



# Pupil & Cognition



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# A multidisciplinary approach to the pupil

## Optics and function

Regulating retinal illuminant and image formation

## Cognition

Pupil : marker of memory load  
attention, emotion

## Psychiatry Neuropsychology

a marker of mental disorders

## Modeling

a 'simple' model of retroactive control

## Anatomy and circuits

an antagonistic control of the pupil through  
sympathetic and parasympathetic pathways



## Pharmacology/Neurology

Sensitivity to drugs/dissecting sub-cortical lesions

## Physiology/Genetics

a new opsine in 'non-visual' retinal ganglion cells  
regulating circadian cycles.

## Vision/Pupil perimetry

Pupillary Light reflex, sensitivity, mechanisms

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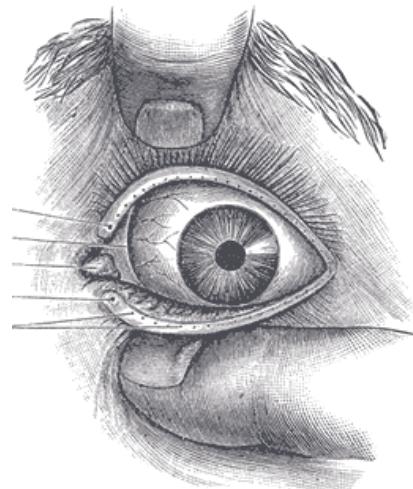
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## Neurology

a tool for dissecting sub-cortical lesions



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## Vision

Pupillary Motor reflex, sensitivity, mechanisms

# Functions of the pupil

## Normal pupil:

### Functions:

- ✓ Regulate the amount of light entering the eye

but changes in pupil surface are small ( $\sim 3 \text{ mm}^2$  -  $\sim 30 \text{ mm}^2$ ) compared to changes in illumination (several log unit changes)

- ✓ Adapting the optics of the eyes

### Pupil size variations :

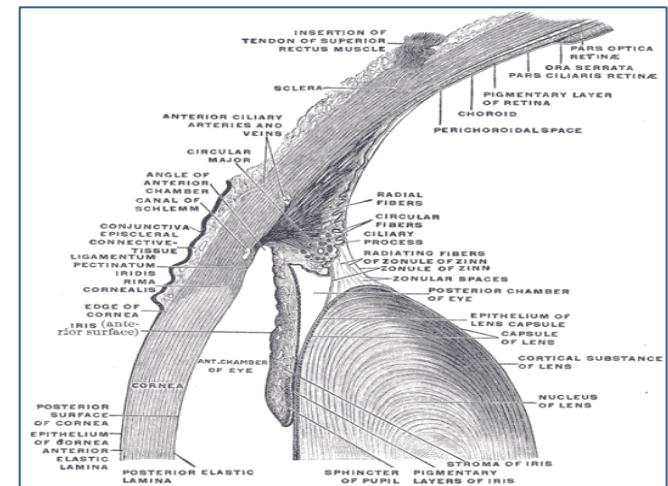
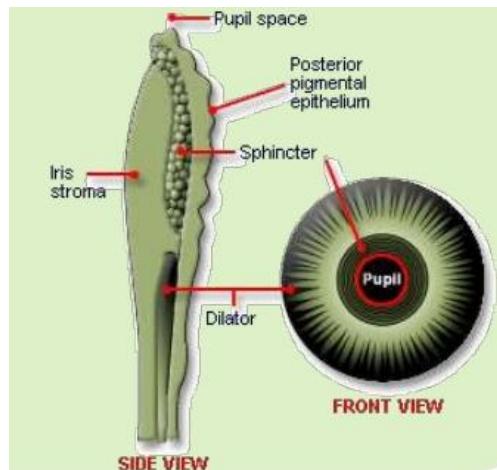
- ✓ always consensual (except in pathologies) : constriction = myosis, dilation= mydriasis
- ✓ Independent of gender and Iris color
- ✓ Depends on vergence and accommodation : the near Triad (detailed thereafter)

### Absolute size depends on:

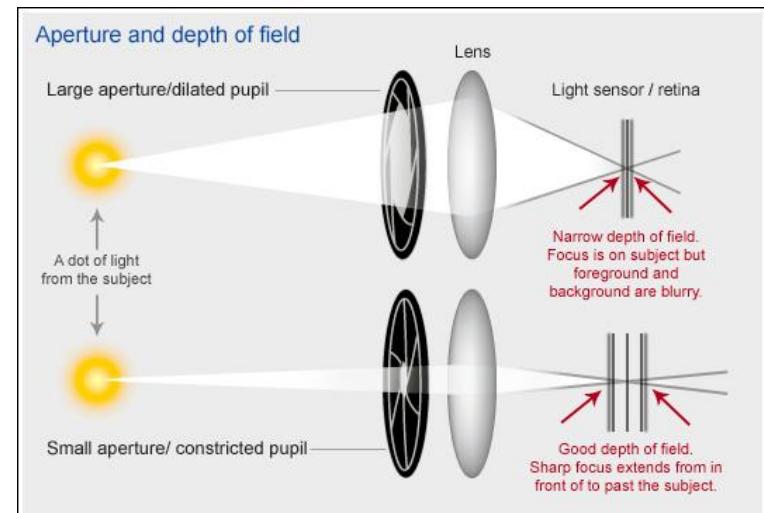
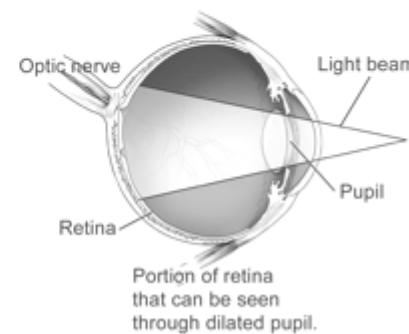
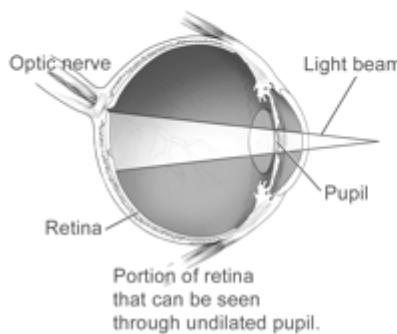
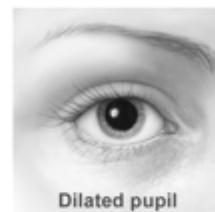
- ✓ Age : smaller in infancy and elderly
- ✓ Sleep: smaller
- ✓ Equal in size (isocoria) with exceptions (anisocoria, in  $\sim 20\%$  of normal individuals)

### Pupil driven by:

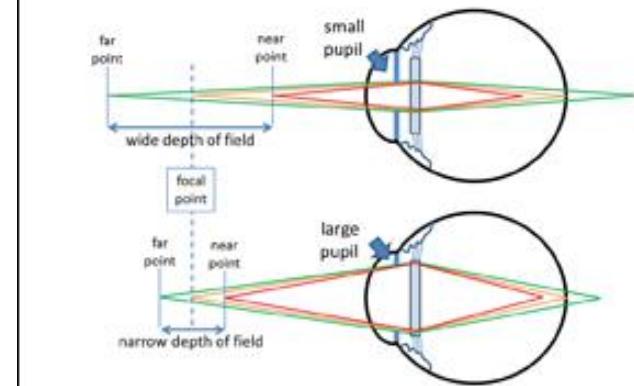
- ✓ Sphincter pupillae
- ✓ Dilator pupillae



# Functions of pupil: optics, depth of field, visual acuity, sensitivity



## Depth of Field vs. Pupil Size



# Functions of pupil: optics, visual acuity, sensitivity

Campbell, F. W., & Gregory, A. H. (1960).

Effect of size of pupil on visual acuity.

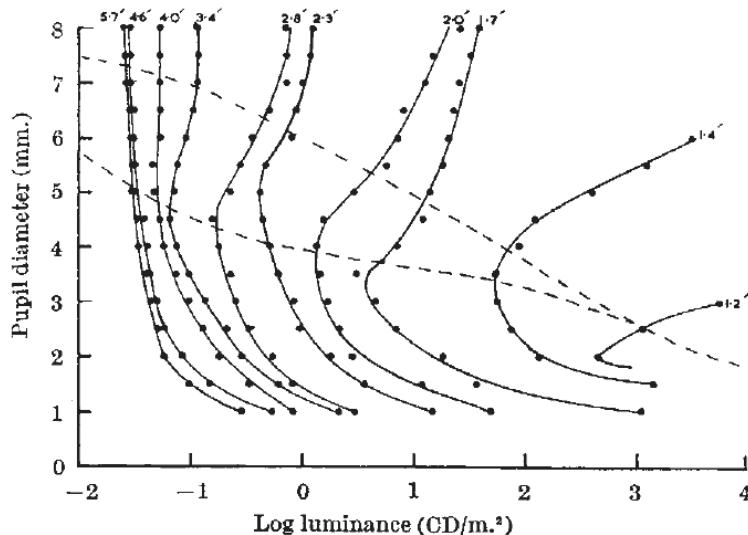


Fig. 1. Results of single run on subject A. H. G. Curves for different acuity patterns represent the lowest luminance at which the pattern is visible at various pupil sizes. Broken lines indicate

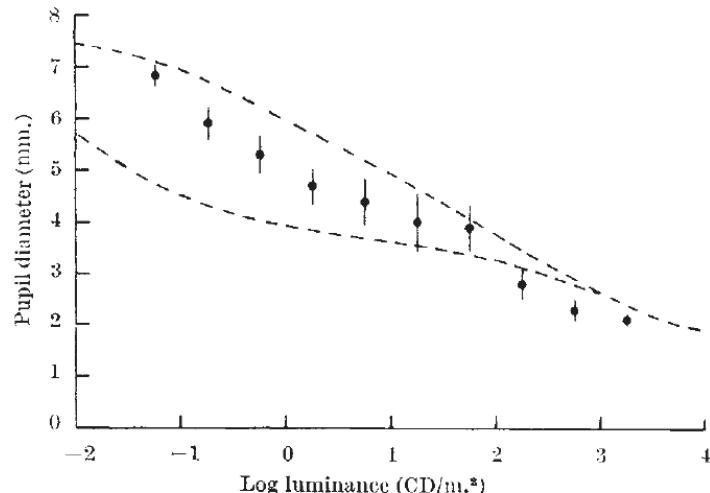


Fig. 2. Mean values of optimum pupil size from maxima of acuity curves such as in Fig. 1. Points represent means from 13 runs on 4 subjects, and extent of vertical lines indicates standard error of mean. Broken lines indicate natural pupil size as in Fig. 1

