An adjusted error score calculation for the Farnsworth-Munsell 100 Hue Test

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Abstract

The Farnsworth-Munsell 100 Hue Test, a test which measures an individual's hue discrimination ability, operates with the fundamental assumption that it is administered using a fixed, standard illuminant. This assumption is violated when the testing illuminant is changed—as is common when testing color discrimination ability of an illuminant—which likely causes a reordering of the caps in the test. To ensure that a participant is not falsely penalized for correctly responding to a hue transposition caused by the new testing light source, an adjusted error score is proposed which reconciles light source-induced hue transpositions and participant performance on the test.

Keywords: color discrimination, transposition, Farnsworth-Munsell 100 hue test, total light source error score, adjusted total error score

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1 Introduction

The Farnsworth-Munsell 100 Hue Test (FM-100) is a physical test of hue discrimination, consisting of 85 colored caps whose chromaticities are distributed around the hue circle. It contains four separate trays of caps—Tray A is nominally red to red-orange, B is yellow to yellow-green, C is green to green-blue, and D is indigo to indigo-magenta—that are moveable between two fixed, colored end caps (**Figure 1**). The test is used to evaluate the hue discrimination ability of an individual, to classify that individual into superior, average, or low discrimination ability, and to identify individual color anomaly [Farnsworth 1957]. The FM-100 hue test is largely used as a research tool to understand normal color vision [Malone and Hannay 1977; Kinnear and Sahraie 2002], and to detect and study its deficiencies [Farnsworth 1943; Moreland and others 2014; Verriest 1963, 1974; Vingrys and others 1992]. It is also used as a clinical screening test of color vision for professionals in color-critical applications such as manufacturing (paints, dyes, etc.) and healthcare.

Concerning a light source, color discrimination describes *the ability of a light source to allow* observers to distinguish between colors of slightly different hue when viewed simultaneously [Thornton 1972]. To quantify this ability, past researchers have used an experimental design that has participants complete the FM-100 hue test under systematically varied light spectra [Boyce and Simons 1977; Esposito 2016; Esposito and Houser 2017; Mahler and others 2009; Rea and Freyssinier-Nova 2008; Royer and others 2012; Wei and Houser 2012]. The ultimate goal is to link light source colorimetric performance parameters—such as color fidelity [CIE 1995; Davis and Ohno 2010; Smet 2015; IES 2015] and gamut area [Thornton 1972; Rea 2008; Davis and Ohno 2010; IES 2015]—to FM-100 error scores, to predict color discrimination ability of light sources. Absolute thresholds for classifying a light source's color discrimination ability have yet to be determined. Esposito and Houser [2017] offered a preliminary proposal using a measure of light source-induced cap transpositions called the Total Light Source Error Score, R_d (described in **Section 3** of this article).

Though varying the light source is necessary for determining a causal link between light source performance parameters and light source color discrimination, doing so violates the intrinsic requirement that the FM-100 hue test be administered with a fixed testing source. In 1957 Farnsworth stated: "reliable results cannot be expected from this test unless standard illumination is used" [Farnsworth 1957]. That standard illumination is CIE Standard Illuminant C (or daylight), because it retains an optimal spacing of the caps in chromaticity space [Farnsworth 1943], which also preserves their numerical order.

Changing the testing light source will alter the hue, chroma, and lightness of the test chips, but it may also swap colored caps, or significantly reorder them altogether [Moreland and others 2014; Esposito 2016; Esposito and Houser 2017]. When the test is administered using a light source that causes such transpositions of caps, errors will be miscalculated and the experimental results distorted.

To right this discrepancy, an *adjusted* Total Error Score is detailed which accounts for the interaction between the light source Spectral Power Distribution (SPD) and the Spectral Reflectance Distribution (SRD) of the FM-100 hue test chips.

