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**Energy and Environment Division**

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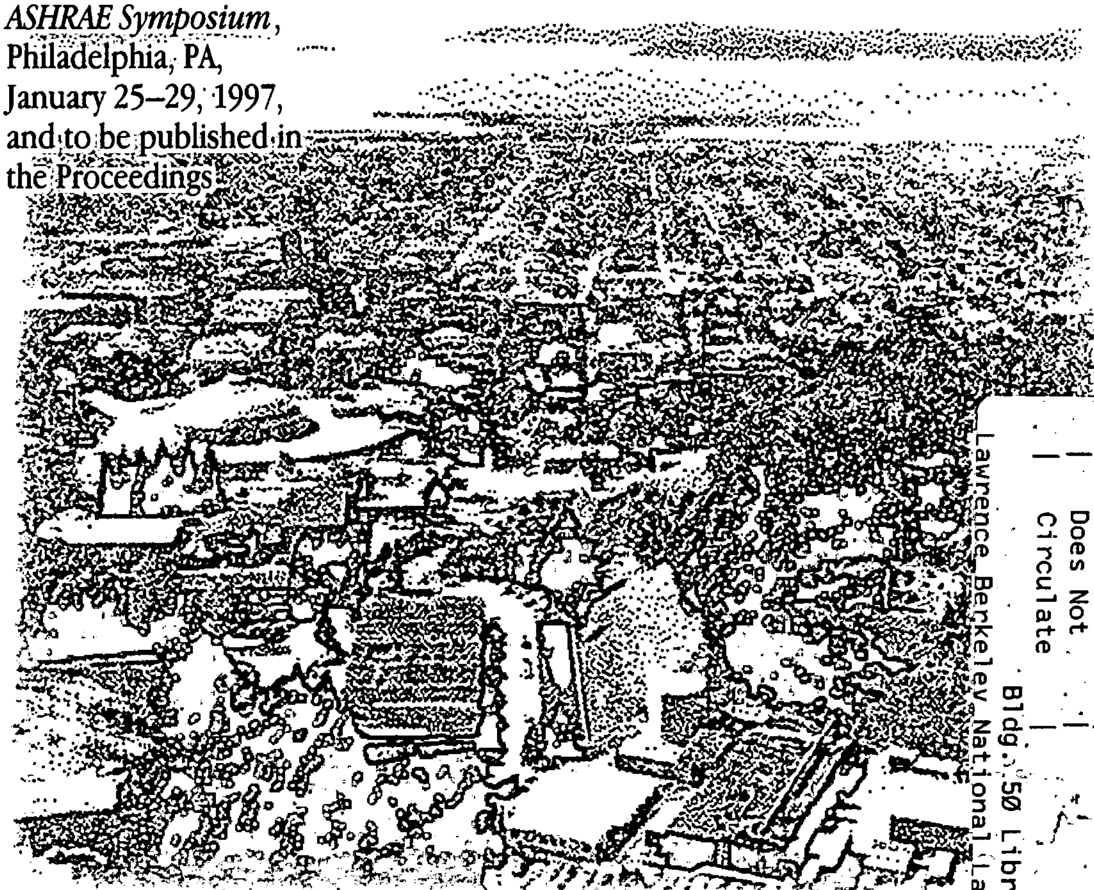

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## ABSTRACT

Measured bidirectional transmittances and reflectances of a buff-colored venetian blind together with a layer calculation scheme developed in previous publications are utilized to produce directional-hemispherical properties for the venetian blind layer and solar heat gain coefficients for the blind in combination with clear double glazing. Results are presented for three blind slat tilt angles and for the blind mounted either interior to the double glazing or between the glass panes. Implications of the results for solar heat gain calculations are discussed in the context of sun positions for St. Louis, MO.

## INTRODUCTION

The features that make venetian blinds useful and popular also make them fit poorly with the standard schemes of calculating building heating and cooling loads or rating windows. A venetian blind can be adjusted to control daylight or glare, which is to say that its effective transmittance is highly variable. It can be adjusted to exclude direct sunlight while (under some conditions) allowing a view of the outdoors, which is to say its transmittance is strongly anisotropic. Anisotropic, highly variable solar-optical elements do not fit gracefully into a world of engineering calculations in which devices are expected to be simply characterized. For example, the most recent edition of the ASHRAE Handbook lists a table characterizing a venetian blind with a single shading coefficient number (ASHRAE 1993) for 0° azimuth and 35° incident angle, (the latter corresponding approximately to the definition of "peak summer conditions," i.e., 30° incident angle). While theoretical (Farber, Smith et al. 1963; Owens 1974) and experimental (Parmelee, Aubele et al. 1953; Smith and Pennington 1964) studies of venetian blind or similar systems have appeared in the literature, and while all of these have at some level dealt with the strong dependence of the properties of these systems on incident direction, the authors have generally reported results as single numbers characterizing the system at particular incident directions (usually chosen to represent varying conceptions of "extreme" or "typical" conditions), and it is these numerical results that have found their way into property tables such as those of ASHRAE. Although modern building simulation programs are capable of sophisticated calculations taking account of

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solar incident direction, given the paucity of data one wonders whether these capabilities are generally utilized.

