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ORIGINAL ARTICLE

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Comparison of the solar spectral ultraviolet irradiance in motor vehicles with windows in an open and closed position

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Abstract The solar ultraviolet (UV) spectrum was measured by a spectroradiometer located inside two common Australian vehicles: a family wagon and a four-wheel-drive vehicle. The entrance optics of the spectroradiometer was orientated, in turn, on a horizontal plane, towards the driver and passenger windows and towards the windshield. UV spectra were recorded when the vehicles' windows were in an open and closed position. For a typical Australian family wagon, on a horizontal plane inside the vehicle, closing the windows decreased, the total UV irradiance by a factor of 3.2, whilst in a four-wheel drive the irradiance decreased by a factor of 2.1. In order to reduce the likelihood of developing of UV-related eye and skin disorders, drivers should use appropriate UV protection whilst driving a vehicle with the windows in an open position. Results gained from this research provide new findings on the exposure of humans to UV in a vehicle.

Keywords UV · Skin damage · Vehicle · Spectral · Erythema

Introduction

Exposure to ultraviolet (UV) radiation is associated with the formation of skin cancers, some eye disorders and skin ageing and damage (Longstreth et al. 1995). Public health campaigns warn the population of the dangers of spending too much time in the sun; however, the exposure of individuals to UV during what are considered, "low-UV-risk" activities, such as driving a vehicle, is not fully documented. This is of particular importance, in Australia and the United States where large fair-skinned populations live at relatively low latitudes and large distances between major population centres can mean that numerous hours each day are spent in a vehicle. In addition, Australia has the highest incidence rates of skin cancer in the world.

Solar UV consists of UVB (280–320 nm) and UVA (320–400 nm) radiation. The glass used in vehicle windows and windshields acts as a barrier to the shorter UVB wavelengths, but still allows the transmission of the longer UVA wavelengths (Parisi and Wong 1997). Although UVB comprises the most energetic wavelengths and is more damaging, recent studies have shown that UVA is also hazardous. UVA wavelengths have been found to produce skin damage (Lavker and Kaidbey 1997; Lowe et al. 1995; Lavker et al. 1995; Sayre et al. 1997; Bissett et al. 1992) and premature skin photoageing and wrinkling as well as eye damage.

Previous studies (Kimlin and Parisi 1999) investigated, through a pilot study, the UV spectral irradiances within a vehicle measured in the field. Prior to this study, other researchers (e.g. Gies et al. 1992) investigated the spectral transmission of automobile glass in the laboratory. The erythemal UV exposure that humans receive to the right shoulder in the right side of a vehicle with the windows in a closed position accumulated over a 6-h period was reported to reach a value of 3.1 mJ cm^{-2} (Parisi and Wong 1998). The annual UVA exposure in a vehicle on a horizontal plane without window tinting in Australia between 0900 and 1500 hours Australian Eastern Standard Time (EST) each day was found to be between 5% and 17% of the ambient UVA on a horizontal plane (Parisi and Kimlin 2000).

Materials and methods

This study extends research to investigate the solar spectral UV irradiance inside a motor vehicle. The measurements were taken to investigate the difference between the solar spectral irradiance within the vehicle when having all the windows are closed and that when all are open, for different receiver directions and orientations, and to assess the effect that the type of vehicle has on UV irradiances inside the vehicle. Measurements were undertaken in an open sports field with the nearest trees and buildings over 30 m away.

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Vehicles used

One of the vehicles used in this study was a Ford Falcon GLi station wagon, without additional (after-market) window tinting. The window glass in this vehicle is Pilkington DOT 298 M50 AS2, EZ-KOOL and the overall size of the vehicle is 4.8 m long, 1.7 m wide and 1.5 m high. This particular vehicle is a popular Australian family station wagon, with the driver's seat on the right-hand side, since vehicles in Australia travel on the left-hand side of the road. It will be referred to as the "family wagon".

The other vehicle used in this study was a Nissan Patrol four-wheel drive (4WD), also a right-hand drive vehicle with no additional after-market window tinting. The window glass is Temperlite TP ASAHI M213 AS 2 DOT-20 43R-00033 and the overall size of the vehicle is 4.9 m long, 1.9 m wide and 1.8 m high. This vehicle will be referred to as the "4WD". The windscreens of both vehicles are laminated. The type and style of the vehicles used in this study are representative of typical modern vehicles driven in Australia. According to the Australian Chamber of Automotive Industries report dated 15 August 2001 (personal communication), the two vehicles used in this study, a family wagon and a four-wheel drive, make up 35.9% and 12.8% of the total Australian vehicle market respectively.