2 Standard Total Error Score

The score for any individual cap of the FM-100 test "is the sum of the [absolute] difference between the number of that cap and the numbers of the caps adjacent to it" minus 2 [Farnsworth 1957]. For example, the arrangement 29-30-31-32 has an error score of zero, and 29-**31**-**30**-32 (one transposition) has an error score of 4 (**APPENDIX A, Scenario 1**). Two transpositions correspond to an error score of 8, three an error of 12, four transpositions an error of 16, and so on. The Total Error Score (*TES*) is computed as the sum of the error scores for each of the four separate trays of the test:

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$$Total\ Error\ Score\ (TES) = \sum_{i=1}^{4} iES = \sum_{i=1}^{4}\left(\left(\sum_{j=1}^{n+2} CE_j\right) - ((n+2)*2)\right)$$

(1)

$$CE_j = |C_j - C_{j-1}| + |C_j - C_{j+1}|$$

where,

i	is a counter for the 4 trays (i=1 is “A”, 2 is “B”, 3 is “C”, and 4 is “D”);
C_j	is the *cap number* of the *j*th cap;[1]
CE_j	is the *cap error* of the *j*th cap;[2]
n	is the number of *moveable* caps in the tray corresponding to i (n = 22 for Tray A, and 21 for Tray B, C, and D)
AES	is the *standard* error score for tray A;
BES	is the *standard* error score for tray B;
CES	is the *standard* error score for tray C;
DES	is the *standard* error score for tray D.

The calculation software that accompanies the physical FM-100 hue test uses (1), and is only applicable when the testing light source preserves the numerical order of caps.

3 An adjusted Total Error Score

The *adjusted* Total Error Score (TES_{adj}) [Esposito and Houser 2017] is a modified Farnsworth-type error score which compares the order of the FM-100 hue test chips illuminated by the testing source—calculated based on hue angle in the *a*’*b*’ plane of the CAM02-UCS [Fairchild 2013; Luo and others 2006]—to a participant’s order of caps. TES_{adj} guarantees that a participant is not penalized for correctly responding to a hue transposition caused by the light source, nor mistakenly rewarded because the analysis does not consider the light source’s impact on cap order. TES_{adj} reconciles the discrepancy between a light source-induced transposition and a transposition arranged by a participant performing the test:

$$TES_{\text{adj}} = \sum_{i=1}^{4} iES_{\text{adj}} = \sum_{i=1}^{4}\left(\left(\sum_{j=1}^{n+2} PE_j\right) - ((n+2)*2)\right)$$

(2)

$$PE_j = |P_j - P_{j-1}| + |P_j - P_{j+1}|$$

where,

i	is a counter for the 4 trays (i=1 is “A”, 2 is “B”, 3 is “C”, and 4 is “D”);
P_j	is the *place number* of the *j*th cap (demonstrated in **APPENDIX A, Scenario 2**);
PE_j	is the *place error* of the *j*th cap;

[1] For this equation to work properly, the terms $|C_j - C_{j+1}|$ and $|C_j - C_{j-1}|$ must each be equal to 1 when the caps are ordered correctly. Because the first free cap in tray A is numbered 85, not 1, the calculation requires a dummy array that assigns cap 85 a value of 1, cap 1 a value of 2, and so on.

[2] The cap error must be calculated for the end caps of the try, otherwise results will be incorrect when errors are made near the tray’s ends; this necessitates the ‘n+2’ term in the equation, the ‘2’ accounting for each end cap.

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n	is the number of *moveable* caps in the tray corresponding to i (n = 22 for Tray A, and 21 for Tray B, C, and D)
AES_{adj}	is the *adjusted* error score for tray A;
BES_{adj}	is the *adjusted* error score for tray B;
CES_{adj}	is the *adjusted* error score for tray C;
DES_{adj}	is the *adjusted* error score for tray D.

The principal difference between **(1)** and **(2)** is the *place number*, which is an nx1 array that is determined by cross-referencing the numerical cap order with their correct *place* in the array of caps illuminated by the testing illuminant.

As an example, if a light source causes the order of caps 29-**31**-**30**-32, and a participant arranges these caps accordingly in tray B of the test, they would not be attributed an error (as opposed to an error score of 4 using **(1)**). In this example, cap number 31 is the 9th cap in the *correct* order (P_j = 9) and cap number 30 is the 10th cap in the *correct* order (P_j = 10). When the light source causes no cap transpositions, place number is equal to cap number ($P_j = C_j$), the *adjusted* total error score is equal to the standard error score ($TES_{\text{adj}} = TES$), and **(2)** collapses to **(1)**.

