Received: 6 February 2023 | Revised: 10 May 2023 | Accepted: 17 June 2023

DOI: 10.1002/col.22877

RESEARCH ARTICLE

COLOR RESEARCH AND APPLICATION WILEY

Aging variations in Ishihara test plates

Alice Plutino[1] | **Luca Armellin**[1] | **Andrea Mazzoni**[2] | **Roberta Marcucci**[2] | **Alessandro Rizzi**[1]

[1]Department of Computer Science, Universit'a degli Studi di Milano, Milano, Italy

[2]Aerospace Medical Institute, Italian Air Force, Rome, Italy

Correspondence
Alice Plutino, Department of Computer Science, Universit'a degli Studi di Milano, Milano, Italy.
Email: alice.plutino@unimi.it

Funding information
Comitato per la Ricerca Sanitaria Militare (CORISAMIL), Grant/Award Number: VSP1707122-04C120PB27182-016

Abstract

The Ishihara test plates are designed to offer a rapid and usable instrument to diagnose color deficiency. The original test, as well as other pseudo-isochromatic plates (PIP), is composed of physical charts produced following proprietary and standard printing procedures. In this work, we aim to measure and assess the color shifts that the aging of the plates may introduce. This work aims to raise the scientific and medical community's awareness of the risks that may occur in using an aged or damaged test, which may still appear in good condition but has been subjected to deterioration over time.

KEYWORDS

color aging, color blindness, color vision, Ishihara Plates

JEL CLASSIFICATION

Y1 Data: Tables and Charts

1 | INTRODUCTION

Since the first publication of the Ishihara test made by Dr Shinobu Ishihara in 1918[1] (also if most authorities put the origin as 1917), this color deficiency screening method has spread all over the world, and today it is still widely used to assess color vision. This test is part of the pseudo-isochromatic plates (PIP) family and consists of a set of plates composed of a circle filled with colored dots of different colors and sizes (see Figure 1). Modern Ishihara color plates are combined with a manual for interpreting the results (e.g., Reference 2), making this test very simple to apply and interpret.

The Ishihara test is widely accepted to diagnose congenital red-green deficit (protanopia, deuteranopia, protanomaly, and deuteranomaly). It was not designed to facilitate the screening for tritanopia (blue-yellow deficit).[2,3] This is not a severe limitation since congenital tritanopia is a rare condition. Tritan-like deficiencies can be caused by retina and/or systemic diseases (e.g., diabetes) that also affect vision. Therefore, tritanopia is more common in older subjects than congenital deficiency in all subjects. The vast majority of cases involve red-green color vision, affecting about 8.8% of males and 0.4% of the female population.[4,5] As a consequence, the Ishihara test is inappropriate for use in the clinic, unless the aim is to detect only late stages of disease when acquired red/green loss more advanced.

The Ishihara test has been published in different versions, the full one made of 38 plates, the concise 24-plate edition, and the new abbreviated 14-plate edition. As Birch et al. presented in,[6] just the 38 full plates version is recommended for clinical practice.

The Ishihara test plates are intended to offer a rapid and usable instrument to diagnose color deficiency. Due to this, this screening test is usually used as a preliminary test for color blindness diagnosis.[7–9] In a recent study conducted by John L. Barbur et al.,[10] it has been

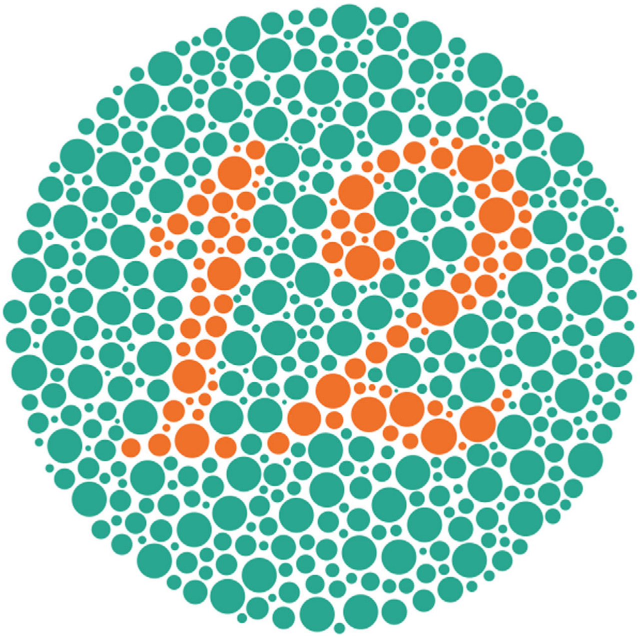

FIGURE 1 Ishihara Plate 01.

demonstrated that the Ishihara test presents a high sensitivity in detecting subjects with congenital red–green color deficiency, even if this method has not been found suitable to discriminate color blindness type.[11,12] As a consequence, even if other screening tests, like Nagel's anomaloscope, are considered the golden standard to diagnose and classify color blindness, the great usability of the Ishihara test and its robustness make this test still one of the most used. In fact, among all the different tests to screen color deficiency, the Ishihara test is used in a wide variety of domains, like in the industry,[13] in schools, and with children, in general,[14,15] but also as part of the multi-test protocol in the army or law enforcement agencies.[3,16]

In this context, the widespread usage of the test can lead to an incorrect method of administration or approximations in the screening test use. Considering the general guidelines and the manuals provided with the Ishihara test plates, it is stated that the plates are designed to be used in an environment lit with "natural light," but there are no recommendations on the specific light sources to use (e.g., D65, D50, A).[2] Concerning the use and maintenance of the charts, it is suggested not to leave them exposed to strong light sources and to put them back in their case.[2] With this work, we aim to underline the importance of measuring and checking for the quality of the Ishihara charts, especially after more than 1 year of usage. The charts are subject to continuous human touching and manipulations. Since the plates are made with physical colorants, they are subject to degradation and fading, like all other colored objects. In this context is critical to underline that, in many cases, degradation can also occur when respecting the conservation guidelines.

In the literature, some works assess the importance of making spectrophotometric analysis on the Ishihara plates to control the quality of the print[17,18] or to quantify the plates aging.[19] These studies aim to analyze the structure of Ishihara plates in depth or demonstrate the variations along different versions to improve the test's validity.

This work presents the spectrophotometric and colorimetric analysis of 36 colors derived from five plates from the official Ishihara tests from 1995, 2000, 2004, 2018, and 2021. The considered colors have been measured and analyzed to define the differences and degradation a single color can undergo through the years. The main scope of this study is to raise the awareness of the scientific and medical community on the risk of using degraded Ishihara plates and on the importance of keeping reasonable control of their quality for color deficiency screening tests.

2 | TEST SETUP

2.1 | Ishihara plates colors

In this work, we have analyzed 36 colors derived from 5 plates from Ishihara 38 plates edition from 1995, 2000, 2004, 2018, and 2021, for a total of 180 measures. The original charts were certified when purchased in the years given above by GIMA[2] and published by Kanehara Trading Inc. (Tokyo), Japan.[20]

The Ishihara 38 plates edition presents a specific classification of the plates depending on the content. The ability to read the numbers from Plate 02 to Plate 21 defines if a red-green defect is present. Plates numbered 22, 23, 24 and 25 are the most useful to recognize and to differentiate green from red blindness and to classify absolute (*protan/deuteran—anopia*) or partial (*protan/deuteran—anomaly*) defects. Plates from 26 to 37 show paths, not numbers, and are shown to illiterates or candidates supposed to have memorized previous plates with numbers. If the subject can read more than 17 plates, the color vision is normal; if the user can read less than 13 plates, a color vision deficit is present. If the correct answer of the user is between 17 and 13, further color vision screening is suggested.[2]

The plates can be divided into several groups. Considering the colors composing the plates, we can have this subdivision:

- Plate 01, plate 38
- Plates 02–05, plates 36–37
- Plates 06–09, plates 34–35

TABLE 1 Analyzed points associated with their color name and Ishihara Plate.

