CIE Technical Committee 1-93: Calculation of self-luminous neutral scale

- Terms of Reference: To recommend a formula or computational method for an achromatic, neutral or grey scale for self-luminous (i.e. non-reflective) surfaces. (This computation complements CIE Lightness, L*, which serves a similar purpose for reflective surfaces.)

Three TC1-93 subtasks:

1. Recommend a formula or computational method.
2. Show that the formula works for calculation of self-luminous color difference.
3. Clarify the meaning of “neutral” in the self-luminous context of this TC.

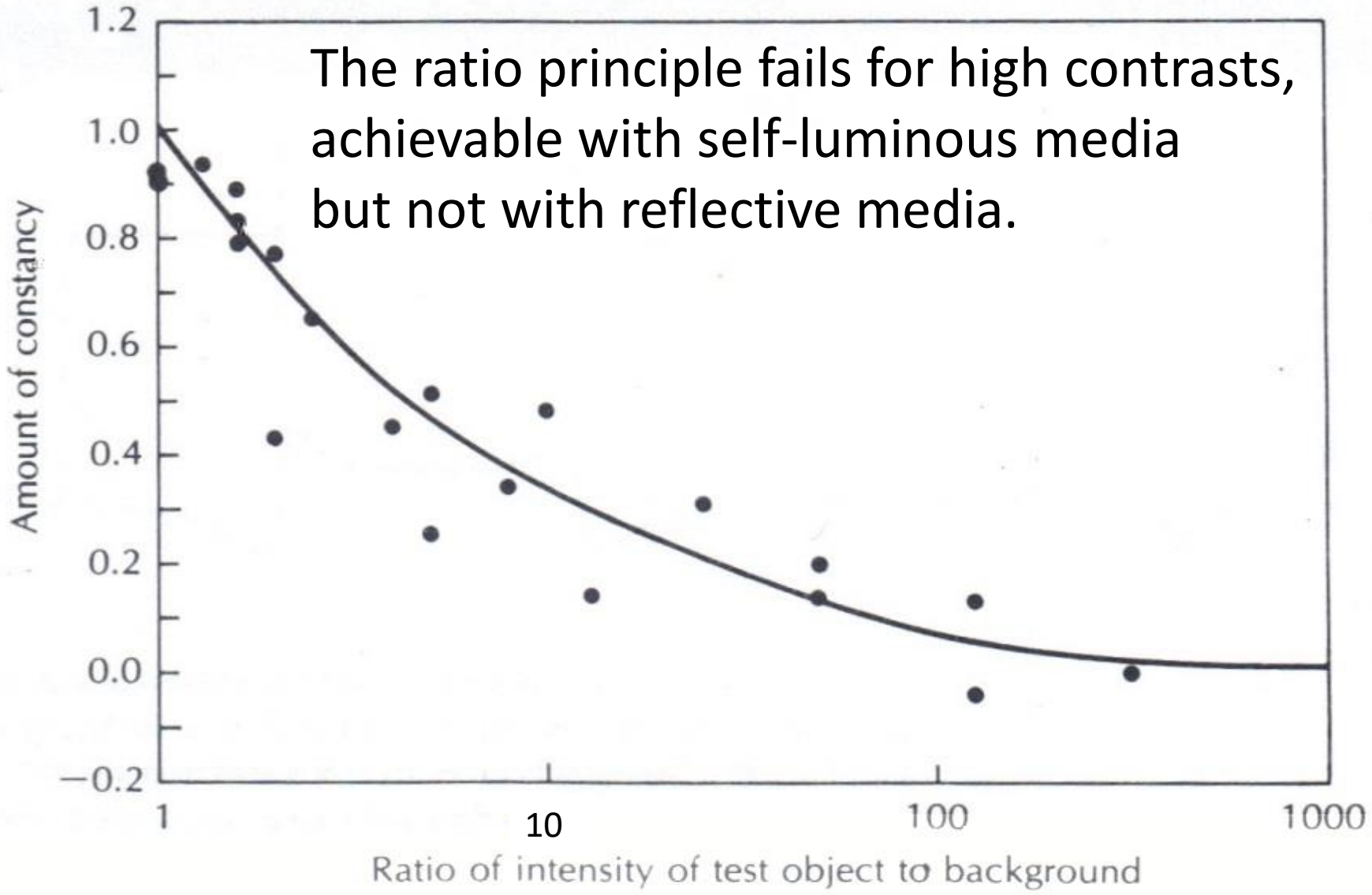
CIE TC 1-93 Status Report

- January publication of CIE technical report 228:2018; Grey-scale Calculation for Self-luminous Devices (90€).
- Terms of reference have been fulfilled; all three subtasks have been successful. CIE ended the TC.
  1. Whittle's 1992 formula is recommended for grey scale (matching, thresholds, equal perceptible differences, similarity) on self-luminous devices
     a. Advantages for high contrast, high resolution and high luminance
     b. Fits classic photopic matching and threshold data, and new data relevant to surveillance or medical imagery
     c. Recommendation accounts for background luminance, and requires absolute (not device- or image-relative) luminance
  2. Substitutes for L* in CIELAB, CIEDE2000; L_{OSA} in OSA-UCS
     a. Related publications by Oleari, Melgosa and others
  3. The meaning of "neutral" is discussed and clarified.
     a. Annex of related terms, mostly from CIE ILV.

Comparison of Three Photopic Self-Luminous Neutral Scales

	Media-relative L*	Whittle's formula	DICOM GSDF
Normalization	Peak luminance Y_n	Min(background, target) luminance	N/A
Independent Variables	Target luminance divided by Y_n, the "ratio principle"	Target & background luminances	Target luminance
Top-end of scale	Corresponds to Y_n	Unlimited	4000 cd/m^2
Expression of crispening	For L*=50 in CIEDE2000	For any background luminance	No
Multiple branches, one for each background	No	Yes, more shades for higher background luminances	No
Recognizes + versus - contrasts	No	Yes	No
Accounts for spatial scale	No	Yes, k	No
Points of inflection	1	2	0

Figure 13.4, p 378, Visual Perception (1970) by Tom Cornsweet



CIE recommends the Whittle (1992, Vision Research) Logarithmic Formula

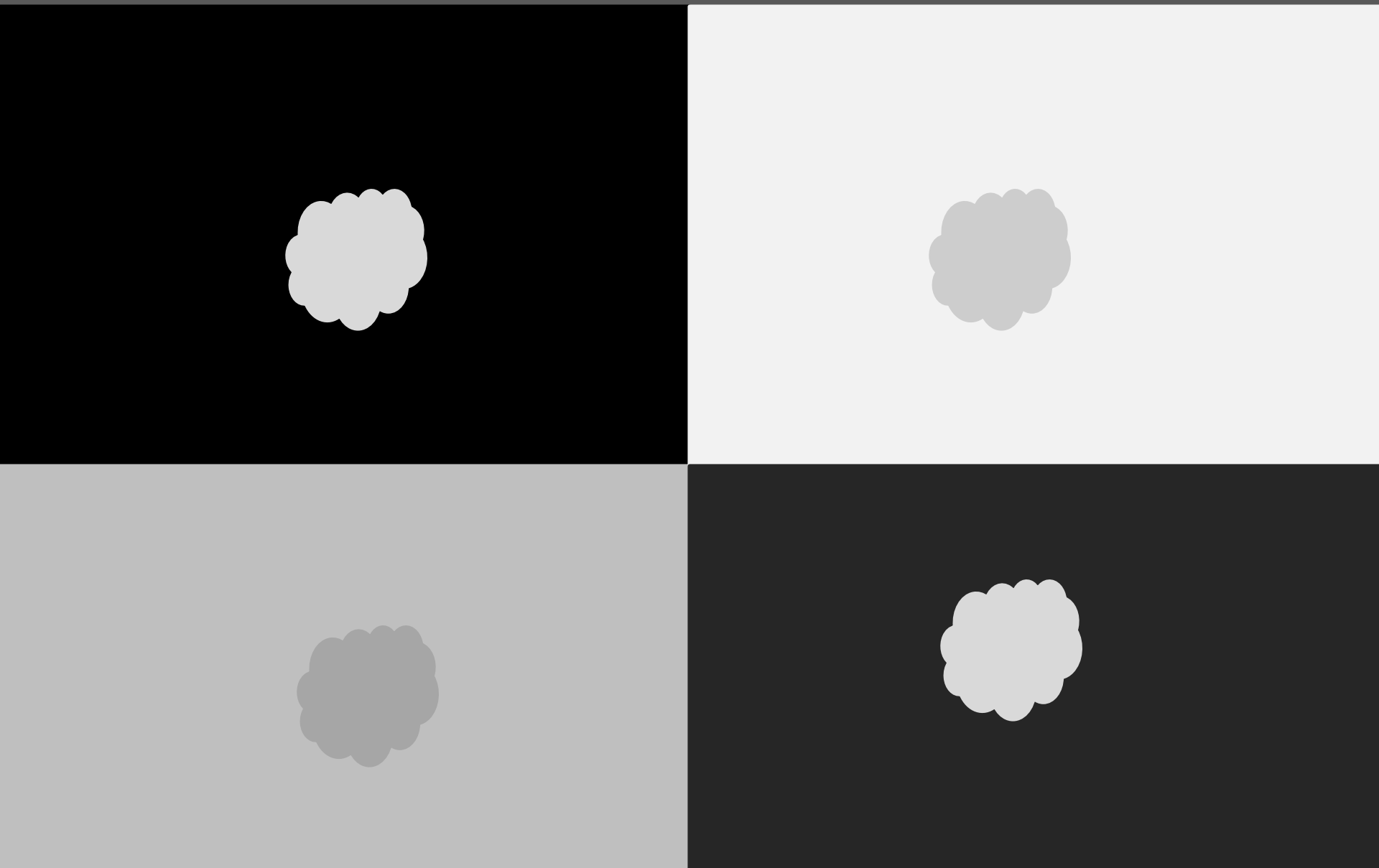
- Endorsed by FAA Kingdom in his 2011 Vision Research review of lightness/brightness
- Whittle counted the number of Equal Perceptible Differences (nEPD) of suprathreshold grey scale (from the background) using the formula:

nEPD = a*Log10(1+bW) where W=abs(L-L_b)/(minimum of L, L_b)