4 Light Source Error Score

Applying **(1)** directly to the cap order under the testing illuminant produces an objective measure of light source-induced cap transpositions, called the Total Light Source Error Score, R_{d} [Esposito 2016; Esposito and Houser 2017]; Esposito and Houser [2017] proposed R_{d} as a measure of color discrimination. R_{d} is a source-specific error score, and is the sum of the source-specific error scores for each of the four trays of the FM-100 hue test:

$$R_{\text{d}} = \sum_{i=1}^{4} R_{\text{d},i} = \sum_{i=1}^{4} \left(\left(\sum_{j=1}^{n+2} CEt_j \right) - ((n+2) * 2) \right) \tag{3}$$

$$CEt_j = \left| Ct_j - Ct_{j-1} \right| + \left| Ct_j - Ct_{j+1} \right|$$

where,

i	is a counter for the 4 trays (i=1 is “A”, 2 is “B”, 3 is “C”, and 4 is “D”);
Ct_j	is the *cap number* of the jth cap, as ordered by the testing light source;
CEt_j	is the *cap error* of the jth cap, as ordered by the testing light source;
n	is the number of *moveable* caps in the tray corresponding to i (n = 22 for Tray A, and 21 for Tray B, C, and D)
R_{d}	is the *total light source error score*;
$R_{\text{d,A}}$	is the *light source error score* for tray A;
$R_{\text{d,B}}$	is the *light source error score* for tray B;
$R_{\text{d,C}}$	is the *light source error score* for tray C;
$R_{\text{d,D}}$	is the *light source error score* for tray D.

An R_{d} of 4 indicates that the *light source* causes one transposition, a value of 8 is two transpositions, 12 is three transpositions, and so on. **Table 1** shows R_{d} values for select light sources.

The R_{d} calculation compares the order of caps illuminated by the light source to the numerical order of caps that occurs, by design, under CIE standard illuminant C. CIE C, then, becomes the *de facto* reference.

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Table 1 R_d **for select light sources from the library of the IES TM-30-15 calculator. Multiple spectra of the same source type sometimes exhibited different** R_d **values. For example, there were multiple phosphor-based LED sources in the library which collectively exhibited all** R_d **values between 0 and 28.**

Source Type	Source Name	R_d
Incandescent	75WA19 Neodymium	12
Incandescent	Halogen/Halogen MR16	4, 8
Incandescent	Filtered Halogen	0
HID	HPS Standard	40, 48
HID	HPS Deluxe	36
HID	Super HPS	40
HID	Mercury	36, 44, 52
HID	CDM940, MHC100UMP4K - Metal Halide	0
HID	CDM830, MHC100/U/MP/3K	4, 8
LED	Mixed (Experimental)	0-40
LED	Mixed (Commercial)	36
LED	Hybrid (Commercial)	0-16
LED	Phosphor	0-28
Fluorescent	Narrowband - F32T8/7XX	8, 12, 24
Fluorescent	Narrowband - F32T8/8XX	0-16, 24
Fluorescent	Narrowband - F32T8/9XX	0, 8
Fluorescent	Narrowband - F40T12/XXU	8, 12, 24
Fluorescent	Broadband	0, 4, 8, 20
Fluorescent	CIE C	0
Fluorescent	CIE F1-F12	0, 8, 12, 20
Model	CIE D-Series (5000 - 8000 K)	0
Model	Equal Energy	0

5 Discussion

Table 1 shows that many common light sources, as well as many experimental spectra, transpose at least one cap of the FM-100 hue test. A recent study by Esposito and Houser [2017] evaluated the color discrimination ability of 24 experimental LED spectra, 17 of which transposed at least one cap of the FM-100 hue test ($R_d \geq 4$). On average, the difference between TES and TES_{adj} for those 17 sources was 7.6 (approximately two transpositions), and as large as 40. **Figure 2** shows a comparison of TES and TES_{adj} for their spectra; the comparison suggests that if the order of caps illuminated by the testing source is not considered, results will be significantly distorted. This may lead to erroneous conclusions about the color discrimination ability of a light source.

