Ophthal. Physiol. Opt. 2002 **22:** 409–415

Reaction times as an index of visual conspicuity when driving at night

S. Plainis and I. J. Murray

Visual Sciences Laboratory, Department of Optometry and Neuroscience, UMIST, PO Box 88, Manchester M6 O1Q, UK

Abstract

Conspicuity refers to the visibility of objects that are either close to threshold or viewed in a cluttered environment. Conventional, threshold-based tests of vision are unlikely to be related to target visibility, because visual systems behave differently under supra-threshold and close-to-threshold conditions, or when low luminance levels are used. In these experiments, Reaction Times (RTs) are tested under a wide range of contrasts, luminances and spatial frequencies commonly encountered in the real world. We show that RTs are closely related to sensitivity and can therefore provide a method of measuring supra-threshold visual performance. The data are interpreted in terms of visual performance when driving, where a reduction in target visibility leads to increases in processing time.

Keywords: conspicuity, night driving, reaction time, road lighting, stopping distances

Introduction

When causes of road accidents are analysed there are inevitably many contributing factors. Apart from defective roads and vehicles, and careless driving, a common observation is the high proportion of perceptual errors made by drivers (Hills, 1980; Leibowitz and Owens, 1986). It seems likely, although the point has not been unequivocally established, that perceptual errors are even more common under low lighting conditions, when visibility is reduced (Owens and Sivak, 1993; Owens and Andre, 1996).

Many studies reinforce the familiar notion that good vision is important for safe driving (e.g. Hills, 1980; Sivak, 1996; Lachenmayr *et al*., 1998), yet much remains to be learned about how drivers use their vision in this complex dynamic task. Conventional vision tests (e.g. visual acuity, visual fields) are unlikely to predict driving performance and accident rates (see Charman, 1997; Wood, 1997 for reviews). This is not surprising as these standard measures do not reflect the visual, perceptual and cognitive complexity of the driving task.

Received: 14 June 2002
Revised form: 26 June 2002
Accepted: 26 June 2002

Correspondence and reprint requests to: S. Plainis, Vardinoyiannion Eye Institute of Crete (VEIC), Department of Ophthalmology, School of Medicine, PO Box 1393, Heraklion, 71110 Crete, Greece.
E-mail address: plainis@med.uoc.gr

On the other hand, central processing time and decision-making tests, like reaction times (e.g. Fergenson, 1971; Mihal and Barrett, 1976), visual search (e.g. Shinar *et al*., 1978; Avolio *et al*., 1985) and the useful field of view (UFOV) (Ball *et al*., 1993; Wood and Troutbeck, 1995; Owsley *et al*., 1998), have been found to be better predictors of crash involvement than simple sensory measures.

The statistics of night driving

As a substantial proportion of annual mileage is driven at night, studies of visual performance at low lighting (mesopic) conditions and safe driving ability are of considerable potential importance. Although it is not possible to directly attribute accidents to poor visibility, there is little doubt that a disproportionate number of accidents occur at night: the rate of fatal accidents (number of accidents per mile driven) has been reported to be three to four times higher at night than during the day (Owens and Andre, 1996; Owens and Sivak, 1996).

Figure 1a, b illustrate the overall night-time accident picture. They present re-analysed data from the 'Road Accidents Great Britain' (RAGB) publications (RAGB 2000), by introducing a new parameter, the severity of accidents. Severity of accidents is defined as the number of fatal accidents per 100 accidents. The term implies that fatal accidents are worse in terms of higher speeds and/or perceptual judgement than non-fatal accidents.