Spectral UV in the vehicle

The spectral UV irradiances in the family wagon (with the windows open and closed) were measured in a field at the campus of the University of Southern Queensland, Toowoomba, Australia (27.5°S) between 0920 and 0950 hours EST on 20 September 2000, and on 29 September 2000 from 0840 to 1140 hours EST, using a calibrated spectroradiometer (Parisi and Kimlin 1999). The solar zenith angle range (SZA) was 35.5°–31.7° and 35.5°–54.4° respectively and the albedo of the ground cover was less than 5%. The spectral UV irradiances in the 4WD (with the windows open and closed) were measured on 22 September 2000 at 0828 hours EST with an SZA of 54.8° at the same location. A mercury vapour lamp was previously used for the wavelength calibration of the spectroradiometer and a 250-W quartz tungsten halogen lamp, powered by a current-stabilised D.C. power supply at 9.500 ± 0.005 A, with a calibration traceable to the Australian National UV Standard, CSIRO, Lindfield, Australia, was used for absolute irradiance calibration. The vehicles were stationary on level ground, with clean windows and orientated with the front of the vehicle facing north at all times during the measurement programme. Although vehicles rarely are orientated in one direction whilst travelling, this research allows the investigation of the changes in spectral UV irradiances inside a vehicle for two types of vehicle when the windows are in an open and closed position. This study was designed to be a general representation of the spectral UV irradiance levels inside the motor vehicle. Parisi and Wong (1997) have previously used dosimetric techiniques to investigate personal UV exposure inside a motor vehicle, as the human form is a complex shape and it is impossible to have multiple orientations of the spectroradiometer detector simultaneously measuring spectral irradiance. This is the advantage of using dosimeter materials for personal UV measurements; however, spectral data are unavailable with dosimeters.

The spectral measurements were undertaken in the driver's seat of the vehicles since this site is occupied by the driver of the vehicle at all times whilst the vehicles are in use. The orientation of the vehicle and site orientations are shown in Fig. 1. The spectral UV measurements were taken at site DS, as shown in Fig. 1, with the input optics of the spectroradiometer orientated to sites PW, WS and DW. All UV irradiance measurements were at site DS, at a height of approximately 20 cm above the seat. The distances of the input optics to the windshield, driver's window and passenger's window were approximately 55 cm, 25 cm and 135 cm respectively for the family wagon and approximately 45 cm, 20 cm and 140 cm respectively for the 4WD.

A scan from 280 nm to 400 nm took approximately 45 s, in which time the solar zenith angle did not change sufficiently to influence the results. As the UV spectral irradiance may change with height inside the vehicle, 20 cm was selected as a standardized height that represents the approximate height of the upper thigh in a seated position to allow comparisons between the vehicles.

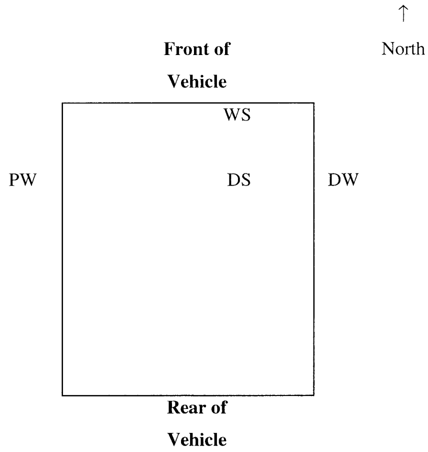


Fig. 1 Location of the UV measurements in the vehicle

The spectroradiometer measured the UV irradiance in 1-nm intervals with the input optics orientated to measure the UV irradiances on a horizontal plane (DS), a vertical plane orientated to the driver's window (DW), a vertical plane orientated to the passenger's window (PW), and a vertical plane orientated to the windshield (WS). Only diffuse measurements were taken inside the vehicle, regardless of detector orientation, that is, no direct beam of radiation passed into the detector. Immediately following the spectral UV irradiance measurements in the vehicle, the spectroradiometer was placed in an open unshaded location outside the vehicle and the solar spectral UV irradiances on a horizontal plane determined. All spectral UV measurements were conducted in clear-sky conditions.