## OPTICAL QUALITY OF THE HUMAN EYE

BY F. W. CAMPBELL AND R. W. GUBISCH\*

*J. Physiol. (1966), 186, pp. 558-578*

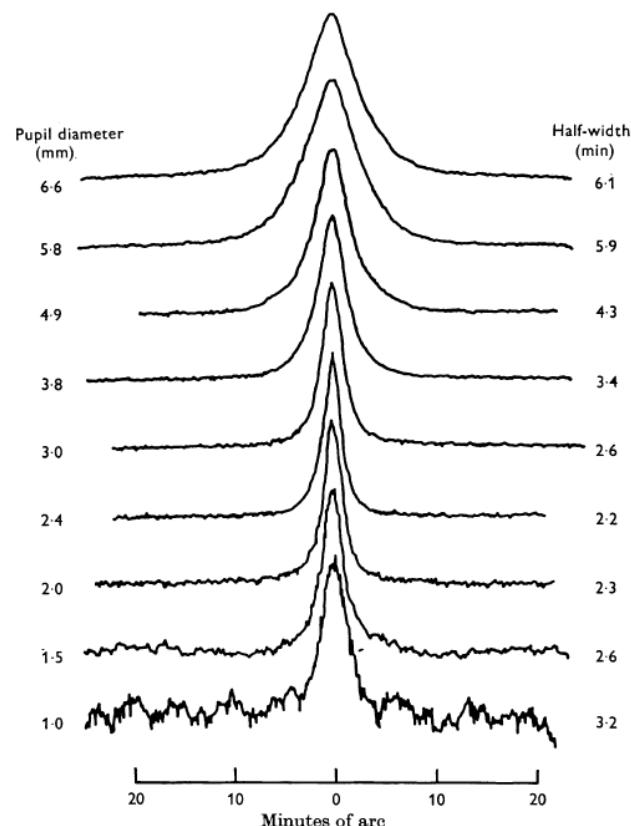
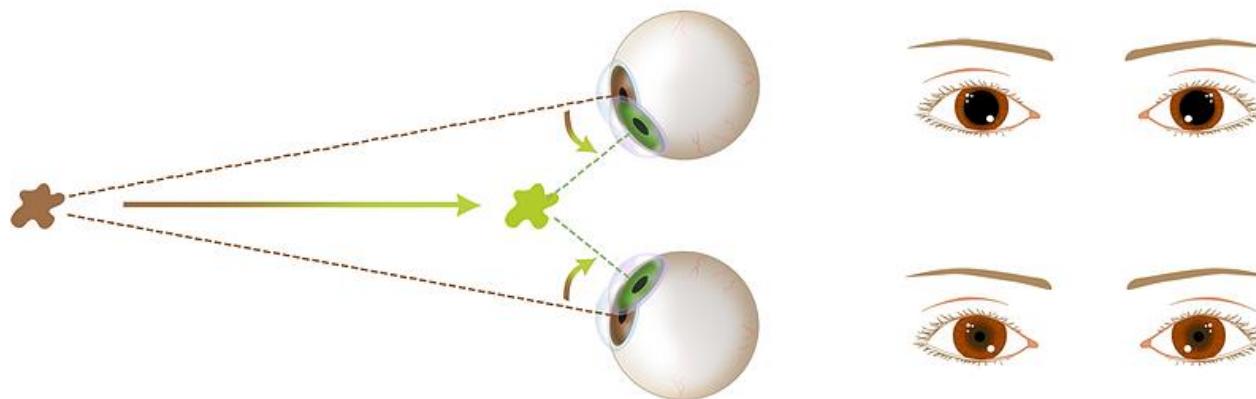
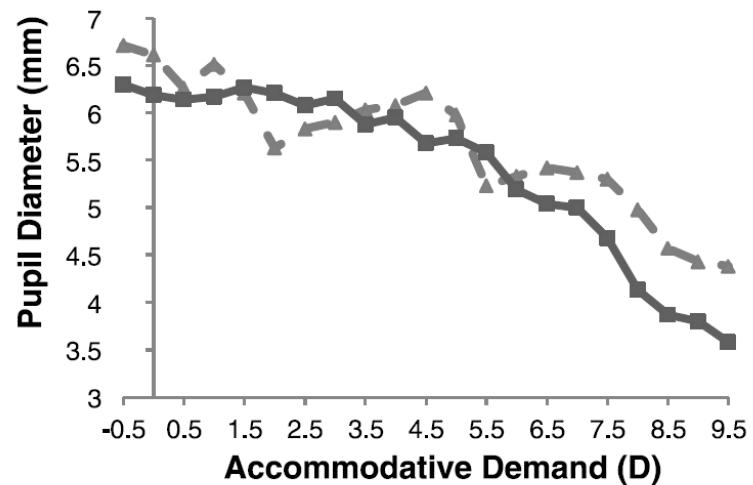


Fig. 5. Linespreads measured external to the eye. Each record is reproduced from a tracing of the averaged response scaled to a constant maximum height. The half-width given at the right is measured across the entire linespread at one-half its maximum height. The subject is R.G.

## Functions of the pupil: The near Triad : vergence – accommodation – pupil myosis



Lara, et al. (2014). Changes in the Objective Amplitude of Accommodation with Pupil Size. *Optometry & Vision Science*, 91(10), 1215-1220. (Low/High ambient light)



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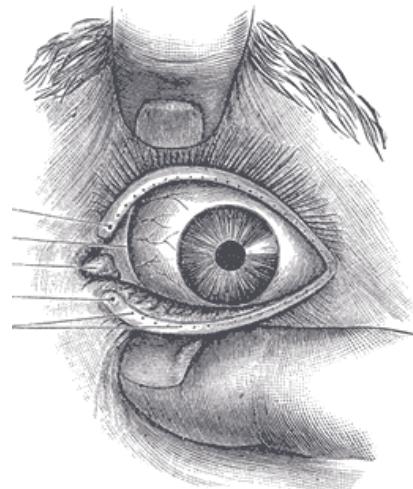
Modeling  
a 'simple' model of retroactive control

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a tool for dissecting sub-cortical lesions



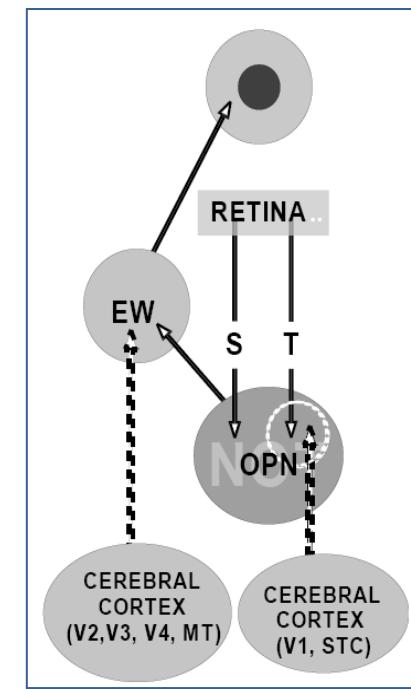
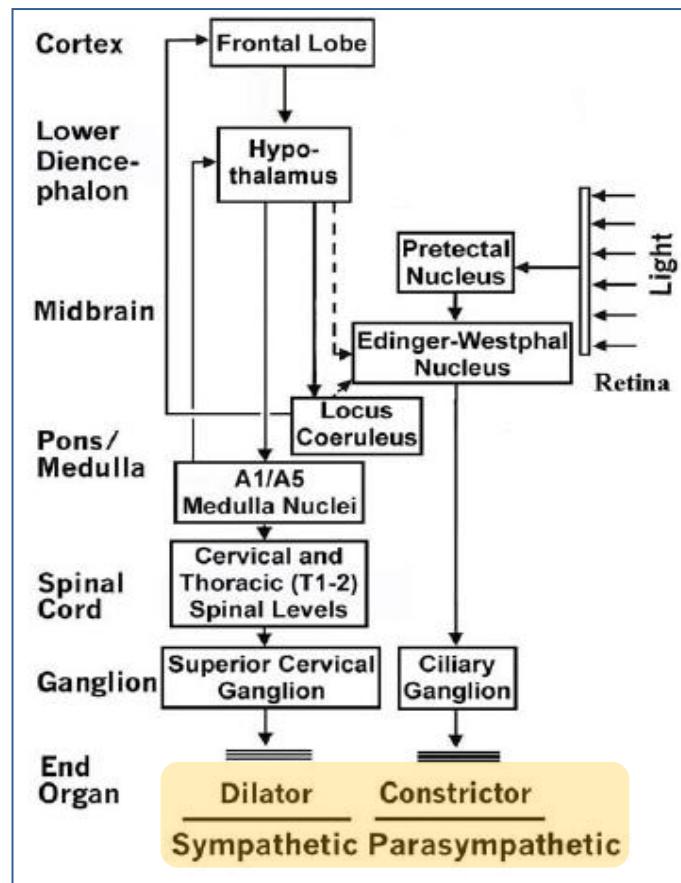
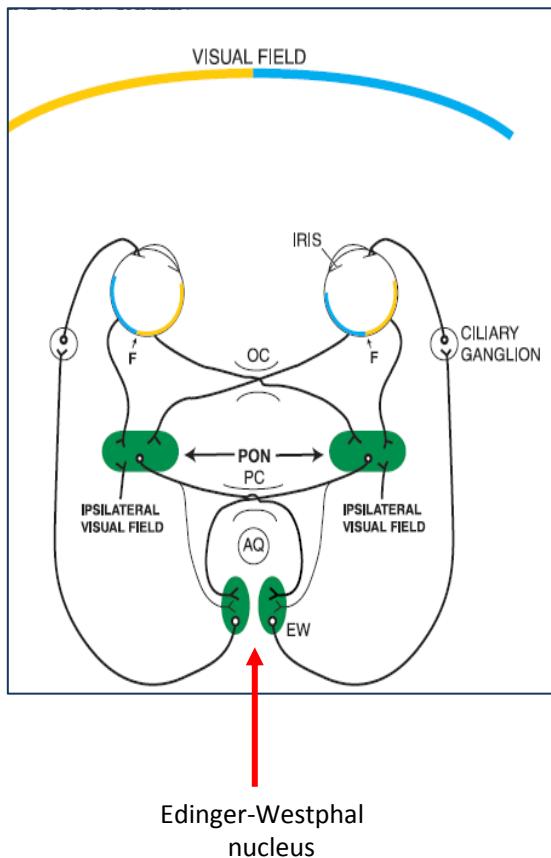
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a new opsine in 'non-visual' ganglion cells  
regulating circadian cycles.

## Vision

Pupillary Motor reflex, sensitivity, mechanisms

# Anatomy and circuits: antagonistic control through sympathetic and parasympathetic pathways



Learning from the pupil: Studies of basic mechanisms and clinical applications [John L. Barbur](#)

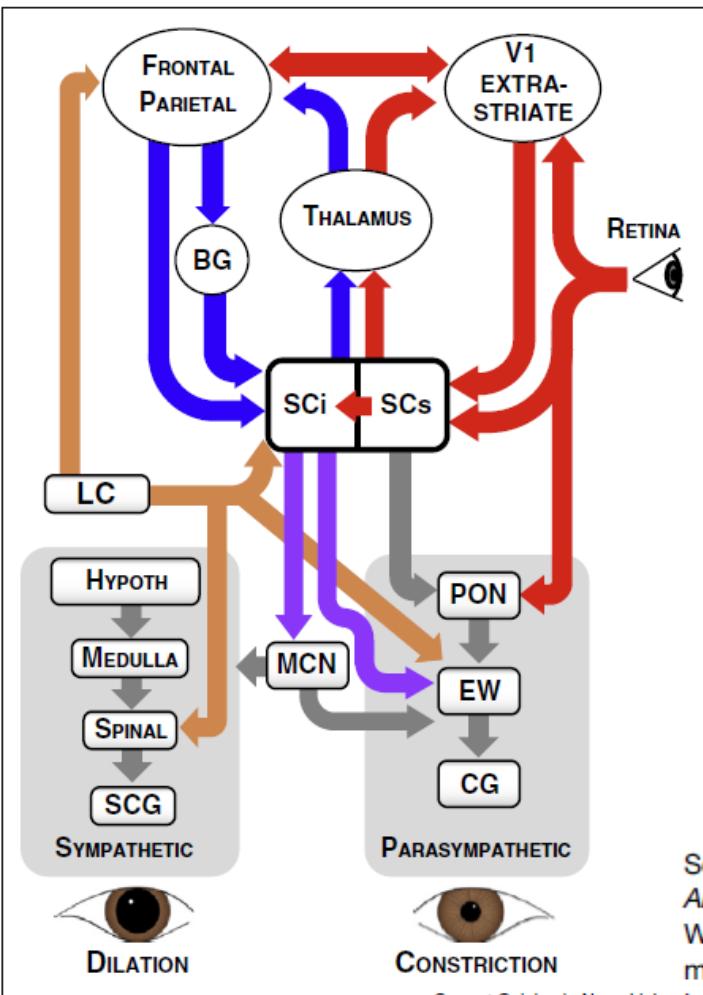
Figure 1. Autonomic neural control of pupil diameter. Solid lines depict excitatory connections between brain areas, broken lines depict inhibitory ones. Reprinted by permission of Sage Publications from Szabadi E, Bradshaw CM. (1996) Autonomic pharmacology of  $\alpha_2$ -adenoceptors. Psychopharmacology, 10 (Supplement 3): 6-18.