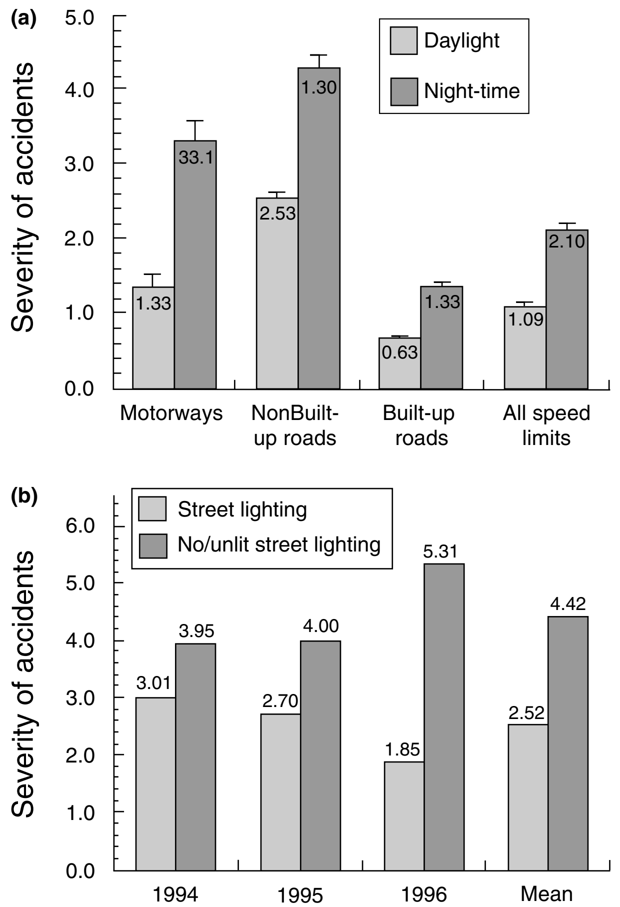

Figure 1. (a) Severity of accidents (fatal accidents per 100 accidents) by daylight and night-time and by different road types. The numbers represent average values for 7 years (source RAGB, 2000). (b) Severity of accidents by street lighting at night on motorways. The numbers represent values for 3 years (1994–1996) (source RAGB, 2000).

As seen in *Figure 1a*, severity of accidents is increased at night by a factor of 2 when averaged across different road types. Sceptics may argue that speed, fatigue, alcohol and other factors contribute disproportionately to night-time accidents. *Figure 1b* shows that, although there are almost certainly other factors, accident severity is inextricably linked to street lighting levels. The severity of accidents on well-lit motorways in 1996 was three times lower than that of unlit motorways. This observation is compelling evidence that low illumination is the major contributory factor in the high night-time accident rate. Consistent with these observations, studies on road lighting and accidents have shown that night-time accidents generally decline with good road lighting (Simons, 1992).

Therefore, a key point in relation to the role of vision in accidents is the actual level of road lighting at night. Road luminances have been found to be of the order of 1 cd m^{-2}, when driving on well-lit urban main roads, with the values decreasing to 0.06 cd m^{-2} on wet country roads illuminated only by car headlights (Hargroves, 1981; Chauhan and Charman, 1993). Luminance values of pedestrians and other objects of interest (e.g. traffic signs) are even lower, into the range of 0.01–0.25 cd m^{-2} (Lachenmayr *et al*., 1994; He *et al*., 1997). Absolute threshold values at these mesopic levels, where both rods and cones mediate perception, ranged between 5×10^{-4} and 5×10^{-3} cd m^{-2} (Plainis *et al*., 2000).

It is now well established that many aspects of visual performance, such as spatial resolution (Sloane *et al*., 1988; Arumi *et al*., 1997), stereoscopic depth perception (Allen *et al*., 1970), accommodation response (Johnson, 1976; Charman, 1986; Jiang *et al*., 1991; Arumi *et al*., 1997) and reaction time (Mansfield, 1973; Roufs, 1974; He *et al*., 1997) deteriorate under low illumination (see Charman, 1996 for a review). In the road scene, objects of interest are usually recognised by differences in colour and/or contrast. Under night-time lighting levels, colour vision is poor and thus it is principally luminance contrast that dominates visual performance.

The purpose of this study was to add to current knowledge about the response of the human visual system under mesopic lighting conditions. Reaction times (RTs) have a direct relevance to the driving task as the speed of the response plays an important role in the perceptual judgements made by drivers. Moreover, RT data can be easily translated into stopping distances.

Plainis and Murray (2000) have derived a model which predicts simple RTs with an equation linking contrast, spatial frequency and luminance. In this study simple RTs to targets presented in the visual field were measured for a range of stimulus variables, such as contrast, luminance and spatial frequency. The objective of the experiments was to determine which are most important when luminances are reduced and the inevitable slowing of responses occurs. Of particular interest were the combinations of parameters which simulate night driving conditions, that is low luminance, low contrast and low spatial frequencies.

