Comparison of Efficacy Determination of SSL products

Marijn van Veghel,
Edgar Vuelban, Jan Snoeij, Petri Kärhä

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Goal

- **Goal**: determination of the state-of-the-art of SSL characterization at NMIs through regular calibration services

- Primary set of parameters:
  - Total luminous flux
  - Electrical power
  - Luminous efficacy
- Secondary set of parameters:
  - Correlated Colour Temperature (CCT)
  - Chromaticity (x, y)

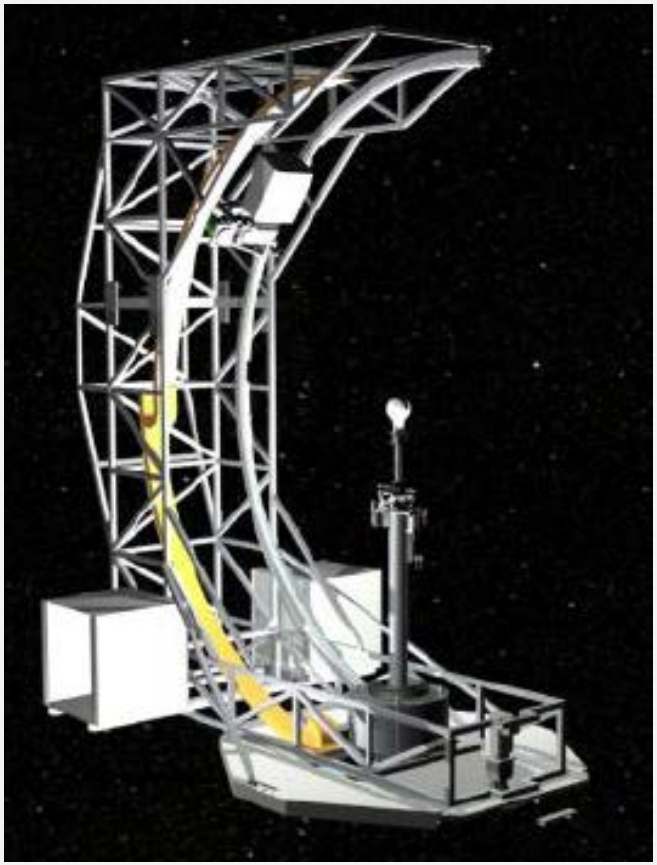
Artefacts

Identifier	Picture	Manufacturer	Model	Nominal CCT	Rated voltage or current	Rated power
1		Philips	Master LED bulb E27	2700 K	230 V AC	12 W
2		Osram	PAR16 20 CW 20°	5000 K	230 V AC	5 W
3		RetroFix	SMD Clear Tube 120 cm length 6000K 140°	6000 K	230 V AC	18 W
4		Osram	64476 BT Sil 100W E27	3000 K	230 V AC	100 W

Participants

Laboratory	Instrument used for luminous flux	Instrument used for colorimetric quantities
Aalto	Sphere photometer (1.65 m)	Sphere spectroradiometer
CSIC	Sphere photometer (3 m)	Sphere spectroradiometer
INRIM	Goniophotometer	Goniospectroradiometer (2.795 m)
LNE	Sphere photometer (2 m)	Sphere spectroradiometer
MKEH	Sphere photometer (1.5 m)	Sphere spectroradiometer
NPL	Goniophotometer	Goniospectroradiometer (1.677 m)
PTB	Goniophotometer	Goniospectroradiometer (2. 5 m)
SMU	Sphere photometer (1m)	Sphere spectroradiometer
SP	Sphere photometer (1.5 and 3 m)	Sphere spectroradiometer
VSL (pilot)	Sphere photometer (3 m)	Sphere spectroradiometer

Instruments



Comparison scheme

- 9 sets of artefacts
  1. Measured by pilot
  2. Measured by one participant lab
  3. Remeasured by pilot
- Motivation:
  - Comparison duration
  - Stability of artefacts

Measurement procedure

- 230 V 50 Hz power supply
  - Measurement of RMS current and RMS power during photometric measurement
- Ambient temperature (25 ± 1) ºC
  - Measured at same height and within 1 m of lamp
  - Correction if measured at different temperature
- All lamps mounted base-up
  - Except TL
- Artefacts seasond by pilot for 100 h
- Stabilization to within 0.5% over 30 min window by participants
  - Light output and electrical power
- **Measurement according to normal calibration procedure**