L_b = background luminance, L = target luminance

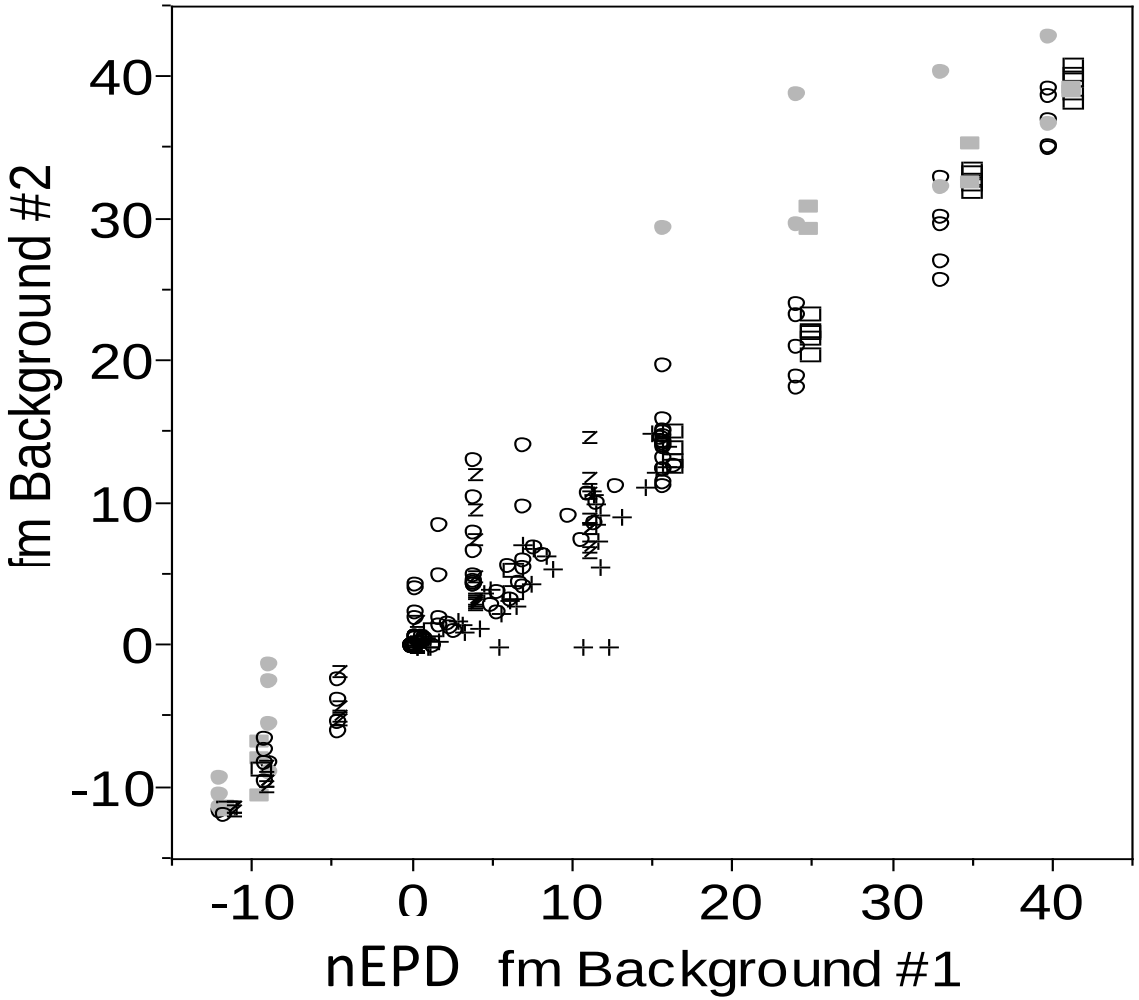
- nEPD between two contrasts is calculated as the difference between the contrasts' nEPD from their respective backgrounds: $nEPD_1 - nEPD_2$
- This formula is unique in its ability to model matching appearances of contrasts from different luminance backgrounds…see next two slides.

Calculating Matched Grays



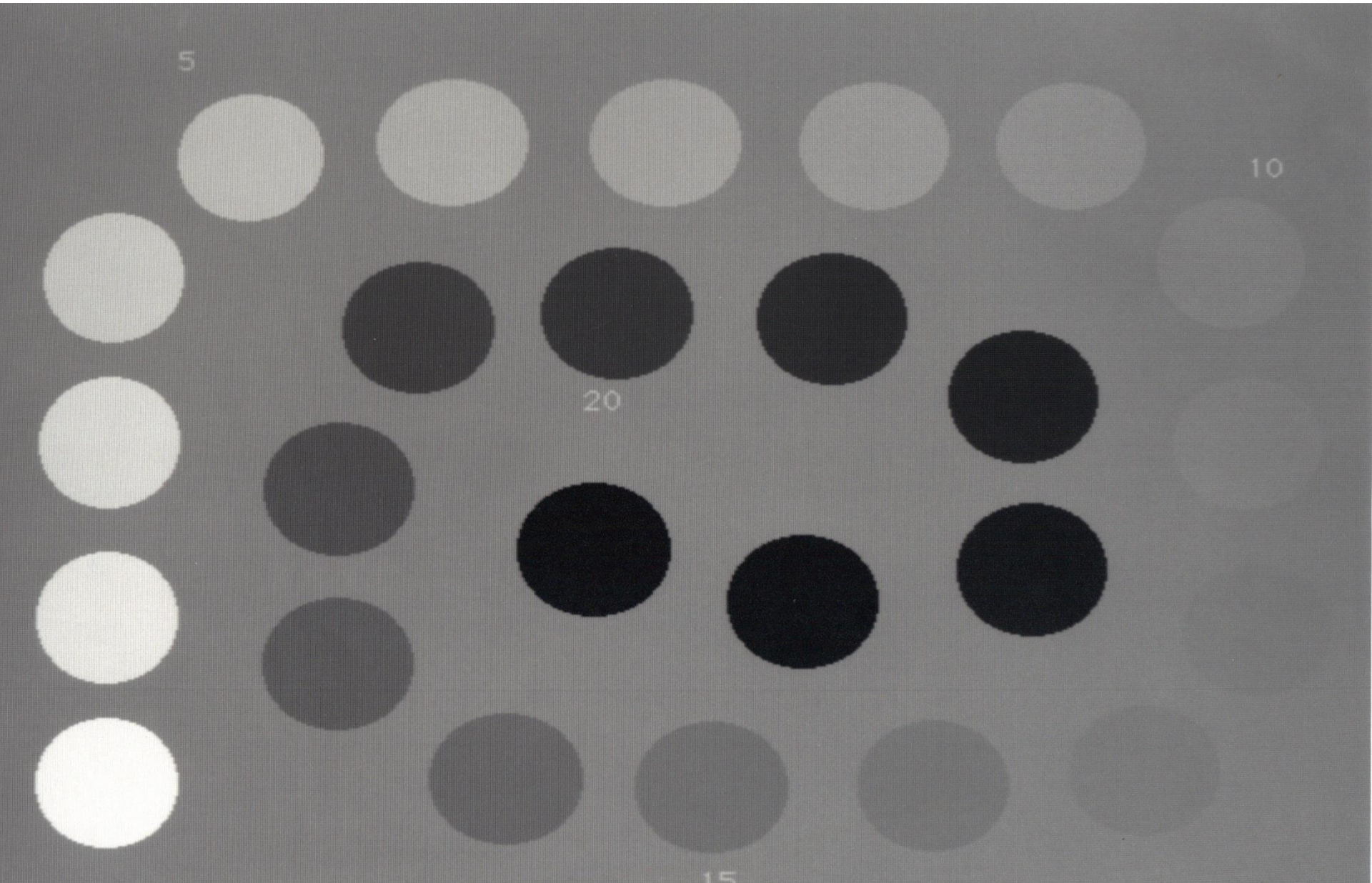
From Carter and Brill, Journal of the Society for Information Display, 2014

2 experimentally matched targets, Heinemann 1961, 30’ disks in illuminated surrounds