Point	Color name	Point	Color name
Plate 1			
01	Green	02	Orange
Plate 3			
03	Dark orange	08	Dark green
04	Light orange	09	Light green
05	Orange	10	Dark army green
06	Light red	11	Light army green
07	Red	12	Army green
Plate 06			
13	Yellow	17	Red
14	Orange	18	Light green
15	Dark red	19	Dark green
16	Light red	20	Green
Plate 12			
21	Water blue	25	Light orange
22	Dark army green	26	Dark orange
23	Light army green	27	Orange
24	Army green		
Plate 22			
	Black	33	Red
	Gray	34	Dark purple
	Light gray	35	Light purple
	Light red	36	Purple
	Dark red		

- Plates 10–13, plates 32–33
- Plates 14–17, plates 30–31
- Plates 18–21, plates 28–29
- Plates 22–27

In the Ishihara plates, some colors are recursive inside the charts; thus, to consider all the colors composing the charts, we selected some representative plates. In this test, we analyzed 36 color points from Plate 1, Plate 3, Plate 6, Plate 12, and Plate 22 (see Table 1).

2.2 | Spectral acquisition

The 36 color points have been acquired through the CM-2600d spectrophotometer by Konica Minolta. This portable instrument works in the visible range (from 360 to 740 nm), has a wavelength pitch of 10 nm and a system of two pulsed Xenon lamps as the light source. A measurement and illumination area of 3 mm in diameter has been chosen for those acquisitions. The measurements have been acquired in SCI mode (specular component included) with an automatic averaging of three measurements. Even if this instrument allows CIELAB coordinates to be measured, we derived those values directly from the spectra.

An example of the acquired reflectance (%) spectra is reported in Figure 2. In those plots, it is possible to see the specific reflectance curve of the analyzed color points for each measured wavelength. In Figure 2A are reported the spectra of green (01) and orange point (02) taken from the Ishihara plate 1 for 2021, 2018, 2004, 2000, and 1995 Ishihara books. Figure 2B reports the reflectance curve of Point 07 from plate 3 from the 2021, 2018, 2004, 2000, and 1995 Ishihara books. Considering the reflectance curves, which reflects the physical properties of the used materials, the curves variations involves mainly changes in spectra intensities, rather than shapes (e.g., Figure 2B curves from 1995 and 2021). Curves flattering can be caused by factors like aging, deterioration, as well as different colorants concentrations in different editions printings.

From the reflectance spectra of the selected color points, it is possible to obtain different colorimetric coordinates. At first, we converted the spectra in CIE XYZ tristimulus values using the D50 as a reference illuminant. Then, from the CIE XYZ, we computed the CIE xyY and the CIE LAB values.[21,22] The coordinates have been computed considering the 2° standard observer.

In this work, we have used the CIE xyY coordinates to obtain a plot of xy chromaticities (see Figure 3), useful to visualize the direction and the magnitude of the color shifts introduced by the Ishihara plates aging since they can best be described in xy coordinates.

The underlying thought of pseudo-isochromatic plates is that a color-deficient person has a reduced or missing capability to distinguish certain colors. The easiest description can be done in the xy color space, where colors on so-called “confusion lines” cannot be distinguished. The confusion lines are lines emanating from a “co-punct”, and different co-puncts describe different color deficiencies. A good overview can be found in “Fundamental studies of color vision” by Judd.[24] Representatives of these confusion lines are shown in Figure 3 using the deuteranope and protanope co-punts by Judd.[23]

In our work, the CIE LAB color space has been used mainly to compute the color difference among colors. In Table 2 are reported the CIE XYZ and CIE LAB values of the 36 analyzed points from the 2021 Ishihara plates.

To objectively define the difference between colors and evaluate the magnitude of the difference introduced by the plates aging, we computed the ΔE_{00} color difference.[21,22] In this work, to compute the color difference

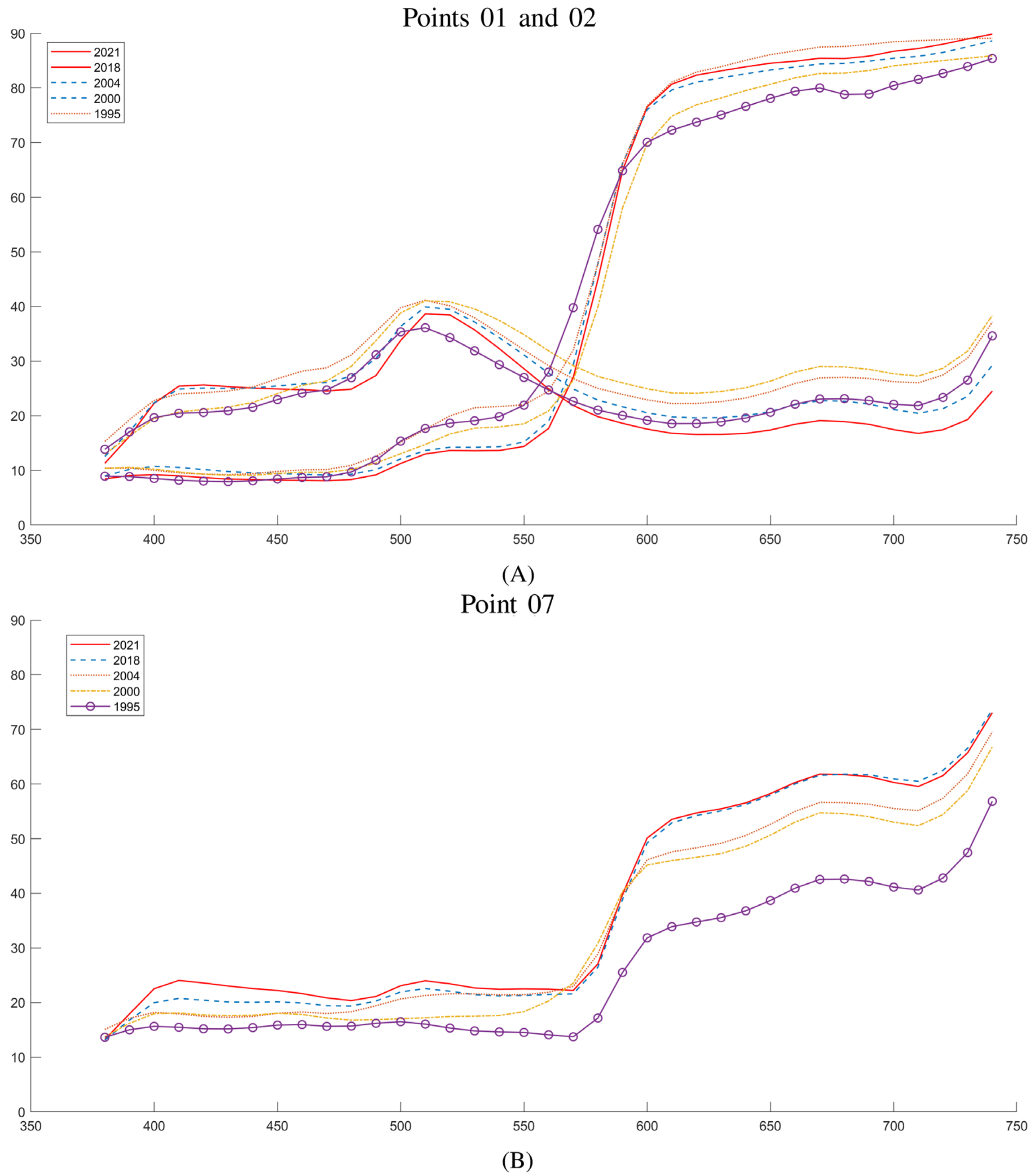

FIGURE 2 Reflectance spectra of the orange and green dots in Ishihara Plate 01 (2A), and of point 7 (2B).

between colors we used the CIE LAB values of the 2021 Ishihara color plates as a reference and defined the values of ΔE_{00} comparing with it each color point from 2018, 2004, 2000, and 1995.