Methods

Stimuli

The stimuli were vertical sinusoidal gratings displayed on a Barco CCID7651 'Calibrator' colour monitor (Kortrijk, Belgium). They were composed of separate red and green patterns that were combined in phase to produce achromatic (yellow–dark yellow) gratings. The subject viewed initially a plain yellow field ($x = 0.508$; $y = 0.437$), which was periodically replaced by the grating with no change in mean hue or luminance. The circular target subtended an angle of 7.13° at a viewing distance of 114 cm. The surround was dark. Subjects fixated on a cross located in the centre of the screen for foveal RTs and on red light-emitting diodes (LEDs) for peripheral RTs. The mean luminance of the screen $[(L_{max} + L_{min})/2]$ was 20 cd m^{-2}, and this was attenuated with neutral density filters to give lower luminances.

The RT data were collected for a range of contrasts from suprathreshold (0.5) to threshold detection. Contrast (C) was defined after Michelson:

$$C = (L_{max} - L_{min})/(L_{max} + L_{min})$$

where L_{max} and L_{min} are the maximum and minimum luminance values, respectively. A series of spatial frequencies (0.49–7.48 c deg^{-1}) and mean luminances (20–0.02 cd m^{-2}) were used. Eccentricities of 0, 5, 10 and 15° for both hemifields were tested.

Procedure

The RTs were determined using a CED 1401 (Cambridge Electronic Design Ltd, Cambridge, UK) smart interface (1 ms temporal resolution) linked to a PC and a purpose-designed computer program. They were measured by displaying the vertical grating for 340 ms with an abrupt onset and offset.

Before the RT measurement procedure began, the subjects adapted to the particular level of luminance between 5 and 15 min. Whenever viewing the display screen, subjects were instructed to fixate the cross/LEDs. A trial (a block of 32 presentations of the corresponding grating) consisted of the following sequence of events. A single warning tone was sounded. This was followed by a random foreperiod varying from 1000 to 3000 ms prior to a 340-ms presentation of the target stimulus. At the onset of the grating, a trigger probe was set and the event triggered the CED 1401 to start its integral clock counter. The subject was instructed to depress the response button immediately he/she detected the stimulus; the response button terminated the clock counter. A time-out occurred if there was no response within 2000 ms. Generally, only responses between 150 and 1000 ms were accepted; RTs over 600 ms were rarely encountered.

Subjects

Three young subjects were used (SP, LG, NH; aged 29, 23 and 21, respectively). Subjects were given a block of practice trials prior to RT recording in which different sets of spatial frequencies were presented. Subjects were optically corrected for the viewing distance with spectacles and viewed the stimuli through natural pupils and binocularly.

Results

RTs as a function of contrast

Piéron's law describes the decrease of simple RT with the increase of supraliminal intensities of a given stimulus by a power function in the form:

$$RT = RT_o + \beta I^{\alpha} \tag{1}$$

where RT_o is the asymptotic RT, β is a free parameter, I is the intensity of the stimulus and α is the exponent of the function (Piéron, 1952; Mansfield, 1973). Parameters a and RT_o appear to be specific for a given sensory modality; RT_o represents the combination of at least two constant parameters: the duration of the motor component and the task itself [e.g. it differs between choice and simple RT tasks; Pins and Bonnet, (2000)].

Plainis and Murray (2000) derived a similar monotonic function when RT was plotted as function of stimulus contrast, with the exponent being equal to −1:

$$RT = RT_o + kC^{-1} \tag{2}$$

where C is Michelson contrast and k is a constant which characterises the steepness of the curve.

From equation 2 it follows that, if the data are replotted as a function of the reciprocal of contrast ($1/C$), the resulting slope would be linear. This relationship is extremely robust for many observers and a wide range of stimulus conditions, as reported in Plainis and Murray (2000). *Figure 2* shows plots of RT vs $1/C$ for a range of luminances (from photopic-20 cd m^{-2}- to low mesopic-0.02 cd m^{-2} levels) and for two spatial frequencies (0.94 and 7.48 c deg^{-1}). It is clear that the slopes become steeper with decreasing luminance for both spatial frequencies, with the effect being more pronounced for 7.48 c deg^{-1}. For low spatial frequencies, small increments/decrements in contrast influence RT very little under photopic conditions. However, at lower luminances and for high spatial frequencies, visibility is reduced and small changes in contrast produce a strong effect on RT. This occurs because stimuli of lower visibility have low sensitivity and therefore, a narrow dynamic range.