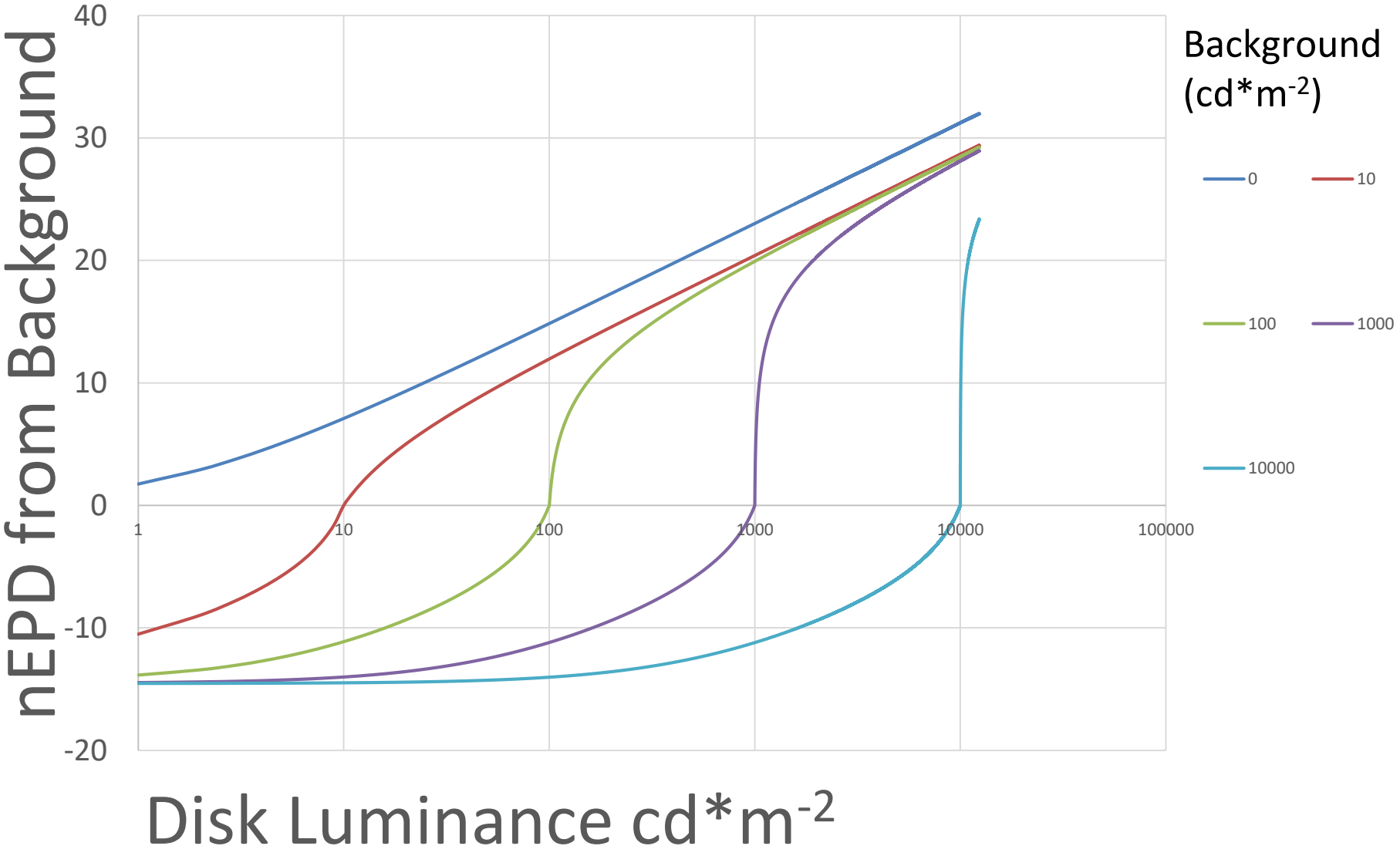


Matching appearances imply equal Whittle nEPD from different background luminances (at least approximately).

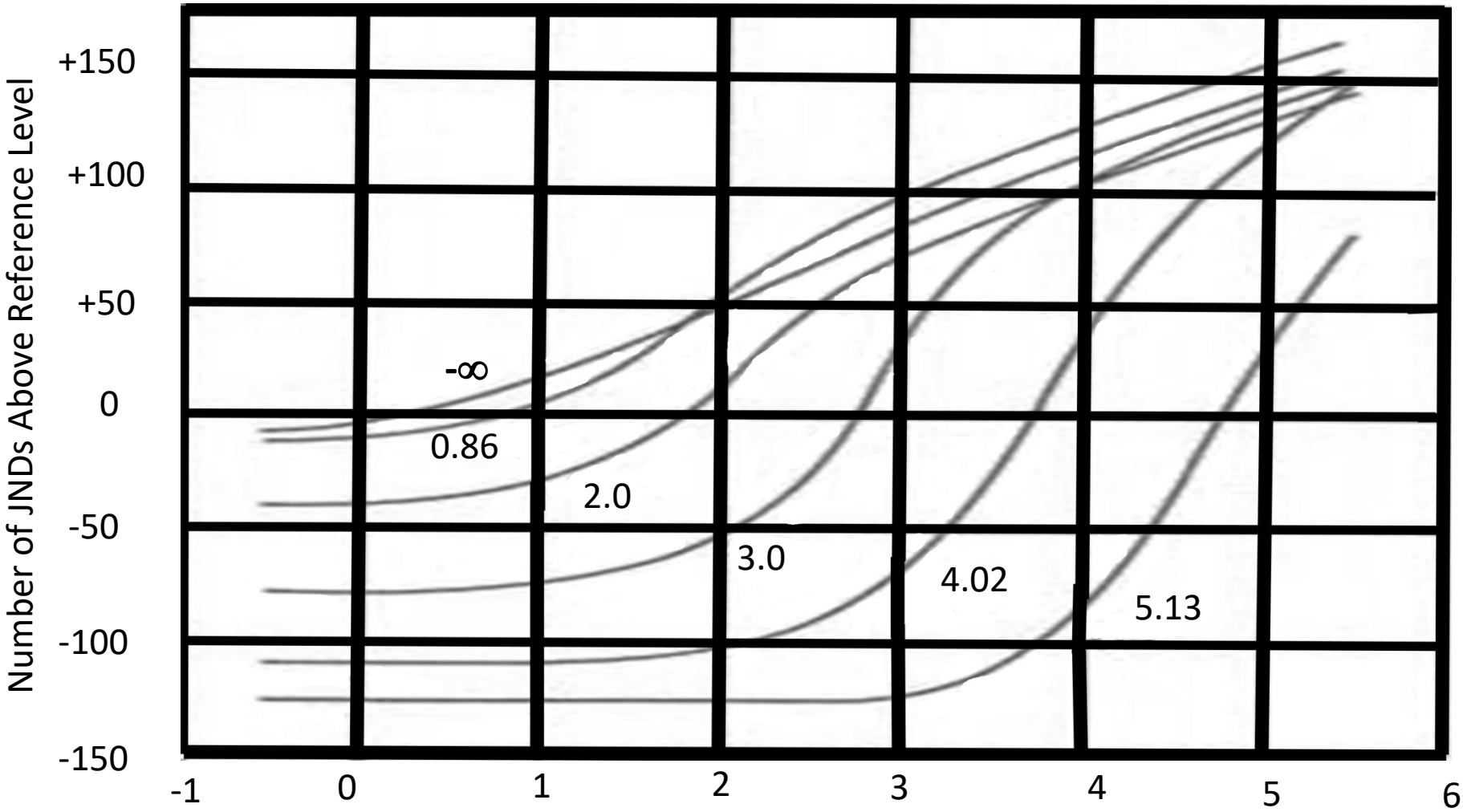
Equal Perceptible Differences (EPD)