In this section, we specify that colorimetric conversions have been made using a D50 reference illuminant. Clearly, a variation in the illuminant systematically affects the colorimetric coordinates; for this reason, it is fundamental to perform PIP tests under standard illumination conditions.

In Figure 4 we reported the CIExy coordinates for Points 28–36 from Plate 22, derived from Ishihara Plates from 2021 and 1995. Here, we compare the Points differences using a D50 (black arrows) and a D65 (blue arrow) reference illuminant. From this example, we can see that the shifts caused by aging have corresponding directions and distances, so physical aging cannot be compensated by the use of different theoretical light sources or colorimetric transformations. Clearly, in this experiment, we are not accounting for any color constancy adjustment, since the human ability to compensate for varying light conditions cannot be explained by a color theory based on a physical model of light–matter interaction.[25]

3 | RESULTS

The CIE chromaticity diagram allows for representing all the colors of the visible spectrum.* Thanks to the conversion of the color point spectra into CIE XYZ coordinates, it is possible to derive the CIE xyY coordinates, where xy represents the chromaticity, and Y is the luminance of a color. Consequently, the representation of the xy coordinates allows for identifying how much color changes independently from its luminance.

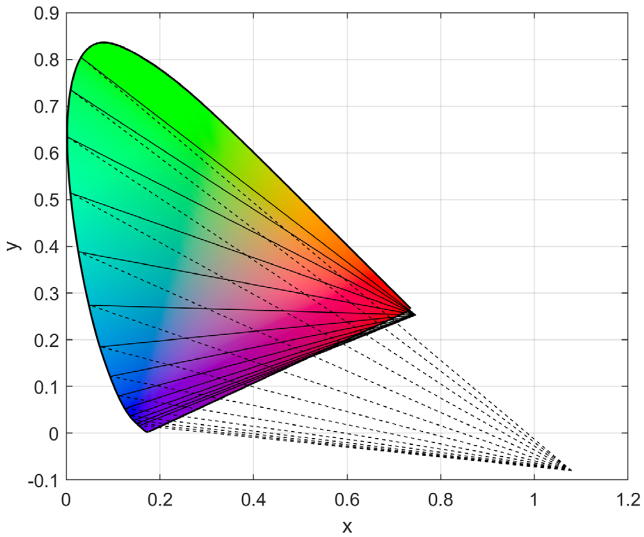

FIGURE 3 CIExy chromaticity diagram with protanope (solid lines) and deuteranope (dashed lines) confusion lines.[23]

Considering that the 2021 Ishihara plates are the most recent, we considered their values as a reference to assess the aging of the other color points. In Figure 5 are reported the xy chromaticities of all the 36 color points from 2021 plates, compared with all the others. The aim of these plots is to visualize the overall color shift undergone by the plates.

To see some examples of CIE xy variations through the years, in Figure 6 are reported the values through the years of Points 01, 02, 33, and 34, together with the protanope and deuteranope confusion lines.

The CIE LAB color space is widely used to assess and measure the color difference. In general, the L* value represents the lightness (from 0 to 100), the a* value represents the red-green opponent colors with negative values toward green and positive values toward red, and b* represents the blue-yellow opponents with negative numbers toward blue and positive toward yellow.[22] In Figure 7, we reported the a*b* chromaticities of all the 36 color points from 2021 plates, compared with all the others. In addition, in this case, the points from the 2021 plates have been considered as references. As for the CIE xy diagram, in Figure 8, we reported the a*b* variations through the years of Points 01, 02, 33, and 34.

TABLE 2 Values of CIE XYZ and CIE LAB of the 36 color points from the 2021 Ishihara plates.

Point	XYZ (2021)	CIELAB (2021)	Point	XYZ (2021)	CIELAB (2021)
01	(0.20 0.26 0.21)	(52.70 −22.88 0.40)	19	(0.24 0.28 0.12)	(56.67 −13.92 26.81)
02	(0.50 0.35 0.07)	(77.37 51.26 52.13)	20	(0.27 0.35 0.19)	(59.83 −25.14 19.02)
03	(0.39 0.34 0.14)	(69.58 21.28 29.45)	21	(0.23 0.28 0.24)	(55.77 −18.08 −1.95)
04	(0.55 0.52 0.18)	(80.19 12.68 40.21)	22	(0.21 0.25 0.10)	(53.40 −13.78 25.25)
05	(0.50 0.43 0.15)	(77.08 23.27 38.26)	23	(0.38 0.46 0.17)	(69.17 −17.90 35.33)
06	(0.53 0.46 0.25)	(79.11 22.70 20.43)	24	(0.25 0.30 0.13)	(58.34 −12.62 25.75)
07	(0.37 0.31 0.18)	(68.59 27.98 13.93)	25	(0.47 0.45 0.15)	(75.17 10.18 40.36)
08	(0.21 0.27 0.15)	(54.05 −21.89 15.00)	26	(0.31 0.30 0.12)	(63.56 9.20 28.40)
09	(0.31 0.39 0.21)	(63.57 −22.54 19.00)	27	(0.40 0.37 0.13)	(70.39 14.74 35.60)
10	(0.26 0.29 0.12)	(58.53 −8.29 26.33)	28	(0.08 0.08 0.07)	(34.51 0.15 −1.24)
11	(0.42 0.47 0.16)	(72.05 −10.21 39.09)	29	(0.16 0.17 0.13)	(47.85 −0.58 1.15)
12	(0.33 0.37 0.14)	(65.43 −8.84 33.29)	30	(0.32 0.33 0.23)	(64.25 −0.35 7.55)
13	(0.62 0.53 0.09)	(84.35 26.98 66.81)	31	(0.58 0.46 0.23)	(81.66 36.04 23.06)
14	(0.57 0.42 0.09)	(81.22 43.99 52.88)	32	(0.28 0.18 0.11)	(61.10 49.58 12.39)
15	(0.31 0.23 0.11)	(63.70 35.98 22.02)	33	(0.38 0.28 0.16)	(69.18 41.41 14.26)
16	(0.55 0.47 0.21)	(80.46 26.68 29.61)	34	(0.16 0.13 0.12)	(47.89 20.82 −4.77)
17	(0.42 0.32 0.14)	(71.68 34.43 25.53)	35	(0.48 0.39 0.28)	(75.77 30.80 5.82)
18	(0.40 0.45 0.18)	(70.67 −10.77 34.33)	36	(0.31 0.24 0.19)	(63.43 29.77 3.06)

Note: The CIE LAB values have been used as a reference in the computation of the ΔE_{00}, see Table 3.

A more objective and single-point analysis of the difference is provided by the ΔE_{00} computation. In this computation, we considered the CIE LAB values from the 2021 Ishihara plates as a reference, as stated above and computed the ΔE_{00} different from those values to the ones from 1995, 2000, 2004, and 2018 respectively. Table 3 reported the ΔE_{00} values of the 36 color points. In general, a high value of ΔE_{00} corresponds not only to a high distance between color, but also to a highly noticeable difference. This means that two distant points are not just numerically different but are also perceived as different. Due to this, in Table 3 we have highlighted the color points which present a ΔE_{00} value greater than 5.

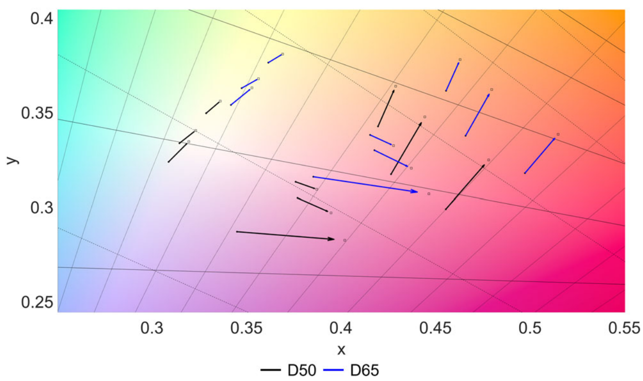

FIGURE 4 Example of CIE xy aging of Points 28–34, using a D50 (black arrows) and D65 (blue arrows) reference illuminants. 1995 is represented by squares and 2021 by filled points. In the images are also reported the protanope and deuteranope confusion lines (see Figure 3).