We now turn to the effect of stimulus eccentricity. *Figure 3* illustrates how RT varies with horizontal ecentricity for two subjects (SP and NH) and for a spatial frequency of 0.49 c deg^{-1} grating at photopic levels (20 cd m^{-2}). The data for both subjects show the same trend with the slope increasing as eccentricity increases. Data for low luminances are not shown as the data superimpose each other. They show a much smaller eccentricity effect as is revealed in *Figure 4*.

The slope k of the RT vs $1/C$ functions reveals how contrast is linked to RT and can therefore be referred to

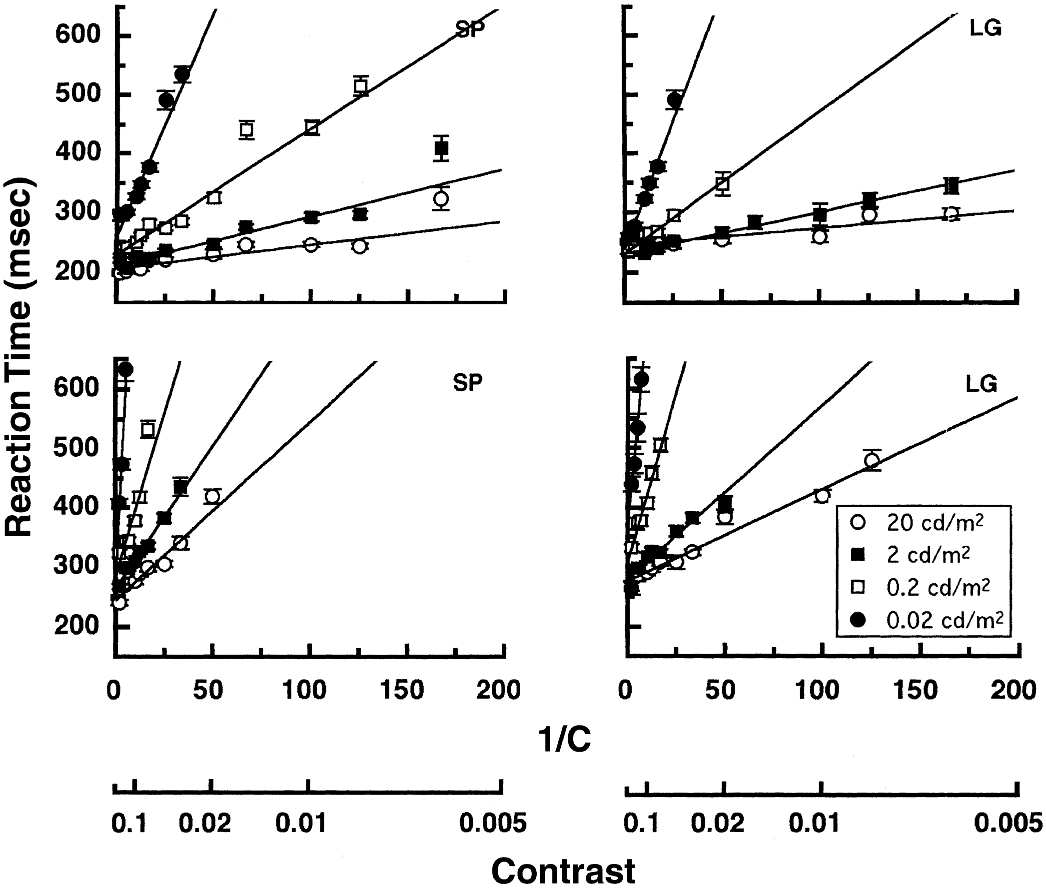

Figure 2. Plots of RT vs the reciprocal of contrast (1/*C*) for a 0.94 c deg^{-1} (upper panels) and a 7.48 c deg^{-1} (lower panels) spatial frequency grating, for a range of luminance levels and for two subjects (SP and LG). Each data point represents the mean of at least 24 measurements (maximum = 32) and the error bars ±1 S.E. The solid lines represent the least squares regression fits.