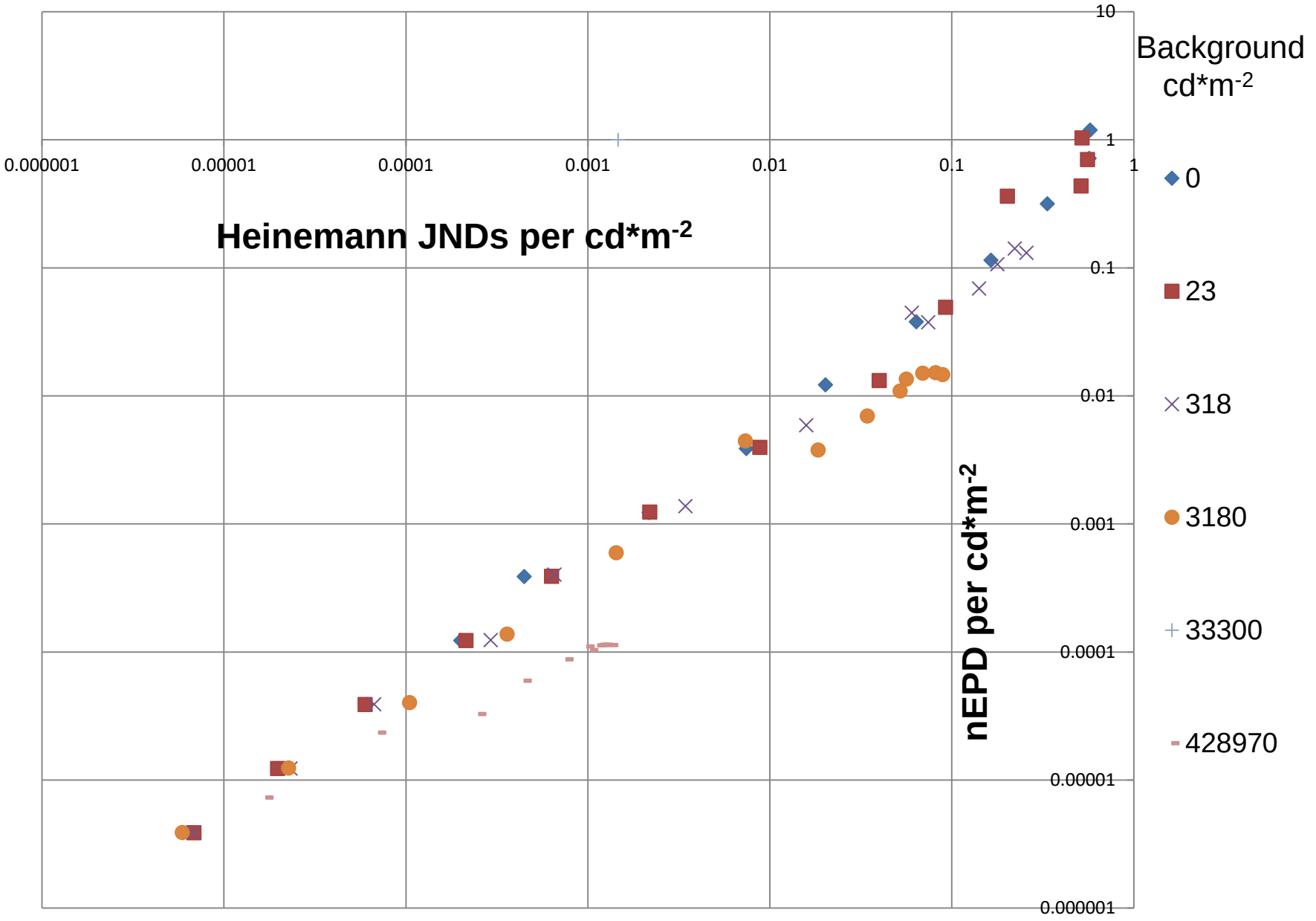


nEPD, 2-degree disks (k=0.055)



Heinemann's (1972) cumulative gray-scale JND curves (Parameter on curves is log background luminance.)



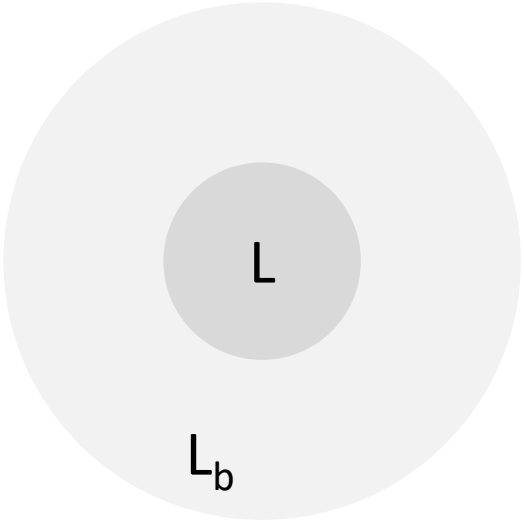

Heinemann JNDs per cd*m-2
nEPD per cd*m-2
0.000001
0.00001
0.0001
0.001
0.01
0.1
1
10
0.000001
0.00001
0.0001
0.001
0.01
0.1
1
Background cd*m-2
0
23
318
3180
33300
428970

"…the simplest and most precise mathematical description" of nEPD

L is target luminance, L_b is background luminance

L_{min} = the minimum of L or L_b

$\Delta L = |L-L_b|$



The number of EPD between L_b and L

nEPD = a log(1 + bW), b = 6.58

Two cases (e.g., negative contrast case is shown in figure; i.e., $L = L_{min}$):

For negative contrast: **W** = $(1-k)\,\Delta L / (L_d + L=L_{min} + k\,\Delta L)$; **a** = -7.07

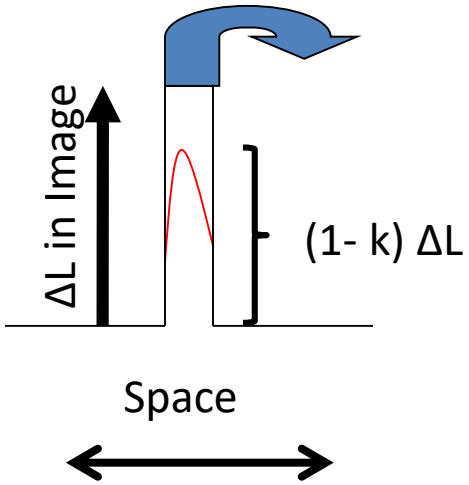
For positive contrast: **W** = $(1-k)\,\Delta L / (L_d + L_b=L_{min})$; **a** = 8.22

where L_d=.39 cd/m^2 represents light perceived in darkness when adapted to photopic conditions and **k** (0<k<1) represents intraocular light scattering and grows with decreasing subtense.

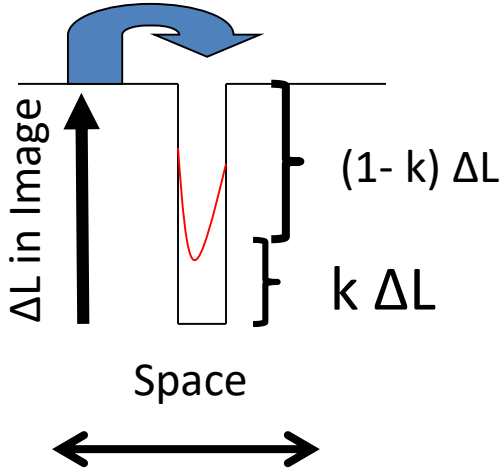
For k ~ 0 (i.e., large subtense) and $(L,L_b) >> (0,0)$, **W** ~ $\Delta L/L_{min}$

Explaining 0<k<1 in the Whittle formula: **intraocular scattering** reduces image ΔL to retinal (1-k)ΔL

- Light from a positive contrast (a target more-intense than its background) is scattered out of the target by the intraocular media:



- Light from the background of a negative contrast (a target less-intense than its background) is scattered into the target by the intraocular media:

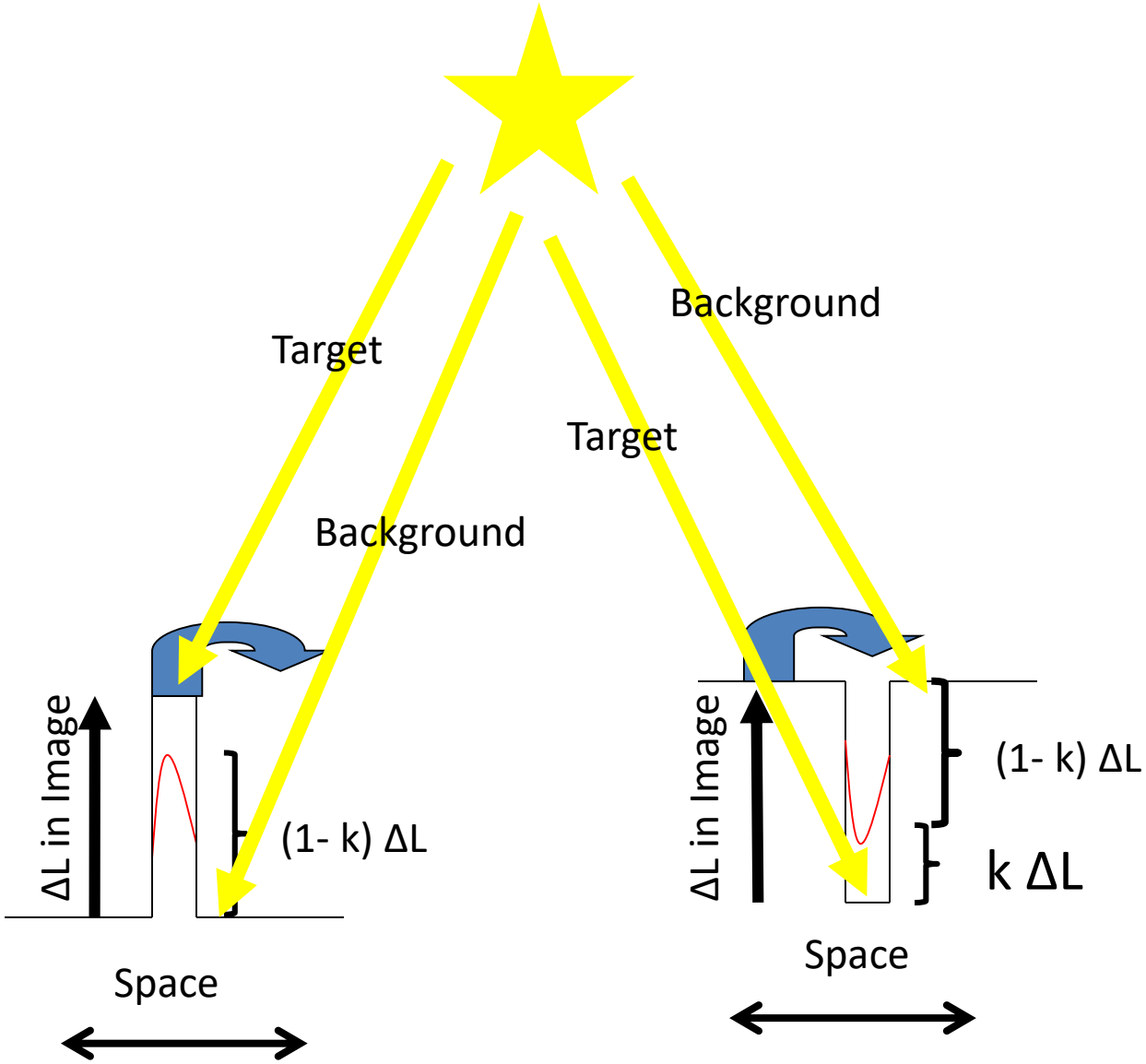


Chad McKee calculated k is the same for + or – contrasts of the same subtense and shape.

