminance of the eye and, at the same time, reduces the contrast of the retinal image, which produces opposite effects on RT. In this work we propose to isolate these two effects and study how RT depends on different components of glare for a range of spatial frequency.

## 2. METHODS

### A. Stimuli

Stimuli were horizontal achromatic sinusoidal gratings displayed during 340 ms on a 19 in. CRT connected to a personal computer through a video adaptor [18]. The monitor was gamma corrected over the luminance range used in the experiments providing a luminance resolution of $0.01\ \text{cd/m}^2$. The system allows us to generate sinusoidal gratings of any orientation with spatial frequencies ranging from less than 1 c/deg to up to 25 c/deg. With this configuration, gratings can be displayed with contrasts between 0.002 and 1, with errors varying between 1.5% and 10%. The spatial frequencies used in these experiments were 1, 2, 4, and 8 c/deg and the Michelson contrast ranged between 0.02 and 0.5. The mean luminance of the stimulus and the surround was $0.14\ \text{cd/m}^2$. The experiments were performed in a dark room. The stimulus was viewed foveally in a circular patch subtending 6.7° at a distance of 1.5 m.

### B. Glare

The glare source was an incandescent lamp whose intensity was regulated by adding neutral density filters. The center of the lamp was located 10° away from the line sight at the same height of the stimulus. The aperture of the source was 1°. Figure 1 shows a scheme of the experimental layout. Glare intensity was expressed in terms of the cornea illuminance, which in this experiment were 15 and 60 lx.

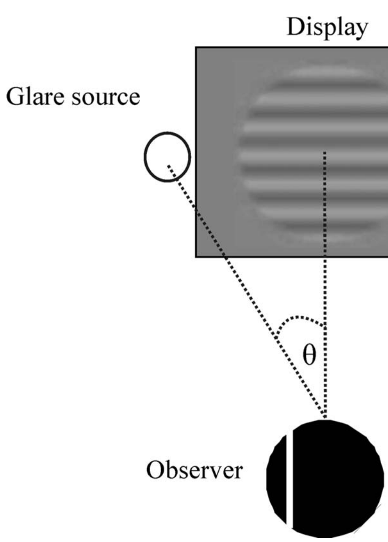


Fig. 1. Experimental layout: The observer is 1.5 m from display. $\theta = 10°$.

### C. Procedure

The experiment was performed in four sessions. In each session only one value of spatial frequency and only one level of glare were tested for all values of contrast, which were randomized. The combinations of spatial frequency and level of glare were also randomized. To start a session, subjects were allotted 10 min to adapt to the mean luminance of the stimulus, which was kept invariable along the whole experiment. The glare source was turned on at the beginning of the adaptation period. After the adaptation period, and on each trial, a sound indicated to the subject that the stimulus was going to come. To avoid anticipatory reactions we left a period of time, which could randomly vary between 1 and 3 s, between the sound and the stimulus presentation. The time elapsed between two trials was 2 s. Subjects had to press the button of the mouse as soon as they detected the stimulus. Each contrast and glare condition was repeated 30 times in each session. Trials with RTs shorter than 100 ms were discarded because they were considered to be anticipatory reactions and RTs longer than 1000 ms were discarded, too, because they were considered to be much longer than that expected.

### D. Subjects

Three subjects took part in this experiment. One of the authors, RA, is a 29-year-old male with experience in psychophysical experiments. The other subjects—MA (23 years old, female), and FG (23 years old, male)—were unaware of the purpose of this experiment and had no previous experience in psychophysics. All observers had normal vision. The experiment was performed monocularly and with natural pupils.