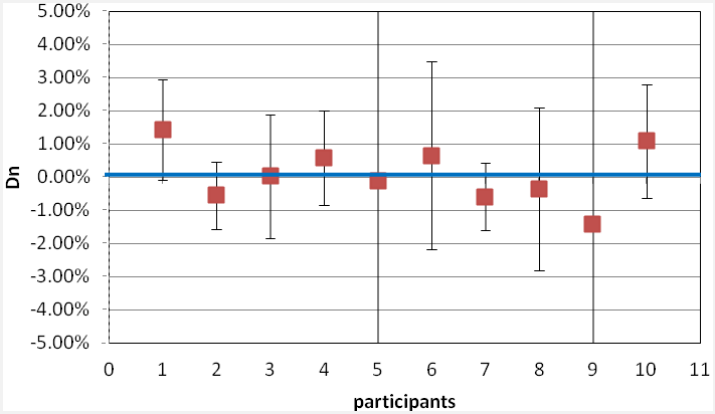
Data analysis

- To compare results there should be a single reference value
- But different artefacts used
- Solution scale back to “virtual” artefact based on pilot lamp data

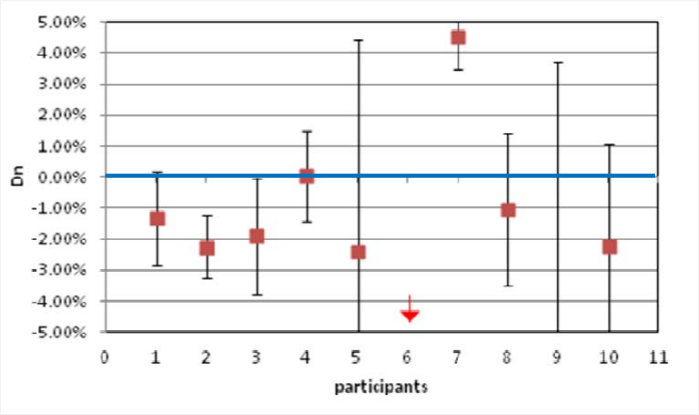
- **Unilateral degree-of-equivalence Dn** : relative difference of participant result to reference vale
- Uncertainty includes both uncertainty of participant and reference

