Journal of Optometry (2017) 10, 233–241

Journal of Optometry

www.journalofoptometry.org

ORIGINAL ARTICLE

The Enright phenomenon. Stereoscopic distortion of perceived driving speed induced by monocular pupil dilation

Andrew Carkeet[a,b,*], Joanne M. Wood[a,b], Kylie M. McNeill[a], Hamish J. McNeill[a], Joanna A. James[a], Leigh S. Holder[a]

[a] *School of Optometry and Vision Science, Queensland University of Technology, Victoria Park Rd, Kelvin Grove Q 4059, Australia*
[b] *Institute of Health and Biomedical Innovation, Queensland University of Technology, 60 Musk Ave, Kelvin Grove Q 4059, Australia*

Received 15 June 2016; accepted 24 August 2016
Available online 17 November 2016

KEYWORDS
Driving;
Enright;
Pulfrich;
Speed distortion;
Monocular dilation

Abstract
Purpose: The Enright phenomenon describes the distortion in speed perception experienced by an observer looking sideways from a moving vehicle when viewing with interocular differences in retinal image brightness, usually induced by neutral density filters. We investigated whether the Enright phenomenon could be induced with monocular pupil dilation using tropicamide.
Methods: We tested 17 visually normal young adults on a closed road driving circuit. Participants were asked to travel at Goal Speeds of 40 km/h and 60 km/h while looking sideways from the vehicle with: (i) both eyes with undilated pupils; (ii) both eyes with dilated pupils; (iii) with the leading eye only dilated; and (iv) the trailing eye only dilated. For each condition we recorded actual driving speed.
Results: With the pupil of the leading eye dilated participants drove significantly faster (by an average of 3.8 km/h) than with both eyes dilated ($p = 0.02$); with the trailing eye dilated participants drove significantly slower (by an average of 3.2 km/h) than with both eyes dilated ($p < 0.001$). The speed, with the leading eye dilated, was faster by an average of 7 km/h than with the trailing eye dilated ($p < 0.001$). There was no significant difference between driving speeds when viewing with both eyes either dilated or undilated ($p = 0.322$).
Conclusions: Our results are the first to show a measurable change in driving behaviour following monocular pupil dilation and support predictions based on the Enright phenomenon.

* Corresponding author at: School of Optometry and Vision Science, Queensland University of Technology, Victoria Park Rd, Kelvin Grove Q 4059, Australia.
E-mail addresses: a.carkeet@qut.edu.au (A. Carkeet), j.wood@qut.edu.au (J.M. Wood), optom_kylie@hotmail.com (K.M. McNeill), hamish.mcneill@qut.edu.au (H.J. McNeill), joanna.james@gmail.com (J.A. James), Leigh_vb@hotmail.com (L.S. Holder).

http://dx.doi.org/10.1016/j.optom.2016.08.001

PALABRAS CLAVE
Conducción;
Auto-movimiento;
Enright;
Pulfrich;
Distorsión de la velocidad;
Dilatación monocular

Fenómeno Enright. Distorsión estereoscópica de la velocidad percibida al conducir, inducida mediante dilatación monocular de la pupila

Resumen

Objetivo: El fenómeno Enright describe la distorsión en la percepción de la velocidad experimentada por un observador que mira lateralmente desde un vehículo en movimiento, y la visión con diferencias interoculares en cuanto a luminosidad de la imagen en la retina, normalmente inducida por filtros de densidad neutra. Investigamos si el fenómeno Enright podría inducirse mediante dilatación monocular de la pupila utilizando tropicamida.

Métodos: Realizamos pruebas a 17 adultos jóvenes con visión normal, en un circuito cerrado de conducción por carretera. Se solicitó a los participantes que viajaran a velocidades predefinidas de 40 km/h y 60 km/h mientras miraban a ambos lados del vehículo con: i) ambos ojos sin dilatación pupilar; ii) ambos ojos con las pupilas dilatadas; iii) dilatación únicamente en el ojo fijador; y iv) dilatación únicamente en el ojo no fijador. Registramos la velocidad real de conducción para cada situación.

Resultados: Con la pupila del ojo fijador dilatada los participantes condujeron a una velocidad considerablemente superior (de 3,8 km/h de media) que con ambos ojos dilatados ($p = 0,02$); con la pupila del ojo no fijador dilatada los participantes condujeron a una velocidad considerablemente menor (de 3,2 km/h de media) que con ambos ojos dilatados ($p < 0,001$). Con el ojo fijador dilatado la velocidad fue superior, de 7 km/h de media, a la velocidad con el ojo no fijador dilatado ($p < 0,001$). No se produjo diferencia significativa entre las velocidades de conducción cuando miraban con ambos ojos, tanto estuvieran dilatadas las pupilas o no ($p = 0,322$).

Conclusiones: Nuestros resultados son los primeros que reflejan un cambio medible en el comportamiento conductor tras la dilatación monocular de la pupila, y respaldan las predicciones que se basan en el fenómeno Enright.

Introduction

The Enright phenomenon is a binocular visual illusion of misperceived motion.[1,2] The illusion can be induced by placing a neutral density filter over one eye of an observer looking sideways from a vehicle. When an observer is in this position one eye will be further forward in the vehicle and we define this as ''the leading eye''. One eye will be closer to the rear of the vehicle and we define this as ''the trailing eye''. If a filter is placed over the leading eye the observer's percept is that they are travelling faster than they actually are. If the filter is over the trailing eye the observer's percept is that they are travelling more slowly than they actually are. Enright, in his original paper[2] on the illusion argued that it was related to the Pulfrich phenomenon,[3] in which inter-ocular differences in retinal illumination cause misperceived depth of moving objects. The misperceived depth of objects moving across the visual field results in a disruption of motion constancy, which the observer misinterprets as travelling at a different speed.

