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RESEARCH ARTICLE

Typical and Atypical Errors made by Color Normal and Defective Observers on Printed Pseudoisochromatic Color Vision Tests

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Abstract:

Background:

Pseudoisochromatic color vision tests are commonly used to screen for color vision deficiency (CVD). Although most color vision normal (CVN) individuals read all plates correctly, a remarkable proportion have errors.

Objective:

This study aimed to determine the typical and atypical error responses to the Ishihara and Waggoner PIP24 (W-PIP24) tests of CVN and CVD individuals.

Methods:

This study recruited 59 CVN and 63 congenital red-green CVD individuals. Participants were tested with the Ishihara and W-PIP24 tests. The participants' responses were recorded, and typical and atypical errors were determined.

Results:

The rate of atypical errors in the CVN group was 21% in the Ishihara test and 9% in the W-PIP24 test, while those in the CVD group were 100% and 60%, respectively. The CVN and CVD groups tended to have more atypical errors on the Ishihara test than on the W-PIP24 test. Moreover, CVD individuals tended to have more atypical errors in the transformation plates in both tests.

Conclusion:

CVN individuals may misread the plates in the Ishihara and W-PIP24 tests for reasons other than the normality of color vision; therefore, counting only typical errors may eliminate the chance of CVN individuals misreading the number on the plates. The most significant finding of this study was that clinicians should perhaps only consider typical errors as "errors" on both tests.

Keywords: Atypical error, Color vision deficiency, Color vision screening, Ishihara, Pseudoisochromatic plates, Waggoner PIP24.

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1. INTRODUCTION

Printed pseudoisochromatic color vision tests are the most widely used tests for screening color vision deficiencies [1 - 6]. The principle of this test is to use color confusion (isochromatic) lines to differentiate between color vision normal (CVN) and color vision deficient (CVD) individuals. The test is referred to as "pseudoisochromatic" because CVN individuals can distinguish between the colors on each plate and read the figures embedded within, whereas the figures are isochromatic to CVD individuals when the colors lie on the same line of confusion [7]. In general, pseudoisochromatic tests consist of several plates with colored dots that vary in size, showing a multicolored figure against a multicolored background. Currently, the Ishihara 38 plate pseudoisochromatic test is the most commonly used color vision test to screen for red-green CVD [4 - 6, 8]. The Waggoner PIP24 (W-PIP24) pseudoisochromatic test has a pattern similar to that of the Ishihara test. However, it is superior to the Ishihara test because it provides red-green and blue-yellow CVD screening plates [9].

The plates used in the pseudoisochromatic color vision

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tests are classified into four categories: demonstration, vanishing, transformation, and diagnostic. The Ishihara test includes an additional category of hidden digits. The demonstration plates can be read correctly by both CVN and CVD individuals, whereas the vanishing plates can be read correctly only by CVN individuals, as those with CVD cannot distinguish the target. The response to the transformation plates varies between CVN and CVD individuals; however, CVD individuals can read numbers in the hidden digit plate, while those who are CVN cannot. Nevertheless, Birch [2] reported a low sensitivity rate for hidden digit plates (approximately 50%). Finally, diagnostic plates were used to distinguish between protans and deutans. Protan refers to an impairment or missing L-cone photopigment, whereas deutan refers to an impairment or missing M-cone photopigment.

A small number of CVN individuals misread one or more pseudoisochromatic plates [1, 10 - 12]. Errors in pseudoisochromatic color vision tests can be categorized as typical or atypical, where typical errors are made by CVD individuals [11, 13]. Atypical errors (misreading), however, are errors made by CVD and CVN individuals; for example, an individual may report digit 3 as an 8, which is defined as a digit confusion error and may be due to one or two spot difference from other digits, such as 3, 5, and 8 [11]. Other factors that may impact the results are age, gender, intelligence, and performance time [11], although the specificity rate may decrease because of misreading [13]. Normal trichromats may make up to six atypical errors (misreadings) in the Ishihara test [1, 13].

Nevertheless, in a study by Birch and McKeever [1], none of the 471 normal trichromats produced typical errors. However, Miyahara [13] reported that none of the CVN individuals had more than two typical errors. Therefore, the examiner should differentiate between typical and atypical (misreading) errors to improve test efficiency. Although scholars have obtained typical and atypical error responses based on normal color [12, 13], this study aimed to determine the typical and atypical error responses of CVN and CVD individuals.