It is possible for a light source to transpose a free cap with a fixed end cap of its given tray. In this scenario, any placement of that cap on the tray is erroneous. Because participants are not permitted to omit caps from the tray—and allowing them to do so is not advisable as to maintain the simplicity of the testing and scoring procedure—the participant should not be penalized for the error. In this scenario, the transposed cap can simply be removed from the tray before administering the test. **Equation 2** will therefore need to be modified to account for the reduced number of caps in the tray; the calculation is otherwise straightforward.

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End cap transpositions are, however, seemingly uncommon; none of the 24 structured LED spectra of Esposito and Houser [2017] transposed any of the free caps of the FM-100 hue test with any of the fixed caps; six high pressure sodium and four mercury vapor lamps (spectra taken from the IES TM-30-15 calculator)—which are known to have poor color discrimination ability and transpose many caps (**Table 1**)—also cause no end cap transpositions.

6 Conclusion

This article details an adjusted error score calculation for the Farnsworth-Munsell 100 Hue Test that considers the impact of a light source's spectra on cap order, which corrects a fundamental discrepancy between actual cap order and participant performance in color discrimination research. Studies that administer the FM-100 hue test without the recommended standard illuminant (CIE C or Daylight) should consider the light source's impact on cap order, and utilize the *adjusted* error score calculation to avoid potentially distorted results.

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8 Disclosure

The author reported no declarations of interest.

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APPENDIX A

Scenario 1

In this example, the light source does not cause any cap transpositions (R_d = 0, See **Section 4**), and a participant makes one transposition in physical test tray B (*BES* = 4). Because the light source does not cause any transpositions, **(1)** applies.

j: cap counter from **(1)**

Response order: is the order of caps of tray B, as ordered by a hypothetical participant

***CE**$_j$*: is the cap error associated with the *j*th cap

j	Response Order	$CE_j = \lvert C_j - C_{j-1}\rvert + \lvert C_j - C_{j+1}\rvert$	
1	**21**	= ABS(21-20) + ABS(21-22)	= 2
2	22	= ABS(22-21) + ABS(22-23)	= 2
3	23	= ABS(23-22) + ABS(23-24)	= 2
4	24	= ABS(24-23) + ABS(24-25)	= 2
5	25	= ABS(25-24) + ABS(25-26)	= 2
6	26	= ABS(26-25) + ABS(26-27)	= 2
7	27	= ABS(27-26) + ABS(27-28)	= 2
8	28	= ABS(28-27) + ABS(28-29)	= 2
9	29	= ABS(29-28) + ABS(29-31)	**= 3**
10	**31**	= ABS(31-29) + ABS(31-30)	**= 3**
11	**30**	= ABS(30-31) + ABS(30-32)	**= 3**
12	32	= ABS(32-30) + ABS(32-33)	**= 3**
13	33	= ABS(33-32) + ABS(33-34)	= 2
14	34	= ABS(34-33) + ABS(34-35)	= 2
15	35	= ABS(35-34) + ABS(35-36)	= 2
16	36	= ABS(36-35) + ABS(36-37)	= 2
17	37	= ABS(37-36) + ABS(37-38)	= 2
18	38	= ABS(38-37) + ABS(38-39)	= 2
19	39	= ABS(39-38) + ABS(39-40)	= 2
20	40	= ABS(40-39) + ABS(40-41)	= 2
21	41	= ABS(41-40) + ABS(41-42)	= 2
22	42	= ABS(42-21) + ABS(42-43)	= 2
23	**43**	= ABS(43-42) + ABS(43-44)	= 2

$$BES = \left(\sum_{j=1}^{n+2} CE_j\right) - ((n+2)*2) = 50 - (21+2)*2 = 50 - 46 = 4$$

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Scenario 2

In this example, the light source causes one transposition in tray B ($R_{d,B}$ = 4, See **Section 4**), and the participant does not correctly respond to that transposition (BES_{adj} = 4). Note that if **(1)** was applied to this participant's response, they would have an error score of zero (BES = 0), which would be erroneous since they did not correctly respond to the light source.

j: cap counter from **(2)**

Source: is the order of the caps of tray B, under a hypothetical light source

Response order: is the order of caps of tray B, as ordered by a hypothetical participant

ID: a fixed dummy array of numbers used as an intermediate variable to determine P_j.

