

1 Photoreceptor inputs into pupil control

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13 **Abstract**

14 The size of the pupil depends on light level. Watson & Yellott (2012) developed a
15 unified formula to predict pupil size from luminance, field diameter, age, and number
16 of eyes. Luminance reflects input from the L and M cones in the retina but ignores
17 the contribution of intrinsically photosensitive retinal ganglion cells (ipRGCs)
18 expressing the photopigment melanopsin, which are known to control the size of the
19 pupil. We discuss the role of melanopsin in controlling pupil size by reanalysing an
20 extant data set. We confirm that melanopsin-weighted quantities, in conjunction with
21 Watson & Yellott's formula, adequately model intensity-dependent pupil size. We
22 discuss the contributions of other photoreceptors into pupil control.

23 In a paper adequately described as a *tour de force*, Watson and Yellott [1] developed
24 a unified formula to predict pupil size from luminance, field diameter, age, and
25 number of eyes. This letter concerns the parametrisation of the retinal intensity,
26 which in Watson and Yellott's model is given in terms of luminance, i.e. the radiance
27 of the stimulus weighted by the photopic luminosity curve $V(\lambda)$. $V(\lambda)$ corresponds to a
28 mixture of the L and M cones in the retina, thereby largely ignoring the potential role
29 of S cones, rods, and the intrinsically photosensitive retinal ganglion cells (ipRGCs)
30 expressing the photopigment melanopsin [2-4].

31 The observation that $V(\lambda)$ -weighted quantities do not predict pupil size is not new [5].
32 In 1962, Bouma [6] noted that the spectral sensitivity of pupil control is neither $V(\lambda)$
33 nor the rod-based $V'(\lambda)$, interjecting that the outcome of his experiments "may turn
34 out to be related to other adaptive processes in the human eye". Bouma himself
35 modelled the spectral sensitivity as a combination of S cones and rods. We know
36 now that steady-state pupil size is largely controlled by melanopsin.

37 To test if Bouma's data is consistent with melanopsin-based pupil control, we
38 reanalysed the intensity-response curves from Bouma [6] as follows. We first
39 extracted the data from Bouma's Figure 1 (Figure **1A**, **B**). For monochromatic lights,
40 which we assumed Bouma used, it is simple to convert the reported $V(\lambda)$ -weighted
41 luminous flux into a melanopsin-weighted radiant flux [7]. As radiant flux describes
42 the total amount of energy emitted by a source, it is not an appropriate measure to
43 describe corneal or retinal intensity, so the absolute quantities are not informative
44 unless a geometry is specified. Allowing for an arbitrary horizontal shift, Watson and
45 Yellott's model accounts well for the shape of the pupil response as a function of
46 melanopic radiant flux, except for long-wavelength lights (Fig. **1C**).

47 There is now a good body of evidence that all photoreceptors can control the
48 diameter of the pupil. The best evidence comes from studies examining pupil size
49 using the method of silent substitution, in which pairs of lights are alternated such
50 that only one photoreceptor class is stimulated [8, 9]. Studies examining pupil control
51 using this method are given in **Table 1**.

52 A key realisation is that while all photoreceptors may contribute to controlling the
53 pupil size, the when and how is important. For example, due to rod saturation [10],
54 rods are not expected to contribute to pupil control at photopic light levels. The
55 temporal regimes in which the photoreceptors contribute are also different. Notably,