[In « Pupil staging and EEG measurement of sleepiness »](#)  
[Merritt, & al. 2004, IJP](#)

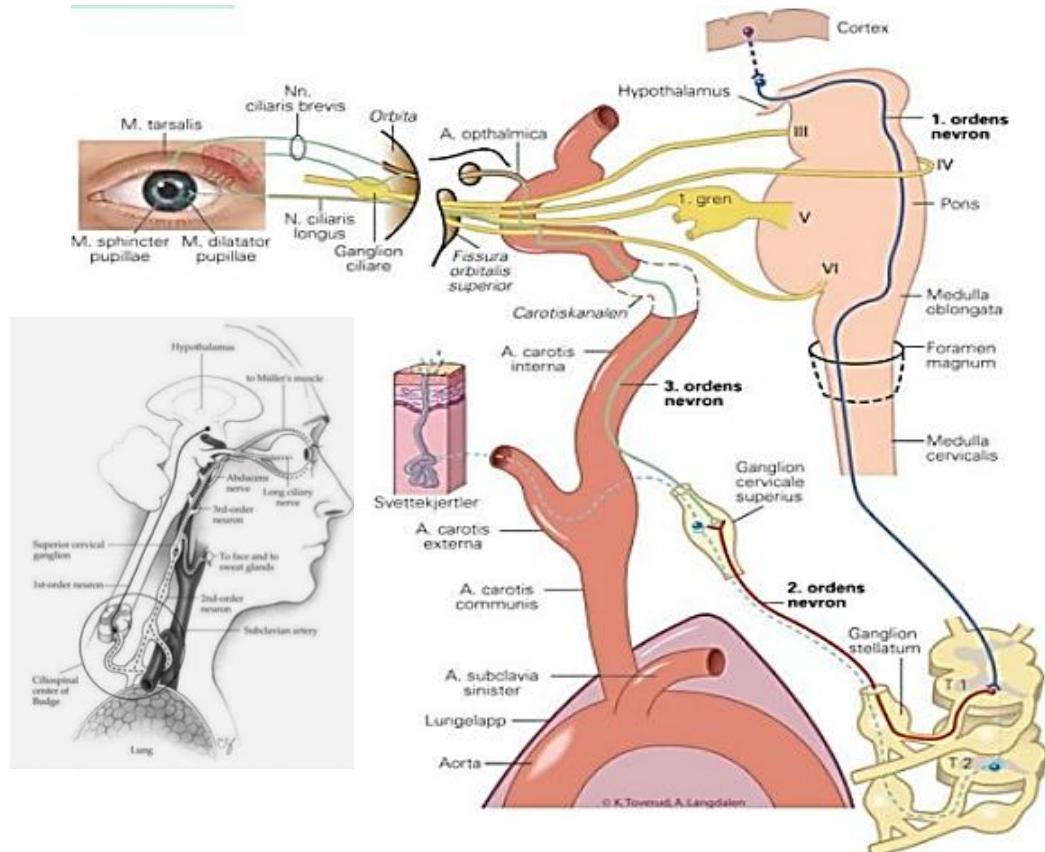
# Anatomy and circuits: antagonistic control through sympathetic and parasympathetic pathways

## A circuit for pupil orienting responses: implications for cognitive modulation of pupil size

Chin-An Wang and Douglas P Munoz



Current Opinion in Neurobiology



Schematic of the pupil orienting circuit. See text for details.

**Abbreviations:** BG, basal ganglia; CG, ciliary ganglion; EW, Edinger-Westphal nucleus; Hypoth, hypothalamus; LC, locus coeruleus; MCN, mesencephalic cuneiform nucleus; PON, pretectal olfactory nucleus; SCi, intermediate layers of the superior colliculus; SCs, superficial layers of the superior colliculus; SCG, superior cervical ganglion; V1, primary visual cortex.

# Anatomy and circuits: pupil and locus coeruleus

An Integrative  
Theory of Locus  
Coeruleus-Norepinephrine  
Function: Adaptive Gain  
and Optimal Performance

Gary Aston-Jones<sup>1,\*</sup> and Jonathan D. Cohen<sup>2,\*</sup>



Figure 1

Illustration of projections of the LC system. Sagittal view of a monkey brain showing LC neurons located in the pons with efferent projections throughout the central nervous system. Note that only few areas do not receive LC innervation (e.g., hypothalamus and caudate-putamen).

Ann. Rev. Neurosci.  
2005. 28:403–50

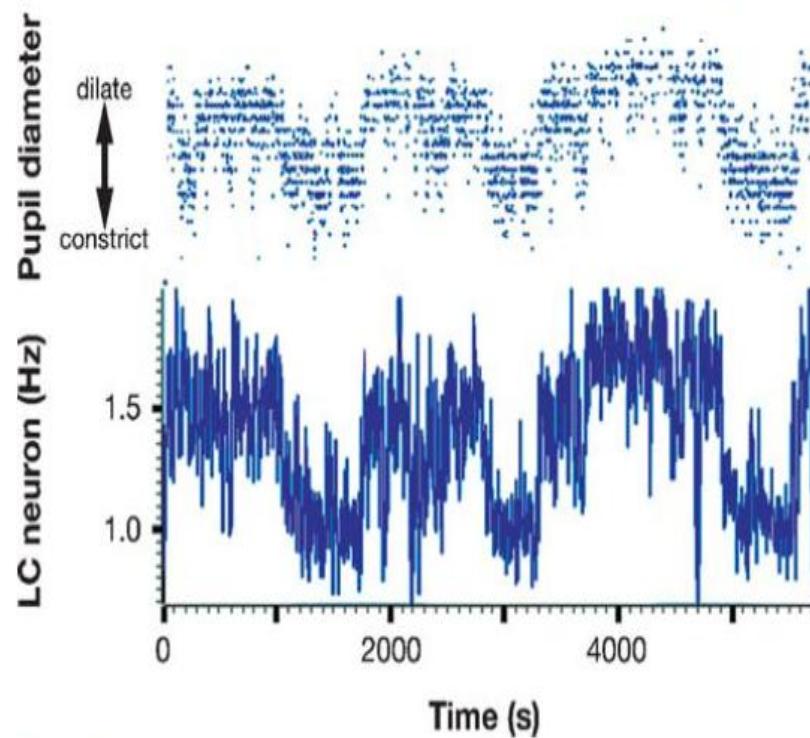


Figure 7

Relationship between tonic pupil diameter and baseline firing rate of an LC neuron in monkey. Pupil diameter measurements were taken by remote eye-tracking camera at each instant in time when the monkey achieved fixation of a visual spot during the signal-detection task (described in text). Note the close direct relationship between the pupil diameter and the rate of LC activity.

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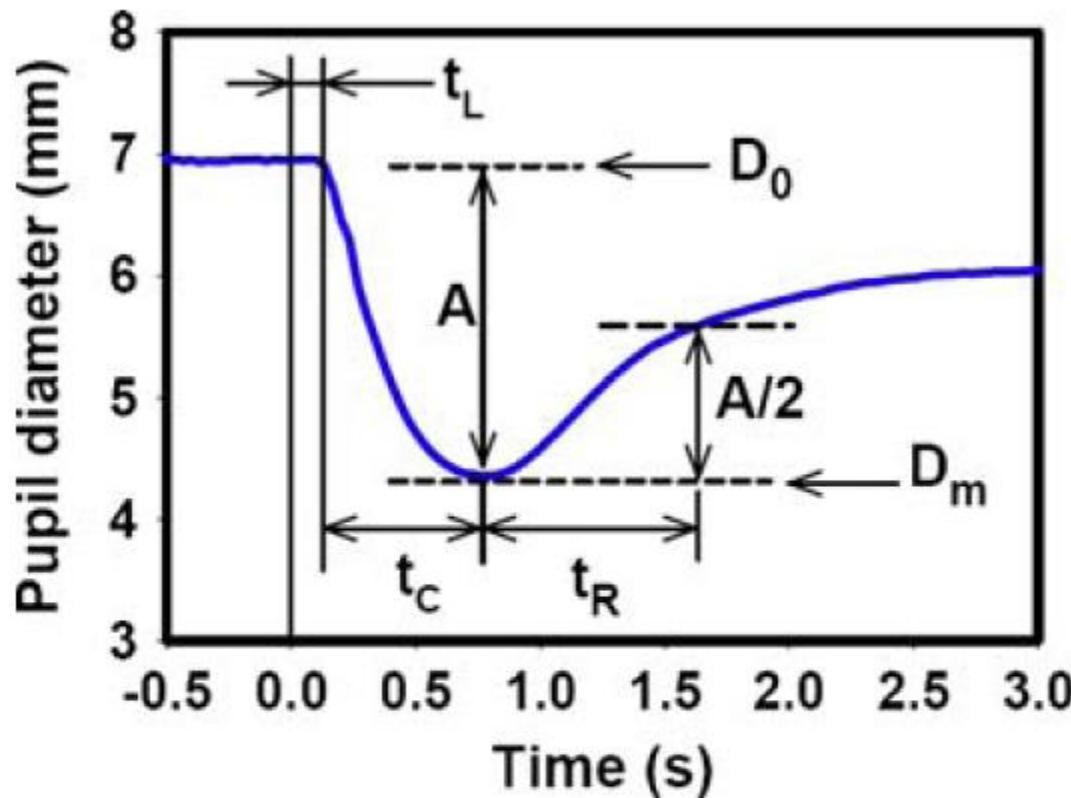
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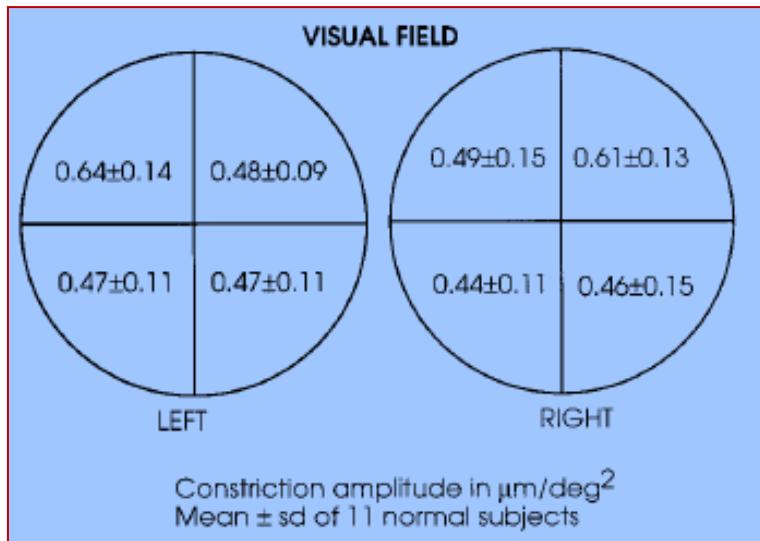
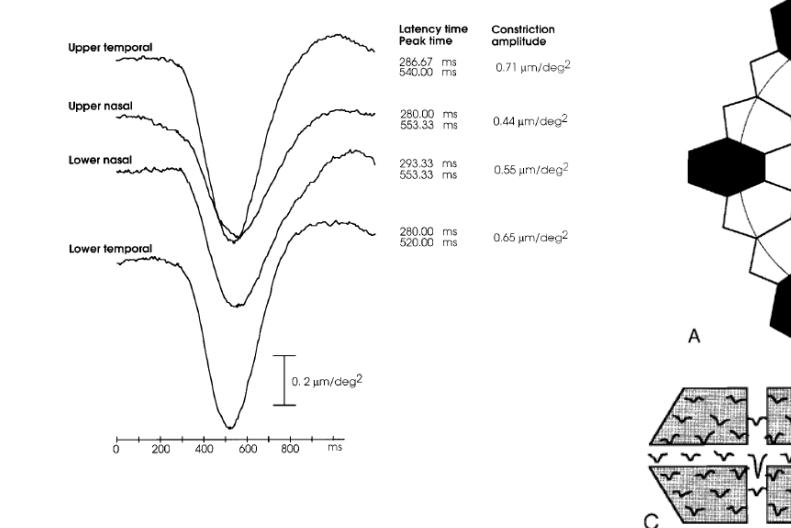
## Pupil responses: Pupillary Light reflex, (PLR)



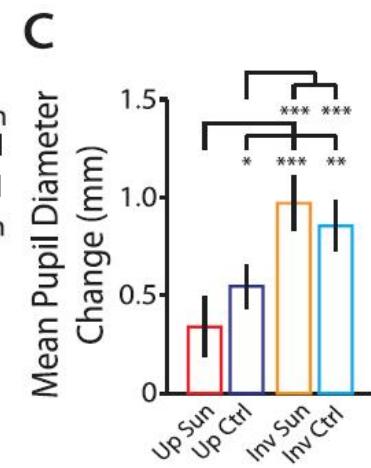
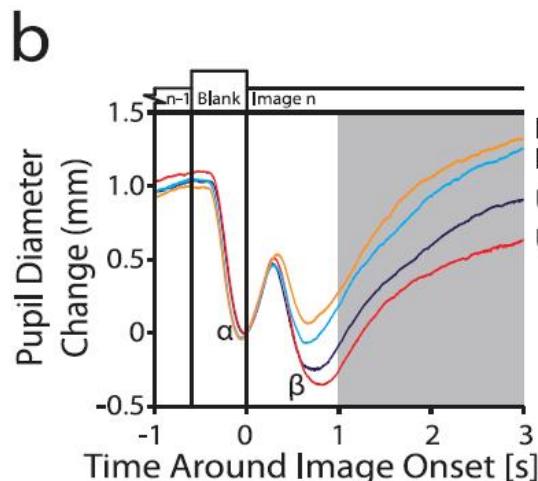
**Fig. 1** An illustration of the pupillogram and extracted pupillary light reflex (PLR) parameters.  $t_L$ : PLR latency;  $t_C$ : constriction time;  $t_R$ : recovery time;  $D_0$ : initial pupil diameter;  $D_m$ : the maximal constricted pupil diameter;  $A$ : constriction amplitude  $A = (D_0 - D_m)$ . The relative constriction was computed as the ratio of constriction amplitude and the initial pupil size  $(D_0^2 - D_m^2)/D_0^2$

# Pupil responses: Pupil perimetry

Wilhelm, et al. (2000). Pupil perimetry using M-sequence stimulation. *Journal of Vision*, 41(5), 1229-1238.