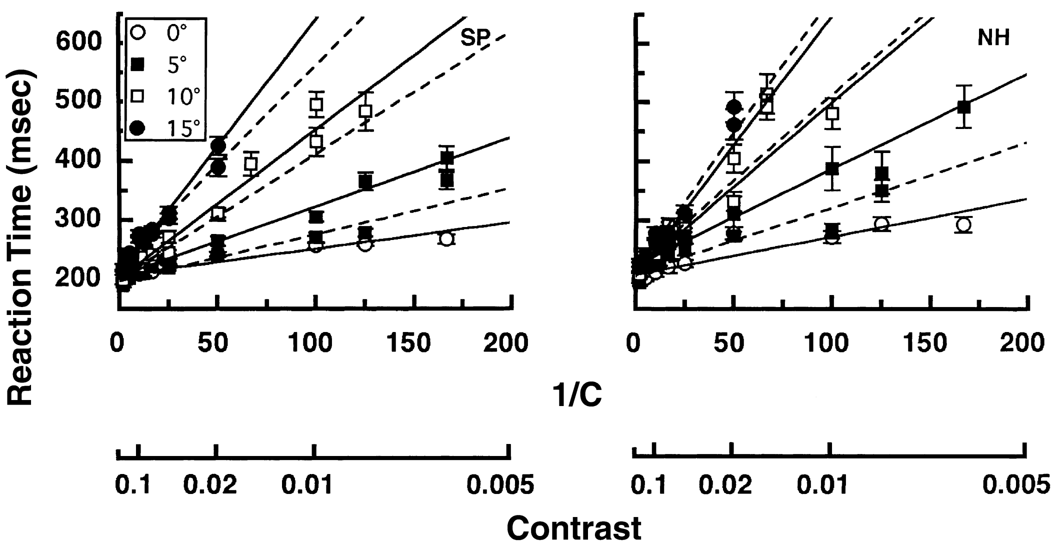

Figure 3. Plots of RT vs the reciprocal of contrast (1/*C*) for a range of stimulus eccentricities and for two subjects (SP and NH). The spatial frequency of the grating was 0.49 c deg^{-1} and the mean screen luminance 20 cd m^{-2}. Each data point represents the mean of at least 24 measurements (maximum = 32) and the error bars ±1 S.E. The solid lines represent the least squares regression fit for the right-hemifield, whereas the dashed lines represent the least square regression fits for the left-hemifield.

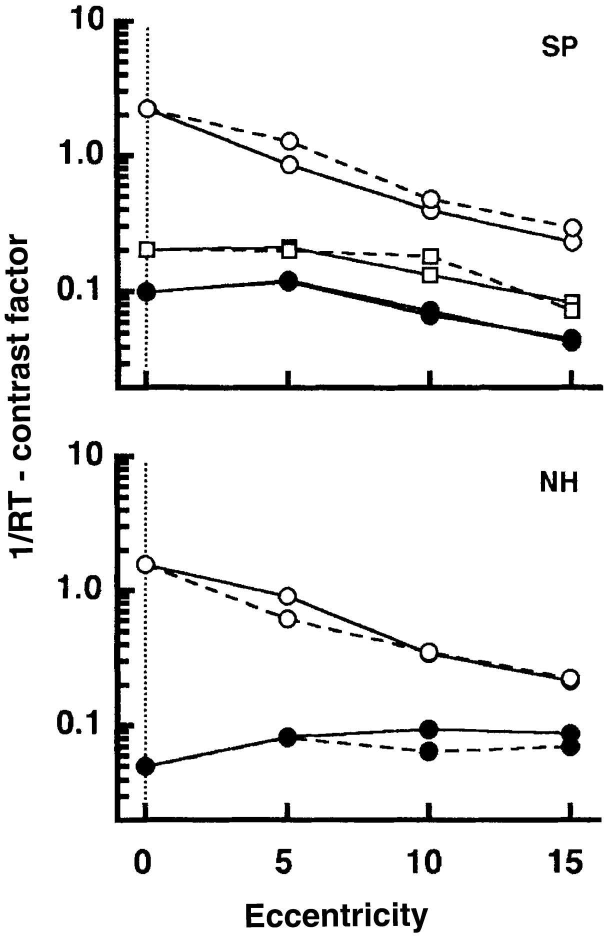

Figure 4. Plots of the inverse of the RT-contrast factor, k (in $ms^{-1} \times contrast^{-1}$) as a function of eccentricity for a range of luminances (in cd m^{-2}) and for two subjects (SP and NH). Spatial frequency was 0.49 c deg^{-1}. Effectively k is the slope of the RT vs $1/C$ function (see Figure 3). The solid lines represent data for the right-hemifield, whereas the dashed lines represent data for the left hemifield. Symbols are as for Figure 2; open circles 20 cd m^{-2}, open squares 0.2 cd m^{-2} and closed circles 0.02 cd m^{-2}.