In this work we present measurement-based data on a venetian blind in combination with clear double glazing that explicitly shows the dependence on solar incident direction. The underlying measurements were of bidirectional, spatially averaged transmittance and reflectance of the blind, which were combined with published angular-dependent glass data. (Rubin 1985) The method of making the measurements and of calculating the solar heat gain coefficient (SHGC) from those measurements was developed as part of the ASHRAE/DOE Joint Research Project 548-RP and has been previously published. (Klems 1994A; Klems 1994B; Klems and Warner 1995)

## BLIND PROPERTIES

The venetian blind studied was a "buff" (or off-white) model designed to be usable between the panes of a double-glazed window, with slat width 17.6 mm (11/16 in.) and spacing 14 mm (0.55 in.). The total reflectance of the slat surface was 65% with a 3% specular component. The total spectral reflectance is shown in **Figure 1**, up to a wavelength of 700 nm. As can be seen from the figure, the reflectance is reasonably flat with wavelength above about 500 nm.

In the calculation method used the blind is characterized as an effective layer with a bidirectional transmittance and reflectance and a directional absorptance. The bidirectional transmittance and reflectance are measured on a large-sample gonioradiometer (Klems and Warner 1995) and are tabulated on a fixed angular grid to form "property matrices" that are intrinsically 4-variable functions (two angles specifying the direction of incident radiation, two angles specifying the direction of outgoing radiation). In order to display the blind property information in a comprehensible way the reflectance and transmittance were converted to directional-hemispherical quantities by a (weighted) summation over all outgoing directions as explained in the cited references. These are displayed in **Figure 3** as functions of the variables $\theta$ (the angle of incidence) and $\phi$ (the azimuthal angle about the normal to the fenestration). The definition of these angles is illustrated in **Figure 2(a)**. (We note that the angles $\theta$ and $\phi$ are the mathematically standard coordinate angles in a 3-dimensional spherical coordinate system for which the polar ($\theta$=0) axis is the normal to the window plane, the azimuthal ($\phi$=0) axis is in the horizontal plane, and $\theta$=90°,$\phi$=90° corresponds to the upward vertical direction. In particular, $\phi$ does not represent the solar azimuth angle as defined in ASHRAE Fundamentals).

The large-sample gonioradiometer was used to measure the venetian blind for three slat adjustments: (a) the slats were closed as tightly as their operation would allow in a skylight-excluding sense, i.e., the outside edges of the slats were downward and the inside edges upward; (b) a 45° slat tilt relative to the horizontal, again in a skylight-excluding or outside-edge-downward orientation; and (c) an "open" configuration, in which the slats were horizontal. In Figure 3 the directional-hemispherical transmittance and reflectance of the venetian blind alone is shown for these three slat adjustments. In these plots the plane is a polar representation of the angles ($\theta$,$\phi$) in which the radius represents the value of $\theta$ and the azimuth angle represents the value of $\phi$. The contours of equal transmittance or reflectance are then plotted in this plane in each of the graphs in the figure.

The plots in **Figure 3** show properties that are readily interpretable. In **Figure 3(a)** the reflectance of the closed blind is the same as the slat reflectance for most incident directions. For upward-going radiation (e.g., $\phi$ in the range 240° to 300°) at greater than 45° incidence it begins to become possible for some light to enter the small gaps between the slats, and the measured reflectance decreases. The irregular shape of the contour corresponding to a reflectivity of 0.60 in this region is an artifact of the rather coarse angular bins (15° intervals) that were used in the measurements. In the transmittance plot for this slat adjustment, for the upper half of the plot, which corresponds to downward-going radiation that strikes the closed slats nearly perpendicularly, the transmission is very low. In the lower half of the plot, transmission (by multiple reflection) through the small gaps between the slats begins to be seen. **In Figure 3(c)**, corresponding to the horizontal slats, the transmittance is unity for radiation in the horizontal plane (along the $\phi$=0° and $\phi$=180° rays) and falls off as the angle from the horizontal increases, either in the upward or downward direction, and the reflectance shows the reverse behavior, falling to zero in the horizontal and increasing above and below. The rectilinear geometry of the blind slats is clearly apparent in these plots. When the slats are at a 45° tilt, as in **Figure 3(b)**, one sees the expectable intermediate behavior, with large transmittance for upward-going radiation and large reflectance for downward-going.

The "vertical angle" characterizing these plots is the profile angle, $\zeta$, which as shown in **Figure 2(b)** is the projection of the incident angle on a vertical plane perpendicular to the window plane. In **Figure 4** the transmittance from **Figure 2(b)** for the 45°-tilted blind is replotted as a function of the profile angle. This plot shows two separate behaviors. For upward-going radiation the transmittance is dominated by the fraction of radiation that passes between the slats without striking them, and this explains the rise to a maximum at cos(45°)=0.707. For the downward-going radiation transmission arises through multiple (diffuse) reflection from the slats, and this varies with the fraction of the slat width that is illuminated (i.e., not shaded by adjacent slats). This quantity is proportional to the cosine of the profile angle. Thus, for the downward-going radiation the transmittance increases linearly with $\cos(\zeta)$ up to $\cos(\zeta)=0.9$, or $\zeta \leq 25°$. At these low profile angles some radiation begins to pass between the slats due to irregularities in blind construction, and again one sees a corresponding steep increase in transmittance with decreasing $\zeta$ [increasing $\cos(\zeta)$].