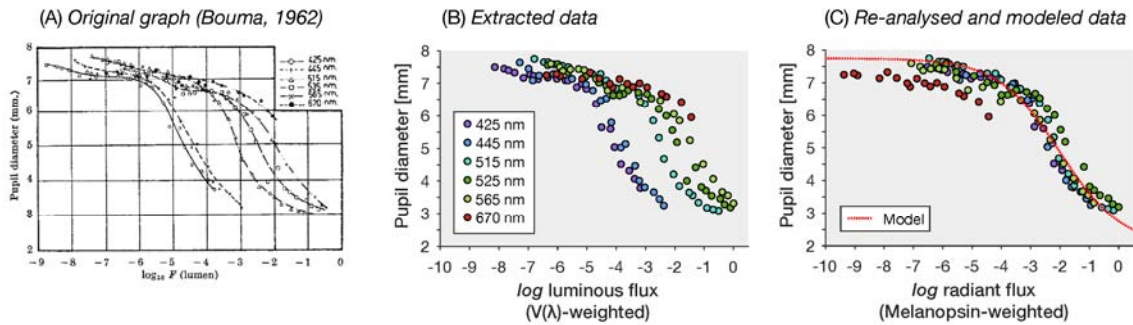
56 L+M stimulation is band-pass, while S cones and melanopsin are tuned to low
57 frequencies in driving the pupil [11]. McDougal and Gamlin [12] found that cones and
58 rods account for pupil constriction between 1 and 10 seconds from the onset of the
59 light exposure, at 100 seconds, pupil size is largely controlled by melanopsin with
60 some contribution from the rods.

61 To what extent does Watson and Yellott's use of luminance as an input parameter
62 call into question the generalizability of their model? From first principles, differences
63 between $V(\lambda)$ -weighted and melanopic quantities are largest with monochromatic
64 lights. But we typically do not live under monochromatic illumination. We explored
65 this question by examining the range of melanopic irradiances at a fixed illuminance.
66 In other words, how wrong would we be if we continued using $V(\lambda)$ -weighted
67 quantities to predict pupil size? Using a database of 401 polychromatic ("white")
68 illuminant spectra [13], we calculated the range of melanopic irradiance while
69 keeping the photopic illuminance fixed at 100 lux (Figure 2). Across all 401 spectra,
70 a 100 lux light source has a melanopic irradiance of 75.5 ± 23.4 mW/m². The range of
71 melanopic irradiances is between 20.4 and 164 melanopic mW/m², i.e. in the worst
72 case a factor of ~8. Whether or not this worst-case misprediction by using a $V(\lambda)$ -
73 weighted quantity has tangible consequences depends on the application. Predicting
74 pupil size in a psychophysical experiment at mesopic light levels requires less
75 stringent estimation of retinal intensity than safety-critical calculations.

76 A recent study reported attempted to derive a formula for predicting pupil size also
77 from melanopsin activation but only focused on a rather narrow luminance range
78 (50-300 cd/m²) [14]. While this is a good start, it might be a useful empirical exercise
79 to collect natural pupil sizes under a large range of illumination conditions (indoors,
80 outdoors) under natural behaviour with conjoint spectral measurements.

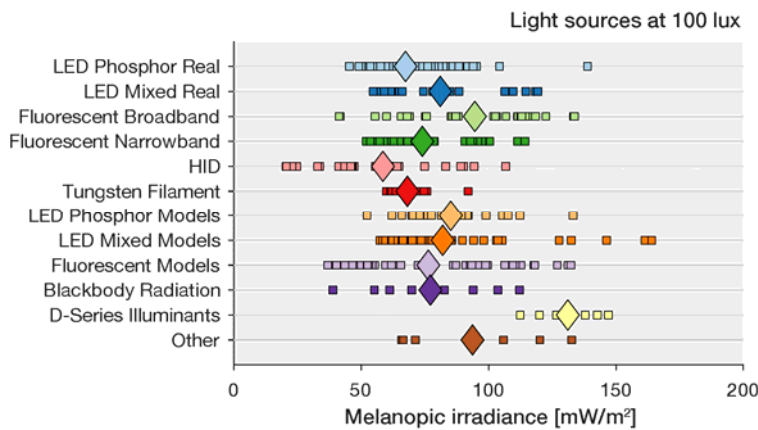
81 **Figures**

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Figure 1. **A** Original graph from Bouma [6] relating luminous flux to pupil diameter in millimeters. **B** Replotted extracted pupil size data (using WebPlotDigitizer, <https://automeris.io/WebPlotDigitizer/>). **C** Re-analysed (in terms of normalised melanopic radiant flux) and modelled pupil size data.