Results: luminous flux

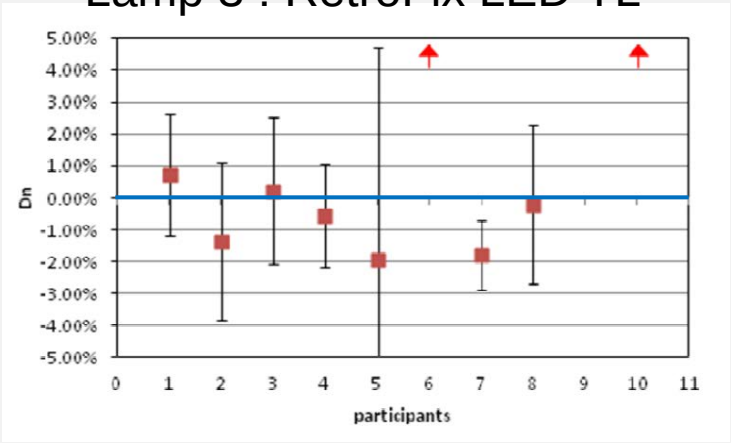
Lamp 1 : Philips Master LED



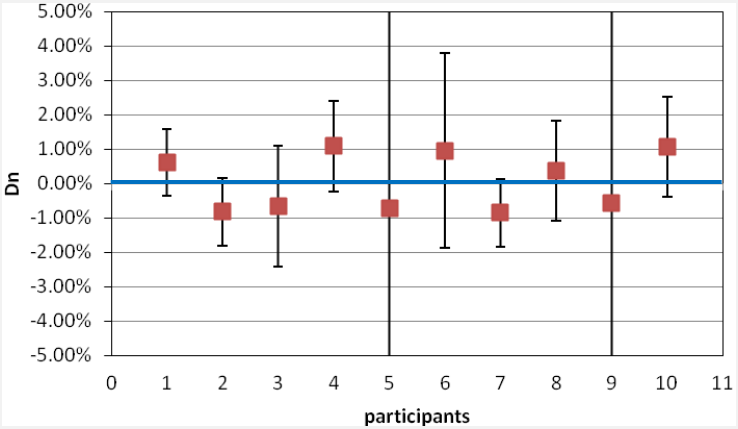
Lamp 2 : Osram LED spot



Lamp 3 : RetroFix LED TL

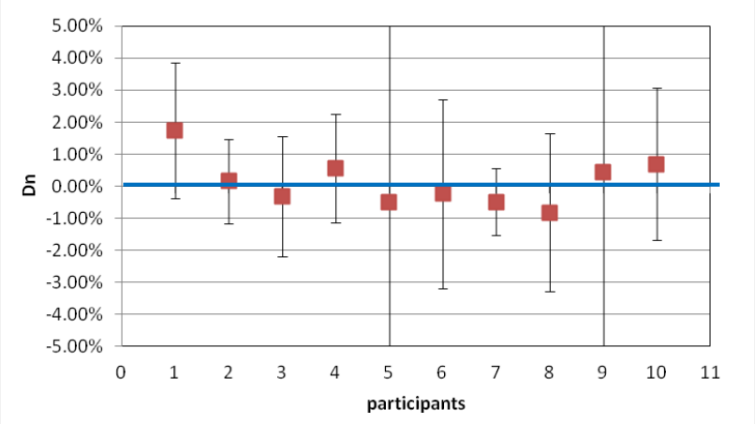


Lamp 4 : Osram incandescent

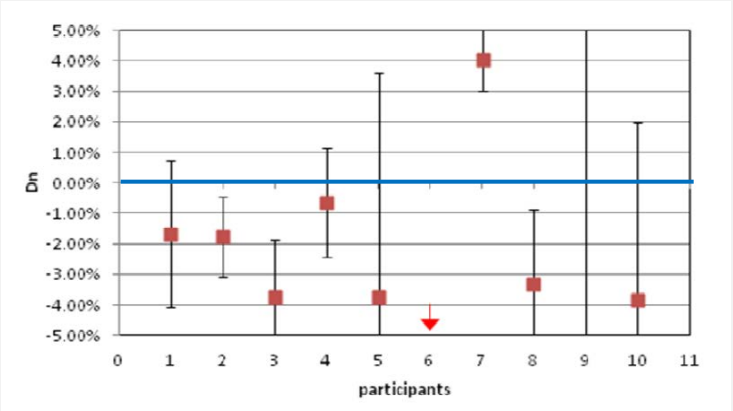


Results: luminous efficacy

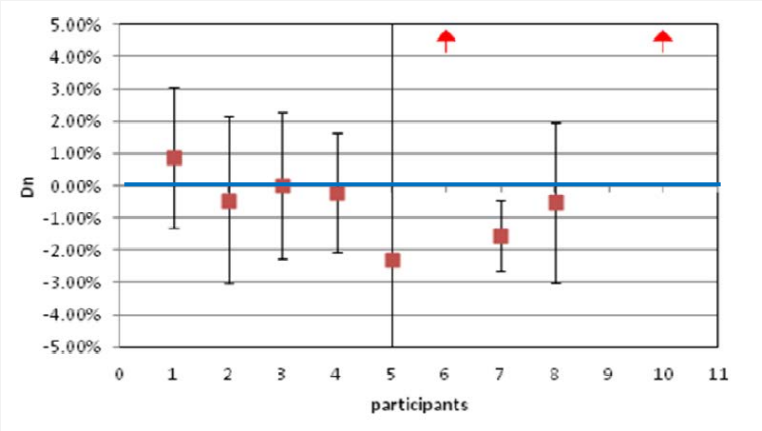
Lamp 1 : Philips Master LED



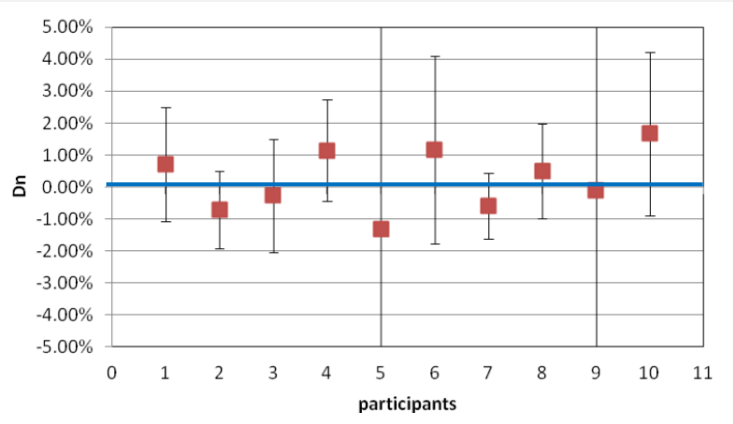
Lamp 2 : Osram LED spot



Lamp 3 : RetroFix LED TL

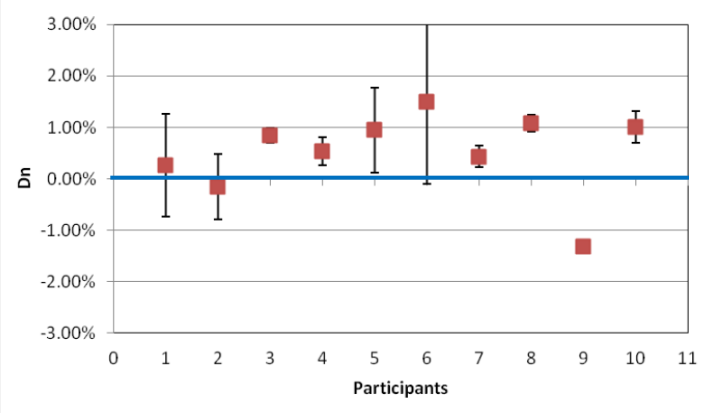


Lamp 4 : Osram incandescent

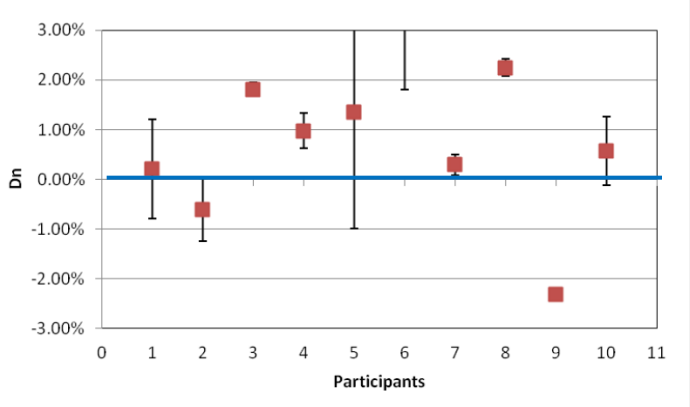


Results: electrical power

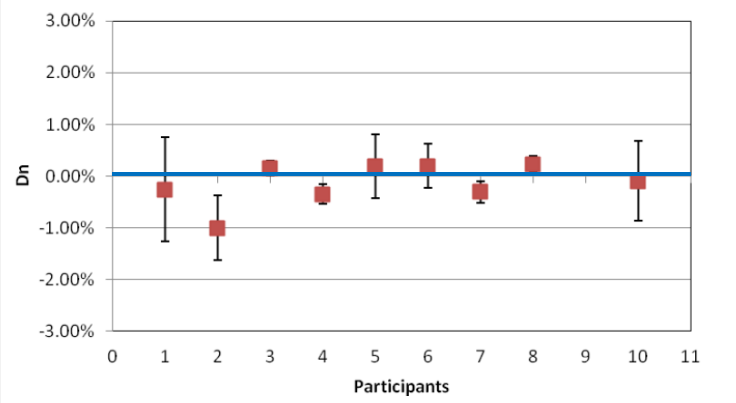
Lamp 1 : Philips Master LED



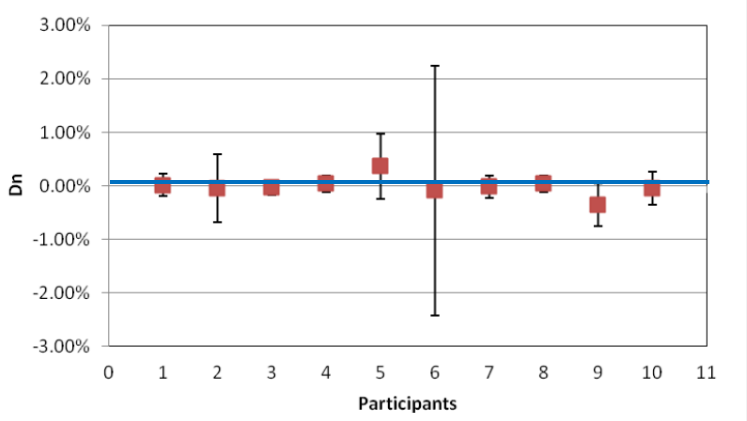
Lamp 2 : Osram LED spot