## FENESTRATION SYSTEM SOLAR HEAT GAIN COEFFICIENTS

The bidirectional transmittance and reflectance matrices for the blind are the basic inputs necessary for determining the SHGC of fenestration systems that include the blind. Directional absorptance is derived from the transmittance and reflectance measurements. In this scheme specular materials such as glass have simplified (diagonal) property matrices that are easily constructed from the known material properties. The quantity relevant to the SHGC is the directional-hemispherical transmittance (as well as layer directional absorptances); however, to determine these for a system consisting of two or more layers (for which there will be multiple reflections between layers), the full bidirectional properties of the layers must be used. In the references (Klems and Warner 1995) and (Klems 1994B) the details of how this is done are explained. The result is a directional-hemispherical transmittance, $T_{fH}$ for the system (i.e., all the layers taken together), and for each layer, i, a directional front absorption $A_{fi}$ for the layer in the system. From these quantities the SHGC is then calculated by the equation

$$SHGC(\theta, \phi) = T_{fH}(\theta, \phi) + \sum_{i=1}^{M} N_i A_{fi}(\theta, \phi), \tag{1}$$

where M is the number of layers and the quantity $N_i$ is the layer-specific inward-flowing fraction for the $i^{th}$ layer. The direction-dependence of this calculation is underlined in equation 1 by explicit inclusion the incident direction angles $(\theta,\phi)$.

The SHGC determination was carried out for a fenestration system consisting of clear double glazing with the buff blind (for each of the three slat tilts) on the interior, and again for a system in which the blind was placed between the clear glazings. In each case the bidirectional property matrices for the blind combined with the glazing property matrices (from published glass properties) yielded values of $T_{fH}(\theta,\phi)$ and $A_{fi}(\theta,\phi)$ [ i=1,3]. We used published measurements (Klems and Kelley 1996) of $N_i$, listed in Table 1, to complete the evaluation of equation 1. The resulting SHGC functions, which depend significantly on the incident direction angles, are shown in **Figure 5**. In a previous publication (Klems, Warner et al. 1996) the data in **Figure 5(b)** for an interior blind were shown to agree with field measurements made on the same system.

**Table 1. $N_i$ Values Used in the SHGC Determinations**

| Fenestration | Layer Number: | 1 | 2 | 3 |
|---|---|---|---|---|
| Double Glazing, | Layer identity | Glass | Glass | Blind |
| Interior Blind | $N_i$ value: | 0.21 | 0.69 | 0.86 |
| Double Glazing, | Layer identity | Glass | Blind | Glass |
| Between-Pane Blind | $N_i$ value: | 0.34 | 0.45 | 0.69 |

The SHGC properties plotted in **Figure 5** are, as one would expect, a convolution of the blind properties with those of clear glass. Clear glass has a reflectance that depends on incident angle: it is relatively constant up to approximately 40° and increases strongly with angle at larger angles. Accordingly, the transmittance and reflectance of clear glass would appear as a series of concentric circles on the polar plots we have been using. In **Figure 5** it can be seen that all of the plots tend to become concentric circles for $\theta$>60°, while inside of that value of incident angle similarities to the corresponding blind transmittance function are noticeable. While the shapes of the plots are similar for the two blind placements (at corresponding slat tilts), the between-pane blind exhibits a lower value of SHGC in most directions. This is due to a combination of the optical transmittance/reflectance and of the differing fractions of the energy absorbed by the blind that goes inward in the two cases.

Absorption of radiation by the blind and subsequent thermal transmission inward produces the dominant features of these plots. To see this, we may consider a particular incident direction, for example $\theta$=35°, $\phi$=90°, and a 45° slat tilt. **Figure 3(b)** tells us that in that direction the blind directional-hemispherical transmittance is 10% and its reflectance is about 42% (which means that its absorptance is about 48%). From **Figure 5(b)** we see, however, that the SHGC for this direction is about 50% for double glazing with an interior blind, and around 30% for double glazing with the blind between the glass panes. From Table 1 we would calculate that of the 48% absorptance, 48% X 0.86 = 41% of the energy incident on the blind should go inward. For the between-pane blind the corresponding fraction would be 48% X .45 = 22%. So a very naive calculation (in which we neglect all the optical effects of the two glass panes) would estimate a SHGC of 10% +41% = 51% for the interior blind and 10%+22% = 32% for the between-pane blind. These are quite close to the actual results, which tells us that for this incident direction the various optical effects largely cancel out, leaving the dominant effect the interception of energy by the blind (primarily by absorption) and its thermal transport inward. If we repeat the interior blind calculation for a different incident direction, such as $\theta$=60°, $\phi$=30°, we would estimate an SHGC of 0.49, while the actual value (from **Figure 5(b)**) is 0.40. The optical effects of the glass are more important because the glass is less transmissive, but one can see that absorption in the blind and subsequent thermal transmission inward is still an important physical effect.

One may read beam SHGC directly from the plots in **Figure 5** by computing the apparent sun angles as seen through a window in a particular location and orientation, locating that point on the appropriate plot, and interpolating between the contours to find the beam SHGC value. Obviously, this will use only points in the upper half of each plot. Inspection of the range of SHGC values obtainable in any given plot should dispel the notion that any single number can be chosen to adequately characterize a venetian blind system for all times and locations. This point will be treated further below.

The SHGC for diffuse solar radiation can be obtained from the plots by an appropriate weighted average over all angles. The upper and lower halves of the plots correspond, respectively, to downward (sky) and upward (ground-reflected) incident radiation, and we denote the corresponding diffuse solar heat gain coefficients by $SHGC_{DS}$ and $SHGC_{DG}$, where the subscript "DS" denotes "diffuse, sky" and "DG" denotes "diffuse, ground." In constructing these quantities we have assumed a uniform sky and a perfectly diffusely-reflecting ground. The resulting sky and ground diffuse SHGC's are given in Table 2.