Biologically effective UV

In order to assess the biologically damaging UV inside the motor vehicles, the collected spectra may be weighted with a particular biological action spectrum. The biologically effective UV irradiance, UVB_e, was calculated from the following:

$$UVB_e = \int_{UV} S(\lambda)A(\lambda)\mathrm{d}\lambda$$

where $S(\lambda)$ is the measured spectral UV irradiance and $A(\lambda)$ is the biological action spectrum. The action spectra used included erythemal (CIE 1987), actinic hazard (IRPA 1989), photokeratitis (CIE 1986) and fish melanoma (Setlow et al. 1993) action spectra. The reason that the action spectrum for fish melanoma was used is that no action spectrum for human melanoma exists and this action spectrum may be indicative of the wavelengths effective in producing human melanoma (Gasparro et al. 1998).

Results

Windows open/closed

The UV spectral irradiance at various orientations inside the family wagon with all windows closed is shown in Fig. 2. The window glass removed all of the UVB component of the measured spectrum. This measurement was

Table 1 The average of the UV and biologically damaging UV irradiances at 0920 hours EST on 20 September 2000 and at 0929 hours EST on 29 September 2000 inside the family wagon with the windows closed, and in the same vehicle with the windows open at 0950 hours EST on 20 September 2000 and at 1016 hours EST on 29 September 2000. The values in parentheses are the irradiance reduction factors

Spectrum	UV irradiance (Wm^{-2})									
	Windows closed					Windows open				
	Solar	Horizontal inside vehicle	Facing driver's window	Facing passenger's window	Facing windshield	Solar	Horizontal inside vehicle	Facing driver's window	Facing passenger's window	Facing windshield
UVB	1.65	0 (50+)	0 (50+)	0 (50+)	0 (50+)	1.60	0.11 (14)	0.43 (4)	0.05 (32)	0.01 (50+)
UVA	28.1	1.95 (14)	4.67 (6)	0.376 (50+)	0.588 (48)	34.3	6.10 (6)	7.86 (4)	0.91 (38)	0.92 (37)
Total UV	29.7	1.95 (15)	4.67 (6)	0.376 (50+)	0.589 (50+)	35.9	6.21 (6)	8.30 (4)	0.96 (37)	0.93 (39)
Erythemal UV	0.125	0.001 (50+)	0.001 (50+)	0.0 (50+)	0.0 (50+)	0.087	0.06 (1.5)	0.02 (4)	0.003 (29)	0.001 (50+)
Actinic UV	0.037	0.0 (50+)	0.0 (50+)	0.0 (50+)	0.0 (50+)	0.020	0.01 (2)	0.005 (4)	0.01 (2)	0.0 (50+)
DNA-damage UV	0.003	0.0 (50+)	0.0 (50+)	0.0 (50+)	0.0 (50+)	0.001	0.00 (50+)	0.00 (50+)	0.00 (50+)	0.0 (50+)
Photokeratitis	0.075	0.0 (50+)	0.0 (50+)	0.0 (50+)	0.0 (50+)	0.049	0.03 (2)	0.01 (5)	0.01 (5)	0.0 (50+)
Fish melanoma	6.34	0.321 (20)	0.875 (7)	0.070 (50+)	0.053 (50+)	7.87	0.867 (9)	1.843 (4)	0.205 (38)	0.108 (50+)

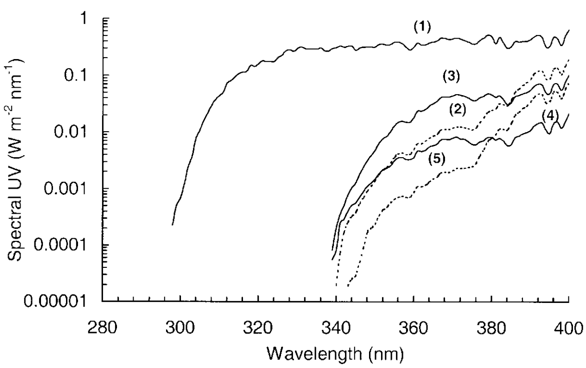


Fig. 2 UV spectral irradiances (*1*) outside the vehicle in full sun, and inside the family wagon with the windows closed for the following orientations: (*2*) horizontal, (*3*) driver's window, (*4*) passenger's window, (*5*) windshield