## 3. RESULTS AND DISCUSSION

Figure 2 shows RT as a function of the inverse of contrast for all spatial frequencies and for the three observers. All these curves are parametric on glare illuminance (no glare, 15 and 60 lx). Data were fitted with Eq. (2)—Pieron's law—which properly describes the dependence of RT on a variety of stimulus parameters,

$$\mathrm{RT} = \mathrm{RT0} + k\frac{1}{C}, \tag{2}$$

where RT0 is the minimum RT that can be reached in a given condition and the slope $k$ is a measure of the contrast gain. Figure 2 shows that the expected linearity for the mesopic no-glare situation [15] holds for both intensities of glare. Consistent with previous results [12,14,16,17,19] the plots show that RT increases with decreasing contrast and increasing spatial frequency in a linear fashion, which occurs for the three glare conditions. The effect of glare on RT is the increase of the slope ($k$) of the lines. Table 1 shows the values of $k$ and RT0 and their standard errors.

We hypothesized that RT0 should not change with glare intensity since it reflects the motor component of RT and the criterion of the subject. We tested this hypothesis and the effect of glare on $k$ by performing a multiple comparison through a one-way analysis of covariance [20]

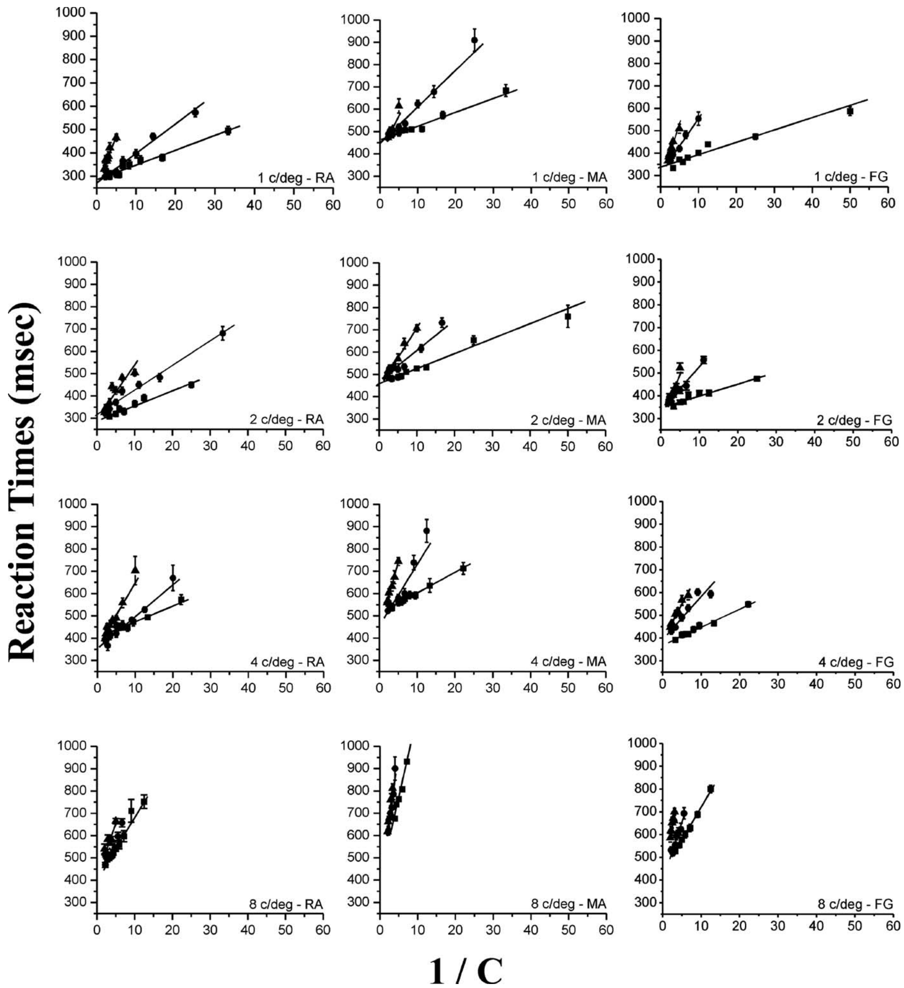


Fig. 2. RT as a function of the reciprocal of contrast (1/C) for the three levels of glare [$E_G$=0 (■), 15 (●) and 60 (▲) lx]. Different panels show data for different subjects (columns) and spatial frequencies (rows). Each data point represents the mean of 30 measurements and the error bars are ±1 SE.