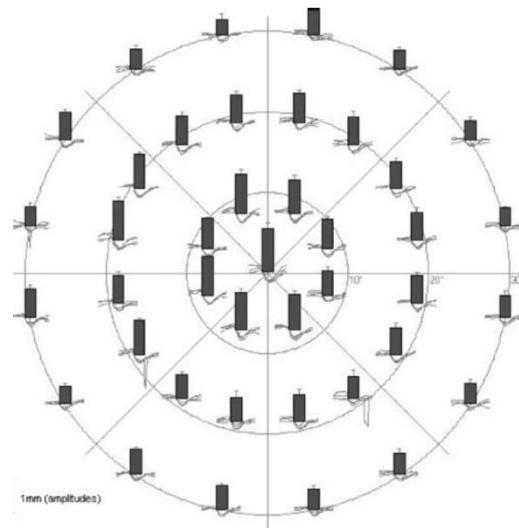
**a** **Image Conditions**



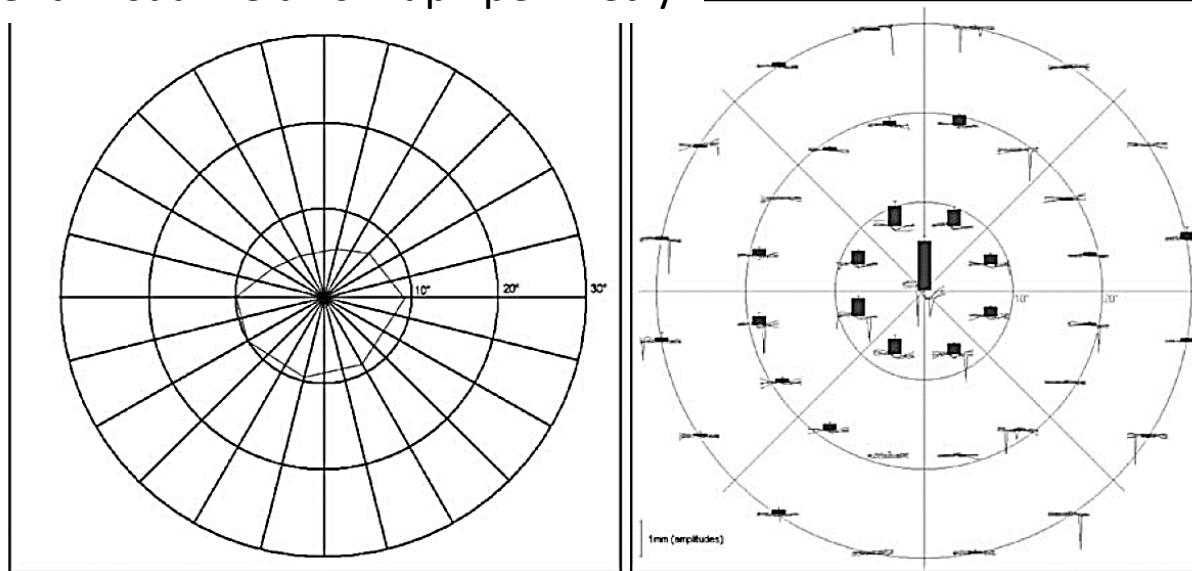
## Pupil responses: Pupil perimetry

Skorkovská, et al (2009). Pupil campimetry in patients with retinitis pigmentosa and functional visual field loss. *Graefe's Archive for Clinical and Experimental Ophthalmology*, 247(6), 847-853.

Normal subject



Patient: Visual field vs. Pupil perimetry



# Pupil responses: Pupil perimetry

## Comparison of Pupil Perimetry and Visual Perimetry in Normal Eyes: Decibel Sensitivity and Variability

Sungpyo Hong,<sup>1</sup> Joanna Narkiewicz,<sup>2</sup> and Randy H. Kardon<sup>3</sup>

These graphs depict the “hill” of **pupil threshold sensitivity** across the horizontal meridian in 10 normal subjects (each subject is a different graph).

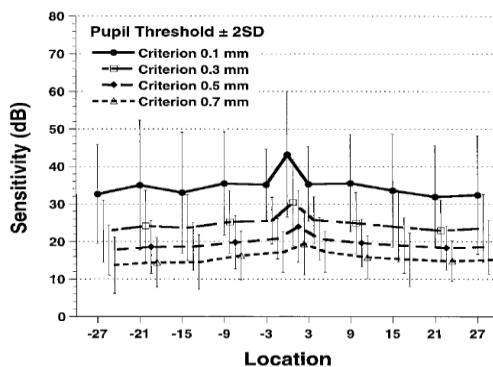
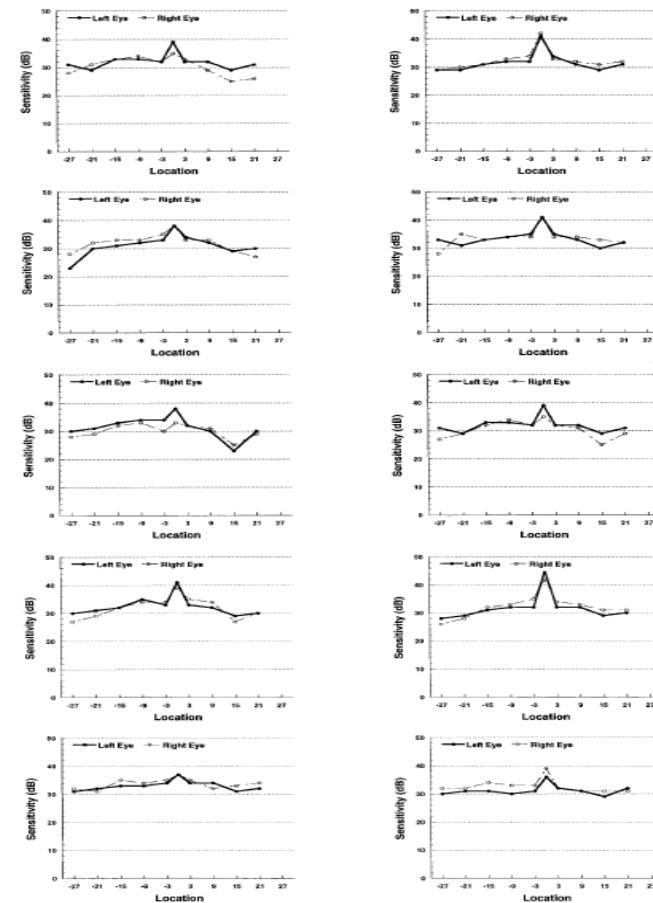


FIGURE 7. Average profile of pupil threshold + two SDs (between

These graphs of **visual threshold** are for the same normal subjects in the same order shown in the graphs of pupil threshold in Figure 4.



## Pupil responses: Pupil “calibration” : sinusoidal modulation of luminance -> Amplitude/Phase

Pupil calibration

Barbur, 2004

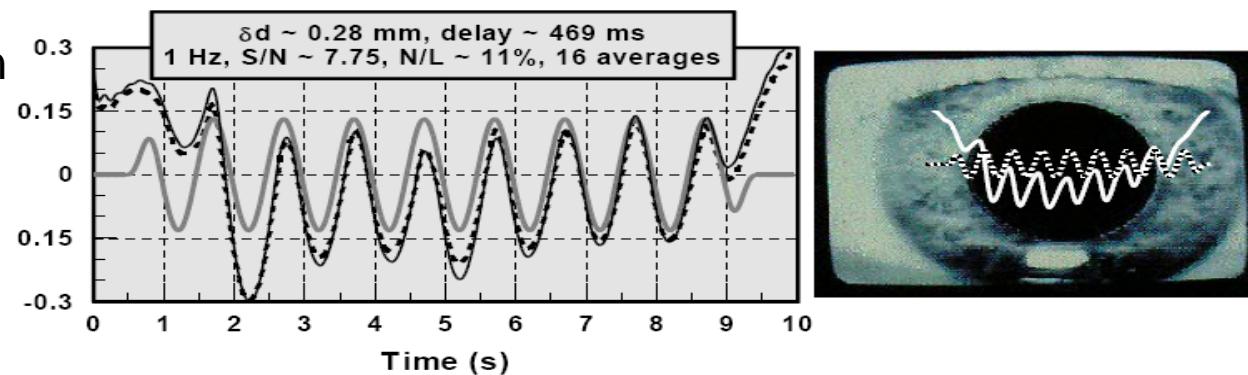
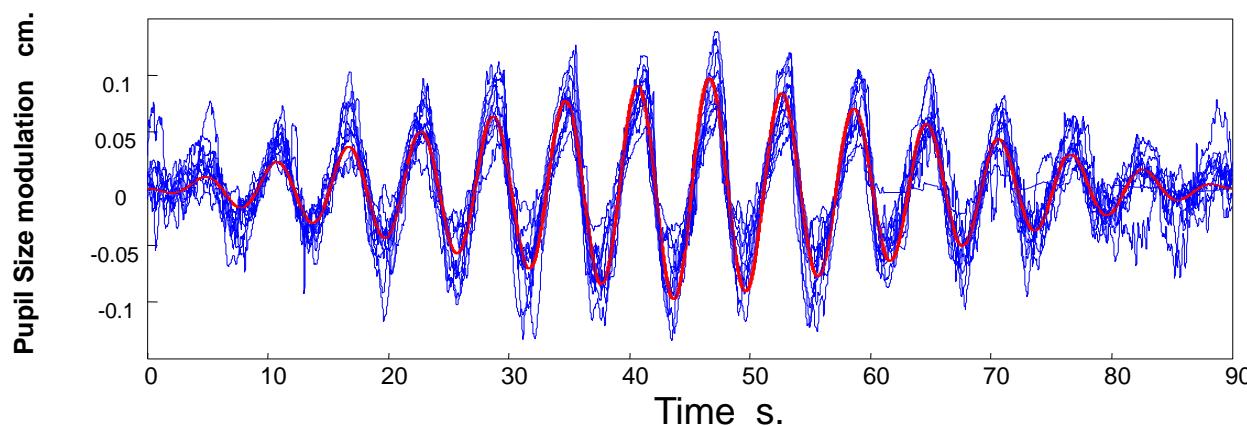


Figure 5. Example of mean pupil response to sinusoidal modulation of stimulus luminance as employed in our pupil perimetry program (see inset to Fig. 6). The stimulus trace (shown in grey) was shifted through 469 ms to match the direct (solid black line) and consensual (dotted line) pupil responses. In normal subjects, no significant differences can be measured between the direct and the consensual responses. The modulation frequency was 1Hz and each stimulus consisted of 10 cycles (with Hanning weighting). Each of the 24 stimulus locations shown in fig. 6 was selected randomly and tested 8 times so as to obtain an averaged response. The signal power and phase shift at the modulation frequency, together with a measure of signal/noise ratio (S/N) and response

Lorencean & Lamirel

Unpublished observations

Pupil Light reflex all Ss (n=9)

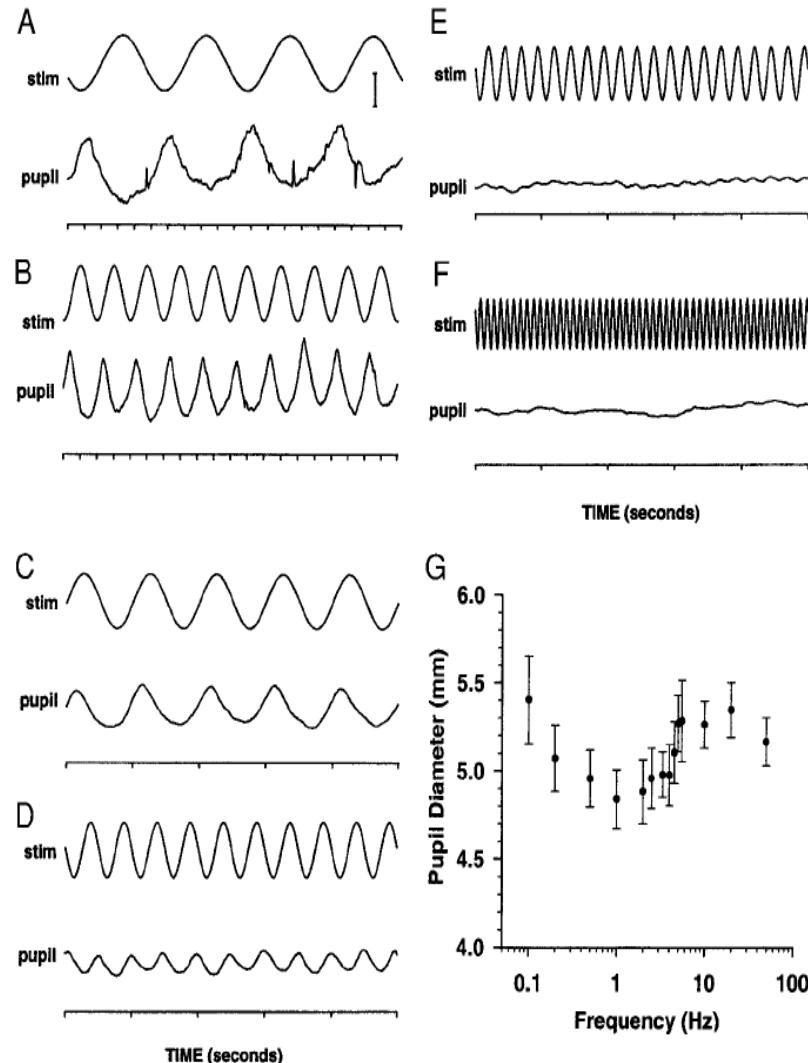


# Pupil responses: Pupil “calibration” : sinusoidal modulation of luminance -> Amplitude/Phase

## Characteristics of the Pupillary Light Reflex in the Alert Rhesus Monkey

Robert J. Clarke, Hongyu Zhang and Paul D. R. Gamlin

*J Neurophysiol* 89:3179–3189, 2003. First published Jan 15, 2003; doi:10.1152/jn.01131.2002