as the RT-contrast factor (Murray and Plainis, 2000; Plainis and Murray, 2000). The RTs are reciprocally related to sensitivity; short RTs are obtained at low spatial frequencies and high luminance whereas long RTs are obtained at high spatial frequencies, low luminance and for eccentric viewing. Hence, in order to be comparable with physiological contrast gain (see Plainis and Murray, 2000 for the neurophysiological interpretation of RTs), the reciprocal of k might be used, so as to provide RT-based functions. *Figure 4* shows plots of the reciprocal of k ($1/$RT-contrast factor) for a 0.49 c deg^{-1} grating as a function of eccentricity (both hemifields) for photopic (20 cd m^{-2}) and low mesopic (0.2 and 0.02 cd m^{-2}) light levels. At 20 cd m^{-2} the reciprocal of RT-contrast factor is maximal at the fovea and decreases almost linearly with eccentricity. At lower luminances (0.02 cd m^{-2}) it hardly varies with eccentricity. Effectively then, for higher luminances and for a range of contrasts there is a strong RT-eccentricity effect whereas for mesopic conditions, although there is a slight effect for one subject (SP), RTs remain largely independent of eccentricity. Note that the functions are symmetrical for the two hemifields (Holmes *et al*., 2000).

Discussion

The data in *Figures 2* and *3* show that RT varied from 200 ms in optimal conditions, usually encountered during daytime driving (i.e. high contrast, photopic luminance), to about 600 ms in non-optimal conditions experienced during night driving (i.e. low luminance, low contrast, eccentric viewing).

Therefore, it is of interest to note how the RT data might translate into critical (safe) stopping distances. The Highway Code recommendations for 'the shortest stopping distances' for various vehicle speeds divides these in to 'thinking' and 'braking' distances. The 'thinking distance' is a component which includes the visual reaction time, the pedal response and the mechanical action of the brakes. This assumes a perception time of 675 ms for optimal conditions.

The 'braking distance' is the time taken to decelerate to zero mph. It assumes a braking deceleration of 6.5 ms^{-2} for dry roads. For example, the overall stopping distance for 50 mph speed is composed of a 15 m thinking distance and a 37.9 m braking distance. Given a perception time of 675 ms for the calculation of the 'thinking distances' under optimal daytime conditions (as suggested by the UK Highway Code), we can estimate the corresponding 'thinking distances' for the non-optimal night-time conditions.

Table 1 illustrates the increase in thinking and overall stopping distances for different speeds, which would occur if the target was of low contrast and luminance. Effectively, we have calculated an increase in RT from 200 to 600 ms. This modest increase in thinking time

Table 1. 'Thinking' and 'stopping' distances (in m) under optimal photopic conditions and non-optimal night-time conditions for different vehicle speeds. The additional distance is the calculated increase in overall stopping distance under night-time conditions. Note that 4 m is the length of an average car.

	Optimal conditions		Non-optimal night-time conditions		
Speed (mph)	Thinking distance	Stopping distance	Thinking distance	Stopping distance	Additional distance
30	9.0	22.6	14.3	27.9	5.3
50	15.0	52.9	23.9	61.8	8.9
60	18.0	72.7	28.7	83.4	10.7
70	21.0	95.4	33.4	107.8	12.4
80	24.0	121.2	38.2	135.4	14.2

results in significant increases in stopping distances despite the conservative characteristics of our model. For example, for a speed of 50 mph the increase in stopping distance, as luminance decreases, is about 8.9 m. Higher speeds (occurring often when driving on motorways) result in greater distances for the vehicle to stop (14.2 m for 80 mph). This may explain the significant increase in severity of accidents during night-time.

Conclusions

Driving is often described as a visuo-motor task, and it seems plausible that many night accidents are caused by reduced visibility (see *Figure 1*). As visual RT is closely linked to target visibility, it might be expected to have a more direct relationship to safe driving than conventional clinical measures of visual performance. It is also intuitively obvious that RTs will increase as targets become less conspicuous.