with a confidence level of 0.95. The method tests the validity of the null hypothesis that the slope and intercept of the lines corresponding to different levels of glare are identical. Results of the analysis are summarized in Table 2. Those cases in which the null hypothesis is rejected are indicated with an "*x*" and those cases in which the null hypothesis is accepted with an "*o*." As can be observed, there are only two cases in which glare produces no effect on *k*: Between 0 and 15 lx for subject RA, and between 15 and 30 lx for subject FG. On the other hand, results show that there are only eight of 36 situations in which RT0s obtained in different situations cannot be considered as equal.

The relationship between the slope of the lines and glare intensity resembles the effect of reducing luminance shown in previous experiments [16]. How can one explain this similarity if, as it is well known (see Introduction), glare actually increases the mean luminance of the retinal image? The scattered light in the ocular media produces a luminance veil that reduces the contrast of the retinal image in a predictable manner [Eq. (1)]. The increase of the retinal luminance improves contrast sensitivity (higher visibility) but this effect is masked by the strong loss of image contrast. To study these effects individually, we need to take apart the stimulus contrast on the monitor and the stimulus contrast on the retina. If $L_{\max}$ and $L_{\min}$ are the maximum and minimum luminance in the stimulus respectively, and $Lv$ is the veiling luminance calculated with the classic Stiles–Holladay formula [Eq. (1)], the effective Michelson contrast on the retina can be expressed as

$$C_{\text{eff}} = \frac{(L_{\max}+Lv)-(L_{\min}+Lv)}{(L_{\max}+Lv)+(L_{\min}+Lv)} = \frac{L_{\max}-L_{\min}}{L_{\max}+L_{\min}+2Lv}, \tag{3}$$

Now, if we replot the results of Fig. 2 as a function of $C_{eff}$ instead of $C$ we eliminate the effect of contrast reduction on RT (Fig. 3). Therefore, the variations of the slopes that we see in the figures should reveal the effect of the luminance component of glare on RT. Figure 3 shows now that glare reduces the slopes of the lines. However, these results do not explain the dependence on spatial frequency since our data suggest that slopes depend more on luminance for high spatial frequency than for low spatial frequency, which is not consistent with previous results [16].

At this point we think the problem is trying to model

**Table 1. Values of *k* and RT0 (and the Corresponding Standard Error, SE) for the Range of Spatial Frequencies and Levels of Glare Tested for Each Subject**