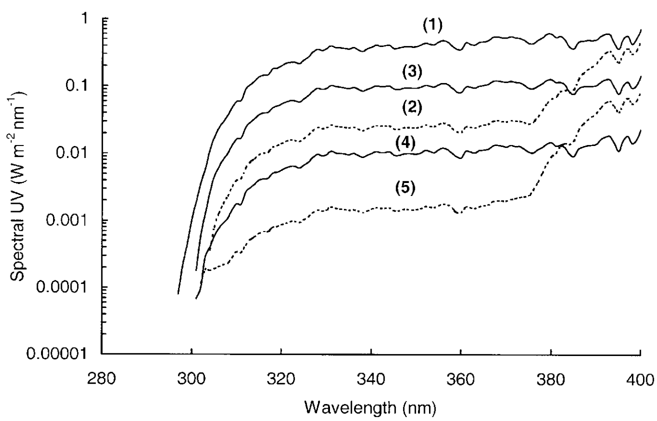


Fig. 3 UV spectral irradiances (*1*) outside the vehicle in full sun, and inside the family wagon with the windows open for the following orientations: (*2*) horizontal, (*3*) driver's window, (*4*) passenger's window, (*5*) windshield

taken at 0920 hours EST on 20 September 2000. The orientation of the detector of the spectroradiometer had an effect on the measured UV spectra transmitted through the glass. For example, the driver's window (DW) orientation had a higher measured spectral irradiance than the horizontal measurement site within the vehicle up to 380 nm, because the position of the sun in the sky directed the radiation through the glass more perpendicularly than obliquely, resulting in a higher transmission. However, above 370 nm, the higher transmission of the windshield allowed the spectral irradiance to increase for the DS and WS orientations. The highest UV irradiances in the family wagon with the windows closed were recorded when the entrance optics of the spectroradiometer was directed to the driver's window (DW) (Table 1). At this orientation, inside the vehicle, reduced the total UV irradiance was reduced, on average, by a factor of 6 when compared to the total UV irradiance in full sun and outside the vehicle. Other detector orientations inside the vehicle, such as those on a horizontal plane, PW and facing the WS, the total UV irradiance by a factor of 15, 50+ and 50+ respectively. Regardless of detector orientation inside the vehicle, no DNA damage, photokeratitis or actinic weighted UV irradiances were recorded inside the vehicle.

Differences between the UV spectrum measured with the windows open and that recorded when they were closed are noted in Fig. 3, which shows the spectral UV irradiance at 0950 hours EST on 20 September 2000 at various orientations inside the family wagon with the windows open. In particular, the UVB part of the spectrum was detected inside the vehicle. With the entrance optics of the spectroradiometer facing DW with the windows in an open position, the total UV irradiance was reduced by a factor of 4 when compared to full-sun total UV irradiances (Table 1).

Table 2 The UV and biologically damaging UV irradiances inside the four wheel drive vehicle at 0828 hours EST on 22 September 2000 with the windows closed and the average of the spectral UV irradiances inside the same vehicle on 22 September 2000 with the windows open. The values in parentheses are the irradiance reduction factors

Spectrum	UV irradiance (Wm^{-2})									
	Windows closed					Windows open				
	Solar	Horizontal inside vehicle	Facing driver's window	Facing passenger's window	Facing windshield	Solar	Horizontal inside vehicle	Facing driver's window	Facing passenger's window	Facing windshield
UVB	1.26	0 (50+)	0 (50+)	0 (50+)	0 (50+)	2.47	0.29 (9)	0.591 (4)	0.064 (38)	0.043 (50+)
UVA	28.5	2.02 (14)	2.12 (13)	0.39 (50+)	0.701 (41)	36.6	4.04 (9)	7.69 (5)	0.820 (45)	0.687 (50+)
Total UV	29.8	2.02 (15)	3.12 (10)	0.39 (50+)	0.701 (43)	39.1	4.34 (9)	8.29 (5)	0.884 (44)	0.730 (50+)
Erythemal UV	0.067	0.01 (7)	0.01 (7)	0.0 (50+)	0.0 (50+)	0.202	0.025 (8)	0.047 (4)	0.001 (50+)	0.002 (50+)
Actinic UV	0.016	0.0 (50+)	0.0 (50+)	0.0 (50+)	0.0 (50+)	0.063	0.008 (8)	0.015 (4)	0.002 (31)	0.001 (50+)
DNA-damage UV	0.001	0.0 (50+)	0.0 (50+)	0.0 (50+)	0.0 (50+)	0.005	0.001 (5)	0.001 (5)	0.0001 (50)	0.0001 (50)
Photokeratitis	0.038	0.0 (50+)	0.0 (50+)	0.0 (50+)	0.0 (50+)	0.122	0.015 (8)	0.029 (4)	0.003 (41)	0.001 (50+)
Fish melanoma	6.49	0.239 (27)	0.361 (18)	0.07 (50+)	0.08 (50+)	8.45	0.905 (9)	1.82 (5)	0.192 (44)	0.075 (50+)

