Testing the Behavior for Metamerism of the New Deviate Observer (JF-DO)

J. A. Martínez,* F. J. Vega, J. A. Díaz, F. Pérez-Ocón, J. R. Jiménez

Departamento de Óptica, Facultad de Ciencias, Universidad de Granada, 18071 Granada (Spain)

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Abstract: Recently, in our laboratories, a set of color-matching functions (cmfs) has been formulated for small fields by using two groups of real observers: JAM, MM, CF and AY, JR, MR, JL, JA, FP. The measurements of these cmfs have been made using different experimental devices and methods and it has enabled us to propose a New Deviate Observer for small fields (JF-DO). This new JF-DO was derived from the average observer of our nine real observers, following the technique used by the CIE to establish the Standard Deviate Observer (CIE-1989 SDO), which was established for fields of 10°, despite the CIE’s assumption that it can be applied to smaller fields. In the present work, we report experimental results of the JF-DO using metameric reflectances in comparison to the CIE-1931 Standard Observer and to the CIE-1989 SDO.

INTRODUCTION

Studies on inherent variability in color-matching functions (cmfs) of the groups of observers with normal color vision have led to the establishment of deviate observers1–5 (DO). Consequently, the Commission Internationale de L'Eclairage (CIE)6 in 1989 proposed a Standard Deviate Observer (CIE-1989 SDO) taking as a basis the cmfs of 20 actual observers for 10° field from the research of Stiles–Burch7 and following the technique of Nayatani et al.3 The objective is to establish an observer whose cmfs are more consistent with the cmfs of real observers than with the cmfs of their average value, all this from the standpoint of metamerism.

Some studies3,4,6 assume that the SDO proposed for 10° fields are also valid for smaller fields, based on the variability of the physiological parameters in the cmfs of real observers. In 1997, a new SDO was proposed for small fields (2°), derived from the cmfs of 10 observers studied by Stiles–Burch8 for small fields, which we called Poza-SDO.9 In our laboratories, we have determined the cmfs of real observers for small fields.10–15 These cmfs were measured for a group of three observers (JAM, MM, CF) and for another group of six observers (AY, JR, MR, JL, JA, FP), and for each group, a different procedure was followed, not only for the measurements but also for the calculation of the cmfs. All the cmfs of the nine observers were referred to an unreal system of primaries16 which we called $X'Y'Z'$ (but derived in a similar way as the system of unreal primaries $XYZ$ of the CIE-1931).7–17 This was necessary because, on trying to refer these observers to the system of unreal primaries $XYZ$ of the CIE-1931, certain negative values at some wavelengths appeared for our nine observers,10–12 as occurs with classical cmfs.18,19

Previous research11,12,18,19–22 demonstrated the variability between the cmfs of some of these observers, as well as certain differences between the CIE-1931 Standard Observer and the CIE-1989 SDO. All this has led us to develop a new Deviate Observer23 (JF-DO) for small fields, from the cmfs of our nine observers, using the techniques as in the CIE3 for which the cmfs were referred to the new system of unreal primaries16 $X'Y'Z'$.

In the present work, we report experimental results working with the new JF-DO in contrast to that of the Poza-SDO and the CIE-1989 SDO.5,9 Thus, we have followed the guidelines of the CIE6 in using metameric reflectances for the CIE-1931 Standard Observer and the CIE-1989 SDO one. All the cmfs of
the three observers used (JF-DO, Poza-SDO, and CIE-1989 SDO) are referred to the unreal primary system $X'Y'Z'$ by using the transformation matrix $T$.

**METHODS**

Two metameric reflectances for one observer (with a certain illuminant) will cease to be so if, for example, we change the observer. The color difference, $\Delta E$, is evaluated in CIELAB space. The results on observers’ metamerism gathered by the CIE, have provided a special metamerism index for evaluation, and a specific procedure for calculating the discrimination ellipse at 95% confidence-interval in a chromatic coordinate diagram, $(u, v)$, from a pair of metameric reflectances for the CIE-1931 Standard Observer. This ellipse should include 95% of the chromaticity coordinates $(u, v)$, which are derived from the discrepancies between the CIE-1931 Standard Observer and cmfs themselves of each of the real observers. In this sense, previous research has shown some disagreement between classical observers and the CIE-1931 Standard Observer. Some of these differences have had a certain importance, particularly when using the Stiles–Burch cmfs for small fields.