| Condition of Glare | | Spatial Frequency (c/deg) 1 | 2 | 4 | 8 |
|---|---|---|---|---|---|
| Subject RA | | | | | |
| No glare | | | | | |
| | k | 6.7 | 6.8 | 7.0 | 27.0 |
| | SE | 0.6 | 0.5 | 0.9 | 1.0 |
| | RT0 | 276 | 294 | 403 | 406 |
| | SE | 3 | 10 | 10 | 5 |
| Glare 15 lx | | | | | |
| | k | 12.6 | 11.2 | 14.1 | 33.4 |
| | SE | 0.8 | 0.9 | 1.0 | 7.0 |
| | RT0 | 272 | 316 | 353 | 385 |
| | SE | 6 | 9 | 9 | 27 |
| Glare 60 lx | | | | | |
| | k | 44.1 | 24.5 | 29.0 | 48.7 |
| | SE | 5.0 | 4.0 | 4.0 | 7.0 |
| | RT0 | 252 | 295 | 360 | 411 |
| | SE | 14 | 22 | 17 | 26 |
| Subject MA | | | | | |
| No glare | | | | | |
| | k | 6.2 | 6.7 | 9.2 | 71.0 |
| | SE | 0.7 | 0.6 | 0.5 | 7.0 |
| | RT0 | 462 | 458 | 510 | 417 |
| | SE | 7 | 6 | 4 | 35 |
| Glare 15 lx | | | | | |
| | k | 15.8 | 13.0 | 27.5 | 128.9 |
| | SE | 1.0 | 2.0 | 4.0 | 15.0 |
| | RT0 | 448 | 471 | 456 | 338 |
| | SE | 8 | 13 | 16 | 45 |
| Glare 60 lx | | | | | |
| | k | 33.2 | 26.8 | 61.3 | 147.0 |
| | SE | 5.0 | 1.0 | 3.0 | 9.0 |
| | RT0 | 402 | 439 | 436 | 323 |
| | SE | 14 | 4 | 8 | 23 |
| Subject FG | | | | | |
| No glare | | | | | |
| | k | 5.0 | 5.2 | 7.9 | 29.2 |
| | SE | 1.2 | 0.6 | 0.4 | 2.7 |
| | RT0 | 343 | 348 | 370 | 395 |
| | SE | 10 | 7 | 5 | 19 |
| Glare 15 lx | | | | | |
| | k | 24.9 | 19.1 | 18.0 | 50.3 |
| | SE | 1.3 | 2.0 | 2.6 | 5.9 |
| | RT0 | 305 | 335 | 399 | 402 |
| | SE | 8 | 11 | 18 | 23 |
| Glare 60 lx | | | | | |
| | k | 46.1 | 48.1 | 31.3 | 90.5 |
| | SE | 3.4 | 5.2 | 2.7 | 12.4 |
| | RT0 | 285 | 267 | 392 | 413 |
| | SE | 10 | 7 | 11 | 32 |

the effect of glare on RT considering only the scattered light and, following this line of reasoning, we have hypothesized that a unique value of veiling luminance is not sufficient to explain the dependence of RT on spatial frequency and glare. Plainis and Murray [16] proposed an empirical model based on Pieron's law to calculate RT as a function of spatial frequency ($f$), contrast ($C$), and stimulus luminance ($L$).

**Table 2. Results of the Statistical Analysis Testing the Hypothesis That Glare Increases the Slope of the Lines (*k*) without Affecting the Intercept (RT0)[a]**

| Subject | Glare Condition | Spatial Frequency (c/deg) 1 | 2 | 4 | 8 |
|---|---|---|---|---|---|
| Parameter: *k* | | | | | |
| RA | 0 | *x* | *x* | *x* | *o* |
| | 15 | *x* | *x* | *x* | *o* |
| | 30 | *x* | *x* | *x* | *x* |
| MA | 0 | *x* | *x* | *x* | *x* |
| | 15 | *x* | *x* | *x* | *x* |
| | 30 | *x* | *x* | *x* | *x* |
| FG | 0 | *x* | *x* | *x* | *x* |
| | 15 | *x* | *x* | *x* | *o* |
| | 30 | *x* | *x* | *x* | *o* |
| Parameter: RT0 | | | | | |
| RA | 0 | *o* | *o* | *o* | *x* |
| | 15 | *o* | *o* | *o* | *o* |
| | 30 | *o* | *o* | *x* | *o* |
| MA | 0 | *o* | *o* | *x* | *x* |
| | 15 | *o* | *o* | *o* | *o* |
| | 30 | *x* | *x* | *o* | *o* |
| FG | 0 | *x* | *o* | *o* | *o* |
| | 15 | *o* | *o* | *o* | *o* |
| | 30 | *o* | *x* | *o* | *o* |

[a]The upper and lower parts of the table analyze the slope and intercept, respectively.

$$\mathrm{RT} = (\mathrm{RT0}_0 + 5f - 20 \log L) + \frac{1}{C} 10^{(0.12+0.09f-0.42 \log L)}. \tag{4}$$

Their contribution to Pieron's law is the development of RT0 and the constant $k$, which depend on spatial frequency and luminance. The constants, including $\mathrm{RT0}_0$, which depends on the subject, were empirically obtained for a wide range of spatial frequency and luminance.