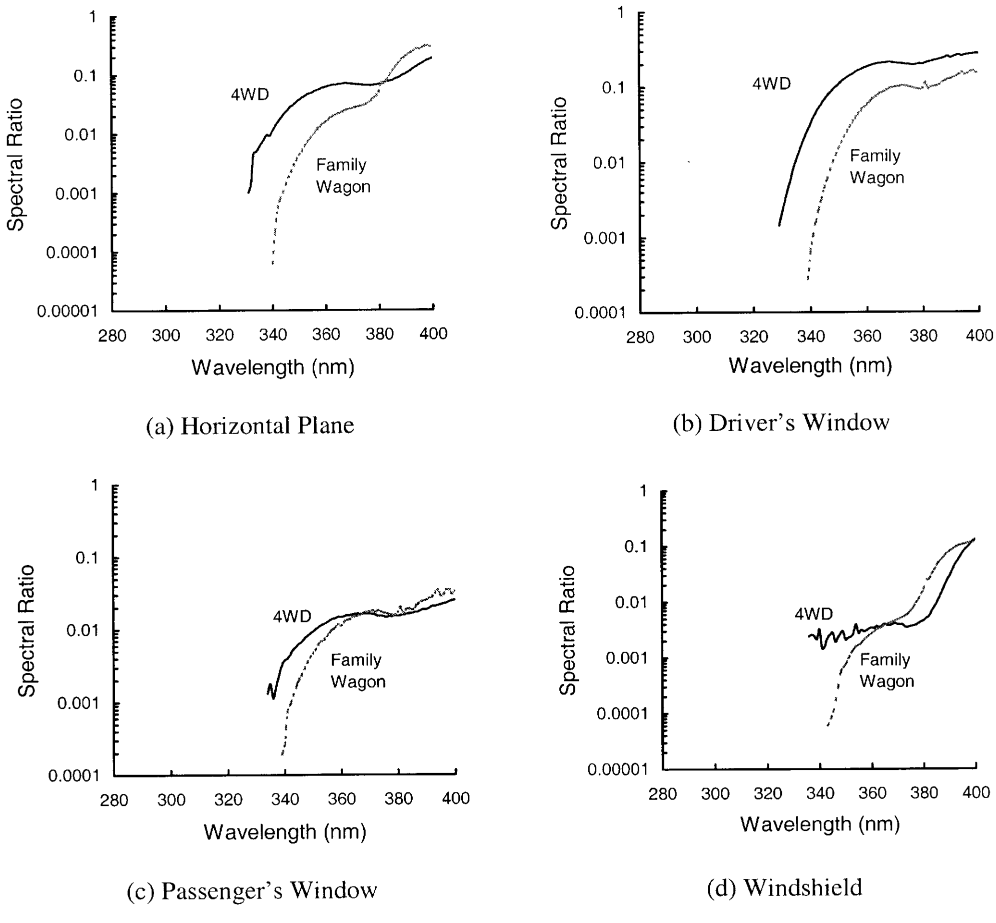


Fig. 4a–d UV spectral ratio for the family wagon and four-wheel-drive vehicle, inside the vehicle with the windows closed for the following orientations: **a** horizontal, **b** driver's window, **c** passenger's window, **d** windshield

The orientation with the lowest measured total UV irradiances in the family wagon was that facing the windshield (WS). However, for this orientation, the measured UV irradiances changed from a reduction factor of 50+ to 39 for closed and open windows respectively.