In this work, we have used four reference reflectances, each one with a different hue—blue, green, yellow, and red—which we call b420, g400, y34, and r57, respectively, following the recommendations of CIE—and we have simulated the D65 illuminant. The method followed to generate the metameric reflectances (given the observer and certain illuminants) from a reference reflectance was based on Fourier analysis, following the guidelines of the CIE.

As stated earlier, the calculations, representations, etc. are given in our reference of unreal primaries $X'Y'Z'$ to avoid having negative values in any color space (Fig. 1 (a,b,c,d)).

Considering the CIE-1931 Standard Observer, we have four reference reflectances: b420, g400, y34, and r57. From each one, we generated three metameric reflectances; thus, for the reference reflectance b420, the three metemers are b240_m1, b240_m2, and b240_m3, and so on. The metameric reflectances for the CIE-1989 SDO which were generated in the same way are shown in Figs. 2 (a,b,c,d).

When we use observers other than the foregoing ones, such as Poza-SDO or JF-DO, the reflectances cease to be metameric and, for each group of four reflectances and for each observer, we get different chromaticity coordinates, the latter being a consequence of the variability between the cmfs of the different observers.

**RESULTS**

We have compared the results between observers on using the metameric reflectances for the CIE-1931 Standard Ob-

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FIG. 1. (a) Reference reflectance b420 and the metameric reflectances generated, b420_m1, b429_m2, and b420_m3, for the CIE-1931 Standard Observer with the illuminant D65 and the system of primaries $X'Y'Z'$. The chromaticity coordinates are $x' = 0.214$, $y' = 0.193$, and $u' = 0.176$, $v' = 0.335$; (b) (c) (d) show the same curves for the reflectancies g400, y34 and r57, respectively, with their corresponding metameric reflectances.
server and for the CIE-1989 SDO. Tables I–IV show the chromaticity coordinates \((x', y')/H_{11032}\) and \((u', v')/H_{11033}\) of the reference reflectances \(b_{420}, g_{400}, y_{34}, r_{57}\) and of the metamers generated \(b_{420\_m1}, b_{420\_m2}, b_{420\_m3}, g_{400\_m1}, g_{400\_m2}, g_{400\_m3}, y_{34\_m1}, y_{34\_m2}, y_{34\_m3}, r_{57\_m1}, r_{57\_m2}, r_{57\_m3}\), for each of the observers studied (CIE-1931, JF-DO, Poza-SDO, and CIE-1989 SDO). As stated above, the reflectances were metameric for the CIE-1931 Standard Observer but not for the rest of the observers: CIE-1989 SDO, Poza-SDO, and JF-DO.

Tables V–VIII show the results regarding the reflectances of each group, which are metameric for the CIE-1931 Standard Observer but not for the rest of the observers: CIE-1989 SDO, Poza-SDO, and JF-DO.

Following the CIE procedure\(^6\), we paired each group of reflectances considered metameric for the CIE-1931 Standard Observer and calculated the corresponding ellipses at 95% confidence-interval. For each hue, we plotted six different ellipses, and, as there were four different hues, we calculated a total of 24 separate ellipses.

The equation of the ellipse was:

\[
\sum^{11}(\Delta u')^2 + 2\sum^{12}(\Delta u')(\Delta v') + \sum^{22}(\Delta v')^2 = \chi^2(2,0.05) = 5.991 \quad (1)
\]

where the \(\Sigma^j\) are the matrix elements to be compared, \(\chi^2(2,0.05) = 5.991\) is 5% of the Chi-squared distribution for 2 degrees of freedom, and

\[
u'' = \frac{4X}{X + 15Y + 3Z} \quad (2)
\]

\[
v'' = \frac{9Y}{X + 15Y + 3Z} \quad (3)
\]

The centers of each of these ellipses corresponded to the chromaticity coordinates \((u', v')/H_{11033}\) in common for each pair of reflectances considered in calculating each ellipse, as these reflectances were metameric for the CIE-1931 Standard Observer.