In Table 4, we reported the average value of ΔE_{00}, the maximum and the minimum value for every considered year.

In Figure 9 are reported the histograms of color difference between 2021 and 1995 color points (Figure 9A), 2021 and 2000 (Figure 9B), 2021 and 2004 (Figure 9C), and 2021 and 2018 (Figure 9D).

Figure 10 is reported a representation of the average ΔE_{00}, maximum ΔE_{00} and minimum ΔE_{00} through the years (see Table 4).

The effect of aging, deterioration or just differences in PIP charts, affects the overall appearance of the plates, as demonstrated in the previous assessments. In this context,

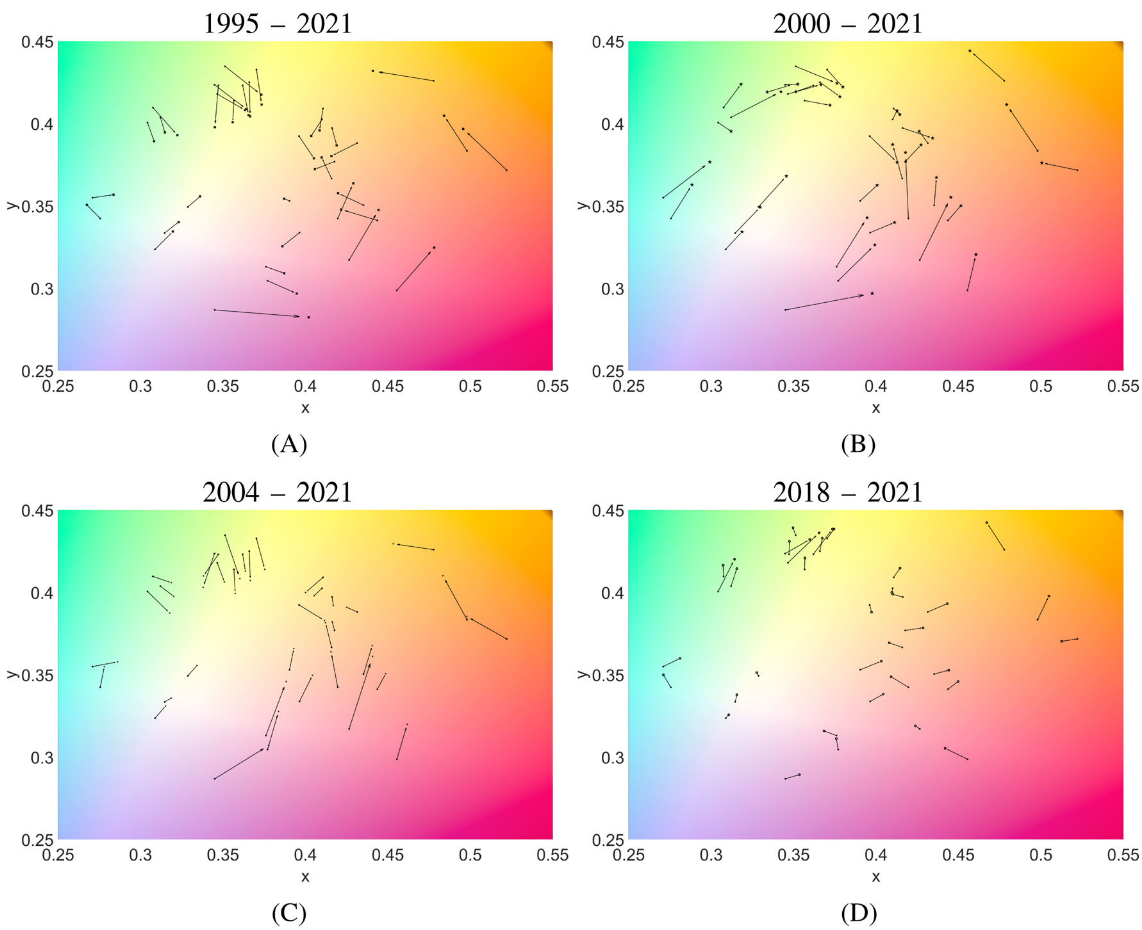

FIGURE 5 Representation of the CIE xy coordinates of the single points from 2021 (filled points) with the ones from 1995 (squares) (5A), 2000 (stars) (5B), 2004 (asterisk) (5C), and 2018 (circles) (5D).

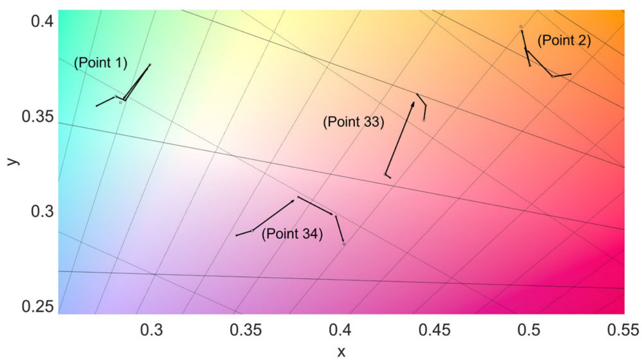

FIGURE 6 Example of CIE xy aging of Points 01, 02, 33, and 34. 1995 is represented by squares, 2000 by stars, 2004 by asterisks, 2018 by circles, and 2021 by filled points. In the images are also reported the protanope and deuteranope confusion lines (see Figure 3).

it is interesting to analyze the contrast shifts inside each plate (intra-plate), thus comparing the color difference amounts between Points of the same Plate, through the years. We report this analysis in Table 5. Here, we report the ΔE_{00}, ΔL^*, and Δa^*b^* between Points in the same Plates, to assess the amount of variation in lightness and chrominance contrast among PIPs from different years.

4 | DISCUSSION

In the analysis and discussion of the results, it is important to remember that the ΔE_{00} values and the chromaticity diagrams are performed in two different color spaces and that the chromaticity diagrams (xy and a*b*)