Lamp 3 : RetroFix LED TL

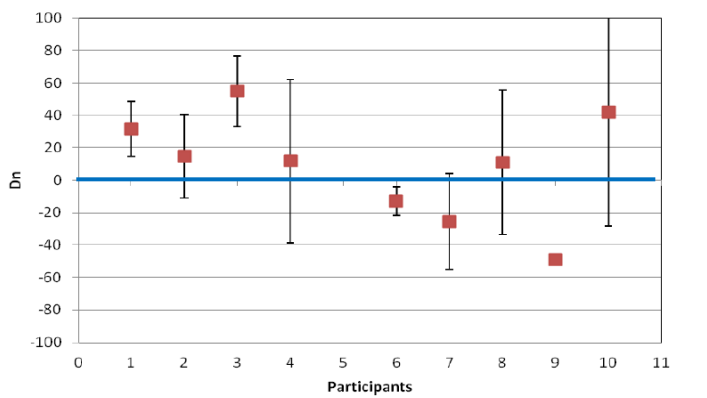


Lamp 4 : Osram incandescent

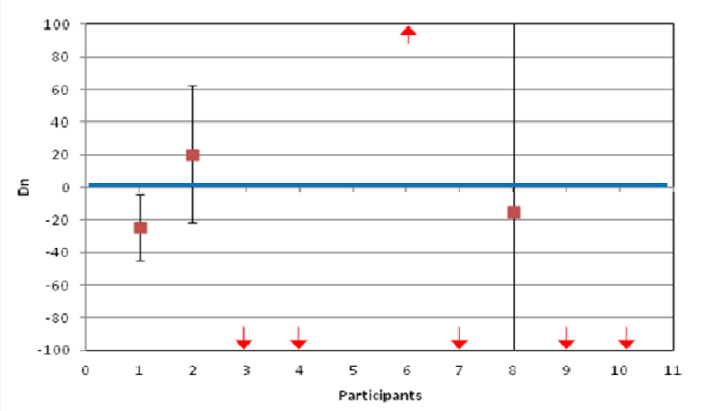


Results: CCT

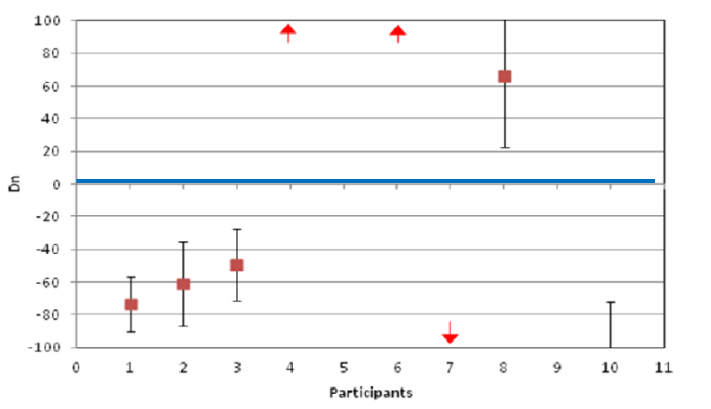
Lamp 1 : Philips Master LED



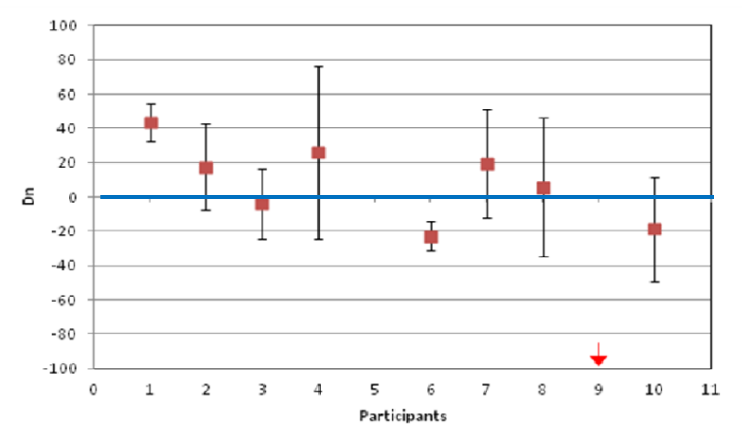
Lamp 2 : Osram LED spot



Lamp 3 : RetroFix LED TL

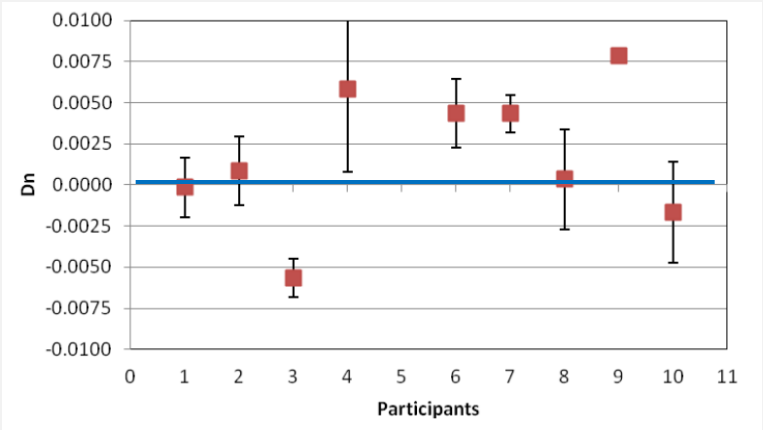


Lamp 4 : Osram incandescent

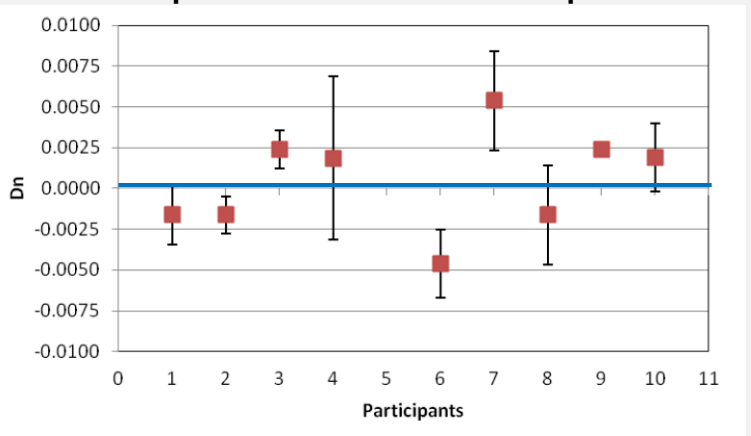


Results: chromaticity x

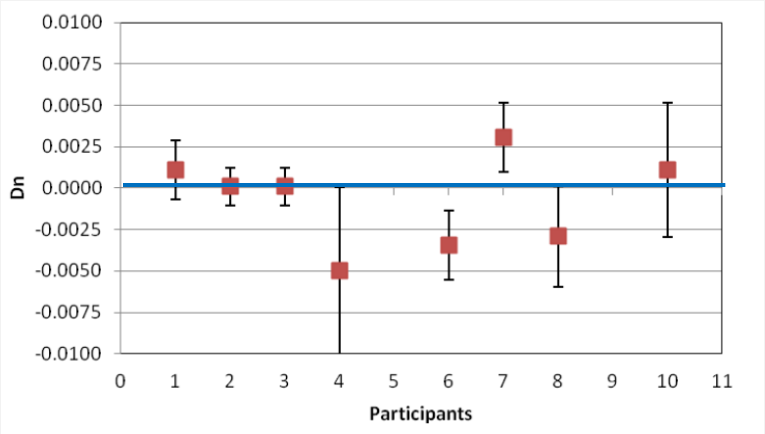
Lamp 1 : Philips Master LED



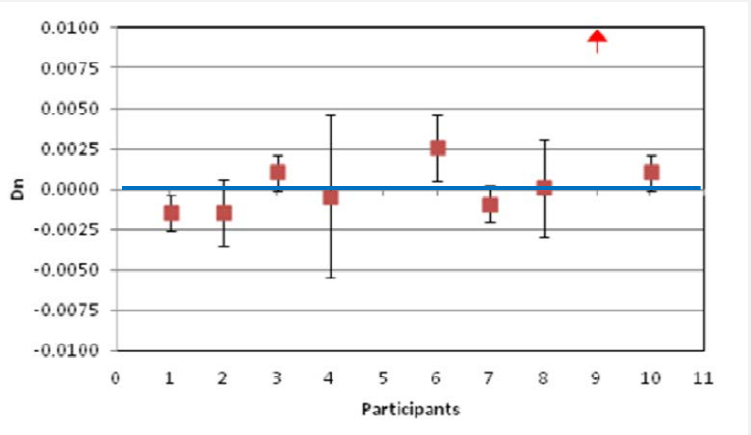
Lamp 2 : Osram LED spot



Lamp 3 : RetroFix LED TL

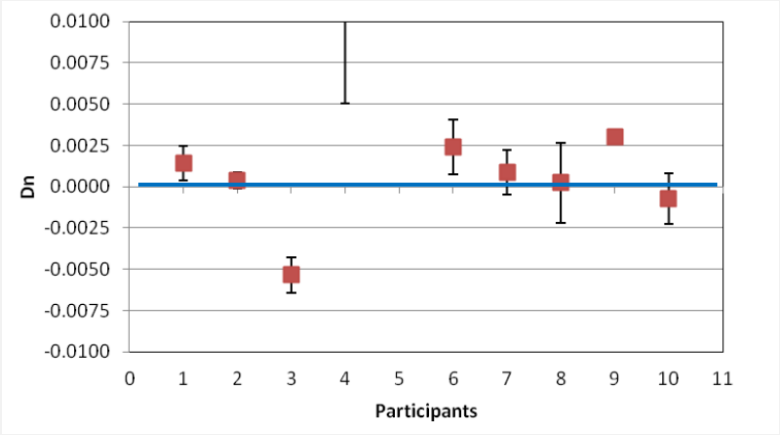


Lamp 4 : Osram incandescent

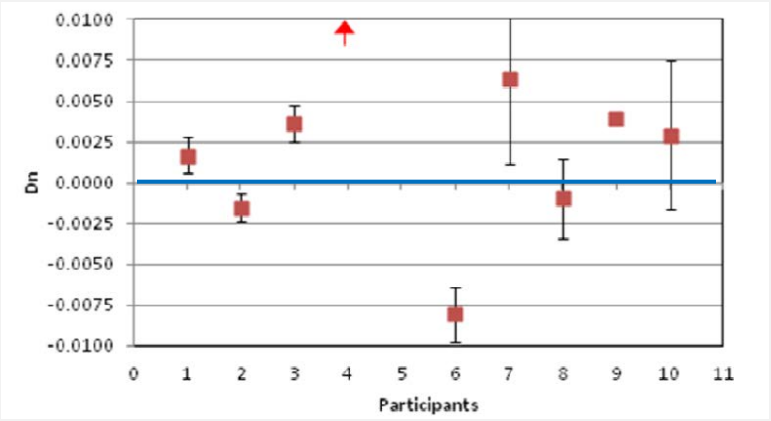


Results: chromaticity y