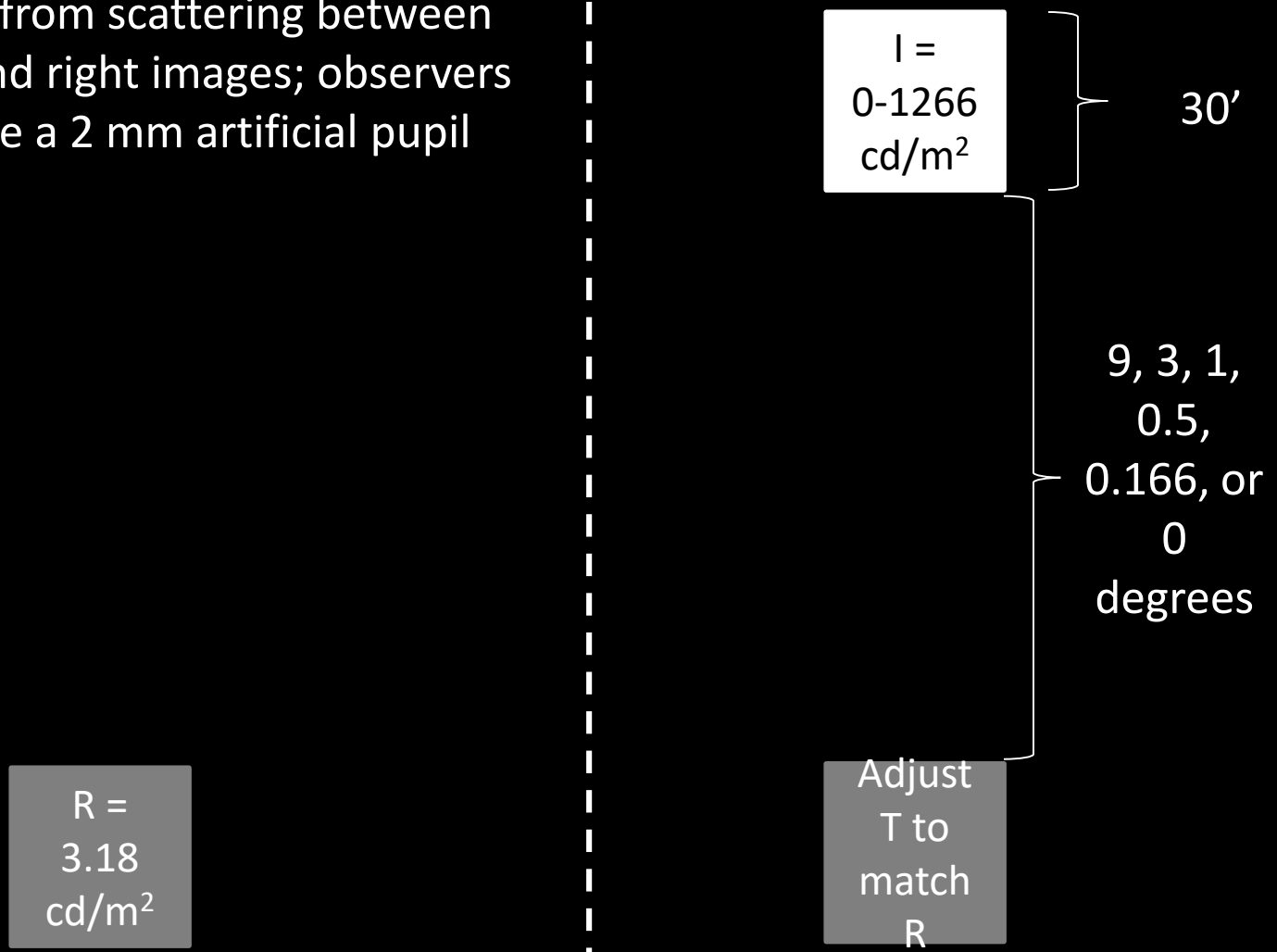
Visual Subtense of Contrast	E with Stroke = 20% of subtense		Disk		Line with 2’ stroke	
	2.5 mm Pupil dia.	5 mm	2.5 mm	5 mm	2.5 mm	5 mm
2°	k=0.0252	0.0174	0.0588	0.072	0.301	0.4822
1°	0.0419	0.0448	0.0563	0.0667	0.2984	0.4845
30’	0.0667	0.0675	0.0536	0.0601	0.2932	0.4702
15’	0.1182	0.2055	0.0782	0.0862	0.2935	0.467
7.5’	0.2554	0.3769	0.1469	0.1881	0.295	0.4873

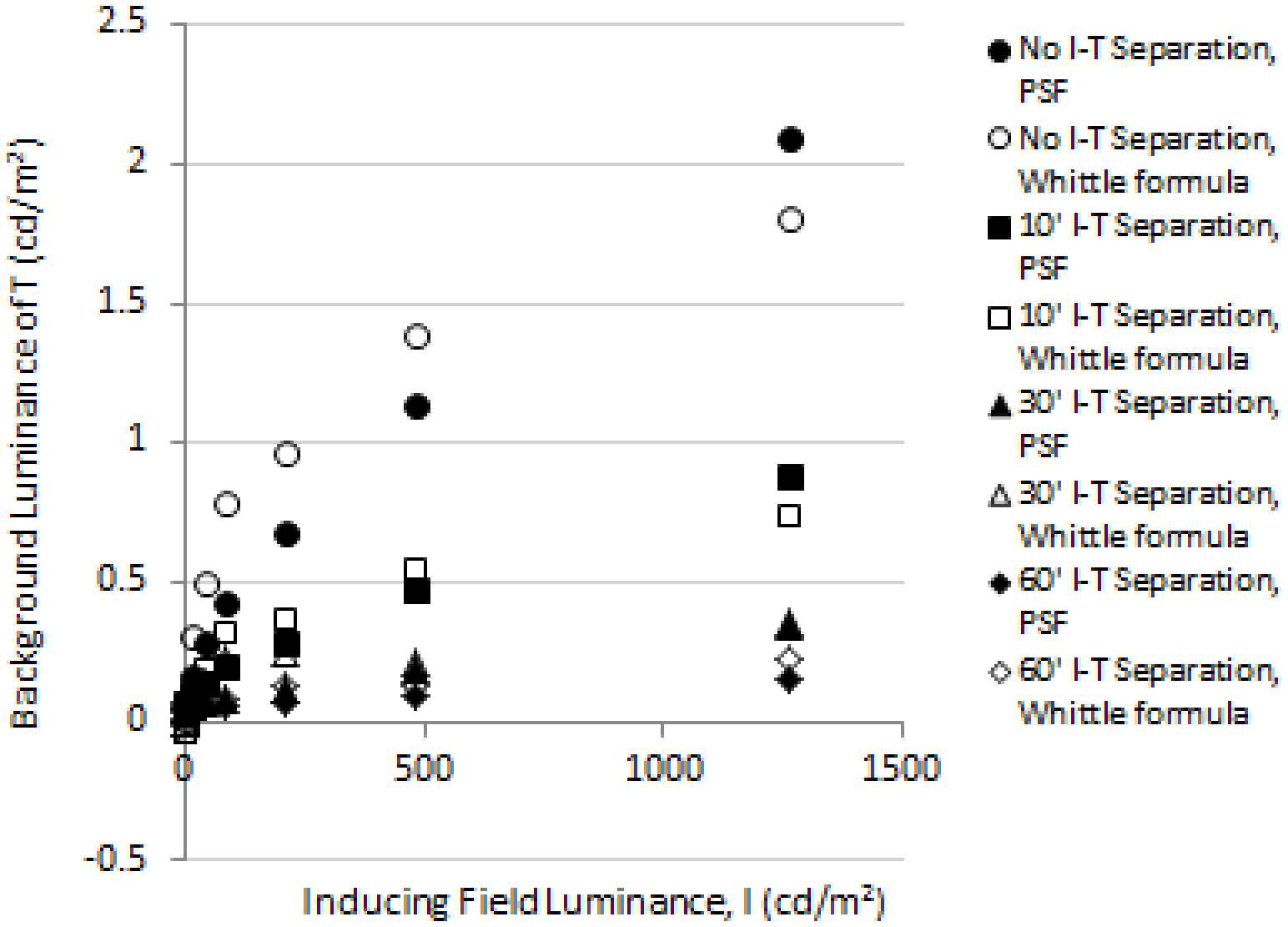
Visual Subtense of Contrast	E with Stroke = 20% of subtense		Disk		Line with 2' stroke	
Pupil diameter:	2.5 mm	5 mm	2.5 mm	5 mm	2.5 mm	5 mm
2°	**24.4 EPD (0-100 cd*m^{-2})**	**25.2**	**22.2**	**21.5**	**15.8**	**12.8**
1°	**23.1**	**22.9**	**22.3**	**21.8**	**15.9**	**12.8**
30'	**21.8**	**21.7**	**22.4**	**22.1**	**16.0**	**13.0**
15'	**19.9**	**17.7**	**21.3**	**20.9**	**16.0**	**13.0**
7.5'	**16.7**	**14.5**	**19.0**	**18.1**	**15.9**	**12.7**