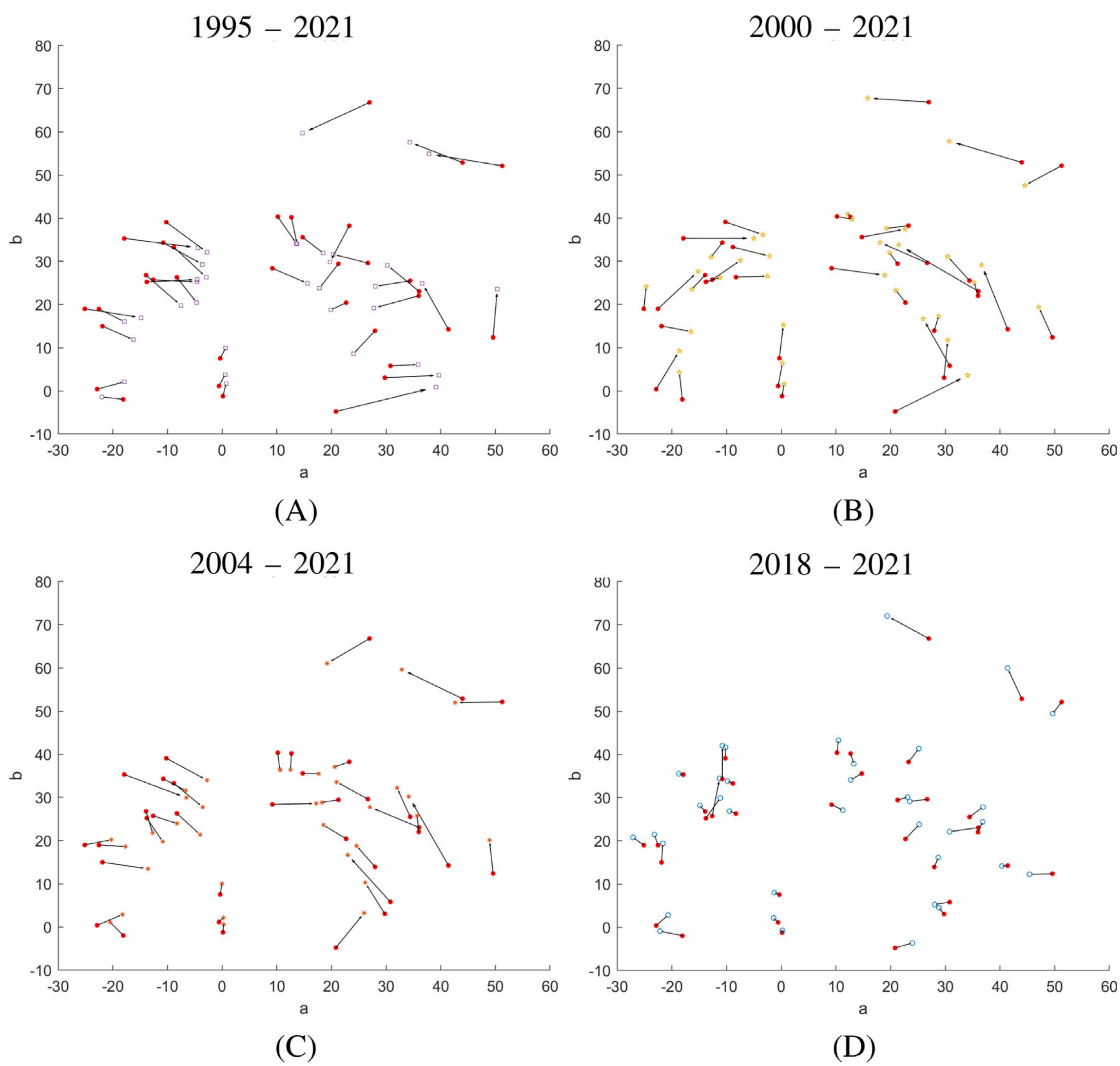

FIGURE 7 Representation of the CIE a*b* coordinates of the single points from 2021 (red filled points) with the ones from 1995 (purple squares) (7A), 2000 (yellow stars) (7B), 2004 (orange asterisks) (7C) and 2018 (blue circles) (7D).

do not include the lightness component, considered in the ΔE_{00} computation.

Considering at first the plates from 1995, they present the highest value of average ΔE_{00} (5.99) of the tested colors and have 70% of ΔE_{00} values over 5.00. The highest ΔE_{00} distances have been found for Point 24 (army green) and Point 07 (red), with values over 10.00. These points are followed by Point 10 (dark army green), Point 22 (dark army green) and Point 23 (light army green), with values above 8.00. The color shift in the green region can also be visualized in Figures 5A and 7A. From this image, we can see that many colors are moving toward a yellowish region, maybe due to the aging of the paper of the Ishihara plates. Furthermore, the 1995 colors are less saturated than the original. Considering those analyses, this test is severely degraded and not trustworthy for clinical screenings.

Considering the plates from 2000, the average ΔE_{00} values are near the one of 1995, and, 58% of colors present values above 5.00. The highest color difference value has been found for Point 21 (water blue), followed by Point 23 (light army green) and Point 24 (army green), which are above 10.00. These points are followed by Point 01 (green) with a value above 09.00 and Point 14 (orange) and 35 (light purple) with values above 8.00. Considering the chromaticity diagram in Figures 5B and 7B, the points from 2000 are slightly near to the ones from 2021, compared with the ones from 1995.

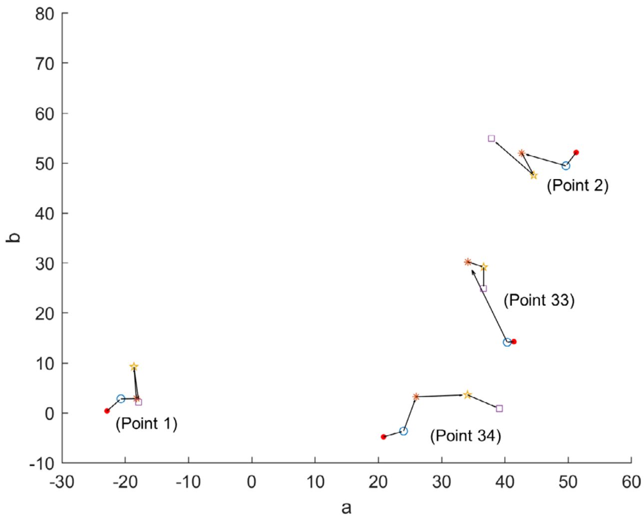

FIGURE 8 Example of CIE a*b* aging of Points 01, 02, 33, and 34. 1995 is represented by purple squares, 2000 by yellow stars, 2004 by orange asterisks, 2018 by blue circles, and 2021 by red-filled points. In the images are also reported the protanope and deuteranope confusion lines.

TABLE 4 Average, maximum, and minimum ΔE_{00} values between the Ishihara from 1995, 2000, 2004, 2018, and 2021 one.

	Avg ΔE_{00}	Max ΔE_{00}	Min ΔE_{00}
1995	5.99 ± 2.00	11.12	2.27
2000	5.71 ± 2.73	12.96	1.92
2004	5.01 ± 2.26	12.07	1.73
2018	2.40 ± 1.32	5.52	0.44

TABLE 3 Values of ΔE_{00} of the points from 1995 to 2018.

ΔE_{00}									
Point	1995	2000	2004	2018	Point	1995	2000	2004	2018
01	3.36	9.05	5.71	3.45	19	5.05	2.69	2.64	1.01
02	7.33	2.49	4.09	0.85	20	5.86	3.03	4.20	1.28
03	6.26	4.28	4.08	3.27	21	5.07	4.75	2.76	2.62
04	3.73	1.92	2.45	2.54	22	8.34	2.01	2.98	3.90
05	6.55	3.72	1.73	1.55	23	8.83	8.61	7.47	1.29
06	4.67	5.56	4.98	1.98	24	6.21	4.85	3.35	5.30
07	10.29	3.11	4.69	1.42	25	4.79	2.11	2.88	1.36
08	6.01	5.32	5.17	4.85	26	6.41	7.78	6.33	1.98
09	3.95	7.29	2.91	2.50	27	4.08	5.13	3.75	1.91
10	8.30	5.48	5.75	2.89	28	7.44	6.56	6.37	0.48
11	5.71	5.06	5.27	1.02	29	7.15	6.21	4.68	1.57
12	5.70	5.60	4.37	3.44	30	2.38	6.20	2.66	2.03
13	6.57	6.80	3.90	5.52	31	7.31	12.96	7.04	3.02
14	6.47	8.55	7.91	3.93	32	7.57	5.65	7.27	1.70
15	4.82	2.09	2.84	1.56	33	7.48	10.58	12.07	0.44
16	4.86	7.22	5.10	1.83	34	11.12	11.05	8.56	4.26
17	3.19	4.91	5.11	1.43	35	2.27	8.52	9.51	1.69
18	5.15	2.33	2.89	3.73	36	5.44	5.95	6.77	2.63

Note: In this Table the values between 5.00 and 5.99 have been evidenced in yellow and the ones above 10.00 in orange.