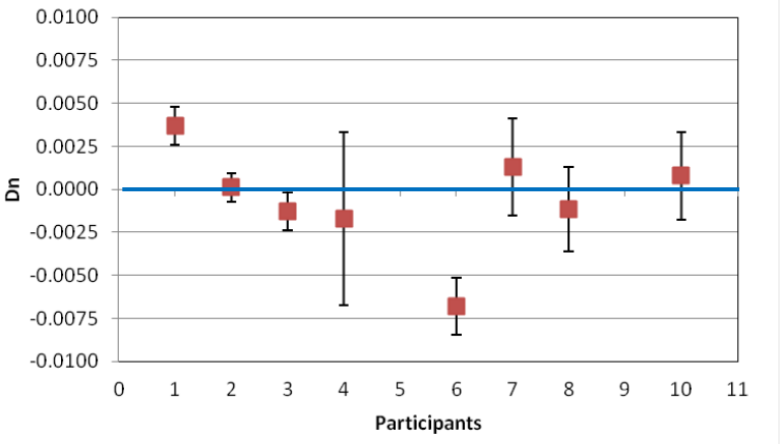
Lamp 1 : Philips Master LED



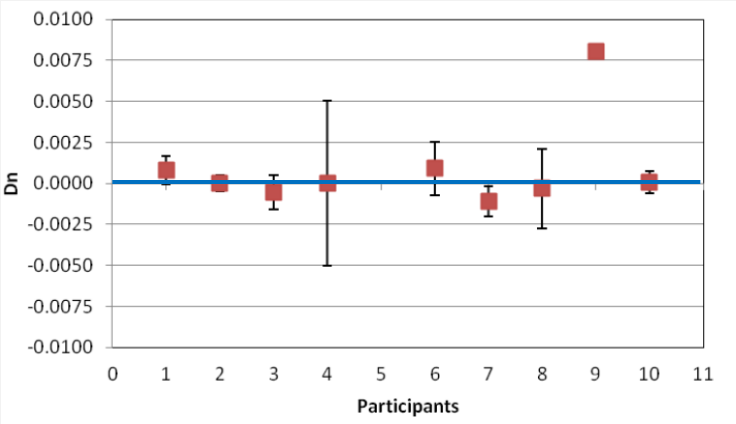
Lamp 2 : Osram LED spot



Lamp 3 : RetroFix LED TL



Lamp 4 : Osram incandescent



Conclusions

- Luminous flux and efficacy:
  - Good agreement for for Philips Master LED
  - Large deviations for LED spot
  - Two extreme outliers; otherwise good agreement for LED TL
- Electrical power: underestimated uncertainties for all three LED lamps
- Colorimetric measurements: large deviations
  - In particular for CCT
  - LED spot and LED TL most difficult
  - No general agreement for incandescent, but better than for LED lamps

Recommendations

- Measurement procedures should be specified in more detail in order to obtain comparable results