The Enright Phenomenon is illustrated qualitatively in Figs. 1 and 2. Fig. 1 shows the Pulfrich Phenomenon,[3] illustrating the case for an observer looking rightwards from a moving vehicle. The leading eye (the eye most forward in the vehicle) is the left eye in this situation. If the leading eye receives less retinal illumination than the trailing eye, as would be the situation where the trailing eye is dilated (as in Fig. 1a) the latency of perception will be slightly longer in the leading eye and objects in the field will appear slightly in front of those presented to the trailing eye, giving rise to uncrossed disparity, and observers will interpret these spurious depth cues as indicating that the object is further away. The reverse occurs when the leading eye receives more retinal illumination than the trailing eye, where the leading eye is dilated (as in Fig. 1b). The latency of perception will be slightly longer in the trailing eye and objects in the field will appear slightly in front of those presented to the leading eye, giving rise to crossed disparity, and participants will interpret these spurious depth cues as indicating that the object is closer. The effect of these spurious depth cues on velocity judgement is shown in Fig. 2, in which the observer is moving to the left causing objects to move across the visual field at a speed V. If the distance of objects is misjudged as being further away, then the apparent velocity V′ of objects moving across the field is interpreted as being larger than it actually is. If the observer judges their self-motion based on these visual cues then they will judge that they are travelling faster than they actually are. If apparent depth of objects is misjudged as being closer, then the apparent velocity V′ of objects moving across the field is interpreted as being smaller than it actually is. If the observer is judging their self-motion based on these visual cues they will perceive that they are travelling slower than they actually are.

The principles illustrated in Figs. 1 and 2 have been used to develop a geometric model of the Enright phenomenon

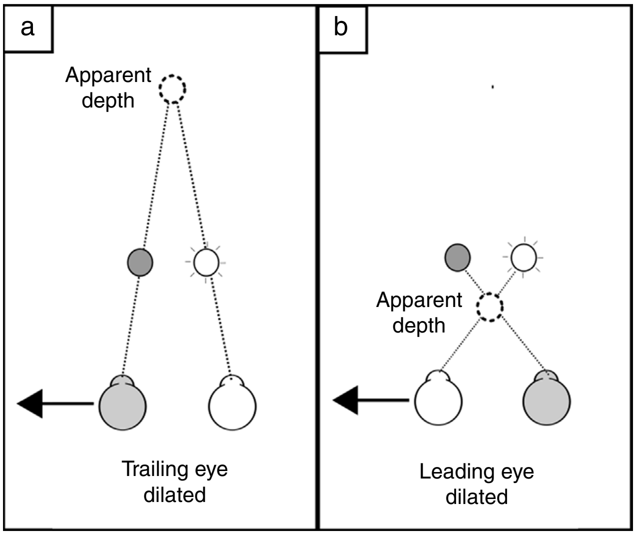

Figure 1 Schematic diagram of the Pulfrich phenomenon. Distortions of apparent depth for a moving observer induced by interocular asymmetry of retinal illuminance, with each eye perceiving the object in a slightly different relative spatial location, the disparity is interpreted as a spurious depth cue. The horizontal arrow indicates the movement of the observer (in this case to the left). (a) Trailing eye (in this case the right eye) receives more retinal illumination (shown unshaded): object is perceived as further away. (b) Leading eye (in this case the left eye) receives more retinal illumination: object is perceived as closer.

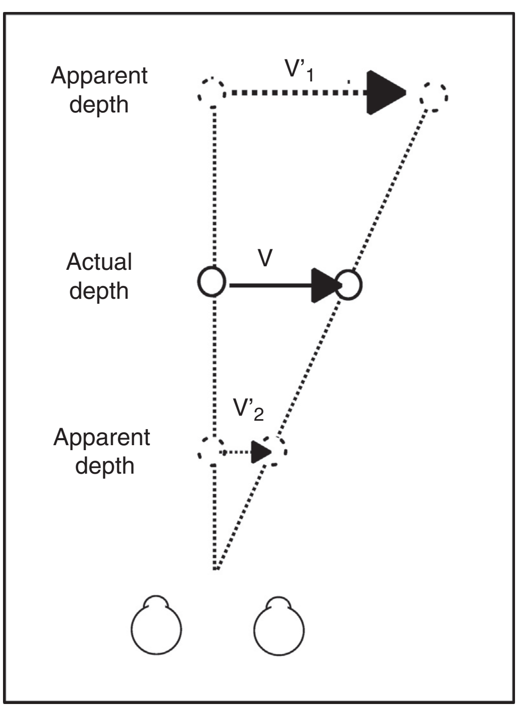

Figure 2 The anomalous depth cues in the Pulfrich stereophenomenon can result in the actual velocity V being misinterpreted as an apparent velocity V′ which will be smaller if the perceived distance is smaller than it actually is (expected if more light enters the leading eye), and larger if the perceived distance is larger than it actually is (expected if more light enters the trailing eye).

which describes the relationship between interocular temporal latency differences and perceived self-velocity.[1] These predictions have also been assessed quantitatively in a previous closed road driving study where participants were asked to drive at different speeds (60 km/h or 40 km/h), while looking sideways with 0.9 ND filters placed in front of the leading or trailing eye.[1] When participants had a filter over the trailing eye they compensated for the percept of travelling slower by speeding up by an average of 8.7 km/h, whereas when the filter was over the leading eye they compensated for the percept of travelling faster by slowing down by an average of 3.7 km/h. This demonstrated that the Enright illusion can have real world consequences for driving behaviour. Carkeet et al.[1] observed, however, that the real world speed distortions induced by the Enright Illusion were somewhat smaller than might be expected from their geometric model, hypothesising that cues such as vehicle vibration, engine noise, and monocular cues to depth, may all act to mitigate the real world consequences of the Enright phenomenon.