**Table 2. SHGC for Diffuse Sky and Ground-reflected Solar Radiation for Clear Double Glazing with Venetian Blind**

| Slat Tilt | Interior Blind | | Between-pane blind | |
|---|---|---|---|---|
| | $SHGC_{DS}$ | $SHGC_{DG}$ | $SHGC_{DS}$ | $SHGC_{DG}$ |
| Closed (skylight excluding) | 0.37 | 0.38 | 0.22 | 0.24 |
| 45° (skylight excluding) | 0.47 | 0.60 | 0.34 | 0.59 |
| Open (horizontal) | 0.61 | 0.60 | 0.56 | 0.54 |

In many situations separate measurements or estimates of sky- and ground-diffuse solar radiation incident on the fenestration will not be available, in which case $SHGC_{DS}$ and $SHGC_{DG}$ may be combined into an overall diffuse $SHGC_D$:

$$SHGC_D = \frac{SHGC_{DS} + \xi \cdot SHGC_{DG}}{1+\xi}, \qquad (2)$$

where $\xi$ is a parameter that depends on both sky and ground conditions:

$$\xi = \frac{2 \cdot \rho \cdot I_H}{I_{DS}}.$$

Here $\rho$ is the effective ground reflectance (albedo), $I_H$ is the total global solar intensity (as would be measured by a horizontal pyranometer), and $I_{DS}$ is the total diffuse solar intensity on a horizontal surface (i.e., $I_{DS} = I_H - I_B \cdot \sin(\beta)$, where $I_B$ is the direct normal beam solar intensity and $\beta$ is the solar altitude).

Since it is precisely the asymmetry in transmission between upward-going (e.g., view) and downward-going (e.g., glare, solar heat) radiation that makes a venetian blind a desirable solar control product, we should consider the 45° slat tilt case as representative of the rule, rather than the exception. One can see from Table 2 that there is a substantial difference in SHGC between sky and ground radiation, even when attention is restricted to diffuse radiation. The parameter $\xi$, which controls the mixing between sky and ground properties in the overall average, can take on a wide range of values, varying from $\xi$=0.4 for overcast conditions with a vegetative-covered ground ($I_H/I_{DS}$=1, $\rho$=0.2), to $\xi$=2.8 for a clear sky under the same ground conditions ($I_H/I_{DS}$=7, $\rho$=0.2), to $\xi$=9.8 for a clear sky with a snow-covered ground ($I_H/I_{DS}$=7, $\rho$=0.7). The resulting variation in the overall diffuse SHGC is shown in Table 3 for the 45° slat tilt.

**Table 3. Variation with Sky and Ground Condition of Effective Diffuse SHGC for Clear Double Glazing with Venetian Blind at 45° Slat Tilt Angle**

| Condition | $\xi$ | $SHGC_D$ | |
|---|---|---|---|
| | | Interior Blind | Between-pane Blind |
| Overcast sky, vegetative cover | 0.4 | 0.51 | 0.41 |
| Clear sky, vegetative cover | 2.8 | 0.57 | 0.52 |
| Clear sky, snow cover | 9.8 | 0.59 | 0.57 |

As can be seen, the effective diffuse SHGC is always significantly higher than $SHGC_{DS}$, with a range of variation due to sky and ground conditions up to approximately 20%.

## IMPLICATIONS OF THE RESULTS

This brings us to the question of what are the practical implications of these results. As we have seen, the entire plots in **Figure 5** are used to construct the diffuse SHGC, and thereafter the lower halves of the plots can be forgotten (except when diffuse solar radiation is a dominant contributor to solar heat gain, or for special ground conditions such as snow or large bodies of water). The beam SHGC's must be read off the upper halves of the plots, but which regions of the plot will be important? The present practice for calculating the SHGC for unshaded glazing is to use the value for normal incidence; how is this practice to be considered in the light of these results?

The solar heat flux, Q, admitted by a fenestration system is calculated from

$$Q[t] = A_f \cdot \{SHGC_B(\theta[t], \phi[t]) \cdot I_B[t] \cdot \cos(\theta[t]) + SHGC_D \cdot I_D[t]\}, \qquad (3)$$

where the subscript B denotes beam ($I_B$ is the direct normal solar intensity) and D denotes diffuse. The time dependence in this equation has been made explicit: solar intensities change and the sun also moves. For any given day and window orientation, the sun direction as a function of time will trace out a particular trajectory on the appropriate plot in **Figure 5**, and along this trajectory both $I_B$ and $\cos(\theta)$ will vary. By reading off values of SHGC along the trajectory one obtains (for a given day) a time-dependent beam SHGC. During periods of high beam solar intensity Q will be dominated by the beam contribution; when solar intensity is low the diffuse term will become important.

This allows us immediately to answer the question about normal incidence. The horizontal axis in **Figure 5** corresponds to sunrise or sunset conditions, when the beam solar intensity is low due to atmospheric attenuation. Under these conditions the behavior of the system is dominated by the diffuse SHGC, so to characterize the system by its normal-incidence SHGC (the center of the plot) is to pick a value that is largely irrelevant.

To further explore this question, we have picked a particular location, St. Louis, MO, particular days of the year, namely, the summer and winter solstices and the spring/fall equinox, and particular window orientations, namely, south-facing and west-facing. St. Louis was chosen as an example location because it is centrally located with respect to the continental US, has substantial summer air conditioning demands, and has a sufficiently cold winter so that winter solar heat gain is of interest. We have then used the sun paths on the chosen days to convert the plots of **Figure 5** into effectively time-dependent SHGC values. These are plotted for an interior blind in **Figure 6**. (We have not included the closed blind in this calculation because the results are not so interesting.)