- Alternatively, anything left open in the specification should be included in the uncertainty
- Extra effort should be put into quantifying the uncertainties for colorimetric parameters

VSL
PO Box 654
2600 AR Delft
The Netherlands

T +31 15 269 15 00
F +31 15 261 29 71
E info@vsl.nl
I www.vsl.nl

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Data scaling

- Participant *n* measures for their artefact of type *m*: $X_{n,m} \quad n = 2,\ldots,10; m = 1,\ldots,4$
- Pilot measures for same artefact: $X^{P}_{n,m} = \frac{1}{2}\left(X^{P,\text{before}}_{n,m} + X^{P,\text{after}}_{n,m}\right)$
- Pilot overall value for artefact type *m*: $X_{1,m} = \frac{1}{9}\sum_{n=2}^{10} X^{P}_{n,m}$
- Large difference between individual artefacts; factor: $f_{n,m} = \frac{X^{P}_{n,m}}{X_{1,m}}$
- **"Virtual" data for participant *n*:** $\tilde{X}_{n,m} = \frac{X_{n,m}}{f_{n,m}}; \quad \tilde{X}_{1,m} = X_{1,m}$

Reference value

- Based on weighted-mean with cut-off, following CCPR guideline:

$$\tilde{X}_m^{\mathrm{RV}} = \sum_{n=1}^{10} w_{n,m} \tilde{X}_{n,m} \qquad w_{n,m} = \frac{u_{\mathrm{adj}}^{-2}(X_{n,m})}{\sum_{n=1}^{10} u_{\mathrm{adj}}^{-2}(X_{n,m})}$$

$$u_{\mathrm{adj}}(X_{n,m}) = \begin{cases} u_{\mathrm{rel}}(X_{n,m}) & \text{if } u_{\mathrm{rel}}(X_{n,m}) \geq u_{\text{cut-off}} \\ u_{\text{cut-off}} & \text{if } u_{\mathrm{rel}}(X_{n,m}) < u_{\text{cut-off}} \end{cases}$$

$$u_{\text{cut-off}} = \mathrm{average}\left(\left\{u_{\mathrm{rel}}(X_{n,m})\right\}\right) \quad \text{for } u_{\mathrm{rel}}(X_{n,m}) \leq \mathrm{median}\left(\left\{u_{\mathrm{rel}}(X_{n,m})\right\}\right)$$

Unilateral DOE

- Participant results are evaluated using the unilateral degree-of-equivalence:

$$D_{n,m} = \frac{\tilde{X}_{n,m}}{\tilde{X}_{m}^{\mathrm{RV}}} - 1$$

$$u_{\mathrm{rel}}(D_{n,m}) = \sqrt{u_{\mathrm{rel}}^2(\tilde{X}_{m}^{\mathrm{RV}}) + u_{\mathrm{rel}}^2(\tilde{X}_{n,m})}$$

$$u_{\mathrm{rel}}(\tilde{X}_{m}^{\mathrm{RV}}) = \sqrt{\frac{1}{\sum_{n=1}^{10} u_{\mathrm{adj}}^{-2}(X_{n,m})}}$$

Outlier summary

	Lamp 1: Philips Master LED	Lamp 2: Osram LED spot	Lamp 3: RetroFix LED TL	Lamp 4: Osram incandescent
Luminous flux	-	4	3	-
Luminous efficacy	-	5	3	-
Electrical power	**7**	**6**	**5**	-
CCT	4	**7**	**8**	3
Chromaticity x	**5**	**5**	3	3
Chromaticity y	**5**	**7**	3	2