## Pupil Cycle Time Thompson, 1978 Lamirel, 2015

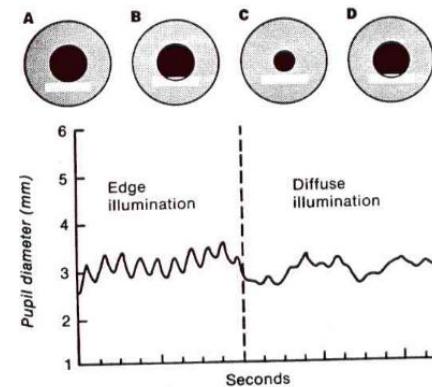


Figure 3-58. Pupillary “edge-light” cycles. The focused beam of the slit lamp was placed horizontally below the patient’s pupil (A), and was then raised slowly until it just grazed the pupil edge (B). This started the cycles of contraction, (C), resulting in shading of the light by the iris, and of dilation (D), resulting in a new light stimulus. The graph shows a pupillographic tracing of the cycles elicited by this maneuver (left). At the division line the slit lamp beam was suddenly defocused so that diffuse light covered the entire eye, and the pupillary oscillations degenerated. Note, however, that the beats (now quite irregular in amplitude) still have roughly the same frequency as during edge-light cycling. (From S.D. Miller and H.S. Thompson, *Amer J. Ophthalmol.*, 85 [1978]:635); published with permission from *The American Journal of Ophthalmology*, ©The Ophthalmic Publishing Company)

FIG. 6. Response characteristics of the right eye pupil to a series of sinusoidal stimulation frequencies of a LED light source presented in Maxwellian view to both eyes. A: 0.2 Hz; B: 0.5 Hz; C: 1.0 Hz; D: 2 Hz; E: 4 Hz; and F: 10 Hz. Top: the changes in stimulus light intensity. Upward deflections in the sinusoidal trace denote increases in light intensity. Bottom: the right eye pupil response to these stimuli. As light intensity increases the pupil constricts as denoted by the downward deflections. G: average pupil diameter in response to sinusoidal illumination between 0.1 and 50 Hz. The minimal pupil diameter is reached between 0.5 and 5 Hz. Scale bar is 1 mm change in pupil diameter. Sharp deflections seen in the pupil trace in A are blinks.

# Pupil responses: sensitivity to visual attributes

## Visual processing levels revealed by response latencies to changes in different visual attributes

J. L. Barbur<sup>1\*</sup>, J. Wolf<sup>1</sup> and P. Lennie<sup>2</sup>

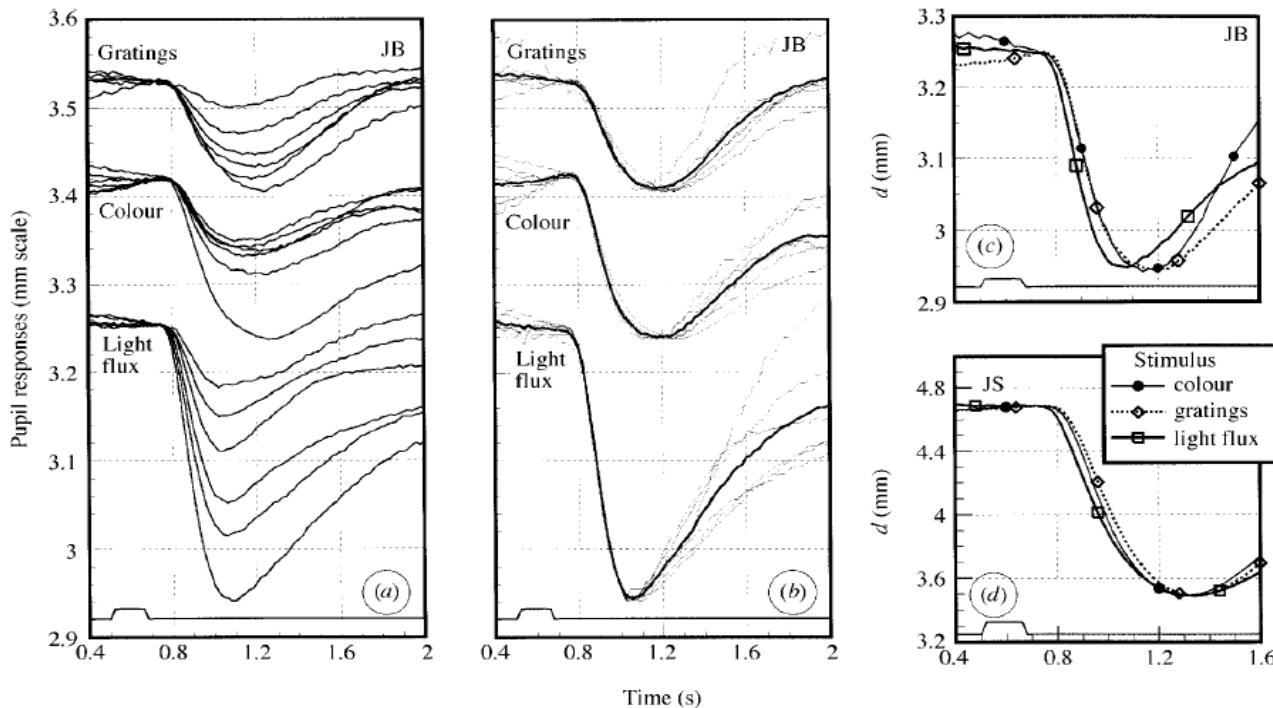


Figure 1. Pupil responses elicited by light-flux increments, a change from an achromatic uniform field to an isoluminant chromatic stimulus, and change from an achromatic uniform field to a grating of the same space-average luminance. The absolute pupil size is that shown for grating stimuli. The remaining sets were then shifted vertically for clarity. The rectangular trace plotted close to the abscissa shows stimulus time. (a) The change with time in pupil diameter following the onsets of gratings of various contrasts (0.08, 0.16, 0.32, 0.48, 0.75, 0.95) at  $4.5 \text{ c deg}^{-1}$ ; uniform fields of various chromatic saturations (0.03, 0.045, 0.06, 0.09, 0.12, 0.16 with each number specifying the chromatic displacement (CD) of the test stimulus away from background chromaticity on the CIE-( $x, y$ ) chromaticity diagram); and luminance increments of varying contrasts ( $\delta L/L_b = 0.3, 0.6, 0.9, 1.2, 1.5, 2.15$ ). Each trace represents the average of 48 measurements. (b) Measurements from (a) scaled for equal peak amplitude of pupil constriction. The scaling procedure involves measurement of the peak response amplitude for each trace, multiplication by the appropriate scaling parameter and subtraction of a constant term so as to align the traces horizontally before the start of the constriction. The heavier line among each set of traces represents the mean of all traces in that group. (c) Means of pupil responses stretched for equal amplitude (from (b)). (d) Average traces (as for (c)) obtained for

# Pupil responses: variability !

J. Sleep Res. (2001) 10, 1–7

Daytime variations in central nervous system activation measured by a pupillographic sleepiness test

BARBARA WILHELM<sup>1</sup>, HENNER GIEDKE<sup>2</sup>, HOLGER LÜDTKE<sup>1</sup>,

EVELYN BITTNER<sup>1</sup>, ANNA HOFMANN and HELMUT WILHELM<sup>1</sup>

<sup>1</sup>Department of Pathophysiology of Vision and Neuroophthalmology, University Eye Hospital and <sup>2</sup>Department of Psychiatry and Psychotherapy, University of Tübingen, Tübingen, Germany

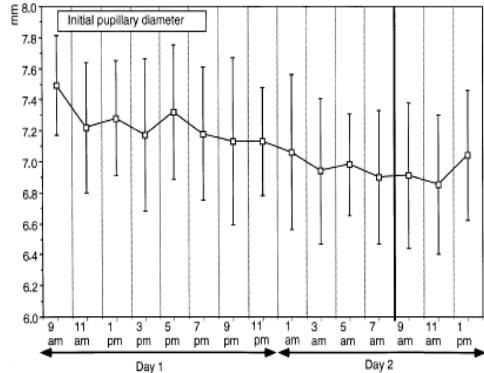


Figure 3. Initial pupil size plotted against time of day of the experiment. Means  $\pm$  SD of 13 subjects. Bold vertical line marks the end of a 24-h period.

Figure 1. Pupillographic sleepiness test (schematic overview) with two different examples for pupillograms (stable = alert, instable = tired).

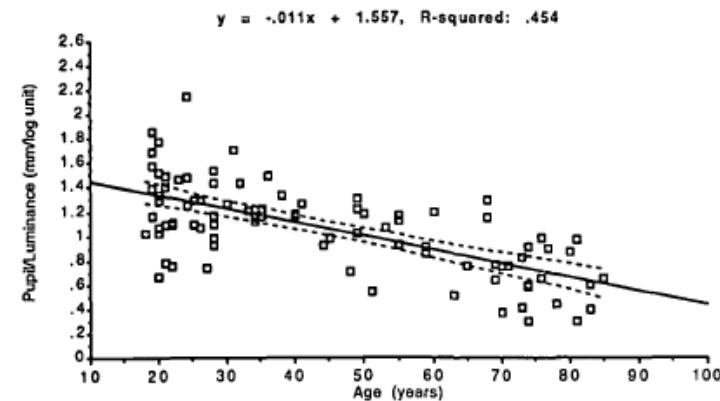
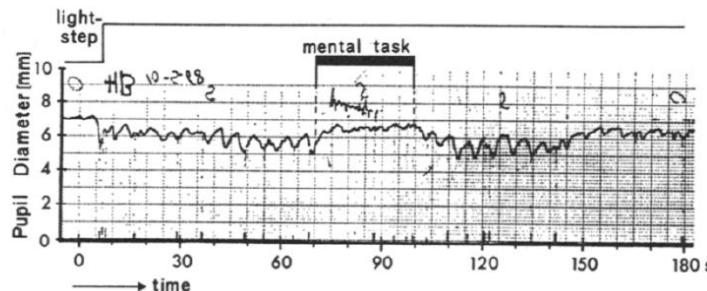
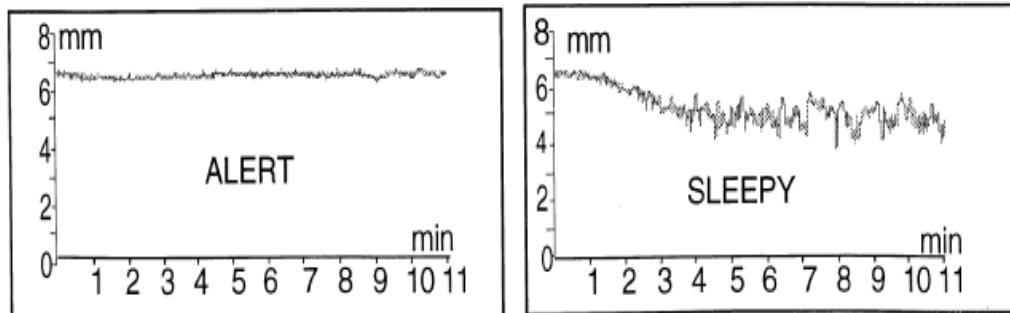


FIGURE 3. Change in pupil diameter per log unit change in stimulus luminance for each subject, plotted as a function of the individual's age. The data are fitted with a best-fitting linear regression.

## Pupillogram printout



4. An existing Hippus disappears during the time that the subject carries out a mental task which in this case, was generating prime numbers starting at 101. Subject HB.