Apart from its consequences for driving, the Enright phenomenon has also been reported independently in the literature on electronic imaging,[4] and has been considered as a possible reason for the crash of two Blackhawk helicopters.[5]

Although the traditional method for inducing the Enright phenomenon and the Pulfrich phenomenon has been to place a neutral filter over one of a participant's eyes, the Pulfrich Phenomena can also be induced by unilateral dilation of a participant's pupil[6,7] or by restricting pupils through the use of apertures[8] resulting in asymmetry of retinal illumination.[9] Given its close relationship with the Pulfrich phenomenon it is likely that the Enright phenomenon can be induced by monocular pupil dilation, and may alter speed judgements while driving in this situation, however, this effect has not been previously explored.

Binocular pupil dilation has been shown to affect drivers' ability to recognise and avoid low contrast hazards and also decreases visual acuity and contrast sensitivity.[10] However, there have been no studies that have investigated the effects of monocular pupil dilation on driving performance. In addition, there appear to be no published studies on the frequency of monocular dilation for fundus examination. Nor could we find clinical guidelines or text books discussing whether monocular dilation is appropriate in ocular examinations. However, for centuries monocular dilation has been used, and is still used, as part of medical therapy for anterior uveitis and this use can continue for weeks to months in a patient.[11,12] The Enright phenomenon is particularly relevant in those driving situations where drivers turn their head to one side for brief intervals when overtaking or judging safe gaps to change lanes or when navigating through intersections. In these situations monocular dilation could affect driving speed and speed judgments. Given the lack of information regarding how monocular pupil dilation affects driving, and the likelihood that monocular dilation could induce an Enright phenomenon, we conducted the current study to assess whether monocular pupil dilation could induce an Enright phenomenon and to determine the magnitude of such effects on real-world driving performance. We hypothesised that monocular dilation of the leading eye in the vehicle would cause the driver to perceive they are travelling slower than they actually are and that drivers would speed up to compensate and that monocular dilation of the trailing eye would cause drivers to perceive they were travelling faster than they actually are and slow down to compensate for the misperceived speed.

Methods

Location and vehicle

Testing was undertaken at a closed road driving circuit,[13] which was free of other motor vehicles. The vehicles used were 2009 Holden Commodore Station Wagons with the participant, who was the driver, seated in the right hand seat of the car, which is the standard for Australia where vehicles travel on the left side of the road. During the experiment the speedometer was occluded so that the driver could not view it.

Testing was conducted along a 600 m long straight section of the road which was 3 lanes wide. The middle lane was used for the experimental runs. On the right hand side of the vehicle the road was bordered by open forest of young eucalypts of approximately 5 m height, with the tree line at a distance of approximately 5 m from the driver. Experimentation took place under bright daylight conditions, with illuminance levels being measured at between 10,000 and 15,000 lux with an illuminance metre held vertically at the driver's side window at the beginning of each of the testing sessions.

Pilot observations

Prior to conducting the experiment, pilot testing was conducted at speeds of 40 km and 60 km an hour at the closed road circuit, using the principal author as the experimental participant. Observations were made looking rightward and then (travelling in the opposite direction) leftward to the forest from the vehicle. Initially this was done with undilated pupils then with the right pupil dilated with one drop of 1% tropicamide. With undilated pupils there was no discernible difference in perceived self-velocity when viewing leftwards compared with viewing rightwards. With the right pupil dilated the percept was that self-velocity was substantially faster looking rightwards (dilated trailing eye) than when looking leftwards (dilated leading eye). The percept of slowing down when looking leftward (leading eye dilated) was more vivid than the percept of speeding up when looking rightward (trailing eye dilated). These percepts were in agreement with Enright's original report[2] that relative reduction of illumination in the trailing eye caused a percept of decreased self-velocity and that relative reduction of illumination in the leading eye caused a less intense perception of increased self-velocity.

Participants

Participants included 17 (12 male 5, female) visually normal adults aged from 20 to 38 years (mean 23.1 ± 4.4 years) who all held valid Queensland Open Drivers' Licences at the time of recruitment. All participants were screened prior to testing and had normal ocular health, with distance visual acuities of 6/6 or better in each eye when wearing their habitual distance driving vision correction. All participants had stereopsis of 60'' or better (TNO stereo test), normal pupil reactions, van Herrick ratios of greater than 0.5 and intraocular pressures less than or equal to 19 mm Hg. The research was conducted with Ethics approval from the Queensland University of Technology Human Research Ethics Committee with all participants providing informed written consent. This research complied with the tenets of the Declaration of Helsinki.

Experimental design

The major purpose of this project was to compare driving performance under 4 conditions where all the participants viewed binocularly with: 1. normal undilated pupils; 2. only the left pupil dilated; 3. only the right pupil dilated; 4. both pupils dilated. This design was similar to a previous study in which interocular asymmetries of retinal illumination were induced with neutral density filters.[1] Testing was conducting over 2 sessions. Given the time it takes to administer the dilating drops and for the pupils to dilate and recover from dilation; these sessions were conducted with a least one week's interval between them. We alternated the order of dilation between participants so that odd numbered participants had their left eye dilated first and even numbered participants had their right eye dilated first.