It has been shown that at illuminance levels close to 0.1 lux the rods, increasing in sensitivity, inhibit perception of certain targets (Plainis *et al*., 2000). Although overall retinal sensitivity increases, the system may 'slow down' notably, which is manifest as increased reaction time. Our data indicate that an increase in processing time occurs as contrast and luminance are decreased (*Figure 2*). It is evident that RT exhibits a simple mathematical relationship to contrast and can therefore be used as an index of target conspicuity (see also Plainis and Murray, 2000). Furthermore, RT is considerably increased in the near-periphery (*Figure 3*), and this is of critical importance when driving. As shown by Scialfa *et al*. (1998) most unexpected objects must be detected when in the periphery.

Finally, we have calculated the extent to which stopping distances must be increased to take account of poor target visibility under night-time lighting conditions. Some aspects of driving are not considered in the analysis. Note that stopping distances increase dramatically in adverse weather conditions and it has been shown that the luminance of wet roads is significantly less than that for dry roads (Chauhan and Charman, 1993). The present data are for young observers; older observers who, generally, have a slower reaction time (and a reduced information processing capacity) will show poorer performance. Finally, other factors, such as tiredness, prolonged effort and alcohol consumption, must severely affect reaction times as illustrated by Summala and Mikkola (1994).

Acknowledgements

Professor N Charman influenced (often unknowingly) much of the thinking behind this work and provided guidance with some earlier data analysis. We are pleased to acknowledge the many fruitful discussions we have had with Professor Charman on this and many other projects. The work is part of a LINK Transport Infrastructure and Operations programme. We gratefully acknowledge the support of the Engineering and Physical Sciences Research Council (EPSRC) and Urbis Lighting Limited. We thank Dr NRA Parry for the use of the RT software and many helpful comments during the course of this research.

References

Allen, M. J., Hazlett, R. D., Tacker, H. L. and Graham, B. V. (1970) Actual pedestrian visibility and the pedestrian's estimate of his own visibility. *Am. J. Optom. Arch. Am. Acad. Optom.* **47,** 44–49.

Arumi, P., Chauhan, K. and Charman, W. N. (1997) Accommodation and acuity under night-driving illumination levels. *Ophthalmic Physiol. Opt.* **17,** 291–299.

Avolio, B. J., Kroeck, K. G. and Panek, P. E. (1985) Individual differences in information-processing ability as a predictor of motor vehicle accidents. *Hum. Factors* **27,** 577–587.

Ball, K., Owsley, C., Sloane, M. E., Roenker, D. L. and Bruni, J. R. (1993) Visual attention problems as a predictor of vehicle crashes in older drivers. *Invest. Ophthalmol. Vis. Sci.* **34,** 3110–3123.

Charman, W. N. (1986) Static accommodation and the minimum angle of resolution. *Am. J. Optom. Physiol. Opt.* **63,** 915–921.

Charman, W. N. (1996) Night myopia and driving. *Ophthalmic Physiol. Opt.* **16,** 474–485.

Charman, W. N. (1997) Vision and driving – a literature review and commentary. *Ophthalmic Physiol. Opt.* **17,** 371–391.

Chauhan, K. and Charman, W. N. (1993) Changes in refractive error under night-time driving conditions. In: *Vision in Vehicles IV* (eds A. Gale, I. Brown, C. Haslegrave, H. Kruyse, and S. Taylor). Elsevier, Amsterdam, pp. 35–44.

Fergenson, P. E. (1971) The relationship between information processing and driving accident and violation record. *Hum. Factors* **13,** 173–176.

Hargroves, R. A. (1981) Road lighting-as calculated and as in service. *Lighting Res. Technol.* **13,** 130–136.

He, Y., Rea, M., Bierman, A. and Bullough, J. (1997) Evaluating light source efficacy under mesopic conditions using reaction times. *J. Illuminating Engineering Soc.* **26,** 125–138.

Hills, B. L. (1980) Vision, visibility, and perception in driving. *Perception* **9,** 183–216.

Holmes, N. P., Plainis, S. and Murray, I. J. (2000) Reaction Times as a behavioural measure of contrast gain; comparison of low and high luminance levels and different eccentricities. *Perception* **29,** 78.

Jiang, B. C., Gish, K. W. and Leibowitz, H. W. (1991) Effect of luminance on the relation between accommodation and convergence. *Optom. Vis. Sci.* **68,** 220–225.