Also see: Hippus !

(pupil unrest of unknown origin :  
~0.2 Hz spontaneous fluctuations)

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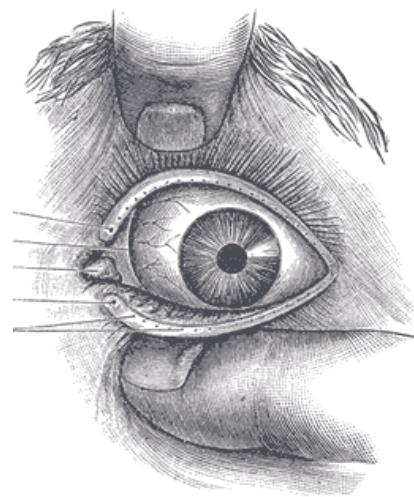
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A marker of drug consumption  
a tool for dissecting sub-cortical lesions

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# Pupil pharmacology : Sensitivity to drugs

## MIOTICS

- The drugs which constrict the pupil are known as miotics.

### MIOTICS

PARASYMPATHOMIMETIC  
(SPHINCTER STIMULATORS)

SYMPATHOLYTICS  
(DILATOR INHIBITORS)

## MYDRIATICS

### MYDRIATICS

SYMPATHOMIMETICS  
(DILATOR STIMULATORS)

PARASYMPATHOLYTICS

### Pharmacologic agents:

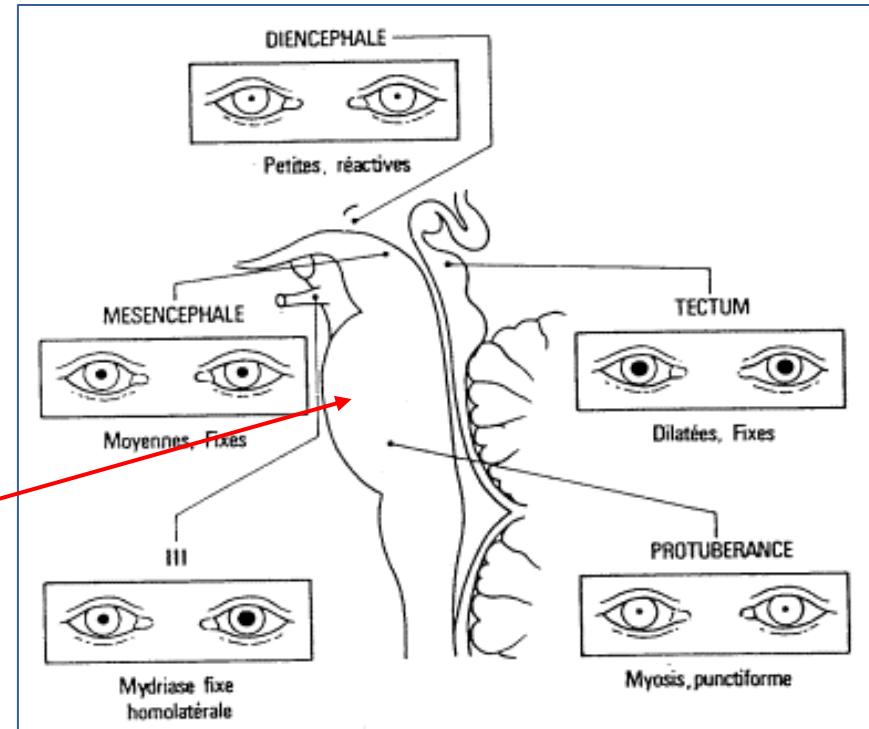
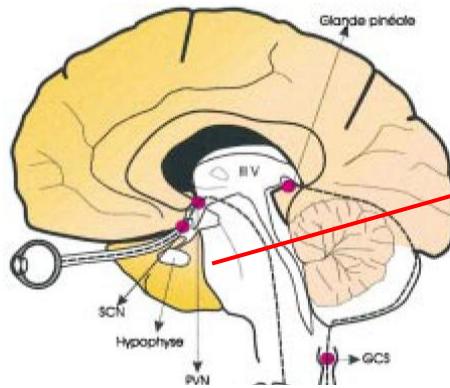
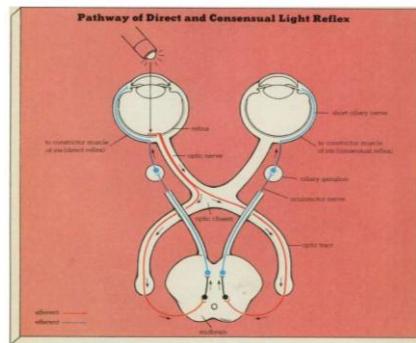
- Unilateral use of dilating drops
  - Atropine, cyclopentolate, homatropine, scopolamine, tropicamide, phenylephrine.
- Handling/administrating of sympathomimetic or anticholinergic agents :
  - Sympathomimetic agents:
    - OTC cold agents containing ephedrine
    - Illegal street drugs: cocaine, amphetamines, methamphetamine
    - Dietary supplements: ephedra alkaloids
    - Very popular illicit designer drugs: 3, 4-methylenedioxymethamphetamine [MDMA, "ecstasy"]

### Other drugs causing mydriasis:

- LSD (lysergic acid diethylamide)
- Alcohol
- Marijuana
- Mescaline
- Jimson weed (*Datura stramonium*) containing belladonna alkaloids (active ingredients are atropine and scopolamine). Some brands of eye make-up contain belladonna alkaloids.

# Neurology and pupil : a tool for dissecting sub-cortical lesions and optic nerve dysfunctions

## The Pupil Check



- ! Plus **PUPIL check** used in a very large number of neuro-ophtalmologic deseases :
  - > ARMD, Glaucoma, Optic neuritis, retinitis pigmentosa, ...
- ! Plus **PUPIL check** used in evaluation of coma, pain, etc..

# Neurology and pupil : a tool for detecting optic nerve dysfunctions

2652

J.L. Barbur et al. / Clinical Neurophysiology 115 (2004) 2650–2658

## Comparison of pupil responses to luminance and colour in severe optic neuritis

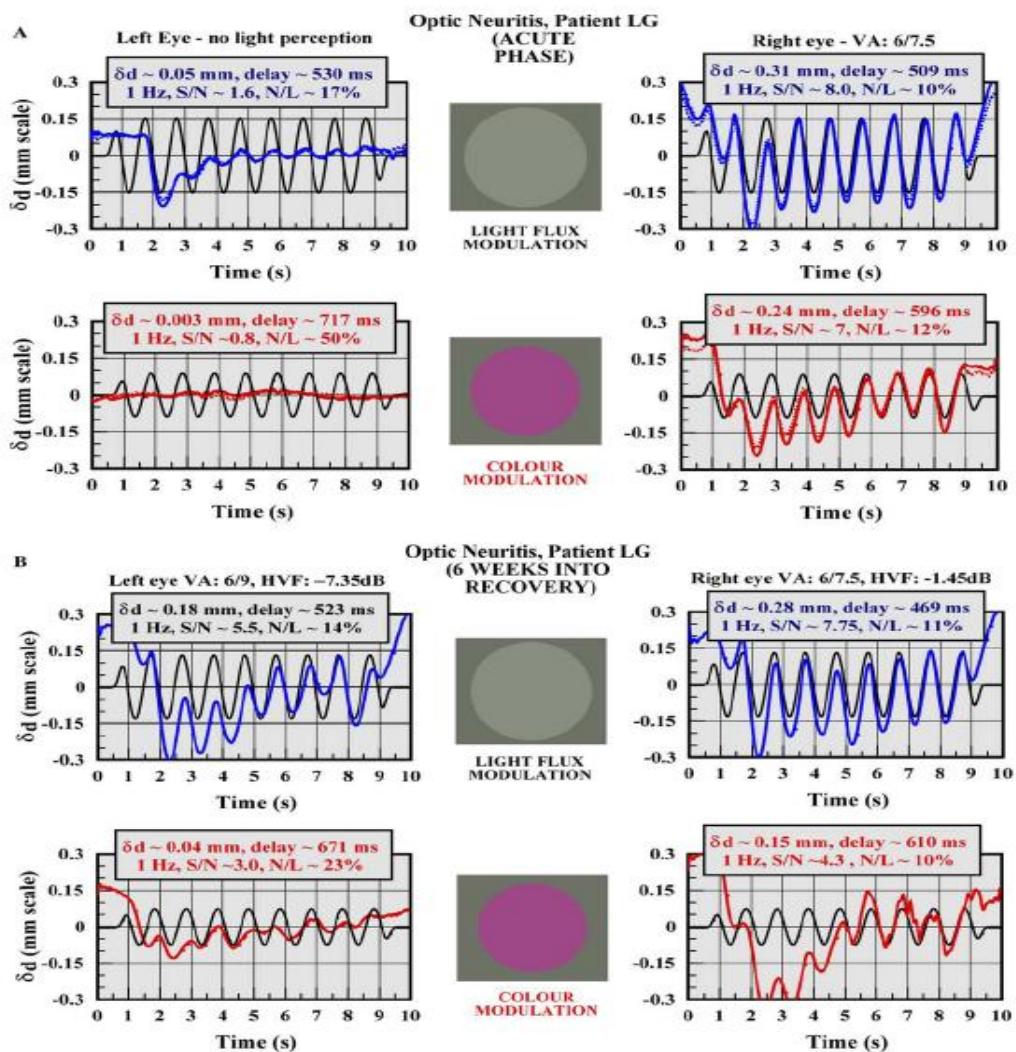
J.L. Barbur<sup>a,\*</sup>, S. Moro<sup>a,1</sup>, J.A. Harlow<sup>a</sup>, B.L. Lam<sup>b</sup>, M. Liu<sup>b</sup>

Fig. 1. (A,B) Examples of pupil responses measured during the acute (Section A) and 6 weeks into recovery (Section B) phases of optic neuritis. The affected eye and the unaffected right eye were stimulated separately with both luminance and chromatic contrast modulation. The affected eye had little or no perception. Each pupillogram is the average of 16 traces. Consensual responses that are almost indistinguishable to those measured in the stimulated eye are shown as dotted traces in Section A. The amplitude and latency of the response, as well as the signal to noise ratio (S/N) and a measure of response non-linearity (N/L), were computed from the fundamental harmonic of the Discrete Fourier Transform of the averaged trace. The response amplitudes are in general ( $\sim 0.3$  mm for the light reflex response and  $\sim 0.24$  mm for the colour response). For the stimulus conditions employed in this study the pupil follows the sinusoidal modulation of either light flux or colour. The responses are well within the normal pupil dynamic range with less than 12% response non-linearity. Similar results were obtained for 7 other patients.

# A multidisciplinary approach to the pupil

## Optics and function

Regulating retinal illuminant and image formation

## Cognition

Pupil : marker of memory load  
attention, emotion

## Psychiatry

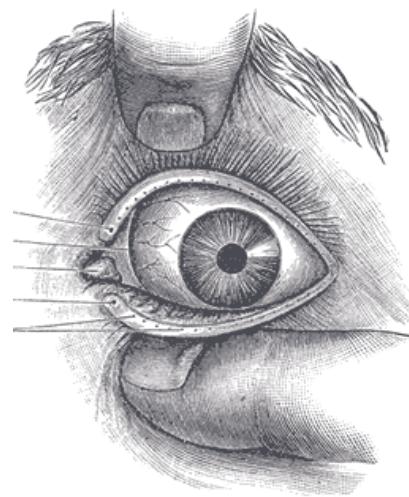
Neuropsychology  
a marker of mental disorders

## Modeling

a 'simple' model of retroactive control

## Anatomy and circuits

an antagonistic control of the pupil through  
sympathetic and parasympathetic pathways



## Pharmacology/Neurology

Sensitivity to drugs/dissecting sub-cortical lesions

## Physiology/Genetics

a new opsine in 'non-visual' retinal ganglion cells  
regulating circadian cycles.

## Vision/Pupil perimetry

Pupillary Light reflex, sensitivity, mechanisms

# Physiology/Genetics: a new opsine in ‘non-visual’ retinal ganglion cells regulating pupil activity (circadian cycles).

## Melanopsin-Containing Retinal Ganglion Cells: Architecture, Projections, and Intrinsic Photosensitivity

S. Hattar,<sup>1,2\*</sup> H.-W. Liao,<sup>2\*</sup> M. Takao,<sup>4</sup> D. M. Berson,<sup>4</sup>  
K.-W. Yau<sup>1,2,3†</sup>

The primary circadian pacemaker, in the suprachiasmatic nucleus (SCN) of the mammalian brain, is photoentrained by light signals from the eyes through the retinohypothalamic tract. Retinal rod and cone cells are not required for photoentrainment. Recent evidence suggests that the entraining photoreceptors are retinal ganglion cells (RGCs) that project to the SCN. The visual pigment for this photoreceptor may be melanopsin, an opsin-like protein whose coding messenger RNA is found in a subset of mammalian RGCs. By cloning rat melanopsin and generating specific antibodies, we show that melanopsin is present in cell bodies, dendrites, and proximal axonal segments of a subset of rat RGCs. In mice heterozygous for tau-lacZ targeted to the melanopsin gene locus,  $\beta$ -galactosidase-positive RGC axons projected to the SCN and other brain nuclei involved in circadian photoentrainment or the pupillary light reflex. Rat RGCs that exhibited intrinsic photosensitivity invariably expressed melanopsin. Hence, melanopsin is most likely the visual pigment of phototransducing RGCs that set the circadian clock and initiate other non-image-forming visual functions.