We also ran additional control testing conditions in which participants viewed monocularly with undilated pupils then with dilated pupils. The purpose of these control experiments was to assess whether monocular dilation would induce any changes in driving behaviour, if stereoscopic cues were removed. Nine participants (odd numbered participants) were tested with the right eye viewing and 8 (even numbered participants) were tested with the left eye viewing. We interleaved these conditions with those of the main study.

The conditions thus tested in the two experimental sessions are illustrated schematically in Fig. 3 and described below:

First session

- Binocular viewing with natural, undilated pupils;
- Monocular testing, viewing with undilated pupil;
- Binocular viewing with unilateral mydriasis (opposite eye dilated from that used for undilated viewing above).

Second session

- Binocular viewing with natural, undilated pupils (to establish baseline for the second session;
- Binocular testing with dilated pupil viewing (the dilated pupil was in the opposite eye to that tested in session 1);
- Monocular testing (viewing with dilated pupil eye);
- Binocular testing with both pupils dilated.

For each condition testing took place twice for each of two Goal Speeds with the order of testing randomised for each participant and viewing condition.

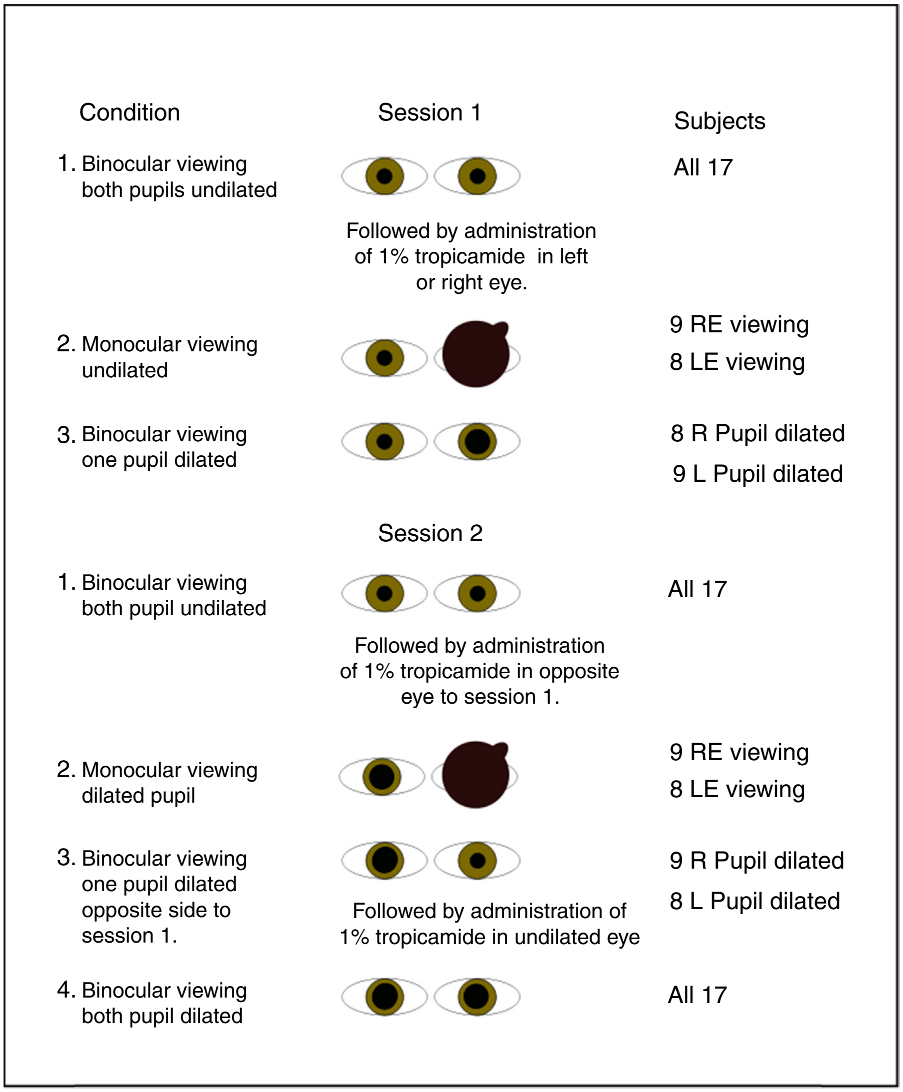

Figure 3 Schematic summary of the pupil dilation conditions tested in the two sessions.

Speed judgments and data collection

Data collection of speed judgements was similar to previous research on the Enright phenomenon.[1]

On a given driving run, the car started from a stationary position and the participant's task was to accelerate to a Goal Speed specified by the experimenter, either 40 km/h (24.9 miles/h) or 60 km/h (37.3 miles/h), while looking sideways to the right side of the vehicle. When the participant achieved what they believed was the desired speed they notified the observer and the actual speed was recorded from the output of a GPS system mounted in the vehicle. Apart from the driver, there were two observers in the car: one sitting in the back seat recording driver performance and one sitting in the front seat holding the steering wheel in order to minimise the risk of the car running off the road while the driver was looking sideways. Two runs were completed for each experimental condition and the mean of the two measurements of actual speed was used as the dependant variable for each participant.

At the start of each session participants underwent two familiarisation runs for each Goal Speed, with the participant viewing sideways from the vehicle with binocular viewing and undilated pupils, but given regular feedback from the back seat observer (approximately every 2 s) regarding the vehicle's speed.