For each spatial frequency and glare level we propose to find the value of the veiling luminance, which we have named "equivalent glare luminance" ($Lg$), that when added to luminance produces the best fit of the model to our data. The computation of the mean luminance was performed by adding $Lg$ to $L$ and the computation of contrast was carried out by adding $Lg$ to $L_{\max}$ and to $L_{\min}$. Therefore, $Lg$ is calculated by minimizing the following argument:

$$\operatorname{Arg\,min}_{Lg} \sum_{i=1}^{Nc} \left\{ \mathrm{RT}_i - [\mathrm{RT0}_0 + 5f - 20 \log(L + Lg)] + \frac{1}{C_i} 10^{(0.12+0.09f-0.42 \log(L+Lg))} \right\}^2, \tag{5}$$

where $\mathrm{RT}_i$ is the experimental value, and $Nc$ is the number of contrasts tested for each spatial frequency and glare level. Table 3 shows the values of $Lg$ calculated for each spatial frequency and glare level. In fact, these different values of equivalent glare luminance do not represent the scattered light in the eye that is clearly a single optical effect, but they indicate that the effect of glare on RT cannot be reduced to such an optical effect.

In Fig. 4, we replot the data as a function of the effective contrasts calculated with the new equivalent glare luminances ($C_{\mathrm{eff},Lg}$). These results not only show that slopes decrease with increasing luminance, which means increasing glare, but they also show that this effect is markedly stronger for low than for high spatial frequencies.

## 4. GENERAL DISCUSSION

In this work we systematized the study of the effect of glare on RT for visual conditions similar to those found during night driving: Mesopic range of adaptation (0.14 $\mathrm{cd/m^2}$), glare levels of the order of those produced by car headlights ($E_G$=15, 60 lx), suprathreshold luminance contrasts, and a variety of spatial frequencies covering the corresponding visibility range (1, 2, 4, and 8 c/deg).

We found that, for the no-glare situation, RT increases with decreasing contrast and increasing spatial frequency, agreeing with previous findings [11–15,17]. When data are plotted as a function of the inverse of contrast, RT varies linearly (Fig. 2), with $k$ (the RT-contrast factor of Pieron's law) as the slope of the lines. The effect of glare on RT is that it increases the slope of these lines similarly to the effect of luminance reduction [16,17]. It is interesting to note that when visibility decreases—that is to say, when contrast and luminance decrease or spatial frequency increases—the slope of these lines increases. The complication in the analysis of the effects of glare on RT is