Johnson, C. A. (1976) Effects of luminance and stimulus distance on accommodation and visual resolution. *J. Opt. Soc. Am. A* **66,** 138–142.

Lachenmayr, B., Berger, J., Buser, A. and Keller, O. (1998) Reduced visual function causes higher risk of traffic accidents. *Ophthalmologe* **95,** 44–50.

Lachenmayr, B., Buser, A. and Müller, S. (1994) What kind of visual information does the driver need to drive safely in road traffic? *Ophthalmologe* **91,** 383–394.

Leibowitz, H. W. and Owens, D. A. (1986) We drive by night. *Psychol. Today* **20,** 54–58.

Mansfield, R. J. W. (1973) Latency functions in human vision. *Vision Res.* **13,** 2219–2234.

Mihal, W. L. and Barrett, G. V. (1976) Individual differences in perceptual information processing and their relation to automobile accident involvement. *J. Appl. Psychol.* **61,** 229–233.

Murray, I. J. and Plainis, S. (2000) A general equation for reaction times to contrast, spatial frequency and luminance. *Invest. Ophthalmol. Vis. Sci.* **41,** S802.

Owens, D. A. and Andre, J. T. (1996) Selective visual degradation and the older driver. *IATSS Res.* **20,** 57–66.

Owens, D. A. and Sivak, M. (1993) The role of visibility in nighttime traffic accidents. In: *2nd International Symposium on Visibility and Luminance in Roadway Lighting*, Orlando, pp. 133–147.

Owens, D. A. and Sivak, M. (1996) Differentiation of visibility and alcohol as contributors to twilight road fatalities. *Hum. Factors* **38,** 680–689.

Owsley, C., Ball, K., McGwin, G., JrSloane, M. E. Roenker, D. L. White, M. F. and Overley, E. T. (1998) Visual processing impairment and risk of motor vehicle crash among older adults. *JAMA.* **279,** 1083–1088.

Piéron, H. (1952) The Sensations. Frederick Muller Ltd., London.

Pins, D. and Bonnet, C. (2000) The Piéron function in the threshold region. *Perception Psychophysics* **62,** 127–136.

Plainis, S. Chauhan, K. Murray, I. J. and Charman, W. N. (2000) Retinal adaptation under night-time driving conditions. In: *Vision in Vehicles VII* (eds A. Gale, I. Brown, C. Haslegrave, and S. Taylor). Elsevier Science BV, North Holland, Marseilles, pp. 35–42.

Plainis, S. and Murray, I. J. (2000) Neurophysiological interpretation of human visual reaction times: effect of contrast, spatial frequency and luminance. *Neuropsychologia* **38,** 1555–1564.

Road Accidents Great Britain (RAGB). (2000) Report 1994–2000. The Department of Environment Transport and the Regions, Great Britain.

Roufs, J. A. J. (1974) Dynamic properties of vision – V: perception lag and reaction time in relation to flicker and flash thresholds. *Vision Res.* **14,** 853–869.

Scialfa, C. T., Esau, S. P. and Joffe, K. M. (1998) Age, target-distractor similarity and visual search. *Exp. Aging Res.* **24,** 337–358.

Shinar, D., McDowell, E. D., Rackoff, N. J. and Rockwell, T. H. (1978) Field dependence and driver visual search behaviour. *Hum. Factors* **20,** 553–559.

Simons, R. H. (1992) Road lighting and accidents. In: *Lightec '92*. Houldershaw Ltd, Essex, pp. 54–57.

Sivak, M. (1996) The information that drivers use: is it indeed 90% visual? *Perception* **25,** 1981–1989.

Sloane, M. E., Owsley, C. and Alvarez, S. L. (1988) Aging, senile miosis and spatial contrast sensitivity at low luminance. *Vision Res.* **28,** 1235–1246.

Summala, H. and Mikkola, T. (1994) Fatal accident among car and truck drivers: effects of fatigue, age, and alcohol consumption. *Hum. Factors* **36,** 315–326.

Wood, J. (1997) Vision & driving: current standards and recent research. *Optom. Today* **37,** 29–32.

Wood, J. M. and Troutbeck, R. (1995) Elderly drivers and simulated visual impairment. *Optom. Vis. Sci.* **72,** 115–124.