These plots show that the effective SHGC of the fenestration varies markedly with time of day, orientation, and season. The strong directional dependances of **Figure 5** do not correspond solely to unusual conditions. In south facing orientation it is true that the SHGC does not change rapidly with time during the periods of high solar intensity (although the change is largest in summer), but seasonally it changes by more than a factor of 2. In west-facing orientation it shows the reverse behavior: there is relatively small change seasonally, but it changes rapidly with time during the afternoon period of high direct solar intensity. These variations with time and season (i.e., with solar position) must be taken into account if building simulation calculations of solar loads are to be accurate, and if venetian blind systems are to be rationally compared with other solar control systems.

One can conclude from these figures, first, that even an open venetian blind gives substantial benefits in summertime (part (a) of the figure). This would indicate that building codes that refuse shading credit for venetian blinds on the grounds that they are user operable are missing an opportunity. Second, one obviously gains something from adjusting the blind, although the specific impact varies with time and season. Third, there is no simple way to choose a single number to characterize the system's SHGC for all periods when there are important solar heat gains. If one follows the prevailing practice of choosing the 4 PM (i.e., 16:00), summer equinox, west-facing value (and this would certainly be better than normal incidence), for the 45° blind this would give a value of about 0.50. This would be a reasonable approximation for the same times of day at other seasons; however, in west-facing the maximum solar intensities tend to occur at more like 14:00 (16:00 is simply the time when the solar load coincident with the lagged cooling demand of a commercial building tends to be a maximum), and at that time one would be overpredicting the solar heat gain by some 30%. One would overpredict the summer solar heat gain for a south-facing window by about a factor of 2. It appears safe to say that any attempt to make fenestration energy choices based on this kind of characterization would give results that would be essentially chaotic.

This is not to say that the plots of **Figure 5** must be the end of the story. These or something similar to them should properly be the inputs to building simulation programs—preferably, embedded in some form of model capable of estimating the properties of systems for which direct measurements are not available, e.g., on the basis of slat reflectivity. But it would probably be possible to approximate, for the purposes of window ratings or conceptual design, the essential results of **Figure 6** in a few numbers that could be used to represent the system with reasonable accuracy. These issues are useful topics for further research.

## CONCLUSIONS

The methodology and results developed in 548-RP, together with laboratory measurements on shading devices, can be used to give a reasonably complete picture of the performance of a complex, operable fenestration. This picture yields information that should make energy calculations for these systems much more accurate and reliable than has been true in the past. The SHGC for fenestrations incorporating venetian blinds depends strongly on the incident direction of beam solar radiation, and this dependence occurs in ways that have a significant impact on solar heat gain. In addition, the effective SHGC for diffuse radiation varies somewhat with sky conditions and ground reflectivity. The view that such fenestration systems can or should be characterized by a single SHGC is demonstratively wrong, and use of such a characterization would lead to nonsensical energy choices (and very probably has done so). Interpolating models of blind properties and rating schemes based on small sets of characteristic SHGC values might provide a fruitful way of utilizing these results and should be pursued.

## ACKNOWLEDGMENTS

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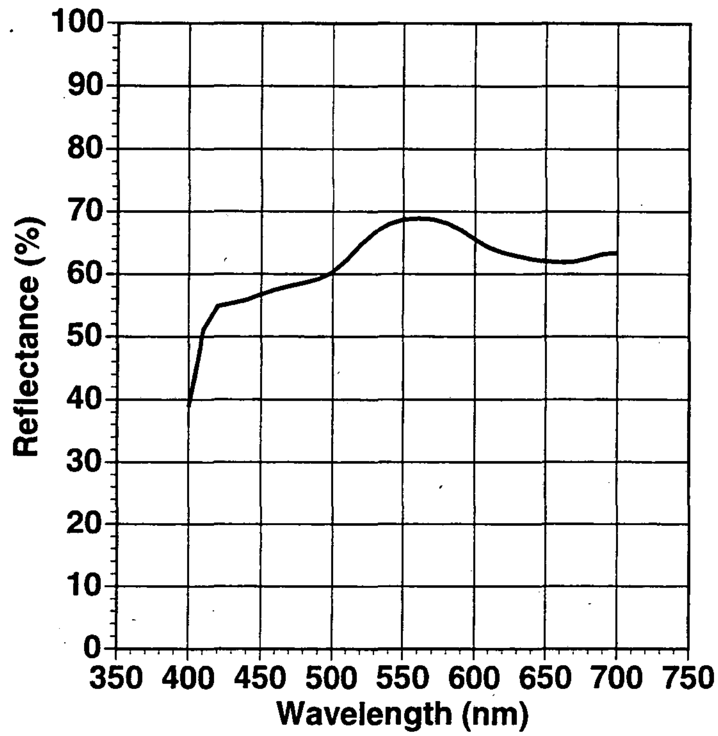