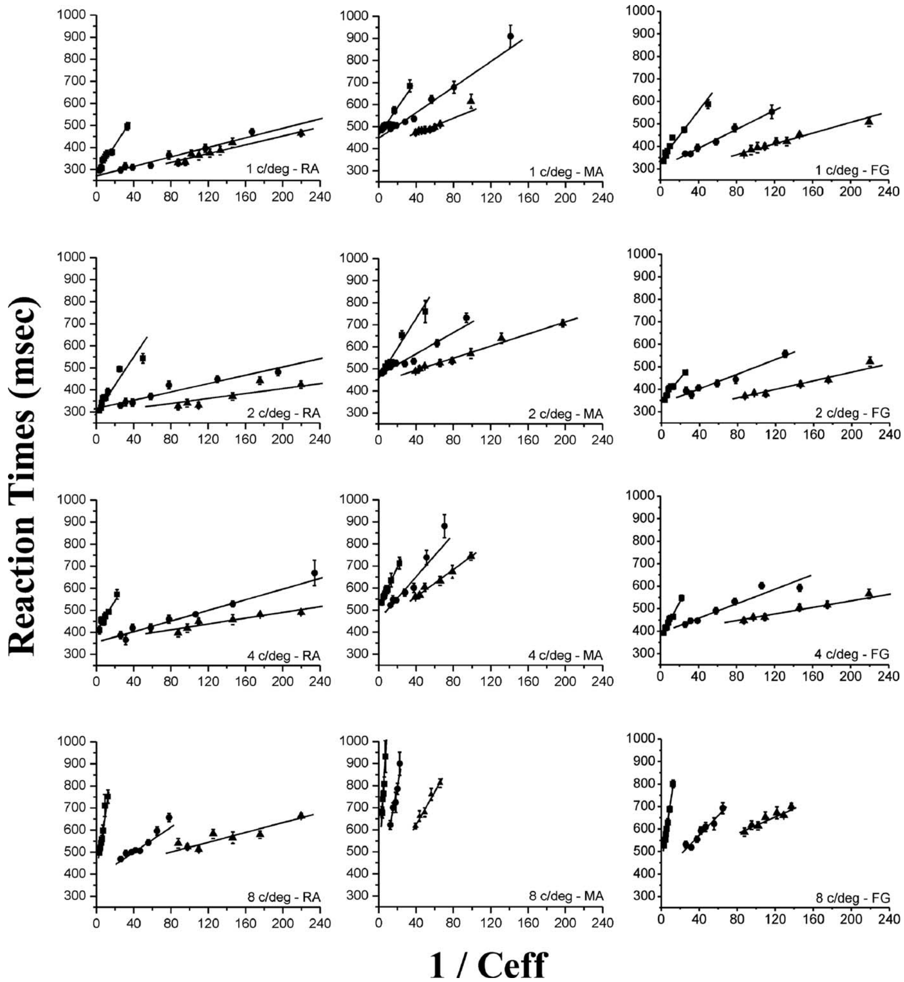


Fig. 3. RT as a function of the reciprocal of the effective contrast ($1/C_{\mathrm{eff}}$) calculated with the $Lv$ obtained from the Stiles–Holladay formula [Eq. (1)], for the three levels of glare [$E_G=0$ (■), 15 (●), and 60 (▲) lx]. Different panels show data for different subjects (columns) and spatial frequencies (rows).

that glare reduces the retinal image contrast and increases the mean luminance, which are two opposite effects in terms of visibility. What the results had shown is that the effect of contrast (reduction of visibility) masks the effect of luminance (increment of visibility) so, as we were able to isolate these two effects by compensating for the contrast losses, we should be able to show that the luminance component of glare actually reduces RT. This prediction is confirmed in Fig. 4.

**Table 3. Values of *Lg* for the Range of Spatial Frequencies and Levels of Glare Tested**

| | Spatial Frequency (c/deg) | | | |
|---|---|---|---|---|
| Glare Conditions | 1 | 2 | 4 | 8 |
| Subject RA | | | | |
| $E_G=15$ lx | 0.96 | 0.60 | 0.16 | 0.36 |
| $E_G=60$ lx | 7.46 | 2.36 | 1.06 | 0.96 |
| Subject MA | | | | |
| $E_G=15$ lx | 1.76 | 1.06 | 1.06 | 0.66 |
| $E_G=60$ lx | 7.16 | 2.86 | 2.36 | 0.89 |
| Subject FG | | | | |
| $E_G=15$ lx | 3.36 | 1.96 | 0.76 | 0.28 |
| $E_G=60$ lx | 7.36 | 4.46 | 2.96 | 1.26 |

In summary, the fact that the effect of glare is different for each spatial frequency implies that this effect cannot be accounted for by the classical approach considering that glare can be replaced by a single veiling luminance. In turn, we show that the effect of glare on RT must be modeled by an equivalent glare luminance that depends on spatial frequency.

### A. Multiple Channels to Explain the Influence of Spatial Frequency

Recent papers suggest that RT is mainly determined by local intensity, defined as the product of contrast by the period of the grating (P), rather than by these two variables independently [18,19,21,22]. The authors of the above-mentioned papers found that in certain situations the lines relating RT and local intensity obtained for different spatial frequencies cannot be differentiated from one another and they suggested that RT is not processed differently by different spatial channels. If this had held for our experimental conditions, we would have expected that for each glare condition the relation between RT and local intensity would not depend on spatial frequency.