A surround highlight preserves retinal ΔL because it increases background and target luminances almost equally



Haploscopic separation prevents light from scattering between left and right images; observers wore a 2 mm artificial pupil




2.5
2
1.5
1
0.5
0
-0.5
0
500
1000
1500
Background Luminance of T (cd/m²)
Inducing Field Luminance, I (cd/m²)
No I-T Separation, PSF
No I-T Separation, Whittle formula
10' I-T Separation, PSF
10' I-T Separation, Whittle formula
30' I-T Separation, PSF
30' I-T Separation, Whittle formula
60' I-T Separation, PSF
60' I-T Separation, Whittle formula

Three subtasks:

1. Recommend a formula or computational method.
2. Show that the formula works for self-luminous color difference calculation.
3. Clarify (and perhaps standardize) the meaning of “neutral” in the self-luminous context of this TC.

Using Whittle's formula in self-luminous color difference

- Several authors have shown that the Whittle formula fits as well as L* in CIELUV and CIELAB.
- Oleari and Melgosa showed Whittle's formula fits full gamut of OSA-UCS.
- Melgosa showed Whittle formula fits in CIEDE2000, using many data sets.

Three subtasks:

1. Recommend a formula or computational method.
2. Show that the formula works for self-luminous color difference calculation.
3. Clarify the meaning of “neutral” **in the self-luminous context of this TC**.

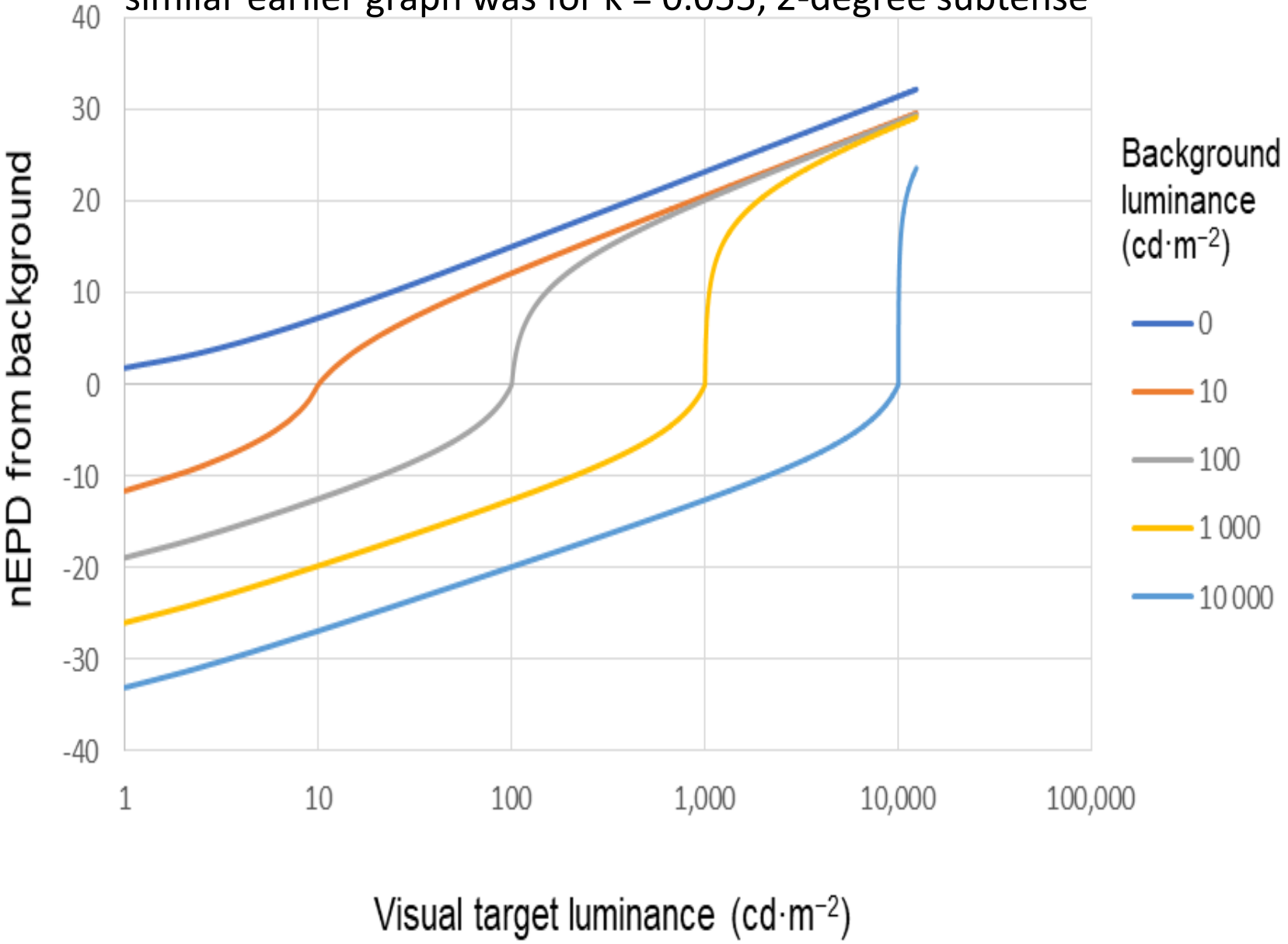
The Meaning of Self-luminous Neutral

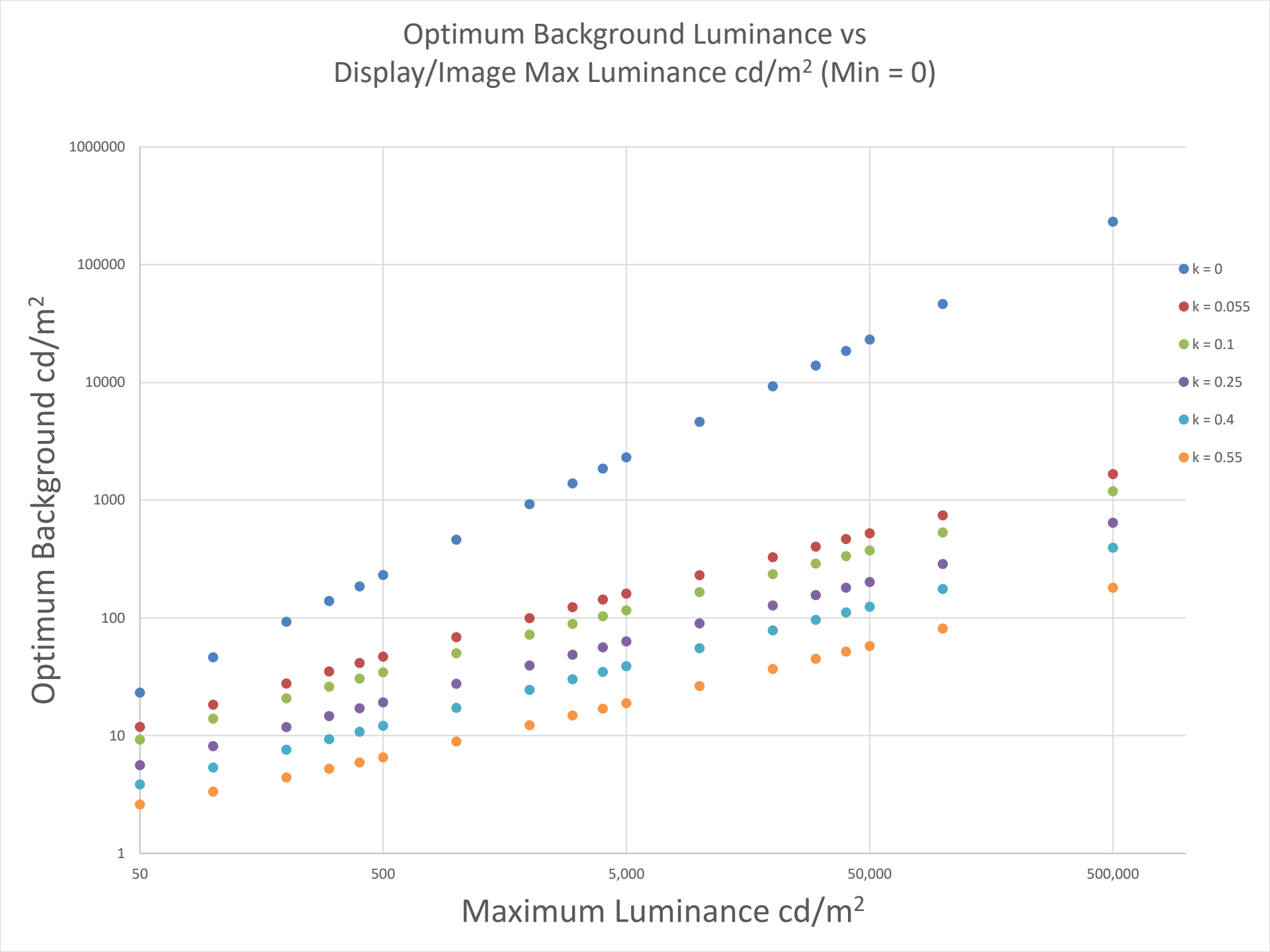
- Adopted Bosten, Beer and MacLeod (JOV, 2015) chromaticity coordinates for neutral.
  - Close to status-quo neutral of D65
  - Presumed, based on preponderance of evidence, to be the same for all levels of luminance.
- Adopted Fairchild's calculation of chromatic adaptation to a self-luminous display.
- A glossary of self-luminous neutral terminology is provided in the TC1-93 report.

nEPD = a log(1 + bW)…What's It Good For?