For conditions involving pupil dilation, mydriasis was achieved by installation of a single drop of 1% tropicamide in the eye, followed by a delay of at least 30 min before testing under the dilated pupil conditions. Pupil dilation and anisocoria were measured by digital photography of the participant's pupils, from a distance of approximately 1 m, with a mm scale placed on the participant's brow for reference, as participants viewed sideways from the car before the start of a run. Prior to the start of the first run for a given visual condition, visual acuity was measured for that viewing condition using a Bailey-Lovie eye Chart[14] positioned at 6 m from the participant who viewed the chart while looking sideways from the car. A termination rule of 3 mistakes or more on a completed line was used[15] and letter-counting was used to calculate the logMAR score as recommended by Bailey.[16]

Analysis

For the main binocular viewing conditions, all participants completed all conditions. This was a 2 factor repeated measure design (Subject (17 levels) × Viewing Condition (4 levels) × Goal Speed (2 levels)) and a repeated measures Analysis of Variance (ANOVA) was used to examine the effect of these factors on actual speed.

The control conditions (monocular viewing, undilated and dilated) were compared with the binocular undilated viewing condition. This was analysed with a mixed three-way Analysis of Variance (ANOVA) with one between-participants variable (Viewing Eye Group), and two repeated variables (Control viewing condition, Goal Speed), *i.e.* Viewing Eye Group (2 levels) × (Subject (9 levels group 1, 8 levels group 2) × Viewing condition (3 levels) × Goal Speed (2 levels)).

Results

The group mean pupil diameters under the different testing conditions are shown in Table 1. Monocular pupil dilation induced an interocular difference in pupil area in $\log_{10}$ units averaging 1.02 ± 0.14 SD with the right eye dilated and 0.99 ± 0.12 SD with the left eye dilated. However, it is well recognised that, under photopic conditions, light entering close to the centre of the pupil is more effective at producing a visual response, than light entering the edge of the pupil. This is known as the Stiles-Crawford effect.[17] Thus for the daylight conditions occurring in this experiment, the impact of the inter-ocular asymmetry of effective retinal illuminance may have been less than that predicted based on the relative ratios of pupil areas alone. Correcting pupil areas for the Stiles-Crawford effect, yielded estimates of interocular differences in effective retinal illuminance averaging $0.80 \pm 0.13 \log_{10}$ units with the right eye dilated and $0.75 \pm 0.11 \log_{10}$ units with the left eye dilated, using the pupil correction equation of Atchison and Smith:[18]

$$c = \frac{(1 - e^{-\beta\rho^2})}{\beta\rho^2}$$

Table 1 Mean pupil diameters under different viewing conditions. Inter-subject standard deviations are shown in parentheses.

Viewing condition	Mean pupil diameter mm (SD)	
	Right	Left
Binocular undilated viewing	2.6 (0.5)	2.6 (0.5)
Binocular dilated viewing	6.9 (0.8)	6.9 (0.7)
Binocular viewing Right Eye dilated	6.8 (0.7)	2.1 (0.4)
Binocular viewing Left Eye dilated	2.2 (0.3)	7.0 (0.6)

Table 2 Mean visual acuity under different viewing conditions. Inter-subject standard deviations are shown in parentheses.

Viewing condition	Mean visual acuity logMAR (SD)
Binocular undilated viewing	−0.20 (0.09)
Binocular viewing one eye dilated	−0.17 (0.12)
Monocular viewing undilated	−0.11 (0.09)
Binocular viewing dilated.	−0.01 (0.13)
Monocular viewing dilated	0.016 (0.13)

where ρ is the pupil radius in mm and the coefficient $\beta = 0.11$ representing the magnitude of the Stiles-Crawford effect under photopic conditions. The coefficient c is the relative correction factor for pupil area, approaching unity as ρ approaches zero and decreasing as ρ increases.

The group means for visual acuity under the different testing conditions are shown in Table 2. Visual acuity did not differ significantly for binocular viewing with an undilated pupil condition between day 1 and day 2 ($t_{16} = 1.251$, $p = 0.229$), thus the visual acuity results reported and analysed are the mean of the two sessions. Visual acuity for the monocular viewing conditions did not differ between the groups that had their right eye or their left eye tested, (for the undilated condition $t_{15} = 0.547$, $p = 0.593$; for the dilated condition $t_{15} = 0.477$, $p = 0.640$). The visual acuity results analysed are the means of both groups. Repeated measures ANOVA showed a significant effect of viewing condition on visual acuity ($F_{4,64} = 20.0$, $p < 0.001$) and *post hoc* analysis (matched pairs *t*-testing) showed that all pairs of viewing conditions in Table 2 had significantly different visual acuity, except for binocular dilated and monocular dilated conditions which did not differ significantly.

Main experimental results

Under binocular viewing conditions, monocular pupil dilation significantly affected driving speed when participants looked sideways from the vehicle. This is shown in Fig. 4

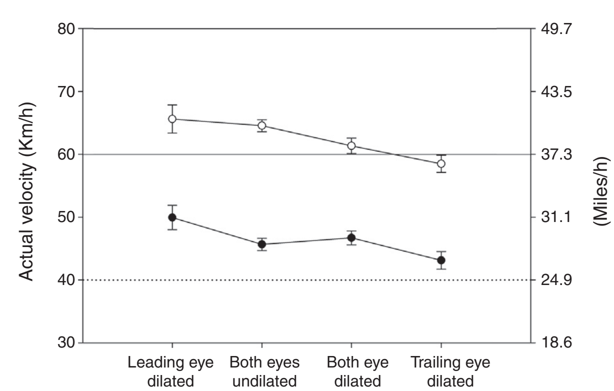

Figure 4 The actual speeds achieved under different binocular viewing conditions. Results are shown as group mean data (17 participants); Error bars are standard errors of the mean. Goal Speed of 40 km/h is indicated by ●. Goal Speed of 60 km/h is indicated by ○.