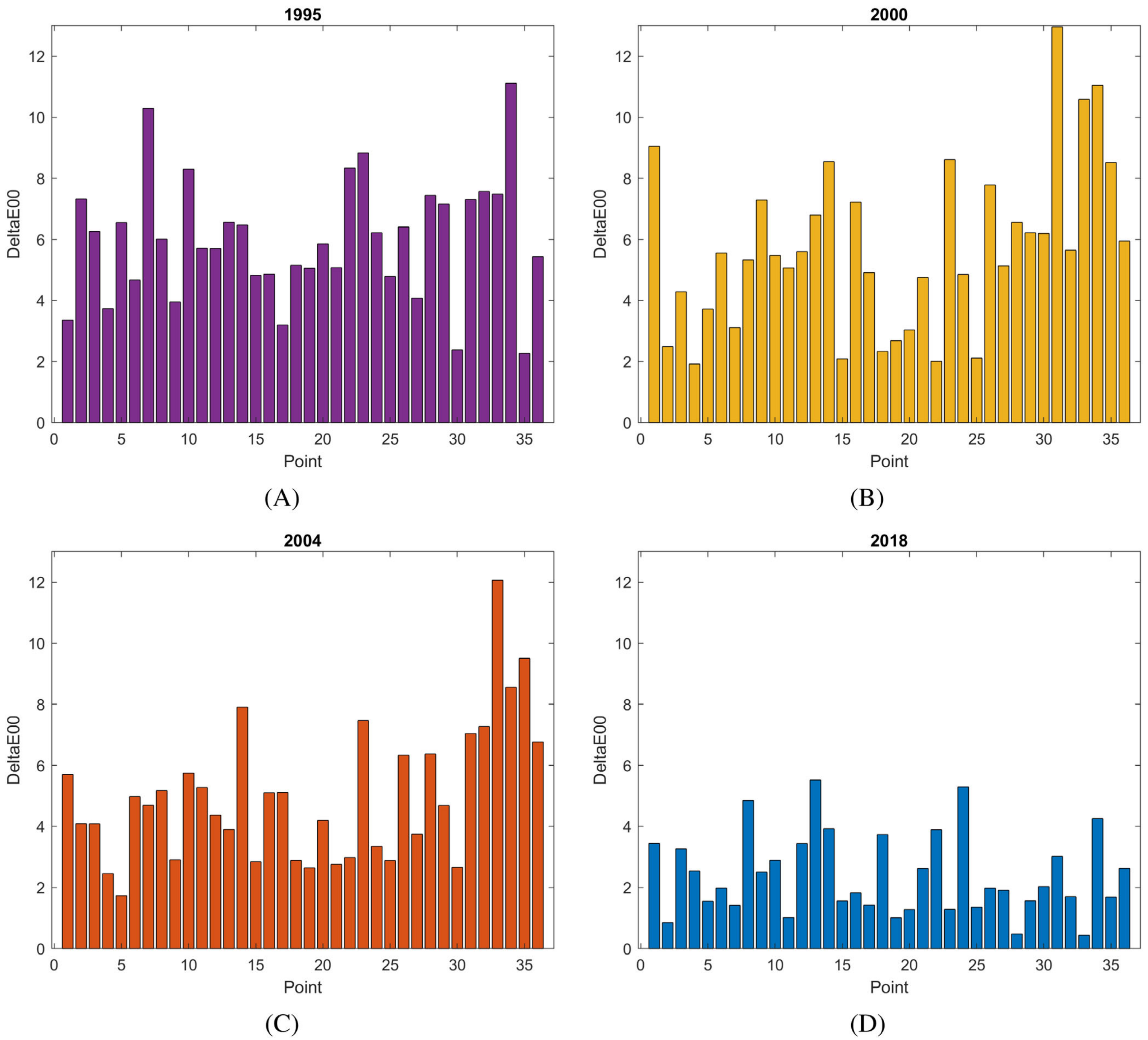

FIGURE 9 Values of ΔE_{00} for the 36 considered patches of 1995 (9A), 2000 (9B), 2004 (9B), and 2018 (9D).

Furthermore, the tendency to the yellowish area of the diagram is diminished. In addition, in this case, the color shift is marked, and these plates are no longer suitable for clinical use.

The plates from 2004 Ishihara present an average ΔE_{00} of 5.01, and in this case, just 44% of color points present a ΔE_{00} value above 5.00. The highest value of color difference has been found for Point 23 (light army green), and this color is followed by Points 14 (orange), 23 (light army green), 31 (light red), 32 (light red), 34 (dark purple) and 35 (light purple), which presents values above 7.00. Considering the chromaticity diagram in Figures 5C and 7C, the points in the green area from 2004 present the most significant color shift compared to the ones from 2000, in particular in the first case the shift is more toward the green-blue region. In addition, in this case, the Ishihara plates can no more be considered valid.

From the analysis of the chromaticity diagrams, it is clear that the 2018 plates are the ones which underwent less deterioration (around 5%). Considering Figures 5D and 7D, many points from 2018 are overlapped with the ones from 2021, and the points in the green area present a lighter shift. The colors in the red-orange region are the ones which present the most significant color shift, and this is confirmed by the ΔE_{00} analysis, in fact, Point 02 (orange) corresponds to the most extensive distance in these plates. This point is followed by Point 24 (army

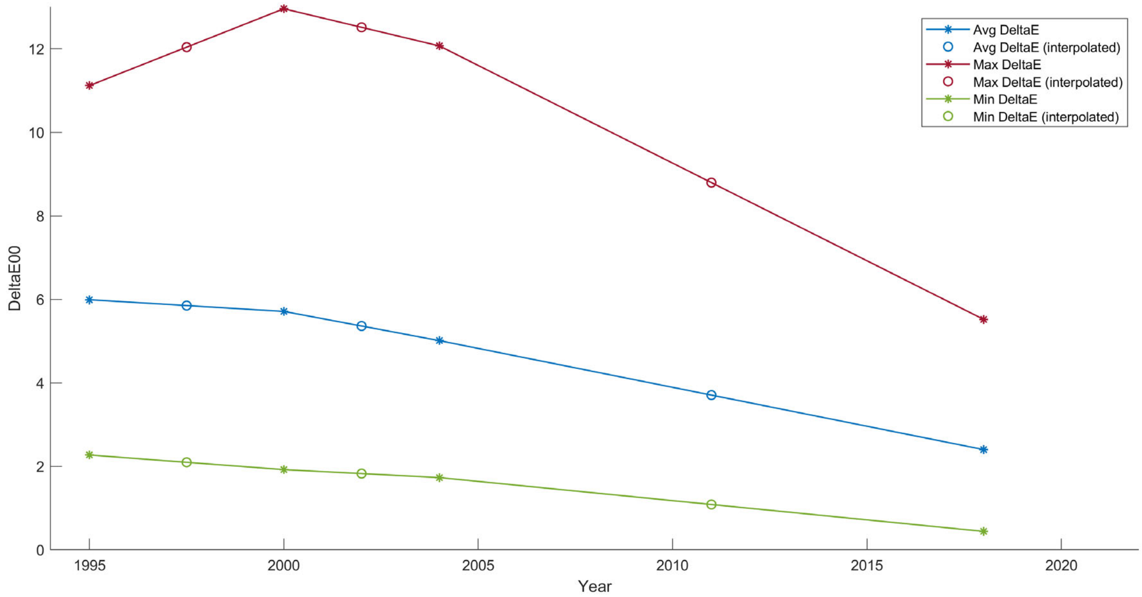

FIGURE 10 ΔE_{00} trend through the years.

green), which presents a ΔE_{00} of 5.30. Compared to the other years, 2018 plates present an extremely low average ΔE_{00} value. Considering this analysis, we can consider these plates still valid.

Considering the overall results, the points which present the highest values of deterioration are Point 34 (dark purple) and Point 33 (red), but from our analysis also, Point 10 (dark army green), 11 (light army green), 14 (orange), 23 (light army green), 26 (dark orange), 28 (black), 31 (light red), 32 (dark red) and 36 (purple) are among the most damaged. On the other hand, Points 04 (light orange), 15 (dark red) and 25 (light orange) are the most stable through the years.

As it is possible to see from Figures 6 and 8 there is not a defined trend in the deterioration of the patches. This is due to the different chemical nature of the pigments composing the Ishihara plates, which undergo different degradation processes which follow different chromatic shifts. Considering Figure 6 it is important to notice that the chromaticity coordinates significantly move from the confusion lines, shifting away, like in Point 34 for the year 2004 (asterisk), or moving near the line, like in Point 1 for the year 2000 (star).