As with the family wagon, the 4WD with the windows closed had the highest UV irradiance measured when the detector was facing the driver's window (Table 2). The total UV irradiance at this orientation was reduced on average, by a factor of 10 when compared to the total UV irradiance outside the vehicle. For other detector orientations inside the vehicle, such as on a horizontal plane, PW and facing the WS, the total UV irradiance was reduced by a factor of 15, 50+ and 43 respectively. Regard-

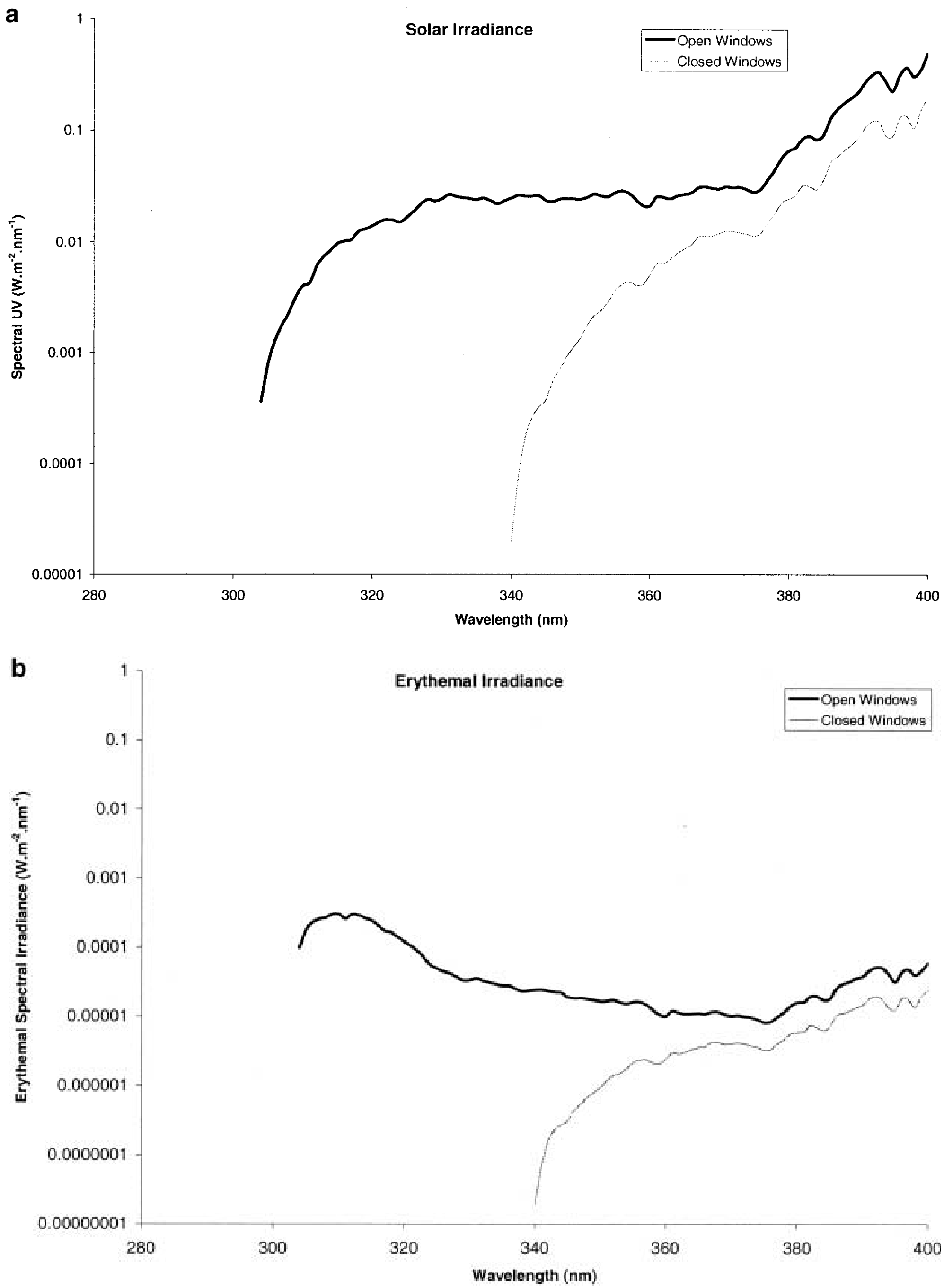


Fig. 5a–d Measured UV spectra (family wagon) for open and closed windows and weighted with the erythemal, actinic hazard and fish melanoma action spectra

less of detector orientation inside the 4WD, no DNA damage, photokeratitis or actinic weighted UV irradiances were recorded inside the vehicle. With the windows open, the 4WD had the highest UV irradiance measured when the detector was facing the driver's window (Table 2). This was due to the orientation of the 4WD and the SZA of the sun at the time of the measurements.