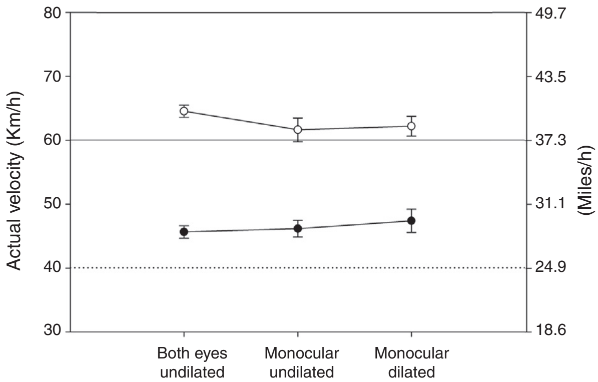

Figure 5 The actual speeds achieved under different control viewing conditions in the control experiments. Monocular viewing (dilated and undilated) is compared with binocular viewing undilated. Graphing conventions are as for Fig. 3. Results are means from 17 participants.

where there was a significant effect of Viewing Condition, ($F_{3,48} = 8.974$, $p < 0.001$). In addition, there was a significant effect of Goal Speed ($F_{1,16} = 308.447$, $p < 0.001$). There was no significant Viewing Condition x Goal Speed interaction on actual speed ($F_{3,48} = 2.045$, $p = 0.12$). *Post hoc* testing showed that participants drove significantly faster when the leading eye was dilated compared to when both eyes were dilated ($t_{16} = 2.57$, $p = 0.02$), but not significantly faster than when both eyes were undilated ($t_{16} = 1.55$, $p = 0.14$). There was no significant difference in speed misjudgements when both eyes were either undilated or dilated ($t_{16} = 1.058$, $p = 0.322$). Participants drove slower with the trailing eye dilated, than with both pupils undilated ($t_{16} = -4.11$, $p < 0.001$), with both pupils dilated ($t_{16} = -3.22$, $p < 0.001$), or with the leading eye pupil dilated ($t_{16} = -4.02$, $p < 0.001$).

Control conditions

The control conditions (Fig. 5), assessing whether actual speed was differentially affected by binocular undilated viewing compared with monocular pupils dilated and undilated viewing, did not yield a significant effect of Viewing Condition ($F_{2,30} = 0.593$, $p = 0.559$). Nor did the factor of monocular Viewing Eye affect actual speed, ($F_{1,15} = 0.369$, $p = 0.553$) but there was a significant effect of Goal Speed on actual speed ($F_{1,15} = 494$, $p < 0.001$), mirroring the results of the main experiment. There was no significant Viewing Condition × Viewing Eye Group × Goal Speed interaction ($F_{2,30} = 0.706$, $p = 0.502$) nor were there significant interactions of Viewing condition × Goal Speed ($F_{2,30} = 1.981$, $p = 0.156$), Viewing Condition × Viewing Eye Group ($F_{2,30} = 1.606$, $p = 0.217$), Viewing Eye Group × Goal Speed ($F_{1,15} = 3.949$, $p = 0.065$). *Post hoc* *t*-test analysis confirmed that there were no mean differences ($p > 0.05$) between actual velocities for the right and left eye viewing groups irrespective of whether they were dilated or undilated, or had a Goal Speed of 60 km/h or 40 km/h.

Discussion

This study is the first to investigate the impact of monocular pupil dilation on driving perceptions and behaviour and demonstrates that monocular pupil dilation can induce distortions of driving speed, in accord with predictions based on the Enright phenomenon. This misjudgement of driving speeds occurs under specific driving conditions, with the observer's head turned sideways in the vehicle, looking perpendicular to the direction of motion of the vehicle, a situation which might arise during shoulder-checks on lane changes. The trend in the results confirmed those stated in the original hypotheses based on the Enright phenomenon. When the pupil is dilated in the trailing eye, retinal illuminance would be increased relative to the leading eye, which in the Enright phenomenon leads to the sensation of increased self-velocity. Hence drivers in the current study tended to slow their driving speeds, compared to the binocular pupil dilation and undilated conditions. Conversely, with the pupil dilated in the leading eye, the retinal illuminance would be less in the trailing eye. According to the Enright phenomenon, this would lead to a sensation of decreased self-velocity and hence it would be predicted that drivers would drive faster to compensate. The results we obtained are qualitatively similar to those of a previous study[1] using similar methods, in which the Enright phenomenon was induced by using 0.9 ND filters to cause asymmetry of retinal illuminance. In the current study, the asymmetry in pupil size resulted in asymmetry of retinal illuminance equivalent to a 1.0 ND difference or, if corrected for the Stiles-Crawford effect, an equivalent difference of approximately 0.75 ND. The speed, with the leading eye dilated, was faster by an average of 7 km/h than with the trailing eye dilated. In comparison, in the previous study using ND filters, the speed with the trailing eye filtered was faster by an average of 12 km/h than with the leading eye filtered; a larger effect than the current study. There are a number of possible reasons for this difference in effect size. First, even with monocular pupil dilation, average retinal image illuminance will be substantially larger across both eyes than when neutral density filters are used. It is known that as average background adaptation increases, there is a decrease in the magnitude of luminance-induced -latency phenomena such as the Pulfrich phenomenon, Hess effect and simple reaction times.[19] Like the Pulfrich phenomenon, the Enright phenomenon may depend on inter-ocular perceptual latency differences and may be similarly reduced by increasing background luminance.[2] Second, it may be that differences in the retinal image quality arising from pupil dilation degrades the stereopsis cues used in the Enright phenomenon, although it should be noted that with clinical stereopsis tests, thresholds are not significantly affected by induced anisocoria or by 0.9 ND filters.[20] Third, It is known from the previous study,[1] that driving speed changes induced by the Enright phenomenon are much smaller than would be expected from the visual latencies likely to be induced by the inter-ocular asymmetries of retinal image brightness. Hence nonvisual cues (*e.g.* vibration and auditory cues), are likely to play a significant role in velocity judgements. Different vehicles were used in the current and previous studies and hence different nonvisual cues to velocity may have been available across the two studies, and contributed to the differences between the two studies in terms of the observed velocity changes.