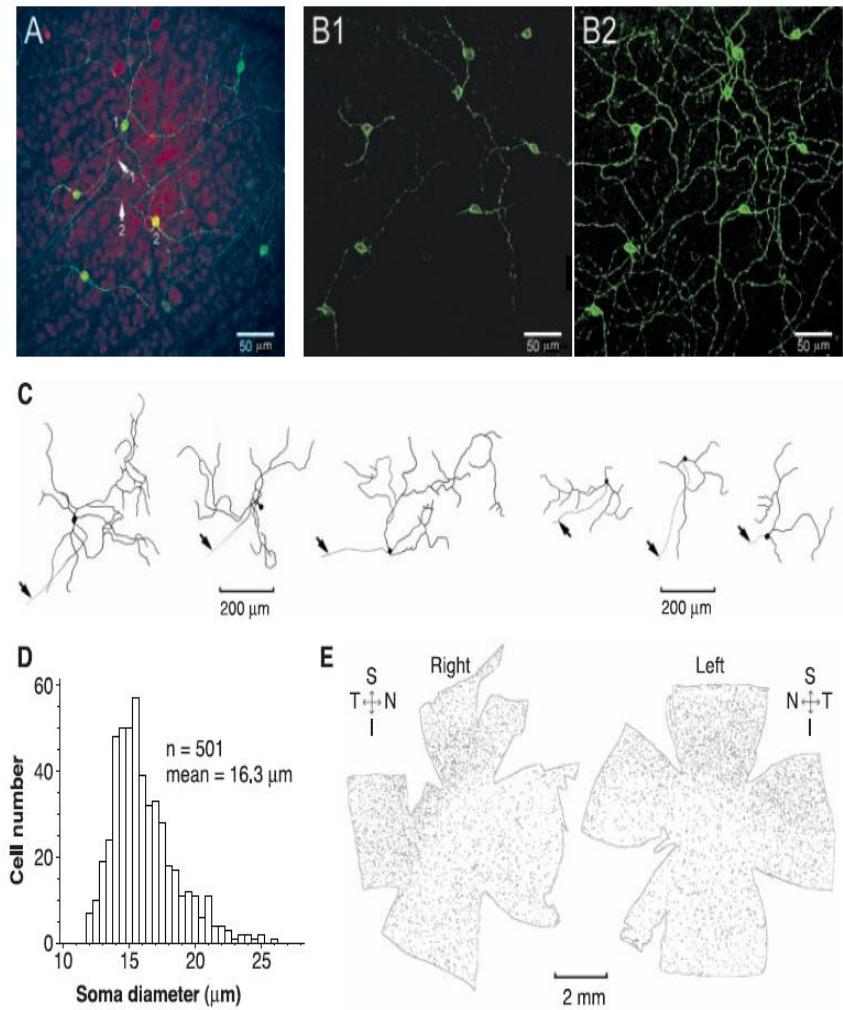
## Diminished Pupillary Light Reflex at High Irradiances in Melanopsin-Knockout Mice

R. J. Lucas,<sup>1\*†</sup> S. Hattar,<sup>2\*</sup> M. Takao,<sup>3</sup> D. M. Berson,<sup>3</sup>  
R. G. Foster,<sup>1</sup> K.-W. Yau<sup>2†</sup>

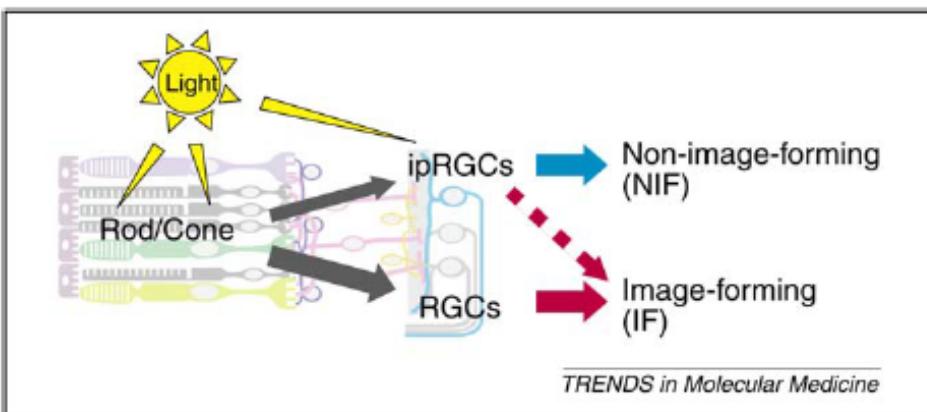
SCIENCE VOL 299 10 JANUARY 2003

SCIENCE VOL 295 8 FEBRUARY 2002

**Fig. 1.** Immunocytochemistry of melanopsin-containing RGCs in the flat-mounted rat retina. (A) Confocal images at the level of the ganglion cell layer showing labeling with the melanopsin NH<sub>2</sub>-terminal specific antibody. The fluorescent immunolabeling is in green, and the nuclei are stained by red fluorescent propidium iodide. Arrows 1 and 2 indicate axons associated with the indicated RGC cell bodies heading toward the optic disc. Note the beaded appearance of the dendrites. Because the image is at a particular focal plane, some dendrites and axons are not visible. (B) Nonstacked (1) and stacked (2) confocal images of the same retinal field from another preparation, but without nuclear counterstaining. The stacked picture combined all focal planes containing labeled processes. Note the peripheral localization of the melanopsin-labeling in the cell bodies in (B1). Because the stacking increased background, the sensitivity of the camera was reduced, making some faint processes not clearly visible. (C) Camera-lucida drawings of several melanopsin-positive RGCs, obtained from stacked images. The beaded appearance of the dendrites is not shown. The left and right panels show nondisplaced and displaced RGCs, respectively. The displaced cells have smaller and apparently more sparse dendritic fields. Arrows indicate axons. (D) Soma size distribution of (a sample of) nondisplaced melanopsin-positive RGCs, which account for >95% of all labeled RGCs. (E) Overall distribution of melanopsin-positive RGCs on the flat-mounted right and left retinas of the same rat. Dozens of local dark-field images were taken separately at low magnification, and the montage was assembled with Adobe Photoshop. Each cell body is represented by a dot of about the appropriate size. Note the higher cell density in the superior and temporal quadrants. Only nondisplaced RGCs (>95% of total) are included. S, superior; I, inferior; N, nasal; T, temporal.

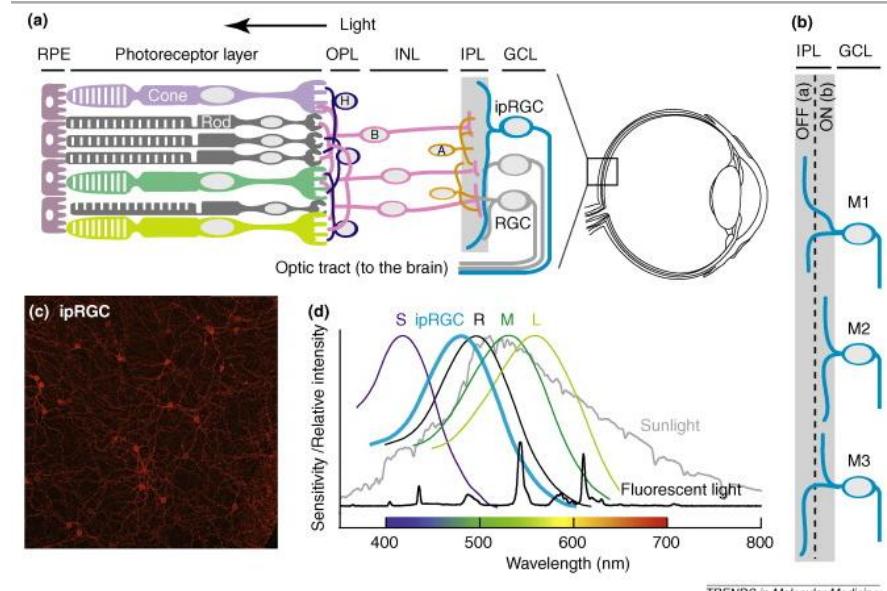


# Physiology/Genetics: a new opsine in ‘non-visual’ retinal ganglion cells regulating circadian cycles.



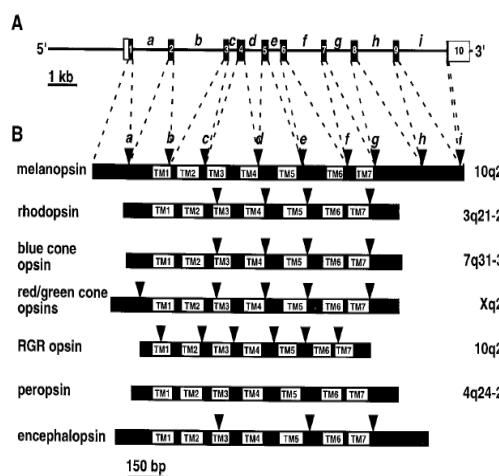
**Figure 3. The ipRGCs as the site of signal integration.**

The rod and cone photoreceptors of the outer retina signal via multisynaptic pathways to the RGCs of the inner retina. The RGCs, in turn, transfer the visual signals from the eye to the brain via their axonal projections. For NIF visual functions, the light information originating from the rods and cones is exclusively transmitted through ipRGCs. The ipRGCs function as the nodes for integrating melanopsin and rod/cone-initiated photoresponses. ipRGCs are likely to participate in the IF vision by two potential mechanisms. In the retina, they also affect the function of the dopamine-responsive amacrine cells [95], which then affect the adaptation of the rod/cone-initiated signals under prolonged illumination. The ipRGCs also send projections to the dorsal lateral geniculate nucleus (LGN) in the brain, which receives extensive innervations from other RGCs [57].



Provencio et al. • Human and Mouse Melanopsins

J. Neurosci., January 15, 2000, 20(2):600-605 601



**Figure 1.** Melanopsin differs from other human opsins. *A*, Structure of melanopsin gene. The 5' and 3' untranslated regions of exons 1 and 10, respectively, are indicated in white. *B*, Comparison of human melanopsin, rhodopsin (Nathans and Hogness, 1984), blue cone opsin (Nathans et al., 1986), red and green cone opsin (Nathans et al., 1986), RGR (Shen et al., 1994), peropsin (Hui et al., 1997), and encephalopsin (Blackshaw and Snyder, 1999) ORFs. Portions of the ORFs corresponding to the transmembrane domains are shown in white and are labeled. Positions of introns are indicated ( $\blacktriangledown$ ), and the respective chromosomal locations are displayed to the right.

# Electrophysiology: Response of pretectal neurons in monkey

## Characteristics of the Pupillary Light Reflex in the Macaque Monkey: Discharge Patterns of Pretectal Neurons

Milton Pong and Albert F. Fuchs  
*J Neurophysiol* 84:964-974, 2000.