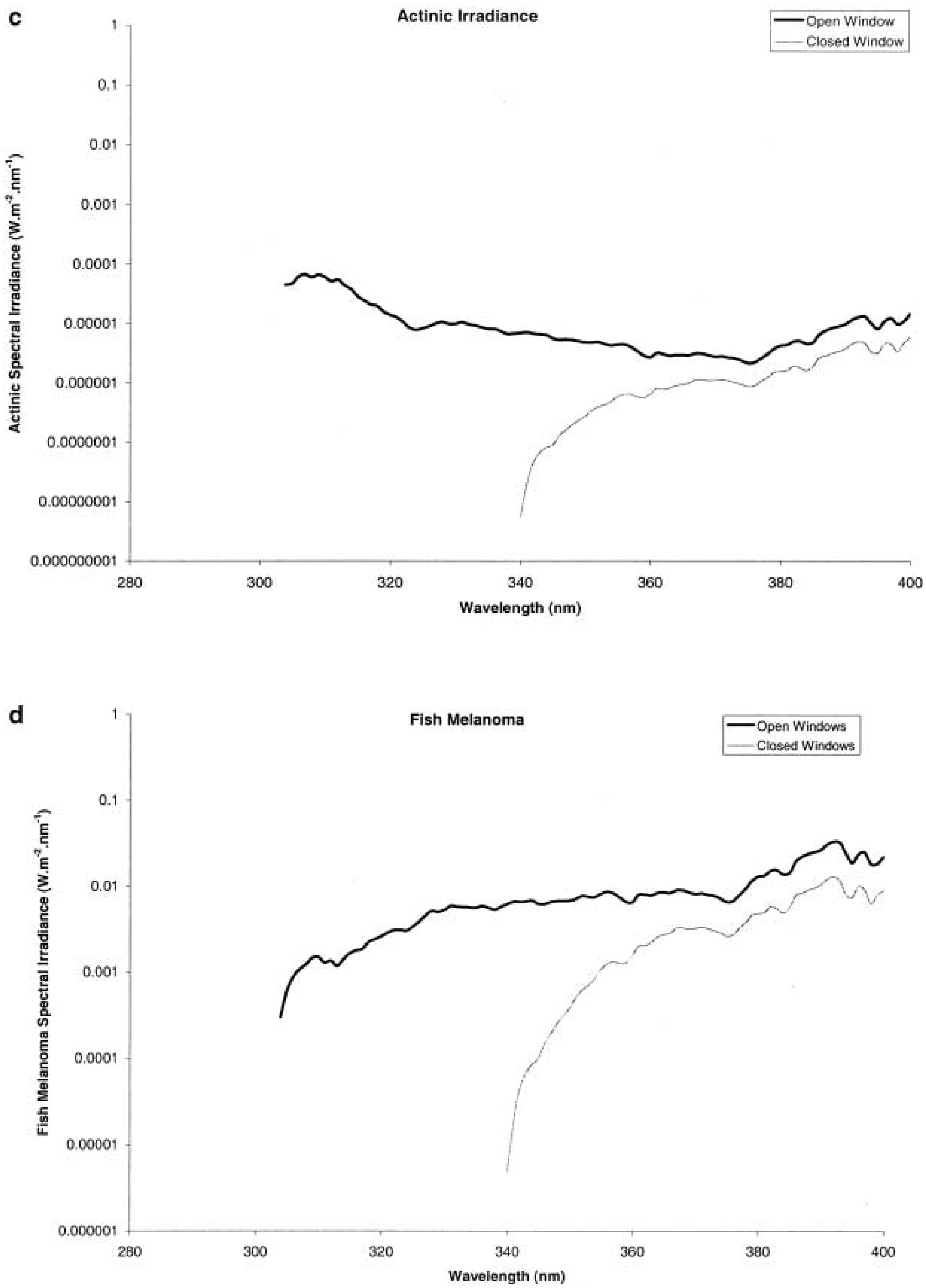
Spectral ratios

The spectral ratio is defined as the ratio of the UV spectral irradiance measured inside the vehicle to the UV spectral irradiance outside the vehicle at each measured wavelength. The average of the spectral ratios inside the vehicle with the windows closed is shown in Fig. 4. Regardless of the orientation of the detector, the UV spectral ratio increased with an increase of wavelength.