- Derived from a self-luminous display; applies to self-luminous contrasts from background.
- Recognizes positive or negative contrasts fm background
- Produces a neutral scale with desired nEPD in any given range of luminance.
- Predicts what luminances match (on different backgrounds)
- Derivative predicts threshold ΔL at any L and L_b
- Accounts for subtense effects (smaller is darker)
- Models crispening and black phenomena
  - Theoretically fruitful: optimum background luminance to maximize nEPD, histogram specification to match human visual discrimination
  - Is good for modeling discriminations during visual search

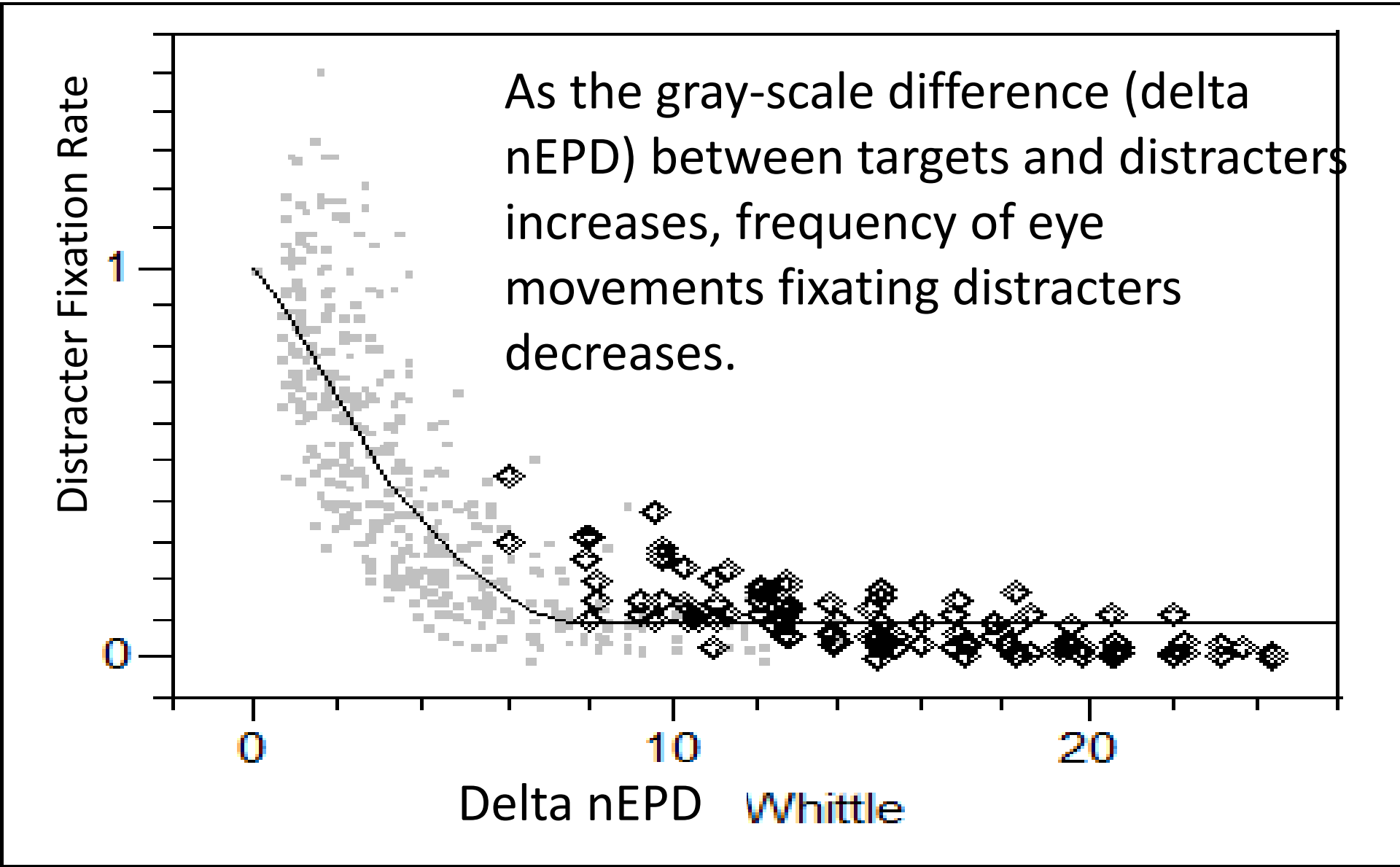
k = 0.0, i.e., for contrast of practically infinite visual subtense;
similar earlier graph was for k = 0.055, 2-degree subtense




Optimum Background Luminance vs
Display/Image Max Luminance cd/m2 (Min = 0)
Optimum Background cd/m2
1000000
100000
10000
1000
100
10
1
50
500
5,000
50,000
500,000
Maximum Luminance cd/m2
k = 0
k = 0.055
k = 0.1
k = 0.25
k = 0.4
k = 0.55

k	Equation for optimum L_b between 0 and L2 cd/m²	R^2
0	Lopt =0 .4624L2	>0.99995
0.055	Lopt = 1.6588L2^0.5328	0.9989
0.1	Lopt = 1.2947L2^0.5244	0.9994
0.25	Lopt = 0.7781L2^0.5142	0.9998
0.4	Lopt =0 .5269L2^0.5048	>0.99995
0.55	Lopt = 0.3746L2^0.4644	0.9985

Calculating Discriminability of Grays (Visual Search)



Limitations of Whittle's Formula:

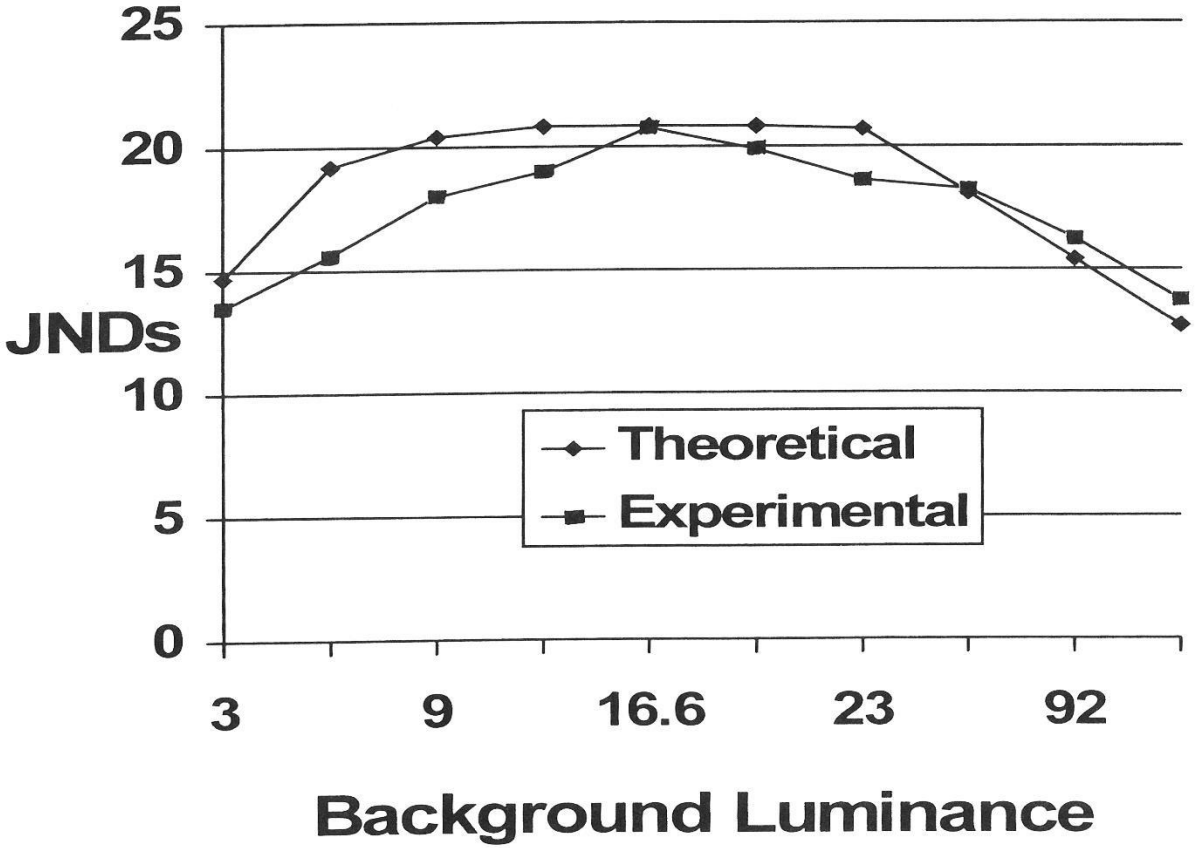
It models retinal & ocular processes, not cortical

- Doesn't include (possible) source illuminant
  - Geld Effect, Adelson Illusion,
    meaning of "neutral"
- Doesn't model 3D appearance
  - Shadows, veil, transparency, depth planes
- Doesn't account for Gestalt "belongingness"
  - Benary Cross, White's Illusion

! Many applications are 2D without an implied source of illumination.