2. MATERIALS AND METHODS

This study followed the tenets of the Declaration of Helsinki and was approved by the King Saud University Office of Research Ethics (approval no. E-19-4297). Fifty-nine participants with CVN and 63 individuals with congenital red-green CVD were recruited for this study. The normal trichromat group had 49% males, whereas the color-deficient group was predominantly (97%) male, which is expected, as congenital red-green CVD is an X-linked recessive trait. The participants were aged 12 to 59 years. The average age was 28.7 years (SD = 11.5 years) for normal trichromats and 25.8 (SD = 10.8) for color-deficient patients. All participants had no known vision problems besides refractive error, CVD, or both. Tinted contact lenses or glasses were not allowed during testing. All participants had a binocular distance visual acuity of 6/9 or better to reduce the probability of a bilateral disorder related to acquired CVD. Red-green CVD was diagnosed based on the failure of the 38-plate edition of the Ishihara and W-PIP24 tests. Although the Nagel anomaloscope test would have been the preferred test, it was unavailable.

The testing protocol began with the Ishihara 38 edition [Kanehara Trading INC, 2011 (Tokyo, Japan)] test, followed by the W-PIP24 test. If the participants reported an error while reading the plates, it was categorized as typical or atypical. The typical error was expected by a CVD individual; however, if a CVN or CVD participant reported a different response than expected, it was considered an atypical error. Scholars have found that CVN individuals made no more than two typical errors on either assessment [1, 13]. However, the CVD participants in this study had three or more typical error responses on both the tests, while none of the CVN participants had more than two typical errors.

A light-emitting diode lamp (NEW POWER, Model no: G45-14 E27) with a calibrated color temperature of 6500 K was used to illuminate the test. The illuminance was 1300 lx (± 5%) in the horizontal plane of the white table where the tests were conducted. The participants viewed binocularly from approximately 50 cm in both tests. The participants were asked not to touch the colored portions of each test.

3. RESULTS

Approximately 21% of CVN individuals had ≤ 3 atypical errors on the Ishihara test, 9% had ≤ 2 atypical errors on the W-PIP24 test, whereas 5% had ≤ 2 typical errors on the Ishihara test, and 2% had one typical error on the W-PIP24 test. All the CVD participants had atypical errors on the Ishihara test, while 60% had atypical errors on the W-PIP24 test. The number of typical and atypical errors for CVN and CVD individuals for each plate in the Ishihara test is shown in Table **1**. None of the CVN participants had typical errors in the transformation or vanishing plates; however, there were typical errors in the hidden design plates (19 and 20). For CVD individuals, plates 9 (transformation) and 12 (vanishing) had 100% of the total errors, with a high percentage being typical errors. Plates 4 and 5 (transformation) and plate 21 (hidden) accounted for more than 50% of atypical errors for CVD participants. Plate 4 had the highest number of atypical errors (75%), whereas plates 10 and 13 had the lowest number of atypical errors (5%) for CVD individuals. Approximately 50% of CVD individuals responded “10” rather than “70” on plate 4.

Table **2** shows the typical and atypical errors in the W-PIP24 test for both CVN and CVD participants. A single CVN individual had typical error on plate 11 (vanishing). All red-green screening plates had a total error of ≥ 90% for CVD individuals, except for plate 7 (76%). Almost all the W-PIP24 plates had lower percentages of atypical errors, except for plates 7, 9, and 10, with 24%, 33%, and 21% of atypical errors, respectively.

The typical errors for plates 6–10 of the W-PIP24 test were a combination of the transformation and vanishing design responses. In this study, we were interested in typical responses to color-deficient transformation plates. The color-deficient typical errors for the transformation plates in the W-PIP24 test are listed in Table **3**. Almost all the typical responses in CVD individuals were nothing (vanishing) rather than the number (transformation). In addition, none of the CVD individuals detected the transformation target on plates 9 or 10.

Table 1. Typical and atypical errors for each plate of the Ishihara test.