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Figure 2. Variability of the melanopic irradiance of 401 polychromatic “white” light sources [13] at 100 lux.

96 **Table 1: Evidence of photoreceptor contributions to pupil control**

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Photoreceptor class	Reference
Melanopsin	Tsujimura, et al. [15] Vienot, et al. [16] Tsujimura and Tokuda [17] Spitschan, et al. [11] Cao, et al. [18] Barrionuevo and Cao [19] Spitschan, et al. [20] Zelevansky, et al. [21]
L cone	Spitschan, et al. [11] (L+M) Spitschan, et al. [20] (L+M+S) Barrionuevo and Cao [19] Murray, et al. [22] Woelders, et al. [23]
M cone	Spitschan, et al. [11] (L+M) Spitschan, et al. [20] (L+M+S) Barrionuevo and Cao [19] Murray, et al. [22] Woelders, et al. [23]
S cone	Spitschan, et al. [11] Spitschan, et al. [20] Barrionuevo and Cao [19] Cao, et al. [18] Murray, et al. [22] Woelders, et al. [23]
Rods	Barrionuevo, et al. [24] Barrionuevo, et al. [25]

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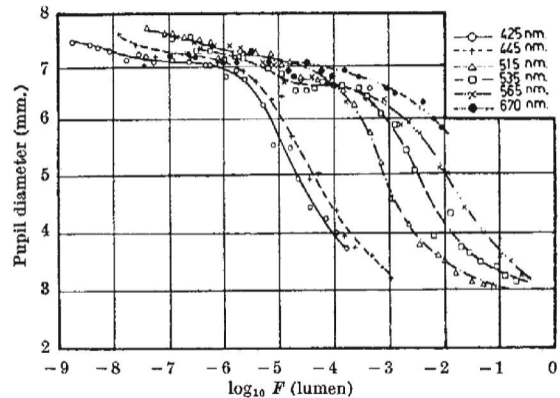
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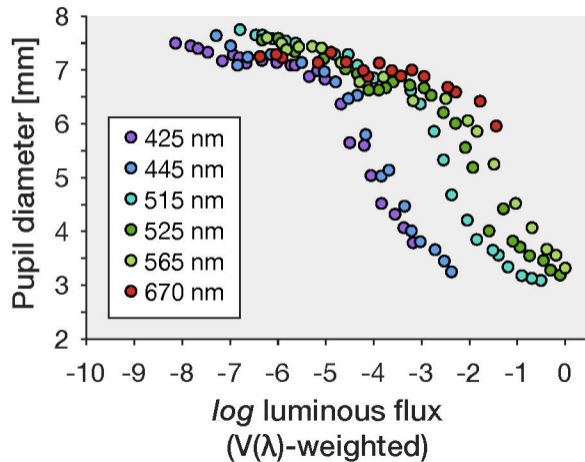
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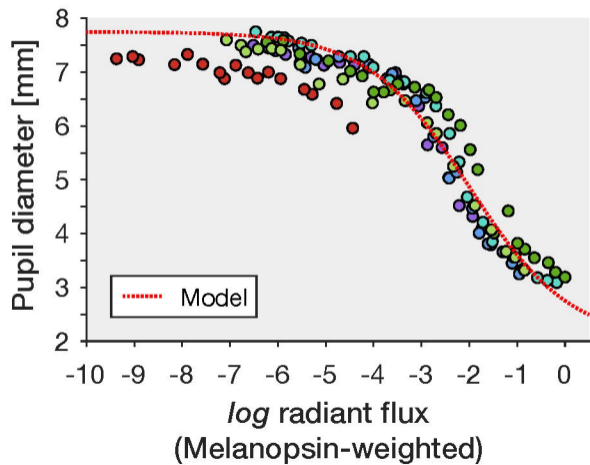
(A) Original graph (Bouma, 1962)



(B) Extracted data



(C) Re-analysed and modeled data



Light sources at 100 lux