Biologically effective UV

Figure 5 shows the biologically damaging spectral UV irradiance measured on a horizontal plane in site DS with the windows in the open and closed positions. When the windows were closed, the biologically damaging spectra

Fig. 5a–d continued



changed significantly. The photokeratitis plot is not shown as no irradiance was detected. These results, for both skin and eye damage, indicate that reductions in human exposure to this damaging radiation may be achieved simply by driving a vehicle with the windows closed.

Discussion

The windshield (WS) orientation consistently recorded low UV irradiance levels, regardless of whether the windows were open or closed. This is due to the lamination of the windshield, which retards the shattering of the glass during an impact. This agrees with previous research (Sliney et al. 1995) that measured the spectral UV transmission of windshields in seven vehicles and found minimal UV transmission below 380 nm. This research shows that the lamination may have another use, that is, the reduction in the transmission of UV irradiances through the windshield. The other glass used in the vehicle is not similarly laminated.

The spectral UV irradiances measured in a vehicle depend on the direction and orientation of the receiver and whether the windows are open or closed. The UV irradiances inside a vehicle also vary with the vehicle orientation. In this case, that variable was fixed by having the front of the vehicles facing north, in order to investigate the effect of the receiver direction and orientation, and having the windows open or closed. This research shows that, for closed windows in the family wagon, the total UV irradiance is reduced by a factor of 5.2 when the UV irradiance on a horizontal plane is compared to that measured when the detector faces the passenger's window. In the family wagon, the ultraviolet protection factor (UPF) for total UV irradiance to a vertical plane orientated towards the driver's window when the windows were closed was 1.8 compared to when they were open. Similarly the UPF values were 3.2, 2.5 and 1.6 for the horizontal plane, PW and WS respectively. For the 4WD, the UPF values for total UV were 2.1, 2.6, 2.3 and 1.0 for the horizontal plane, DW, PW and WS respectively. The results were for a SZA range of 35° to 55° and may change quantitatively for angles outside this range; however, qualitatively the findings from this research are still applicable.

The biologically weighted UV irradiances collected inside the vehicles have significant implications for human health, in particular for skin cancer and eye disease. Although, in Queensland, Australia, the density of squamous cell and basal cell carcinomas on a particular site relative to their density on the body as a whole is highest on the face and ears, which are generally exposed when outdoors, it is still relatively high on the forearms and backs of the hands (Armstrong and Kricker 2001). The UV exposures in a vehicle contribute to the cumulative UV exposure and consequently contribute to the risk of developing these carcinomas. In both vehicles, when the windows were closed, no photokeratitis UV irradiance was measured; this was regardless of detector orientation. However, when the windows were open, photokeratitis UV irradiances were detected. Although different vehicle manufacturers use different types of glass and individual countries have various regulations governing the use of vehicle glass, the differences between results for open and closed windows should apply to similar right-hand drive family wagons and 4WD vehicles in other countries having cloud-free conditions and an SZA of 35°–55°.

In conclusion, the present study suggests the following recommendations regarding solar UV in vehicles:

- UV irradiances inside a vehicle are high enough to require the total exposure of humans in a vehicle to be considered when the lifetime exposure is estimated. This information should also feature in future public health campaigns.
- The differences between having windows open and closed can be extended qualitatively to similar vehicles and conditions, to assess UV exposures.
- In order to reduce the likelihood of the development of UV-related eye disorders, drivers should wear appropriate eye protection with side protection whilst driving a vehicle with the windows open.

Further work is required to investigate the spectral UV irradiances in the back seats of vehicles. This includes the effect of sitting in the middle of the back seat and the influence of window shade devices that may be attached to the rear windows of cars to protect children in the back.

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