**DISCUSSION AND CONCLUSIONS**

With respect to the four reflectances of each group (hue) that were metameric for the CIE-1931 Standard Observer, the dispersion of the results between the chromaticity coordinates \((u', v')/H_{11033}\) was greater when calculated from the cmfs of the JF-DO than when calculated from those of the Poza-SDO and even more so from the cmfs of the CIE-1989 SDO. This indicates high variability among the different
TABLE I. Chromaticity coordinates of the reflectance b420 and their metamers b420_m1, b420_m2, and b420_m3 for the CIE-1931 and chromaticity coordinates for the JF-DO, SDO-Poza, and SDO-CIE observers.

<table>
<thead>
<tr>
<th>Observer</th>
<th>Reflectance</th>
<th>Chromaticity coordinates</th>
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<tbody>
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<td></td>
<td></td>
<td>u'</td>
<td>v'</td>
<td>x'</td>
<td>y'</td>
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</tr>
<tr>
<td>CIE-1931</td>
<td>b420</td>
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<td>0.335</td>
<td>0.214</td>
<td>0.193</td>
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TABLE II. Chromaticity coordinates of the reflectance g400 and their metamers g400_m1, g400_m2, and g400_m3 for the CIE-1931 and chromaticity coordinates for the JF-DO, SDO-Poza, and SDO-CIE observers.

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<td>v'</td>
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<td>g400_m1</td>
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TABLE III. Chromaticity coordinates of the reflectance y34 and their metamers y34_m1, y34_m2, and y34_m3 for the CIE-1931 and chromaticity coordinates for the JF-DO, SDO-Poza, and SDO-CIE observers.

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<th>Reflectance</th>
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<td>0.401</td>
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<td>0.534</td>
<td>0.398</td>
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</tr>
</tbody>
</table>

Observers considered, and especially between the observers JF-DO, Poza-SDO, and CIE-1989 SDO, with respect to a given stimulus.

As commented in the foregoing section, for each color corresponding to each reference reflectance, we obtained six different ellipses at 95% confidence, according to the CIE procedure. For the sake of representation, in each of the figures presented below (Figs. 3 and 4), we show one ellipse...
TABLE IV. Chromaticity coordinates of the reflectance r57 and their metamers r57_m1, r57_m2, and r57_m3 for the CIE-1931 and chromaticity coordinates for the JF-DO, SDO-Poza, and SDO-CIE observers.

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<th>Observer</th>
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<th>Chromaticity coordinates</th>
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<td>CIE-1931</td>
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<td>JF-DO</td>
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<td>r57_m2</td>
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<td>SDO-Poza</td>
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<tr>
<td></td>
<td>r57_m3</td>
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TABLE V. Chromaticity coordinates of the reflectance b420 and their metamers b420_m1, b420_m2, and b420_m3 for the CIE-1989-SDO and chromaticity coordinates for the JF-DO and SDO-Poza observers.

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TABLE VI. Chromaticity coordinates of the reflectance g400 and their metamers g400_m1, g400_m2, and g400_m3 for the CIE-1989-SDO and chromaticity coordinates for the JF-DO, and SDO-Poza observers.

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<th>Observer</th>
<th>Reflectance</th>
<th>Chromaticity coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>u'</td>
</tr>
<tr>
<td>SDO- CIE</td>
<td>g400</td>
<td>0.127</td>
</tr>
<tr>
<td>JF-DO</td>
<td>g400</td>
<td>0.133</td>
</tr>
<tr>
<td></td>
<td>g400_m1</td>
<td>0.136</td>
</tr>
<tr>
<td></td>
<td>g400_m2</td>
<td>0.131</td>
</tr>
<tr>
<td></td>
<td>g400_m3</td>
<td>0.135</td>
</tr>
<tr>
<td>SDO-Poza</td>
<td>g400</td>
<td>0.131</td>
</tr>
<tr>
<td></td>
<td>g400_m1</td>
<td>0.130</td>
</tr>
<tr>
<td></td>
<td>g400_m2</td>
<td>0.131</td>
</tr>
<tr>
<td></td>
<td>g400_m3</td>
<td>0.130</td>
</tr>
</tbody>
</table>

TABLE VII. Chromaticity coordinates of the reflectance y34 and their metamers y34_m1, y34_m2, and y34_m3 for the CIE-1989-SDO and chromaticity coordinates for the JF-DO, SDO-Poza observers.