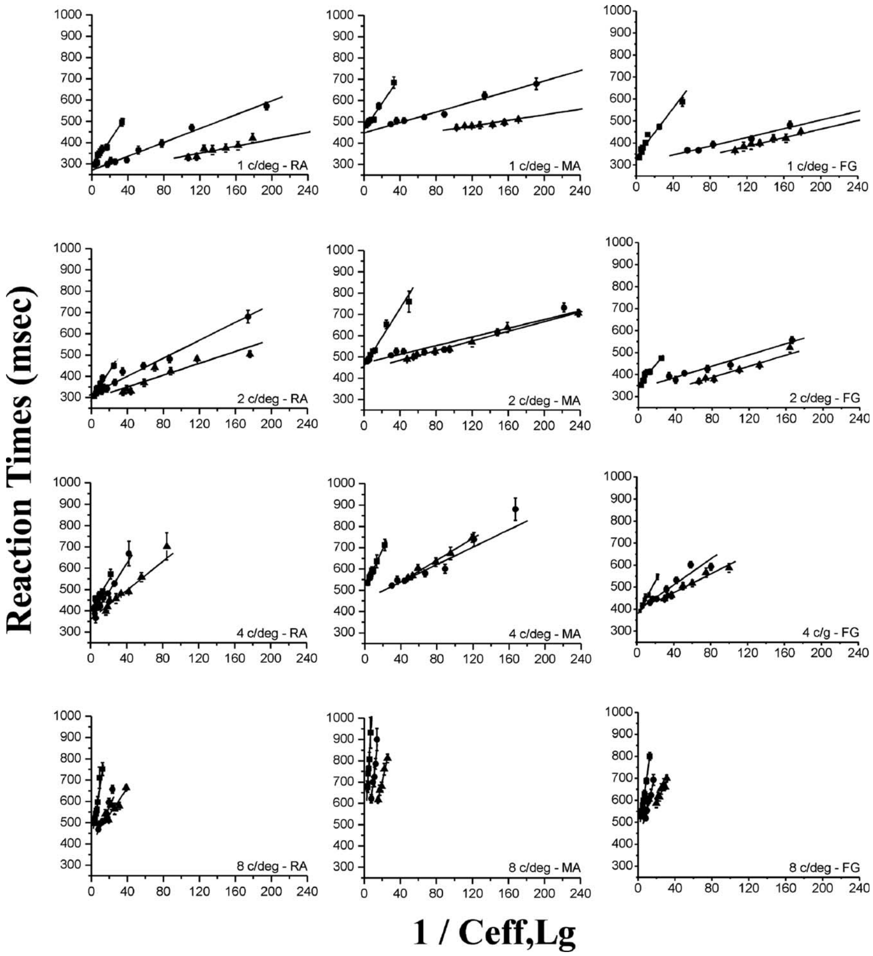


Fig. 4. RT as a function of the reciprocal of the effective contrast ($1/C_{\mathrm{eff},Lg}$) calculated with $Lg$, which was obtained by fitting the model of Plainis and Murray [16] [see Eq. (5)], for the three levels of glare [$E_G=0$ (■), 15 (●), and 60 (▲) lx]. Different panels show data for different subjects (columns) and spatial frequencies (rows).