Plate Design	Plate Number	Normal Reading	Color-deficient Reading (Typical Error)	Atypical Error Responses (N)		Total Errors N (%)		Typical Errors N (%)		Atypical Errors N (%)	
				Normal	Color Vision Deficient (CVD)	Normal	CVD	Normal	CVD	Normal	CVD
Demonstration	1	12	12	-	-	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Transformation	2	8	3	-	X (7), 2 (1), 6 (1)	0 (0)	46 (73)	0 (0)	37 (59)	0 (0)	9 (14)
	3	6	5	-	X (4), 6 (2), 8 (1), 3 (1)	0 (0)	42 (67)	0 (0)	34 (54)	0 (0)	8 (13)
	4	29	70	-	10 (31), X (5), 20 (3), 28 (2), 0 (2), 2 (1), 19 (1), 86 (1), 90 (1)	0 (0)	60 (95)	0 (0)	13 (21)	0 (0)	47 (75)
	5	57	35	-	X (8), 85 (8), 25 (7), 36 (4), 5 (3), 55 (2), 26 (1), 27 (1), 51 (1), 53 (1), 58 (1), 60 (1), 65 (1), 86 (1), 87 (1), 95 (1)	0 (0)	59 (94)	0 (0)	16 (25)	0 (0)	43 (68)
	6	5	2	-	X (9), 8 (8), 6 (2), 3 (1)	0 (0)	59 (94)	0 (0)	39 (62)	0 (0)	20 (32)
	7	3	5	8 (2)	8 (6), X (4), 6 (3)	2 (4)	57 (90)	0 (0)	44 (70)	2 (4)	13 (21)
	8	15	17	-	19 (3), 11 (2), X (1), 1 (1), 12 (1), 13 (1), 14 (1), 16 (1)	0 (0)	54 (86)	0 (0)	43 (68)	0 (0)	11 (17)
	9	74	21	71 (2)	14 (3), 24 (2), X (2), 91 (1), 94 (1)	2 (4)	63 (100)	0 (0)	54 (86)	2 (4)	9 (14)
Vanishing	10	2	X	-	8 (3)	0 (0)	60 (95)	0 (0)	57 (90)	0 (0)	3 (5)
	11	6	X	-	8 (2), 5 (1), 10 (1), 13 (1), 25 (1)	0 (0)	57 (90)	0 (0)	51 (81)	0 (0)	6 (10)
	12	97	X	87 (2)	15 (5), 5 (3), 13 (1), 21 (1), 22 (1), 27 (1), 87 (1)	2 (4)	63 (100)	0 (0)	50 (79)	2 (4)	13 (21)
	13	45	X	46 (5)	5 (1), 15 (1), 40 (1)	5 (9)	61 (97)	0 (0)	58 (92)	5 (9)	3 (5)
	14	5	X	-	8 (1), 11 (1), 18 (1), 44 (1),	0 (0)	51 (81)	0 (0)	47 (75)	0 (0)	4 (6)
	15	7	X	-	1 (2), 4 (1), 6 (1), 22 (1), 53 (1)	0 (0)	53 (84)	0 (0)	47 (75)	0 (0)	6 (10)
	16	16	X	-	18 (6), 15 (4), 12 (1), 13 (1), 34 (1)	0 (0)	57 (90)	0 (0)	44 (70)	0 (0)	13 (21)
	17	73	X	78 (2), 13 (1), 28 (1)	81 (2), 8 (1), 13 (1), 21 (1), 22 (1), 23 (1), 28 (1), 70 (1), 78 (1)	4 (7)	62 (98)	0 (0)	52 (83)	4 (7)	10 (16)
Hidden	18	X	5	-	11 (2), 7 (1), 21 (1), 81 (1)	0 (0)	40 (63)	0 (0)	35 (56)	0 (0)	5 (8)
	19	X	2	-	8 (8), 2 (1), 12 (1)	3 (5)	48 (76)	3 (5)	38 (60)	0 (0)	10 (16)
	20	X	45	-	15 (2), 41 (2), 4 (1), 5 (1), 11 (1), 25 (1), 42 (1), 43 (1)	1 (2)	34 (54)	1 (2)	24 (38)	0 (0)	10 (16)
	21	X	73	2 (1)	21 (11), 20 (4), 23 (4), 25 (4), 75 (3), 71 (2), 10 (1), 13 (1), 28 (1), 93 (1)	1 (2)	33 (52)	0 (0)	1 (2)	1 (2)	32 (51)

Note: X refers to nothing. The atypical error responses in plate 2, where seven CVDs individuals did not see the plate, while one CVD saw the plate as number 2, and the other CVD saw the plate as number 6.

Table 2. Typical and atypical errors of each plate of the W-PIP24 test.