$\boldsymbol{P_j}$: Place number from **(2)**, which renumbers the participant's order of caps based on their correct "place" as compared to the "Source" order. In this example, Excel function *VLOOKUP* was used to calculate P_j.

$\boldsymbol{PE_j}$: is the error associated with the *j*th place.

j	Source	ID	Response Order	P_j	$PE_j = \lvert P_j - P_{j-1}\rvert + \lvert P_j - P_{j+1}\rvert$	
1	21			0	= ABS(0-(-1)) + ABS(0-1)	= 2
2	22	1	22	1	= ABS(1-0) + ABS(1-2)	= 2
3	23	2	23	2	= ABS(2-1) + ABS(2-3)	= 2
4	24	3	24	3	= ABS(3-2) + ABS(3-4)	= 2
5	25	4	25	4	= ABS(4-3) + ABS(4-5)	= 2
6	26	5	26	5	= ABS(5-4) + ABS(5-6)	= 2
7	27	6	27	6	= ABS(6-5) + ABS(6-7)	= 2
8	28	7	28	7	= ABS(7-6) + ABS(7-8)	= 2
9	29	8	29	8	= ABS(8-7) + ABS(8-10)	**= 3**
10	**31**	9	**30**	**10**	= ABS(10-8) + ABS(10-9)	**= 3**
11	**30**	10	**31**	**9**	= ABS(9-10) + ABS(9-11)	**= 3**
12	32	11	32	11	= ABS(11-9) + ABS(11-12)	**= 3**
13	33	12	33	12	= ABS(12-11) + ABS(12-13)	= 2
14	34	13	34	13	= ABS(13-12) + ABS(13-14)	= 2
15	35	14	35	14	= ABS(14-13) + ABS(14-15)	= 2
16	36	15	36	15	= ABS(15-14) + ABS(15-16)	= 2
17	37	16	37	16	= ABS(16-15) + ABS(16-17)	= 2
18	38	17	38	17	= ABS(17-16) + ABS(17-18)	= 2
19	39	18	39	18	= ABS(18-17) + ABS(18-19)	= 2
20	40	19	40	19	= ABS(19-18) + ABS(19-20)	= 2
21	41	20	41	20	= ABS(20-19) + ABS(20-21)	= 2
22	42	21	42	21	= ABS(21-20) + ABS(21-22)	= 2
23	43			22	= ABS(22-21) + ABS(23-22)	= 2

$$BES_{adj} = \left(\sum_{j=1}^{n+2} PE_j\right) - \left((n+2)*2\right) = 50 - (21+2)*2 = 50 - 46 = 4$$

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Supplemental material

An Excel spreadsheet, which performs the computations described herein, accompanies this manuscript and is available online and linked by the same DOI as this manuscript.