Considering the intra-plate variations reported in Table 5, the average ΔE_{00} goes from 22.7 of 1995 to maximums of 24.44 (2018) and 24.31 (2021). Here, the differences in lightness are pretty stable, except for Plates from 2000, where ΔL^* decreases to 13.04. Considering chrominance values, Plates from 2000 present the highest difference (18.56), followed by Plates from 2018 (17.16); Plates from 2004 and 2021 are very similar, and Plates from 1995 present the lowest difference. The variables which lead to these intra-plate variations can be different (aging, degradation, colorimetric approximations), and it is still hard to determine to what extent these differences affect the appearance of the Plates.

This analysis and this study do not aim at providing a decay model since the deterioration of those tests is strictly linked to their usage and condition of conservation. Furthermore, even if Ishihara plates are certified by the producer, some variations among different editions can be related to printing conditions or colorants concentrations, which may cause slight variations, like in editions of 2018 and 2021. The aim of this work is to raise awareness of the risks of using an expired or damaged test, which may still appear in good condition but has been subject to the passage of time.

Here, one must remember that the charts used in this analysis were handed by an unknown number of users over time. There was no controlled degrading experiment, rather than a "real-life-usage" degrading involved.

In conclusion, an important consideration for the continued usage of a single Ishihara test set is the aging of the test charts. Ishihara test and other PIP tests are composed of physical charts that follow proprietary and standard printing procedures that guarantee accuracy at the time of production. However, the widely different usage scenarios might lead to a deviation from that accuracy over time, as we showed in this paper.

These tests are available today in digital versions, and their efficacy has been evaluated using different devices.[26,27] In this context, using a digital Ishihara test must seem a good solution to go against the passage of

TABLE 5 Intra-plate differences obtained computing the ΔE_{00}, ΔL^*, and Δa^*b^* between Points in the same Plates through the years.

Year	Points	ΔE_{00}	ΔL^*	Δa^*b^*	Year	Points	ΔE_{00}	ΔL^*	Δa^*b^*
1995	01–02	75.56	21.23	72.52	2000	01–02	71.69	14.46	70.22
	03–04	18.27	14.24	11.44		03–04	17.82	12.61	12.59
	06–07	19.46	15.66	11.56		06–07	12.50	6.62	10.61
	08–09	11.94	10.94	4.79		08–09	20.23	14.73	13.86
	10–11	22.00	18.67	11.63		10–11	16.91	13.74	9.85
	15–16	24.12	18.68	15.27		15–16	26.35	16.44	20.60
	18–19	17.94	14.97	9.88		18–19	15.94	13.89	7.84
	22–23	12.37	9.90	7.41		22–23	17.28	13.81	10.39
	25–26	14.59	10.97	9.63		25–26	17.98	10.36	14.70
	28–29	12.10	11.90	2.18		28–29	11.44	10.32	4.92
	31–32	23.21	8.88	21.44		31–32	32.99	12.50	30.54
	34–35	20.83	19.64	6.92		34–35	23.79	17.01	16.63
	AVG	**22.70**	**14.64**	**15.39**		*AVG*	**23.74**	**13.04**	**18.56**
2004	01–02	76.11	18.68	73.78	2018	01–02	82.25	19.48	79.91
	03–04	15.84	12.34	9.93		03–04	17.09	11.44	12.70
	06–07	12.17	8.81	8.40		06–07	13.27	9.71	9.04
	08–09	13.44	11.36	7.18		08–09	11.45	11.10	2.80
	10–11	21.70	17.65	12.62		10–11	22.24	16.60	14.81
	15–16	23.42	15.35	17.69		15–16	22.02	16.36	14.75
	18–19	19.05	15.64	10.87		18–19	22.15	17.25	13.89
	22–23	20.77	17.87	10.59		22–23	15.65	12.14	9.87
	25–26	16.42	12.43	10.73		25–26	20.57	12.68	16.19
	28–29	10.70	10.58	1.61		28–29	14.27	13.84	3.48
	31–32	26.23	10.39	24.09		31–32	25.42	16.56	19.29
	34–35	23.43	18.67	14.17		34–35	26.94	25.30	9.24
	AVG	**23.27**	**14.15**	**16.81**		*AVG*	**24.44**	**15.21**	**17.16**

Year	Points	ΔE_{00}	ΔL^*	Δa^*b^*
2021	01–02	88.10	21.77	85.37
	03–04	17.61	10.64	14.03
	06–07	13.73	10.45	8.91
	08–09	10.27	9.40	4.12
	10–11	18.55	13.24	13.00
	15–16	21.09	16.75	12.82
	18–19	15.73	13.70	7.73
	22–23	19.15	15.63	11.07
	25–26	16.40	11.31	11.88
	28–29	13.52	13.27	2.57
	31–32	27.30	20.77	17.72
	34–35	30.31	27.23	13.30
	AVG	**24.31**	**15.35**	**16.88**

Note: In this Table, we report comparisons among points of similar hues forming numbers or the backgrounds in Ishihara Plates. For example, dark orange (Point 03)—Light orange (Point 04); light red (Point 06)—Red (Point 07); dark green (Point 08)—light green (Point 09).

time. Still, many other constraints must be considered when performing a digital test. At first, it is mandatory to use calibrated displays, it is essential to control the light in the test environment (as well as performing the physical test), and it is essential to use standard and correctly reproduced PIP plates. This last point is critical when using online versions of Ishihara tests since there is often a lack of certification and control over the materials and images available online. Furthermore, in many color blindness tests performed on screen, there are no recommendations on monitor calibration and no control over the displays. Thus, the digital test screening (performed in controlled conditions and using calibrated devices) could be a good solution that does not suffer the deterioration of the plates. However, the physical test (performed with certified plates) still provides a more accessible and usable way to perform the test. Thus, aging is a small price compared to uncontrolled and non-calibrated conditions of non-standard digital PIP plates.

5 | CONCLUSION

In the experiments described above, we analyzed the physical deterioration of a determined set of pseudo-isochromatic charts. We did not test the difference in the performance of the charts for a set of known color-deficient observers. The Delta E metric used is standard in Color Science but, there are theoretical possibilities to make significant changes in color that would still be consistent with the pseudo-isochromatic assumptions. However, for this reason, we examined the resultant color shifts (see Figures 5 through 8) and showed that the shifts observed do violate the confusion line assumptions for pseudo-isochromatic confusion lines. Based on these observations, we contend that the charts have changed their characteristic substantially.

In this work, we have analyzed 36 color points measured from Ishihara plates of different years (1995, 2000, 2004, 2018, and 2021). After measurement of the reflectance spectra, we have converted the data into colorimetric coordinates in the CIE XYZ, CIE xyY and CIE LAB color space. Thanks to this, it has been possible to plot the chromaticity diagrams and measure the ΔE_{00} color difference between the reference colors (from 2021 plates) and the ones from the other years.

From the analysis of the results, we have determined that 70% of colors in plates from 1995 were strongly damaged, 58% of colors in plates from 2000, 44% of colors in plates from 2004, and 5% of colors in plates from 2018. From this, we have derived that the plates from 2018 could still be considered suitable for clinical tests, despite all the other plates. In this study, we have identified the more stable patches over time and those more subject to fading. Still nevertheless, we did not aim to provide a decay model or assess the degradation of the colorants forming the plates since the degradation strictly depends on the conservation conditions and the usage of the test.

Thanks to this study, it has been possible to provide a preliminary analysis of the Ishihara plate degradation and confirm the need to define expiration dates for the tests to avoid errors and problems in color blindness screening tests.

AUTHOR CONTRIBUTIONS

Alice Plutino: methodology, data acquisition, data analysis, writing – original draft; **Luca Armellin:** Data collection, data analysis, writing – review and editing; **Andrea Mazzoni:** funding acquisition, project administration, writing – review and editing; **Roberta Marcucci:** literature review, data interpretation, writing – review and editing; **Alessandro Rizzi:** supervision, conceptualization, methodology, writing – review and editing.