Plate Design	Plate Number	Normal Reading	Color Defective Reading (Typical Error)	Atypical Error Responses (N)		Total Errors N (%)		Typical Errors N (%)		Atypical Errors N (%)	
				Normal	Color Vision Deficient (CVD)	Normal	CVD	Normal	CVD	Normal	CVD
Demonstration	1	16	16	-	-	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Vanishing	2	2	X	-	8 (1), 26 (1)	0 (0)	62 (98)	0 (0)	60 (95)	0 (0)	2 (3)
	3	42	X	-	2 (1), 4 (1), 12 (1), 19 (1)	0 (0)	63 (100)	0 (0)	59 (94)	0 (0)	4 (6)
	4	28	X	23 (1), 26 (1)	24 (1)	2 (4)	62 (98)	0 (0)	61 (97)	2 (4)	1 (2)
	5	8	X	-	0 (1), 3 (1), 13 (1), 28 (1)	0 (0)	56 (89)	0 (0)	52 (83)	0 (0)	4 (6)
Transformation	6	74	21 or X	14 (1), 71 (1)	71 (2), 1 (1), 4 (1), 14 (1), 81 (1)	2 (4)	62 (98)	0 (0)	56 (89)	2 (4)	6 (10)
	7	15	13, 17, or X	-	1 (6), 25 (2), 2 (2), 4 (1), 8 (1), 12 (1), 16 (1), 18 (1)	0 (0)	48 (76)	0 (0)	33 (52)	0 (0)	15 (24)
	8	5	2 or X	-	13 (1), 18 (1), 26 (1)	0 (0)	56 (89)	0 (0)	53 (84)	0 (0)	3 (5)
	9	29	70 or X	-	20 (5), 19 (2), 0 (1), 2 (1), 3 (1), 8 (1), 10 (1), 17 (1), 18 (1), 22 (1), 23 (1), 25 (1), 27 (1), 28 (1), 30 (1), 75 (1)	0 (0)	60 (95)	0 (0)	39 (62)	0 (0)	21 (33)
	10	57	35 or X	-	25 (2) 51 (2), 1 (1), 2 (1), 5 (1), 6 (1), 15 (1), 27 (1), 36 (1), 47 (1), 85 (1)	0 (0)	57 (90)	0 (0)	44 (70)	0 (0)	13 (21)
Vanishing	11	5	X	3 (1)	83 (1)	2 (4)	62 (98)	1 (2)	61 (97)	1 (2)	1 (2)
	12	45	X	46 (2)	9 (1), 49 (1)	2 (4)	60 (95)	0 (0)	58 (92)	2 (4)	2 (3)
	13	10	X	16 (1)	85 (1)	1 (2)	60 (95)	0 (0)	59 (94)	1 (2)	1 (2)
	14	6	X	-	4 (1), 9 (1), 72 (1)	0 (0)	58 (92)	0 (0)	55 (87)	0 (0)	3 (5)
	15	7	X	-	1 (1), 4 (1)	0 (0)	57 (90)	0 (0)	55 (87)	0 (0)	2 (3)
Blue-yellow plates	17	2	X |Tritan defect	-	8 (1), 12 (1)	0 (0)	4 (6)	0 (0)	2 (3)	0 (0)	2 (3)
	18	7	X |Tritan defect	-	1 (1)	0 (0)	4 (6)	0 (0)	3 (5)	0 (0)	1 (2)

Note: X refers to nothing. The atypical error responses in plate 2 were: one CVD saw the plate as number 8, whereas the other CVD saw the plate as number 26.

Table 3. Color-deficient typical errors for the transformation plates on the W-PIP24 test.

Plate Design	Plate Number	Normal Reading	Color-deficient Reading (Typical Error)	Typical Error Responses (N)
Transformation	6	74	21 or X	X (46), 21 (10)
	7	15	13 or 17 or X	X (27), 13 (3), 17 (3)
	8	5	2 or X	X (51), 2 (2)
	9	29	70 or X	X (39)
	10	57	35 or X	X (44)

Note: X response refers to nothing.

4. DISCUSSION

Various studies have determined the typical and atypical error responses based on CVN using the Ishihara test [12, 13]. This study aimed to extend the work of previous studies by determining the typical and atypical error responses of CVN and CVD individuals on the Ishihara and W-PIP24 tests. Tables **1** and **2** show that individuals have an atypical error response on each plate in both tests. However, there was a higher percentage of atypical error responses on the Ishihara plate than on the W-PIP24 plate. For example, 12 CVN participants had ≤ 3 atypical error responses, while 5 CVN had ≤ 2 atypical errors on the W-PIP24 test. Scholars have found that normal trichromats can have ≤ 6 atypical error responses [1, 13].

CVD participants tended to have more atypical errors on the Ishihara test than on the W-PIP24 test, and approximately

40% of the CVD had zero atypical errors on the W-PIP24 red-green screening plates, while the remaining 60% of the CVD had ≤ 5 atypical error responses. The exception was a Single CVD individual with ten atypical errors in the W-PIP24 test. However, none of the CVD participants had zero atypical errors in the Ishihara test, which may be due to the transformation and hidden plates used in that test. The W-PIP24 test does not contain hidden plates, and their transformation plates are combined with both the transformation and vanishing designs. If the Ishihara contained only vanishing design plates, > 55% of the CVD participants would have zero atypical error responses.