Our control study, looking at the effects of monocular viewing on driving speed judgement, while looking sideways from the vehicle, gave largely negative results. Monocular viewing, either dilated or undilated, failed to result in a significant change in driving speed at either of the Goal Speeds, and there was no significant difference between the group that viewed with their left eye or the right eyes. We note however that because of limited access to testing facilities this was a mixed repeated measures/between groups design. A design where all factors were repeated across all participants would be a more powerful approach to investigate the effects of viewing with either the right eye or the left eye, and this may be a consideration for future research. Nonetheless, the control experiments support the theory that the anomalous speed judgements in the main experiment are dependent on binocular vision and are in agreement with Enright's explanation of the effect.[2]

Even with normal binocular viewing, participants tended to travel faster than their Goal Speed by an average of 5 km/h for both the 40 km/h Goal Speed and the 60 km/h Goal Speed. This is in accord with previous research investigating speed estimation of drivers in normal traffic conditions, with speed underestimation errors of 4 km/h at a speed of 40 km/h and of 3 km/h at a speed of 60 km/h.[5] On a closed circuit the participants in one study[21] underestimated their speed by 7 km/h at 60 km/h. In comparison, a previous study[1] of the Enright phenomenon, completed under similar conditions to the current study, showed that under conditions where retinal illumination was similar in each eye, participants matched their Goal Speed at 60 km/h, but travelled faster than the Goal Speed of 40 km/h by nearly 12 km/h (7.5 miles/h).

Although monocular dilation is relatively uncommon, there are other potential sources of clinically induced anisocoria, for example unilateral corneal inlays such as Acufocus Kamra, which provide an artificially reduced pupil size to improve depth of field in presbyopia.[22]

It may be that such patients will experience perceived speed distortions found by the current study and clinicians should be aware of this as a potential complication of such procedures.

Visual acuity (with habitual driving spectacle correction) was affected by the different pupil dilation conditions. Worst acuity occurred under conditions in which the participant viewed through either one or both dilated pupils. Even under these conditions, acuity was still good, averaging 0.00 logMAR (6/6). The worst acuity from a participant was 0.24 logMAR (6/10.4), obtained under monocular viewing dilated conditions. This worst case visual acuity is still a line better than the 0.34 logMAR (6/13.1) (Bailey-Lovie chart) which would be required to meet the Australian standards for a private driver's licence.[23]

When considering the implications of these findings it is important to note that the experiments were conducted under carefully controlled conditions on a closed track. The drivers achieved these speeds, looking sideways from a standing start, without access to information from the speedometer. The changes in velocity of 3–4 km/h induced by the Enright effect were relatively small. Therefore it is worth considering how these findings potentially translate to driving in real world traffic conditions.

The changes in speed associated with monocular dilation of pupils occur under specific driving conditions, when the driver is looking sideways from a moving vehicle. Such conditions, though infrequent, do occur during normal driving, for example, when drivers are checking for other vehicles/road users before changing lanes. Such sideways head movements usually take place over a short interval of time, typically a number of seconds. If drivers are appropriately cautious in maintaining appropriate distances between themselves and traffic in front, then the velocity distortions induced by pupil dilation described here are unlikely to cause collisions. For example, if drivers are maintaining a 2 s interval between cars, then the gap between vehicles would be 22 m for traffic travelling at 40 km/h. At such a distance if a car increased its speed by 4 km/h, then it would close the gap to the car in front in 20 s. For traffic travelling at 60 km/h a 2 s gap would correspond to a separation of 33 m and if a car increased its speed by 4 km/h the gap would be closed in 30 s. However, there is evidence that, for motorway driving at these speeds, drivers leave a median spacing of approximately 1 s between vehicles[24] and so these times to contact would be reduced to 10 s at 40 km/h and 15 s at 60 km/h. Similar time frames to contact the car behind would be experienced if a driver slowed the car and the driver behind failed to take appropriate evasive action. It would be highly unusual for drivers to adopt such a sideways head posture for such a period of time. Thus the effects described in our research would be unlikely to be the sole factor contributing to an accident, but they are nonetheless important to be aware of and could be a contributing factor in more complicated accident scenarios.