**Figure 1. Venetian Blind Slat Hemispherical Spectral Reflectance**

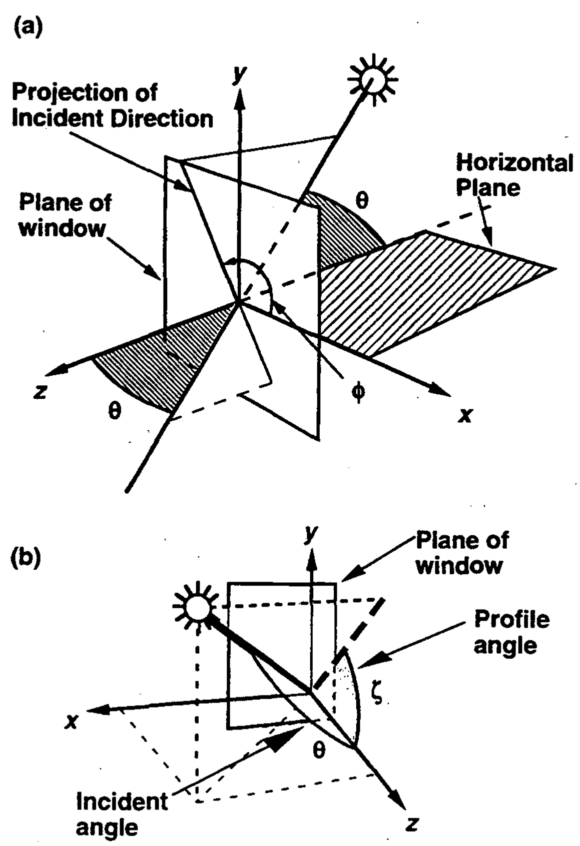


**Figure 2. Definition of angles**. (a) Incident and azimuthal angles, (θ,φ). (b) Profile angle, ζ, compared with incident angle.

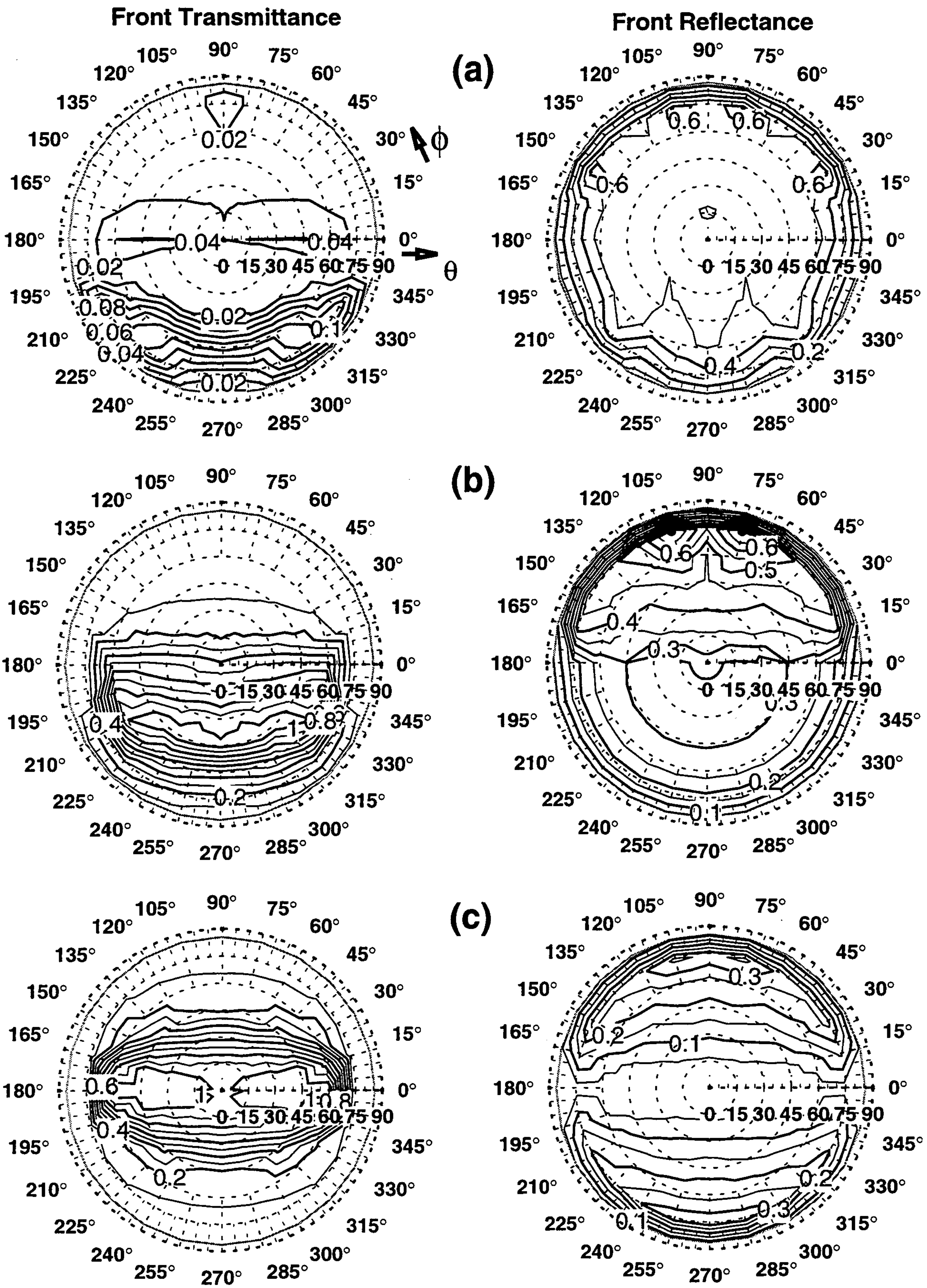


**Figure 3. Directional-hemispherical front transmittance and reflectance of the venetian blind for three slat positions.** **(a)** Closed (downward), **(b)** 45° tilt (downward) **(c)** Open (horizontal). Contours of constant transmittance or reflectance are displayed in a polar plot projection (window plane, looking outward) in which the radius is the angle θ (degrees) and the azimuth is the azimuthal angle ϕ about the normal to the window plane.