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Figures

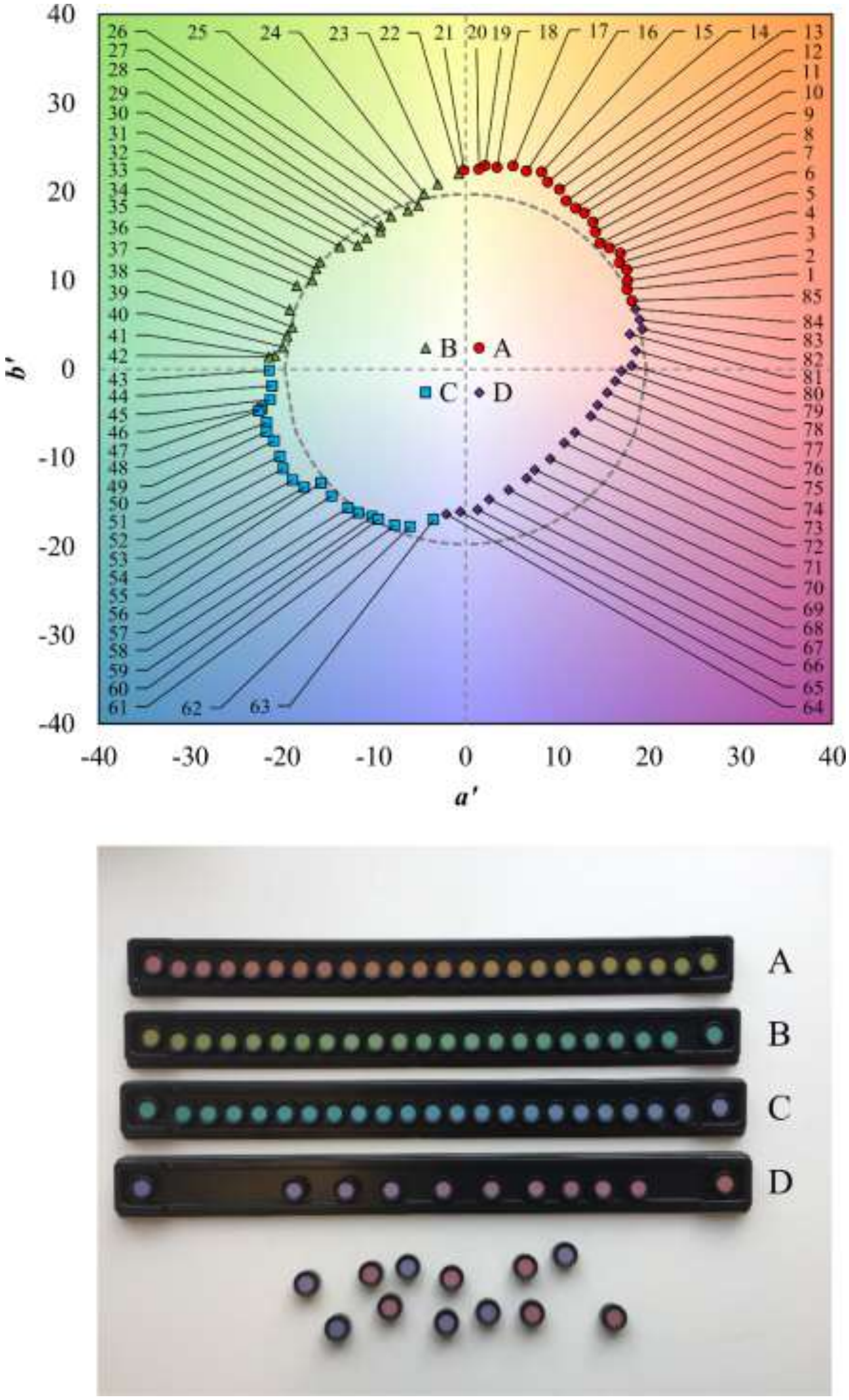

Figure 1 (Top) The distribution of caps of the FM-100 hue test in the *a*'*b*' plane of CAM02-UCS (using the CIE 1964 10° Standard Observer) illuminated by CIE Standard Illuminant C. The caps have an average lightness correlate (*J*') of 60.15 and an average colorfulness correlate (*M*') of 19.73 [Luo and others 2006]. The dashed circle shows an equal colorfulness of 19.73 across all hues. Number labels indicate cap number. (Bottom) Top view of the four physical test trays of the FM-100 test. Tray A has 22 moveable caps between two fixed end caps; trays B, C, and D have 21.