<table>
<thead>
<tr>
<th>Observer</th>
<th>Reflectance</th>
<th>Chromaticity coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>u'</td>
</tr>
<tr>
<td>SDO-CIE</td>
<td>y34</td>
<td>0.224</td>
</tr>
<tr>
<td>JF-DO</td>
<td>y34</td>
<td>0.196</td>
</tr>
<tr>
<td></td>
<td>y34_m1</td>
<td>0.197</td>
</tr>
<tr>
<td></td>
<td>y34_m2</td>
<td>0.195</td>
</tr>
<tr>
<td></td>
<td>y34_m3</td>
<td>0.196</td>
</tr>
<tr>
<td>SDO-Poza</td>
<td>y34</td>
<td>0.209</td>
</tr>
<tr>
<td></td>
<td>y34_m1</td>
<td>0.209</td>
</tr>
<tr>
<td></td>
<td>y34_m2</td>
<td>0.209</td>
</tr>
<tr>
<td></td>
<td>y34_m3</td>
<td>0.209</td>
</tr>
</tbody>
</table>
TABLE VIII. Chromaticity coordinates of the reflectance r57 and their metamers r57_m1, r57_m2, and r57_m3 for the CIE-1989-SDO, and chromaticity coordinates for the JF-DO and SDO-Poza observers.

<table>
<thead>
<tr>
<th>Observer</th>
<th>Reflectance</th>
<th>Chromaticity coordinates</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>u'</td>
<td>v'</td>
<td>X'</td>
<td>y'</td>
</tr>
<tr>
<td>SDO-CIE</td>
<td>r57</td>
<td>0.311 0.495</td>
<td>0.470</td>
<td>0.333</td>
</tr>
<tr>
<td>JF-DO</td>
<td>r57</td>
<td>0.264 0.494</td>
<td>0.419</td>
<td>0.348</td>
</tr>
<tr>
<td></td>
<td>r57_m1</td>
<td>0.266 0.486</td>
<td>0.411</td>
<td>0.334</td>
</tr>
<tr>
<td></td>
<td>r57_m2</td>
<td>0.264 0.498</td>
<td>0.423</td>
<td>0.354</td>
</tr>
<tr>
<td></td>
<td>r57_m3</td>
<td>0.265 0.490</td>
<td>0.415</td>
<td>0.341</td>
</tr>
<tr>
<td>SDO-Poza</td>
<td>r57</td>
<td>0.285 0.507</td>
<td>0.458</td>
<td>0.362</td>
</tr>
<tr>
<td></td>
<td>r57_m1</td>
<td>0.284 0.502</td>
<td>0.451</td>
<td>0.355</td>
</tr>
<tr>
<td></td>
<td>r57_m2</td>
<td>0.285 0.509</td>
<td>0.461</td>
<td>0.366</td>
</tr>
<tr>
<td></td>
<td>r57_m3</td>
<td>0.284 0.505</td>
<td>0.455</td>
<td>0.359</td>
</tr>
</tbody>
</table>

as a representative example of the six different ellipses constructed for each color tone corresponding to each reference reflectance, given that the results for the rest of the ellipses were similar. Furthermore, we also show in each of the Figs. 3 and 4, the points corresponding to the chromaticity coordinates (u',v') of the four metameric reflectances (that of reference and its three derivates) for the CIE-1931 Standard Observer (Figs. 3 and 4a) and for the CIE-1989 SDO (Fig. 4(b,c,d,e)), on employing the cmf's of the rest of the observers used here, since for these they cease to be metameric reflectances where the center of each ellipse corresponds to the common chromaticity coordinates (u',v') for the CIE-1931 Standard Observer (Figs. 3 and 4a) and for the CIE-1989 SDO (Fig. 4(b,c,d,e)).

Figures 3 and 4 are represented at different scales so that they can be more readily appreciated by the reader, since when they were constructed at the same scale the ellipses had a very small area and were not easily viewed. However, the fact that the scales differ does not affect the results, as the orientation of the ellipses as well as the trend and

FIG. 3. (a) Ellipse generated for the pair of the metameric reflectance of the reflectances g400_m1/g400_m2 for the CIE-1931 Standard Observer and the chromaticity coordinates of these reflectances for the JF-DO, Poza-SDO, and CIE-1989 SDO; (b) (c), (d) show the same ellipses for the metameric pairs b420_m1/b420_m2, g400_m1/g400_m3 and y34_m1/y34_m2, respectively.
distribution of the points that represent the chromaticity coordinates \((u', v')\) remain.