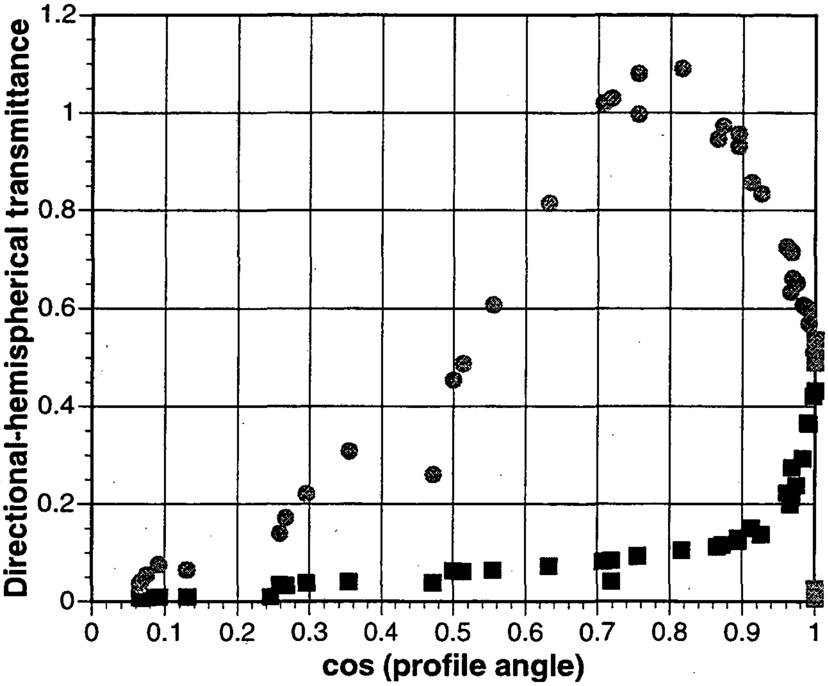


**Figure 4. Directional-hemispherical transmittance vs profile angle.** The transmittance of the buff blind at a 45° (downward) slat tilt is essentially a function of the profile angle, but shows different dependences for downward (squares) and upward (solid circles) incident radiation. Measurement uncertainties in the data can be as large as 10%, as can be seen from the fact that the transmittance exceeds 1 for the groundward hemisphere near 45°.