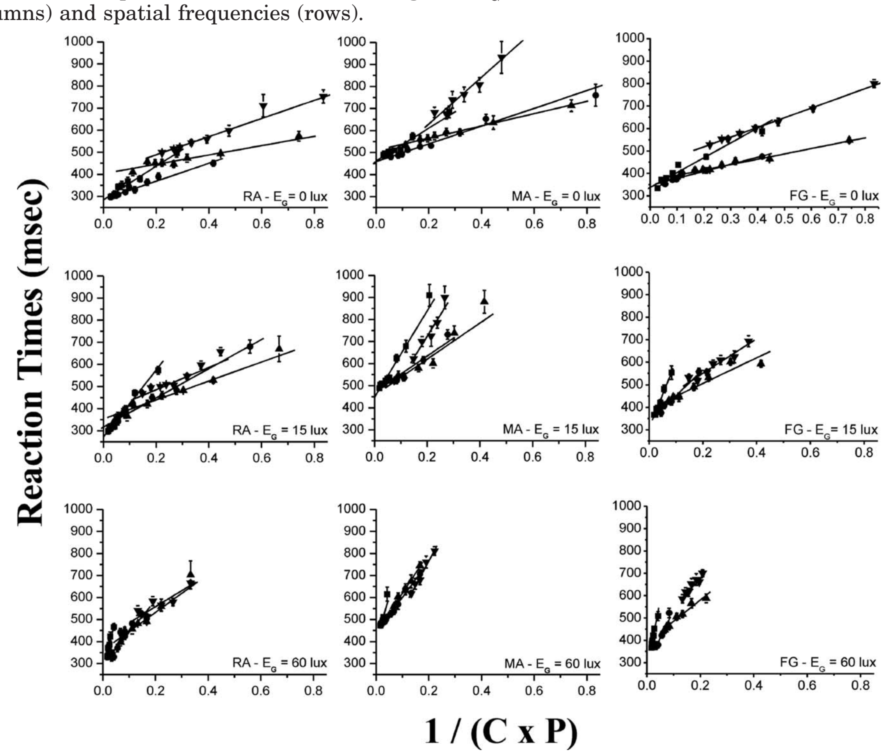


Fig. 5. RT as a function of the reciprocal of the product of contrast and the sinusoidal grating period [$1/(C \times P)$] for the four spatial frequencies. Different panels show data for different subjects (columns) and different glare levels (rows).

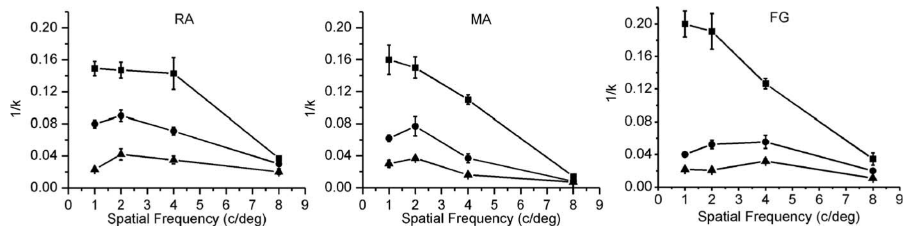


Fig. 6. $1/k$ as a function of spatial frequency for the three levels of glare and subjects.

However, our results show that this is not our case. We plotted RT as a function of the inverse of the local intensity and found that our data cannot be explained by a single function for all spatial frequencies. The lines for lower spatial frequency are steeper than those for higher spatial frequency thus suggesting that we can differentiate at least two effective spatial channels working in this situation (Fig. 5).

### B. Reaction Times and Contrast-Sensitivity Function

In a recent study, Plainis and Murray [23] compared the contrast gain from RT with results from neurophysiological data revealing the activity of two different mechanisms: The magnocellular system, which dominates the performance close to the detection threshold, and the parvocellular system, which dominates detection at higher contrasts when the magnocellular system saturates. These results reinforced the idea that there is a relation between RT and the contrast-sensitivity function (CSF). Because $1/k$ is a measure of the contrast gain of the system working over the threshold of contrast [16], the expected result would be a similar representation of the CSF when it is plotted as a function of the spatial frequency. Figure 6 shows, for all observers, $1/k$ versus spatial frequency, where the values of $k$ in these curves come from Table 1 (Fig. 2). These plots show that the curves of $1/k$ against spatial frequency are very similar to those of CSF, suggesting a possible link between RT and CSF, but this should be analyzed in future works.

It is interesting to note how the shape of the curves of the inverse of $k$ changes with glare. For the no-glare situation, the curves correspond to a low-pass filter and, as the level of glare increases, they became more bandpass, which reveals the glare effect of increasing adaptation luminance. Finally, the similar effects of glare on RT and CSF are shown: In both cases glare affects more low than high spatial frequencies. These results are consistent with several studies exploring the effect of visibility losses on CSF [24,25].

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