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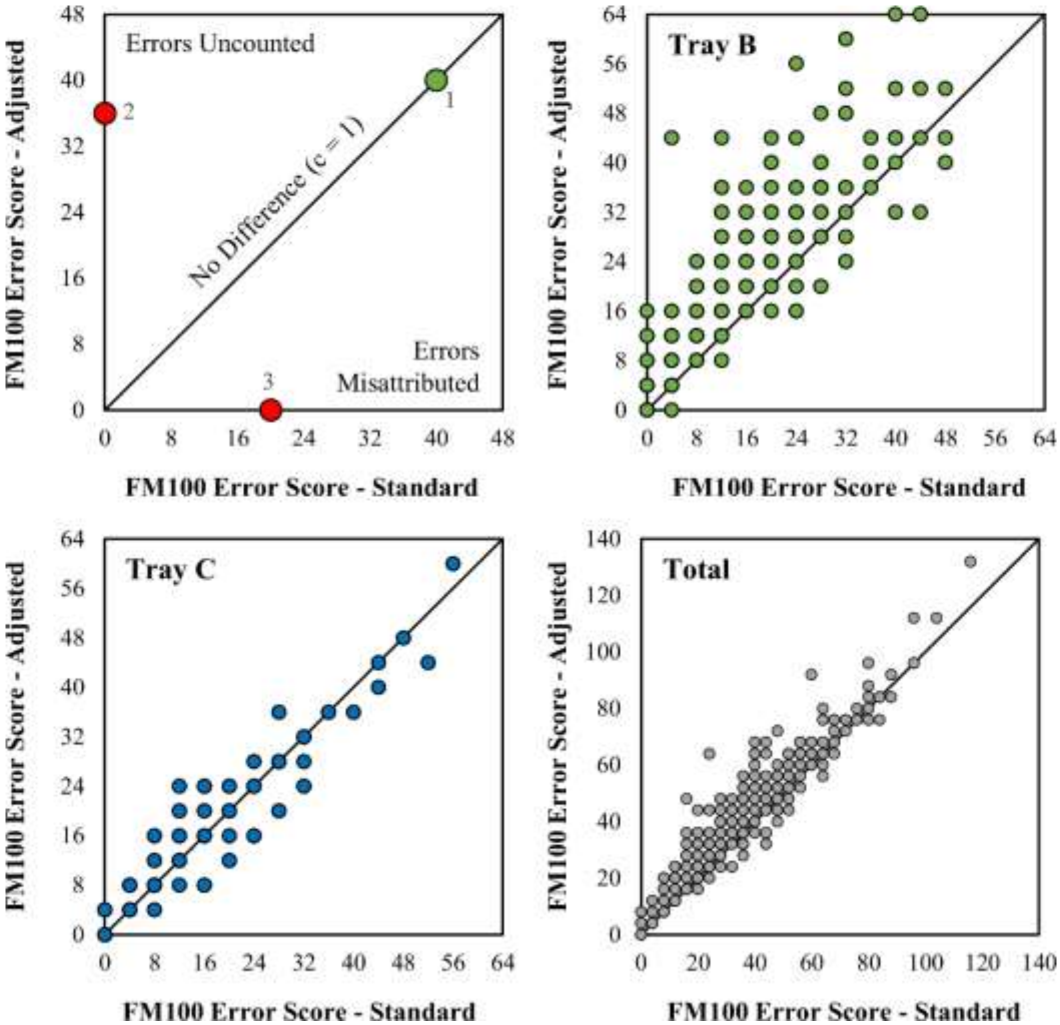

Figure 2 (Top left) A generalized comparison of standard Error Score and adjusted Error Score. Point 1 indicates that the standard error score equals the adjusted error score (i.e. $ES = ES_{adj}$), which only occurs when a light source causes no cap transpositions ($R_d = 0$). Equation 1 assumes that the light source causes no cap transpositions and that all resulting participant error scores fall on the c=1 line. For point 2, the adjusted error score is higher than a standard error score of zero (i.e. $ES_{adj} > ES = 0$), which occurs when a light source causes many transpositions and the participant orders their caps in exact numerical order; in this scenario, many errors would be uncounted using the standard error score calculation. For point 3, the standard error score is higher than an adjusted error score of zero (i.e. $ES > ES_{adj} = 0$), which occurs when the light source causes several transpositions, and the participant exactly responds. In this scenario, errors are misapplied to the participant using the standard error score calculation because the correct order of caps is not the numerical order. (Top right/Bottom left) Tray B and C Error Score comparison, respectively, for 480 responses (24 spectra x 20 participants) from Esposito and Houser [2017]. (Bottom Right) Total Error Score comparison for the same study. Seventeen of their 24 experimental spectra caused at least one hue transposition, which resulted in a large overall discrepancy between TES and TES_{adj}. It is clear that the assumption that all responses fall on the c=1 line will result in significant error. Note that these panels are a new calculation from the data of Esposito and Houser [2017].

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