! A later comprehensive model including "cortical" factors will need a retinal-ocular component.

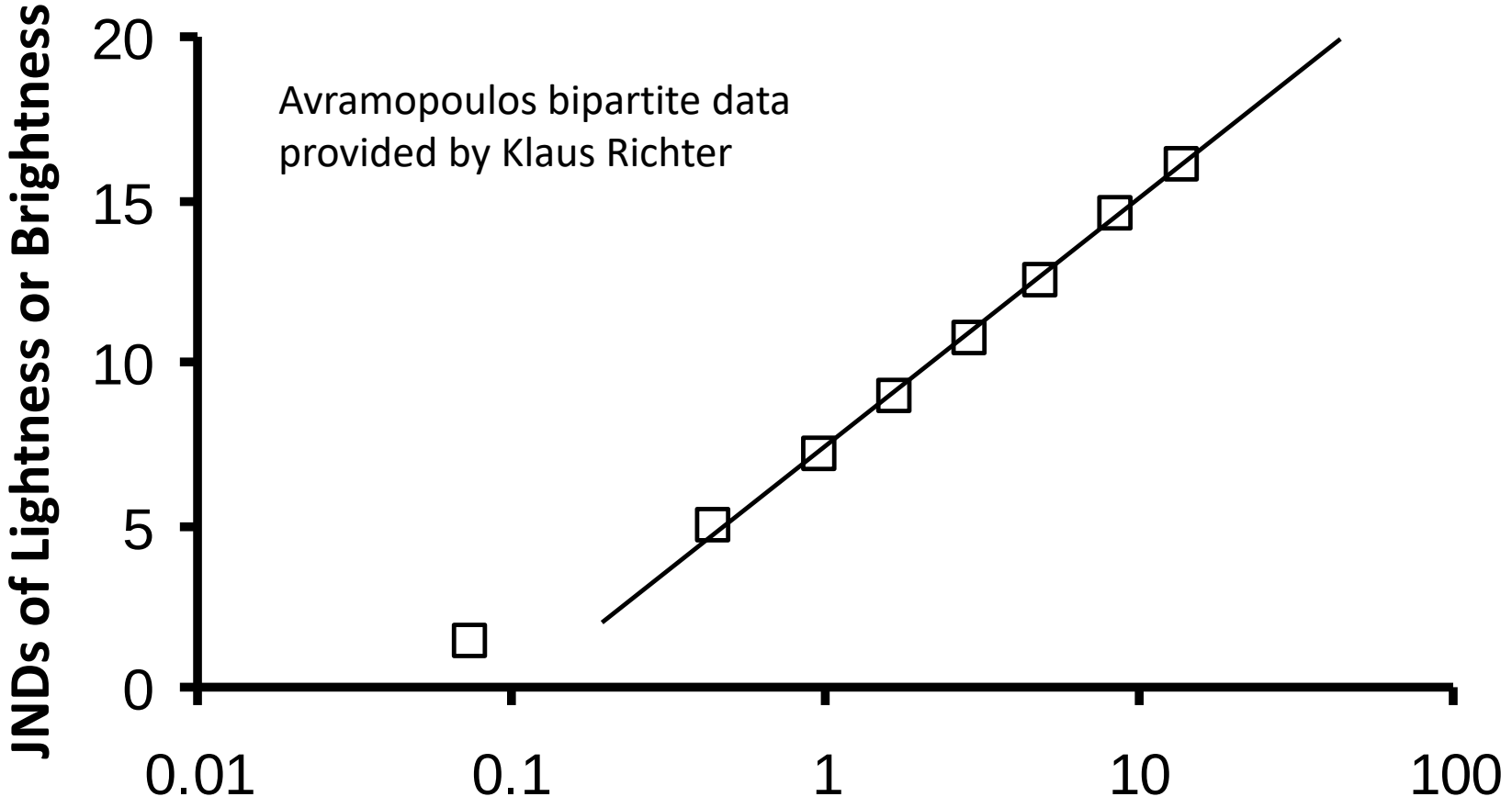
Target JNDs from 3 to 111 cd/m^2



Whittle Formula Applied to Bipartite Threshold Data,

formerly successful with periodic and disk discriminations

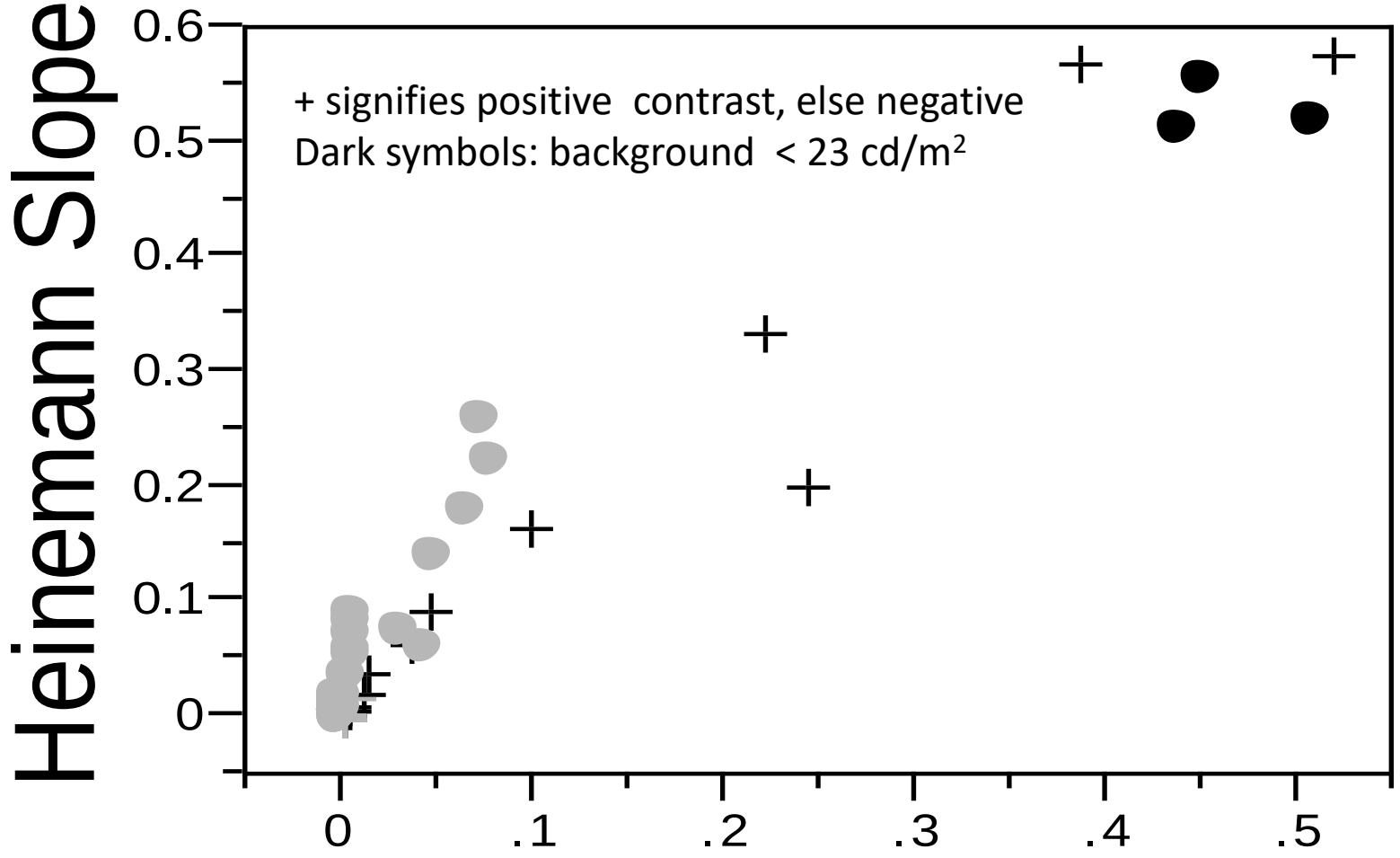
Analysis and plotting by Thorstein Seim, personal communication, 2015



1992, Vision Research for a similar plot re suprathreshold disks

Plot of independent slope estimates

78 combinations of target and background luminances (> 5 log units)



CIE Technical Committee TC1-93

CIE Division 1, Vision Subdivision, completed January 2018

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