In addition, the presence of the Enright phenomenon demonstrated in this research also suggests the potential for monocular dilation to induce other perceptual latency related stereophenomena which may affect driving. For example, the related stereoscopic anomaly, the Pulfrich phenomenon, might occur with a driver's head in a more normal posture (*i.e.* looking more or less straight ahead). Under these circumstances objects travelling past a driver's ear on the side with the undilated pupil would appear to swing in towards the driver as they pass, and objects passing on the side with the dilated pupil would tend to swing away.[25] This may have implications for driving tasks such as lane keeping, so future research in this area is warranted in order to ensure that administering drops which result in monocular dilation do not impact on driving ability and safety.

In summary, this study shows that monocular dilation of pupils can affect driving speed perceptions and choices, in a manner that is consistent with previous studies of the Enright phenomenon. This effect is likely to have its origins in anomalous stereoscopic judgements of the depth of moving objects, arising under conditions where retinal illumination is different between eyes. Although previous researchers have reported that driving behaviour is affected by binocular pupil dilation, the current study is the first to report that monocular dilation of pupils can affect aspects of driving behaviour.

Conflicts of interest

None declared.

Funding

None declared.

Acknowledgements

The first author would like to thank Noelene Kelly, Peter Long and Phil Smith whose skills contributed to the author's translation of some of the references.[3,6,9]

References

1. Carkeet A, Wood JM, Robinson A, McCorriston JJ, Pesic N, Warlow SL. Driving speed is altered by monocular neutral density filters: the Enright phenomenon. *Optom Vis Sci*. 2012;89:38–43.
2. Enright JT. Distortions of apparent velocity: a new optical illusion. *Science*. 1970;168:464–467.
3. von Pulfrich C. Die Stereoskopie im Dienste der isochromen und heterochromen Photometrie. *Naturwissenshaften*. 1922, 553–564, 569–574, 596–601, 714–722, 735–743, 751–761.
4. Hyzer WG. More idiosyncrasies of motion. *Photoelectron Imaging*. 1995;38:48–49.
5. Mclean W. An assessment of luminance imbalance with ANVIS at an army helicopter training airfield. *USAARL Rep*. 1997;97:1–28.
6. Gramberg-Danielsen B. Ursachen des Pulfrich-Phänomens und seine Bedeutung im Strassenverkehr. *Klin Monatsbl Augenheilkd*. 1963;142:738–742.
7. Heron G, McQuaid M, Morrice E. The Pulfrich effect in optometric practice. *Ophthal Physiol Opt*. 1995;15:425–429.
8. Plainis S, Petratou D, Giannakopoulou T, Radhakrishnan H, Pallikaris IG, Charman WN. Interocular differences in visual latency induced by reduced-aperture monovision. *Ophthalmic Physiol Opt*. 2013;33:123–129.
9. Lanthony P. Pulfrich phenomenon. *J Fr Ophtalmol*. 1984;7:575–587.
10. Wood JM, Garth D, Grounds G, McKay P, Mulvahil A. Pupil dilatation does affect some aspects of daytime driving performance. *Br J Ophthalmol*. 2003;87:1387–1390.
11. Travers. Clinical Lecture Delivered by Mr Travers, on Tuesday last, December the 30th 1823, at St Thomas's Hospital, on Syphilitic Iritis. *Lancet*. 1824;2:6–10.
12. Gerstenblith AT, Rabinowitz MP. *The Wills Eye Manual: Office and Emergency Room Diagnosis and Treatment of Eye Disease*. Philidelphia: Lippincott, Williams and Wilkins; 2012.
13. Wood JM, Chaparro A, Hickson L. Interaction between vision, distracter modality and age on measures of daytime driving performance. *Vision Res*. 2009;49:2225–2231.
14. Bailey IL, Lovie JE. New design principles for visual acuity letter charts. *Am J Optom Physiol Opt*. 1976;53:740–745.
15. Carkeet A. Modeling logMAR visual acuity scores: effects of termination rules and alternative forced-choice options. *Optom Vis Sci*. 2001;78:529–538.
16. Bailey IL. Designation of visual acuity in logarithmic units. *Optom Mon*. 1980;71:80–85.
17. Stiles WS, Crawford BH. The luminous efficiency of rays entering the eye pupil at different points. *Proc R Soc Lond B Biol Sci*. 1933;112:428–450.
18. Atchison D, Smith G. Light level at the retina. In: *Optics of the Human Eye*. Oxford: Butterworth Heinemann; 2000: 117–128.
19. Williams JM, Lit A. Luminance-dependent visual latency for the Hess effect, the Pulfrich effect, and simple reaction time. *Vision Res*. 1983;23:171–179.
20. Lovasik J, Szymkiw M. Effects of aniseikonia, anisometropia, accommodation, retinal illuminance, and pupil size on stereopsis. *Invest Ophthalmol Vis Sci*. 1985;26:741–750.
21. Wood JM, Troutbeck R. Effect of visual impairment on driving. *Hum Factors*. 1994;36:476–487.
22. Atchison DA, Blazaki S, Suheimat M, Plainis S, Charman WN. Do small-aperture presbyopic corrections influence the visual field? *Ophthalmic Physiol Opt*. 2016;36:51–59.
23. Austroads. *Assessing fitness to drive for commercial and private vehical drivers. Medical standards for licensing and clincal management guidelines. A resource for health professionals in Australia. March 2012 as amended up to 16 March 2013*; 2013:116–117.
24. Brackstone M, Sultan B, McDonald M. Motorway driver behaviour: studies on car following. *Transp Res F-Traffic*. 2002;5:31–46.
25. Spiegler J. Apparent path of a Pulfrich target as a function of the slope of its plane of motion: a theoretical note. *Am J Optom Physiol Opt*. 1986;63:209–216.