This study found that the most atypical error responses for CVD participants were in the transformation plate design for both tests. The Ishihara test had the highest percentage of atypical errors on plate 4 (transformation; 75%), with most of the CVD participants responding with "10" rather than "70," which may be because the rounded dots of the 7 were not clear to the participants. This indicates that the examiner might count the response of "10" as a color-deficient response. In contrast, plate 5 (transformation) of the Ishihara test had the highest number of incorrect responses to atypical error responses for CVD individuals. This might be because the typical CVD response of 35 could be confused and misread with various numbers, such as 2, 6, and 8.

W-PIP24 plates 6–10 are a combination of transformation and vanishing plates, based on the instruction sheet. Eighty-two percent of the CVD responses vanished on plates 6 and 7, 96% on plate 8, and 100% on plates 9 and 10. Furthermore, most CVD individuals could not detect the transformation plates. These results indicate that W-PIP24 plates 6–10 were mainly designed as vanishing plates rather than transformation plates.

Three CVN participants had ≤ 2 typical errors on the Ishihara test, and one CVN participant in the W-PIP24 test had a single typical error. The three CVN participants with typical errors in the Ishihara test were female. These typical errors could be due to the female participants being carriers of red-green CVD, which affects 15% of Caucasian females [14, 15], while heterozygous carriers may cause mild abnormalities in color discrimination [16 - 18]. Miyahara [13] reported that none of the normal trichromats had more than two typical errors. However, Birch and McKeever [1], found in their study that none of the normal trichromats had typical errors.

Eighty-four percent of the CVD participants had at least one error (typical or atypical) in each of the four hidden digit plates. Most of the hidden plate errors were typical except for plate 21. Approximately all the responses for plate 21 were atypical, except for a single CVD individual who had a typical error. Three CVN individuals had typical errors on plate 19, and one CVN participant had a typical error on plate 20. Miyahara [19] explained that the ability of CVN individuals to read the numbers on the hidden plates was because some individuals could extract the difference in the S-cone while reading the plates, regardless of the distraction made from the L/(L + M) axis. Miyahara [13] reported that 2% of normal trichromats had typical errors in the hidden plates, while other studies found that none of the CVN individuals had errors in the hidden digit plates [1, 10].

Plates 17 and 18 of the W-PIP24 test were used to screen for blue-yellow defects for which none of the CVN participants had typical or atypical errors. However, three CVD individuals (males) had a single atypical error, one (female) had a single typical error, and two (one male and one female) had two typical errors. All CVD participants were below 40 years of age and failed the W-PIP24 red-green screening plates, with eight or more typical errors. The participants denied any ocular or systemic disease related to acquired CVD, the reason for which was uncertain.

In clinical practice, clinicians must consider factors affecting the color vision test results. First, the light source must satisfy a considerable criterion. Many scholars have investigated the color of lightning used in color vision tests [20 - 24]. They reported that the light source should have a correlated colored temperature between 5500 and 7500 K. Second, illuminance is a significant factor that affects the color vision test performance [25 - 28]. High illuminance will cause both normal and abnormal color vision individuals to perform well; however, illuminance that is too low will cause all participants to perform poorly. The recommended illumination level should be at least 350 lx [29].

CONCLUSION

This study showed that CVN and CVD individuals had typical and atypical errors in both the 38-plate edition of Ishihara and W-PIP 24 tests. CVD individuals showed more atypical errors on the Ishihara test than on the W-PIP24 test and tended to have more atypical errors on the transformation plates in both tests. CVN individuals may misread the plates in both tests for reasons other than the normality of color vision; therefore, counting only the typical errors may eliminate the chance of misreading the number on the plates for CVN individuals. The most significant information derived from the results of this study was that clinicians should perhaps count only typical errors as "errors" in both tests.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The study was approved by the King Saud University Office of Research Ethics (approval no. E-19-4297).

HUMAN AND ANIMAL RIGHTS

No animals were used for studies that are the basis of this research. All the humans were used in accordance with the ethical standards of the committee responsible for human experimentation (institutional and national), and with the Helsinki Declaration of 1975, as revised in 2013 (http://ethics.iit.edu/ecodes/node/3931).

CONSENT FOR PUBLICATION

Informed consent was obtained from all the participants of this study.

AVAILABILITY OF DATA AND MATERIALS

The data presented in the study are available in the article.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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