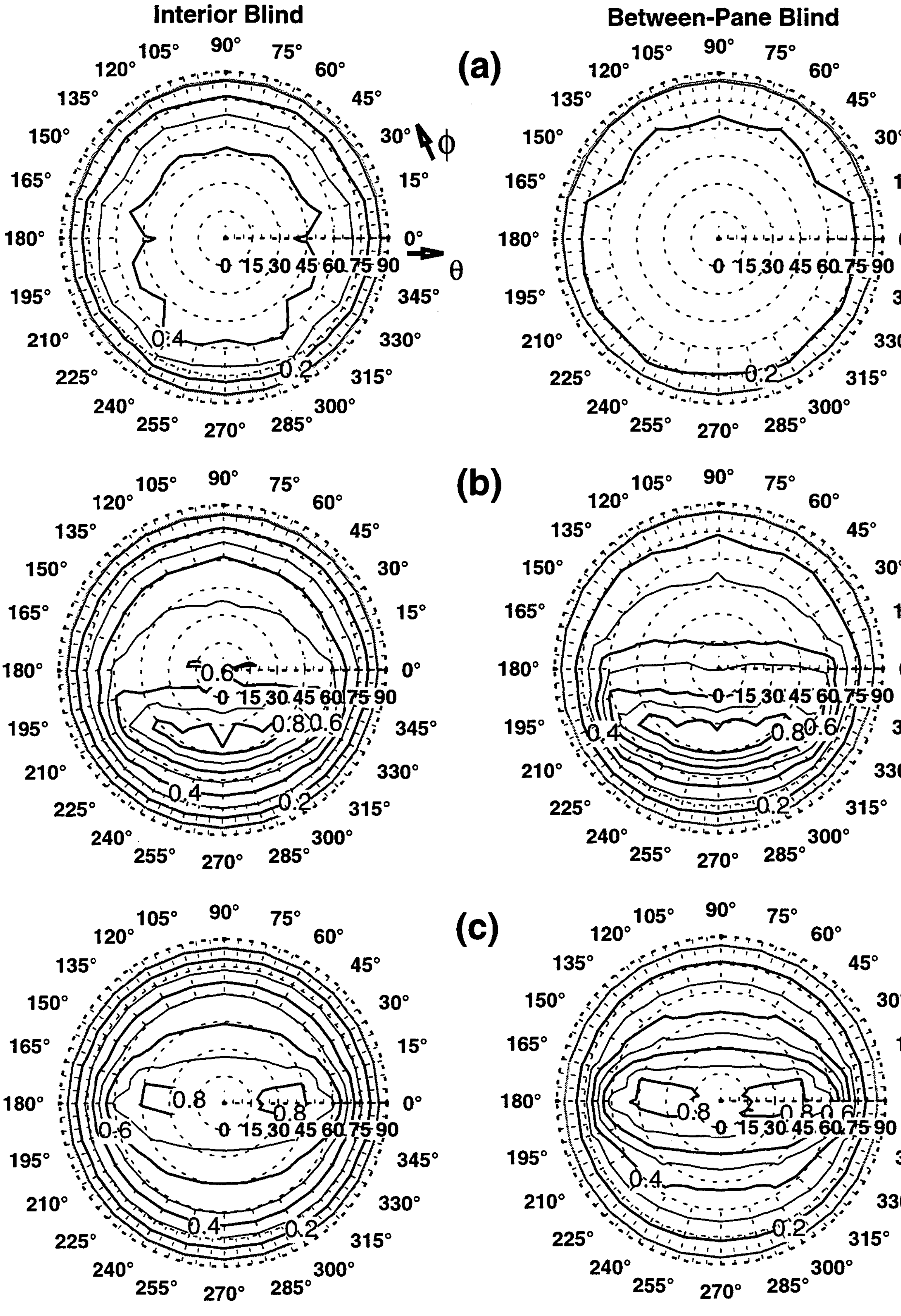


**Figure 5. Solar heat gain coefficient for double glazing interior and between-pane blinds.** The measurement-derived solar heat gain coefficient as a function of incident direction for clear double glazing in combination with the buff blind placed as an interior blind (left-hand plots) or between-pane blind (right-hand plots) for three slat adjustments: **(a)** Closed (downward), **(b)** 45° tilt (downward) **(c)** Open (horizontal). Contours of constant transmittance or reflectance are displayed in a polar plot projection (window plane, looking outward) in which the radius is the angle θ (degrees) and the azimuth is the azimuthal angle φ about the normal to the window plane.

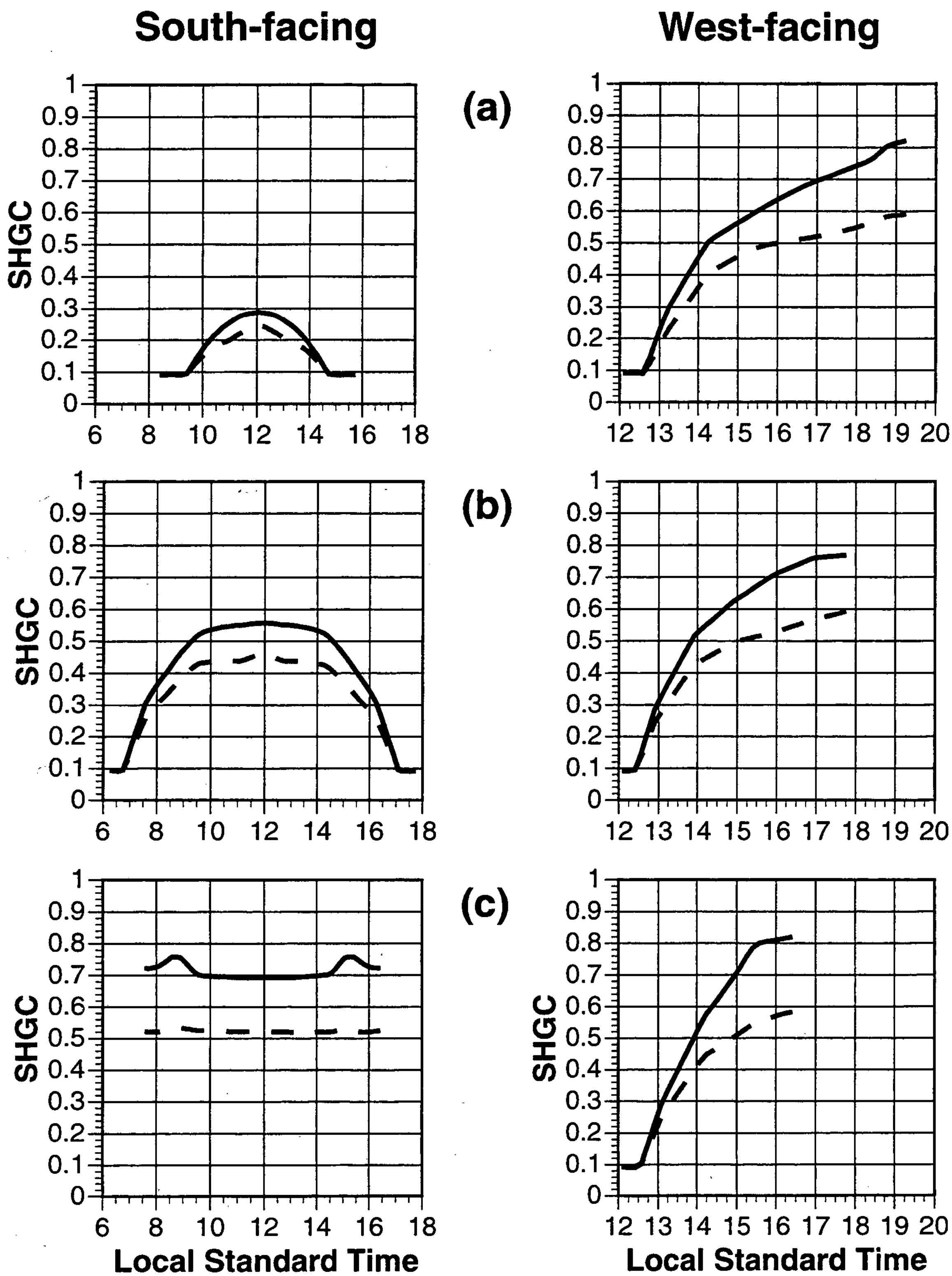


**Figure 6 Effective SHGC as a function of time for clear double glazing with interior buff blind.** For sun positions as would occur in Saint Louis, MO, the SHGC that would occur for a blind with horizontal slats (solid curves) or a 45° slat tilt (dashed curves) are shown for south-facing (left) and west-facing (right) orientations for **(a)** the summer solstace, **(b)** the sping/fall equinox, and **(c)** the winter solstace.

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