ACKNOWLEDGEMENTS

There are no specific individuals to be acknowledged for their contributions to this work.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Alice Plutino https://orcid.org/0000-0002-6749-0783
Alessandro Rizzi https://orcid.org/0000-0001-6240-4383

ENDNOTE

* Please, note that those images are just simulations because it is impossible to correctly represent all the colors of the visible spectrum due to the different devices' gamut limits.

REFERENCES

[1] Ishihara S. Tests for color blindness. *Am J Ophthalmol*. 1918; 1(5):376.
[2] GIMA. *Ishihara Colour Test – Book of 38 plates*. 2021. Accessed September 15, 2021 https://www.gimaitaly.com/
[3] Rodriguez-Carmona M, Evans BEW, Barbur JL. Color vision assessment- 2: color assessment outcomes using single and multi-test protocols. *Color Res Appl*. 2021;46(1):21-32.
[4] Birch J. Worldwide prevalence of red-green color deficiency. *J. Opt. Soc. Am. A*. 2012;29(3):313-320.
[5] Wright WD, Martin LC. *Researches on Normal and Defective Colour Vision*. Vol 45. Kimpton London; 1946.
[6] Birch J, McKeever LM. Survey of the accuracy of new pseudoisochromatic plates. *Ophthalmic Physiol Opt*. 1993;13(1):35-40.

[7] Birch J. Efficiency of the Ishihara test for identifying red-green colour deficiency. *Ophthalmic Physiol Opt*. 1997;17(5):403-408.
[8] Cole BL. Assessment of inherited colour vision defects in clinical practice. *Clin Exp Optom*. 2007;90(3):157-175.
[9] Dain SJ. Clinical colour vision tests. *Clin Exp Optom*. 2004; 87(4–5):276-293.
[10] Barbur JL, Rodriguez-Carmona M, Evans BEW. Color vision assessment- 3. An efficient, two-step, color assessment protocol. *Color Res Appl*. 2021;46(1):33-45.
[11] Lakowski R. Theory and practice of colour vision testing: a review part 1. *Occup Environ Med*. 1969;26(3):173-189.
[12] Lakowski R. Theory and practice of colour vision testing: a review. Part 2. *Occup Environ Med*. 1969;26(4):265-288.
[13] Jurgensen CE. Industrial use of the Ishihara tests for color blindness. *J Appl Psychol*. 1947;31(1):1-8.
[14] Gambino O, Minafo E, Pirrone R, Ardizzone E. A tunable digital Ishihara plate for pre-school aged children. *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE; 2016:5628-5631.
[15] Niroula DR, Saha CG. The incidence of color blindness among some school children of Pokhara, Western Nepal. *Nepal Med Coll J*. 2010;12(1):48-50.
[16] Evans BEW, Rodriguez-Carmona M, Barbur JL. Color vision assessment- 1: visual signals that affect the results of the Farnsworth D-15 test. *Color Res Appl*. 2021;46(1):7-20.
[17] Le Grand H, Hardy GR, Rittler MC. Tests for detection and analysis of color blindness: I. an evaluation of the Ishihara test. *Arch Ophthalmol*. 1945;34(4):295-302.
[18] Lee DY, Honson M. Chromatic variation of Ishihara diagnostic plates. *Color Res Appl*. 2003;28:267-276.
[19] Hyon JY, Lee JH, Wee WR. Shift of colorimetric values in ishihara pseudoisochromatic plates with plate aging. *Korean J Ophthalmol*. 2005;19(2):145-148.
[20] Kanehara Trading Inc. *Ishihara's Test for Color Deficiency – 38 Plates Edition*. Kanehara Trading Inc; 2021.
[21] Justin LB. *Useful Color Equations*. 2021. Accessed September 16, 2021 http://www.brucelindbloom.com/
[22] Oleari C. *Standard Colorimetry: Definitions, Algorithms and Software*. John Wiley & Sons; 2016.
[23] Judd DB. Standard response functions for protanopic and deuteranopic vision. *J. Opt. Soc. Am*. 1945;35(3):199-221.
[24] Judd DB. Fundamental studies of color vision from 1860 to 1960. *Proc Natl Acad Sci USA*. 1966;55.6:1313.
[25] Marini D, Rizzi A, Rossi M. Color constancy measurements for synthetic image generation. *J Electron Imaging*. 1999;8(4): 394-403.
[26] Seshadri J, Christensen J, Lakshminarayanan V, Bassi CJ. Evaluation of the new web-based "colour assessment and diagnosis" test. *Optom Vis Sci*. 2005;82(10):882-885.
[27] Sorkin N, Rosenblatt A, Cohen E, Ohana O, Stolovitch C, Dotan G. Comparison of Ishihara booklet with color vision smartphone applications. *Optom Vis Sci*. 2016;93(7): 667-672.

AUTHOR BIOGRAPHIES

Alice Plutino (Phd, Università degli Studi di Milano, 2021) is Postdoctoral Fellow at Università degli Studi di Milano. Her research interests are color science, colorimetry, image enhancement, image digitization and archiving, with a particular interest in Cultural Heritage applications. She is the author of the book "Tecniche di Restauro Cinematografico" and of several journal and conference papers of national and international relevance. She is an Adjunct professor at Università degli Studi di Milano and Centro Sperimentale di Cinematografia, teaching digital film restoration and digital media conservation. She is a member of the Italian color group (Gruppo del Colore), deputy editor of the Color Culture and Science Journal (CCSJ), and vice-coordinator of Division 1 and 8 of NC CIE Italy. In 2023, Alice was awarded a Marie Skłodowska-Curie Postdoctoral Fellowship, which will support her research at the University of Amsterdam.

Luca Armellin is currently a master's degree student in Computer Science at the University of Milano (Italy). His research interests mainly focus on vision impairments with particular attention to color vision deficiencies colorimetry and color science; lighting, image processing and computer vision. Formerly he co-founded and worked as a technician and software developer in a laboratory for film processing and digitizing in Milan.

Andrea Mazzoni Ophthalmologist MD, PhD, Italian Air Force Medical Officer serving at the Aerospace Medicine Institute in Rome. His main task is military and civilian airworthiness. Specialized in clinical and instrumental diagnosis, mostly in the anterior segment of the eye. He has been dealing with human visual system perception of colors in a long time. He is currently the head of the research study: "Screening of color blindness in complex operational profiles of military flight: study and analysis of new alternative diagnostic methodologies" collaborating with UNIMI, the University of Milan.

Roberta Marcucci Ophthalmologist MD, Italian Air Force Medical Officer at Aerospace Medicine Institute in Rome. Her clinical field of application is aviation medicine and the assessment of medical fitness of military and civilian aviation personnel, according to their special duty status. Her professional background includes medical retina, cornea, and refractive surgery.

Alessandro Rizzi is a Full Professor at the Department of Computer Science at the University of Milano (Italy), teaching Multimedia, Colorimetry and Film restoration. He is doing research since 1990 in the field of digital imaging with a particular interest on color, visualization, photography, HDR, VR and on the perceptual issues related to digital imaging, interfaces, and lighting. He is the head of the MIPS Lab at the Department of Computer Science. He has been one of the founders of the Italian Color Group, Secretary of CIE Division 8, IS & T Fellow and Vice President. In 2015, he received the Davies medal from the Royal Photographic Society. He is co-chair of the IS & T Conference "Color Imaging: Displaying, Processing, Hardcopy and Applications", Topical Editor for "Applied Color Science" of the Journal of Optical Society of America A, Associate Editor of Journal of Electronic Imaging, member of several program committees of conferences related to color and digital imaging, and author of about 400 scientific works.

How to cite this article: Plutino A, Armellin L, Mazzoni A, Marcucci R, Rizzi A. Aging variations in Ishihara test plates. *Color Res Appl*. 2023;1-14. doi:10.1002/col.22877