Except for the ellipse calculated considering the pair of metameric reflectances g\textsubscript{400-1} and g\textsubscript{400-2} for the CIE-1931 Standard Observer, which encompasses the three points corresponding to the chromaticity coordinates \((u', v')\) calculated with the cmfs of the CIE-1989 SDO (Fig. 3a), none of the remaining ellipses contains any of the \((u', v')\) chromatic coordinates calculated with the cmfs of the other observers (CIE-1989 SDO, Poza-SDO, and JF-DO). This implies a strong point against the CIE procedure.\(^6\) As an example of the case described, we show Fig. 3 (b,c,d). The area of the ellipses varied on considering the different pairs of reflectances but did not vary in orientation, which supports, in our opinion, the CIE procedure.\(^6\)

The points corresponding to the chromaticity coordinates \((u', v')\) calculated from the cmfs of the JF-DO deviate more than do those of the corresponding groups of points of the other observers, but their orientation agrees more with the orientation of the corresponding ellipses (on their principal semi-axes). The trend of the distribution of the points of observer JF-DO is similar to that of the CIE-1989 SDO;
however, this distribution trend differs for the Poza-SDO, as reflected in Fig. 3 (b,c,d) and 4a. In this sense, the new JF-DO shows better behavior than does the Poza-SDO and agrees better with the CIE-1989 SDO.

With regard to the points represented in Fig. 3d, we should clarify that in addition to the four points corresponding to the chromaticity coordinates (u’,v’) of the four reflectances y34, y34_m1, y34_m2, and y34_m3 (which are metameric for the CIE-1931 Standard Observer), when obtained using the cmf’s of the JF-DO Observer, the three points corresponding to the chromaticity coordinates (u’,v’) of the four reflectances mentioned also appear, these obtained using the cmf’s of the Poza-SDO Observer. This is because, for the Poza-SDO Observer the reflectances of y34 and y34_m3 appear metameric, and, on the other hand, also in this figure, two points appear that correspond to the chromaticity coordinates (u’,v’) of the four reflectances mentioned and obtained now on using the cmf’s of the CIE-1989 SDO Observer. This is because, for the CIE-1989 SDO Observer, the reflectances y34 and y34_m2 appeared metameric, on the one hand, and the reflectances y34_m1 and y34_m3 on the other hand (see Table III).

Also, Fig. 4a shows, among others, three points that represent the chromaticity coordinates (u’,v’) of the reflectances r57, r57_m1, r57_m2, and r57_m3 (which are also metameric for the CIE-1931 Standard Observer) obtained on using the cmf’s of the CIE-1989 SDO Observer. This is also because, for the CIE-1989 SDO Observer, the reflectances r57_m1 and r57_m3 are metameric (see Table IV).

When the reflectances were metameric for the CIE-1989 SDO, the results resembled and confirmed those mentioned earlier in terms of dispersion and orientation of the ellipses. However, more importantly, our observer (JF-DO) shows better behavior than the Poza-SDO, with respect to the orientation of the ellipses. An example is provided in Fig. 4 (b,c,d,e).

In summary, the present findings confirm the validity of the results of previous works, where other experiments were performed with the CIE-1989 SDO, among others, as the only deviate observer. This study also corroborates the strong influence of the cmfs in general on color observation, whether corresponding to normal or deviate observers.

Major differences among the different deviate observers have been demonstrated with the CIE procedure in relation to the CIE-1931 Standard Observer and, especially, among the different deviate observers (CIE-1989-SDO, Poza-SDO and JF-DO). Furthermore, the results reflect that the New JF-DO, comparatively, differs more markedly than do the deviate observers considered, as appears to have been deduced in a previous work. However, in terms of its trend, that DO observer is more similar to the CIE-1989 SDO than to the Poza-SDO, although, as stated earlier, color observation for each observer (CIE-1989 SDO, Poza-SDO, and JF-DO) is different.