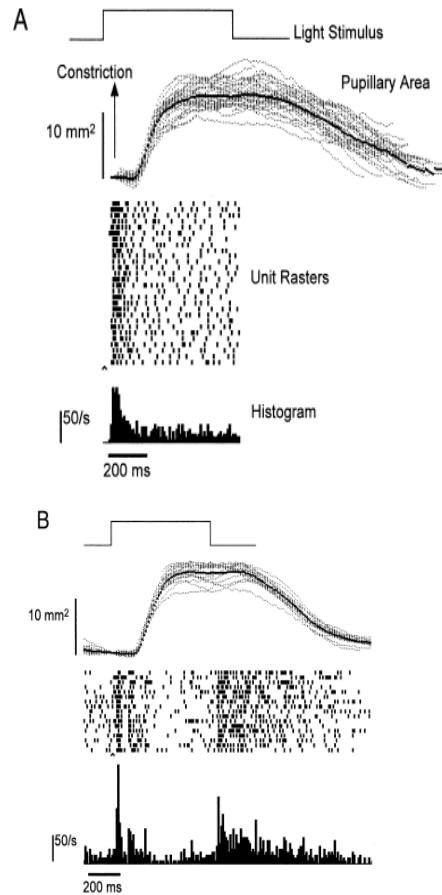
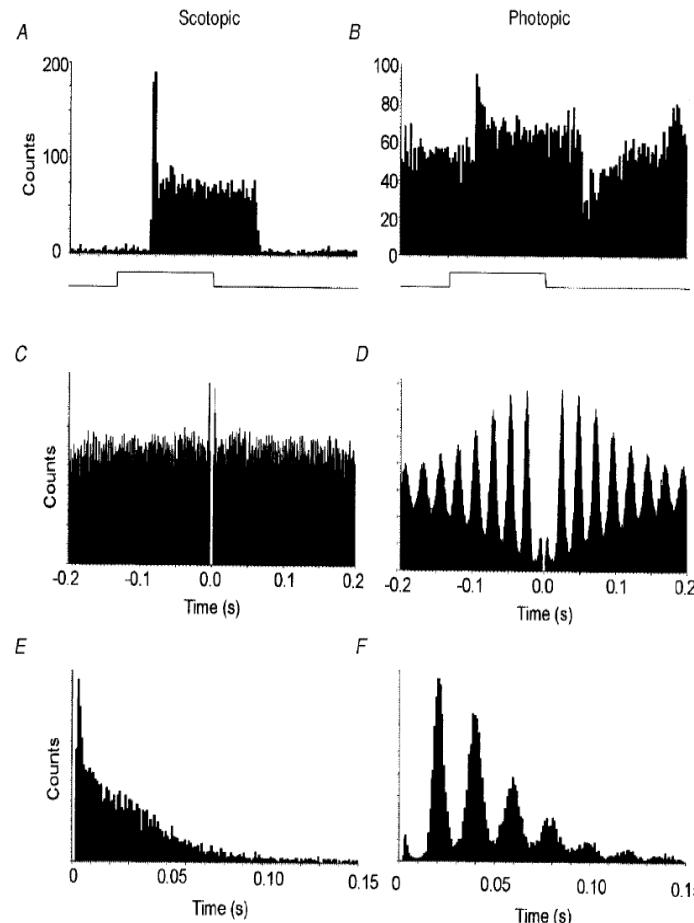


FIG. 2. Firing patterns of the 2 types of pretectal neurons to the standard visual stimulus (~1 s duration, full-field binocular flash of random-square pattern with lighted areas at 4 cd/m<sup>2</sup>). *A*: 28 responses of a burst-sustained neuron in monkey S aligned on stimulus onset. After a latency of 52 ± 6 (SD) ms, a burst of 77 ± 28 imp/s lasted for 73 ± 35 ms. Subsequent steady firing (18 ± 4 imp/s) continued throughout the stimulus. *B*: 17 responses of a transient neuron in monkey S to the standard stimulus (same parameters as in the preceding text) aligned on stimulus onset. After a latency of 46 ± 59 ms, the burst at light onset averaged 127 ± 92 imp/s for 59 ± 43 ms. At light offset, after latency of 50 ± 71 ms, the burst averaged 96 ± 93 imp/s for 118 ± 83 ms. The histogram binwidths are 10 ms. In this and all other similar figures, upward deflection of the pupillary area trace indicates pupillary constriction.

## Responses of neurones of the rat suprachiasmatic nucleus to retinal illumination under photopic and scotopic conditions

Nicholas C. Aggelopoulos and Hilmar Meissl

*J. Physiol.* 2000;523:211-222



under light adaptation, however, the spike intervals occur at preferred frequencies which are multiples/harmonics of a basic frequency at 22 ms.

# A multidisciplinary approach to the pupil

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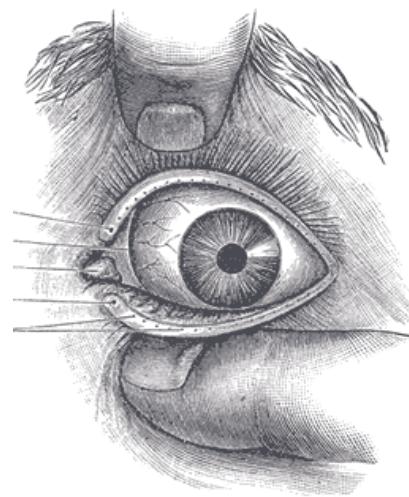
Psychiatry  
Neuropsychology  
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a 'simple' model of retroactive control

## Anatomy and circuits

an antagonistic control of the pupil through  
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## Pharmacology/Neurology

Sensitivity to drugs/dissecting sub-cortical lesions

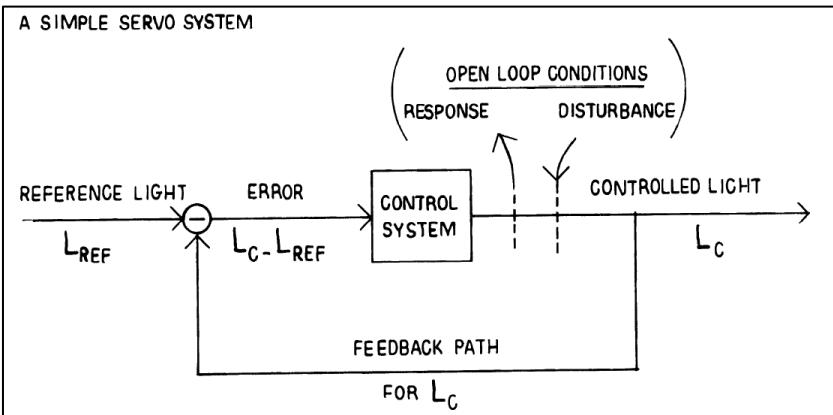
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Pupillary Motor reflex, sensitivity, mechanisms

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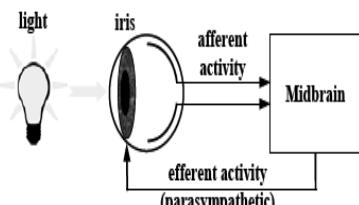
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VOLUME 58, NUMBER 3

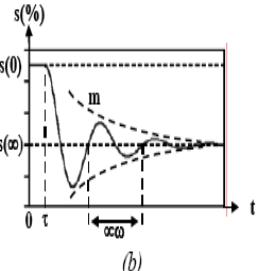
SEPTEMBER 1998

Spontaneous oscillations in a nonlinear delayed-feedback shunting model of the pupil light reflex

P. C. Bressloff and C. V. Wood



(a)



(b)

Figure 4: Modeling of the reflex loop based on physiologic knowledge (a) by the response of second order linear system (b).

## A SERVOANALYTIC STUDY OF CONSENSUAL PUPIL REFLEX TO LIGHT<sup>1</sup>

LAWRENCE STARK AND PHILIP M. SHERMAN

Section of Neurology and Department of Electrical Engineering,  
Yale University, New Haven, Connecticut

(Received for publication July 9, 1956)

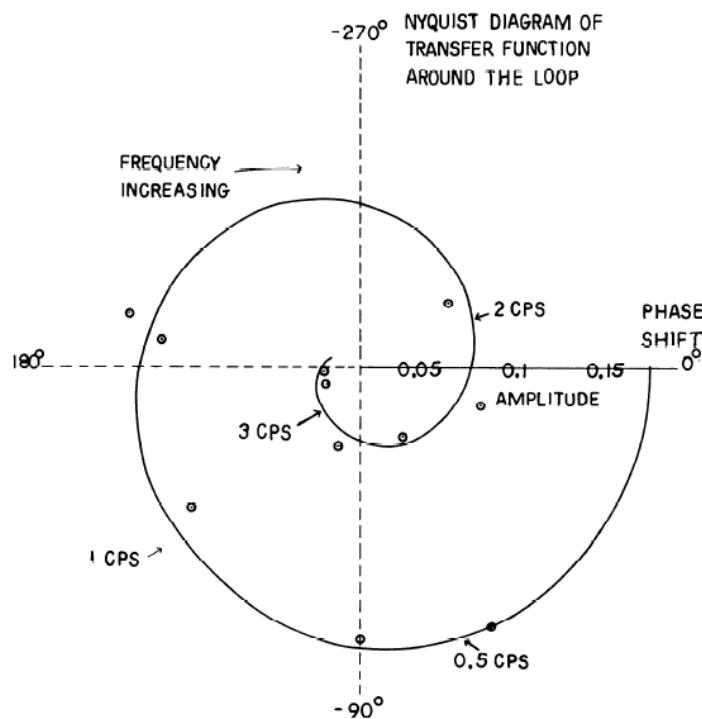


FIG. 7. Nyquist diagram of the transfer function around the loop (open). Vector plot of gain (amplitude) and phase shift. Dimensionless scale of modulus is shown. A few frequencies are indicated. Line is derived from fitted lines of Fig. 6, while points are experimental. It is to be especially noted that gain at 180° phase shift is only 0.12. This indicates that system is very stable.

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attention, emotion

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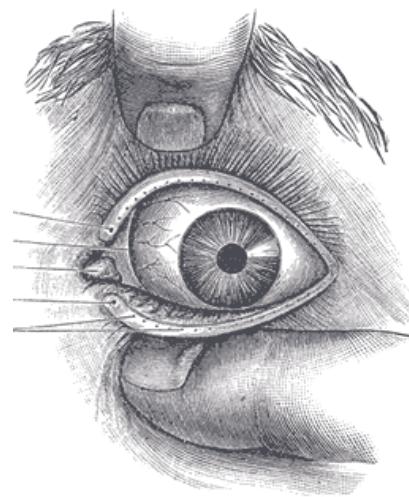
a marker of mental disorders  
and neuropathologies

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Sensitivity to drugs/dissecting sub-cortical lesions

## Physiology/Genetics

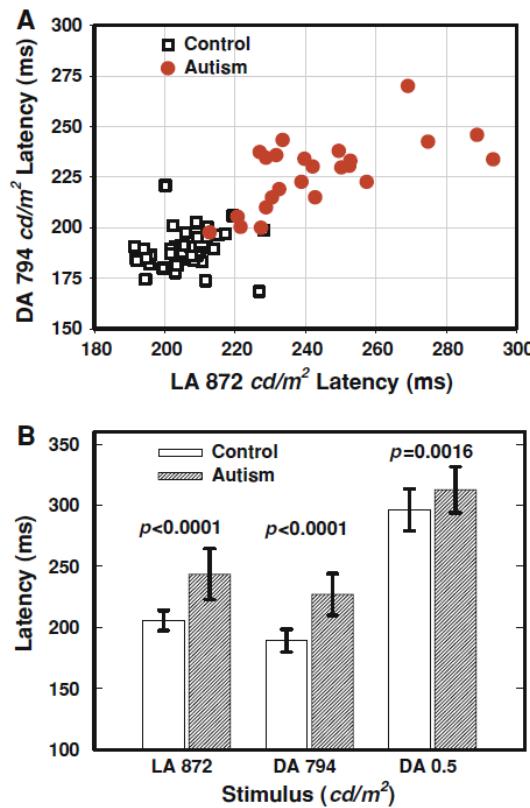
a new opsine in 'non-visual' retinal ganglion cells  
regulating circadian cycles.

## Vision/Pupil perimetry

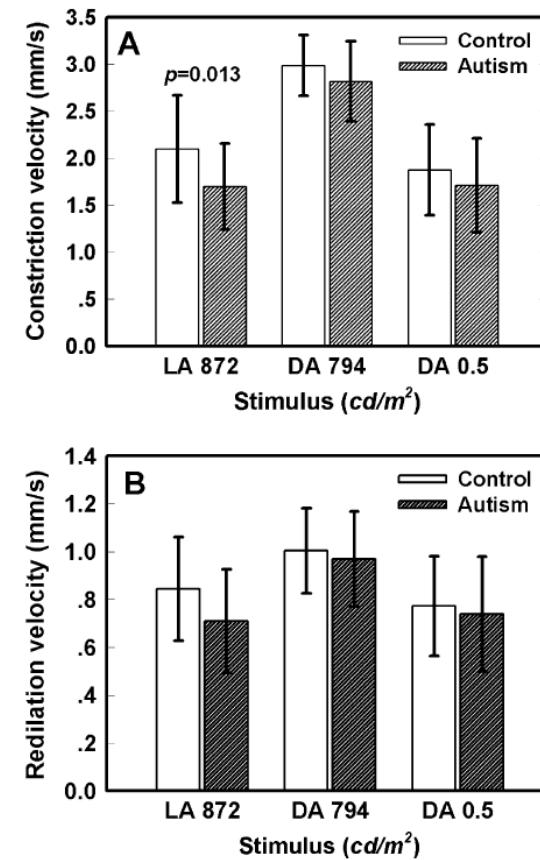
Pupillary Motor reflex, sensitivity, mechanisms

# Psychiatry Neuropsychology : a marker of mental disorders

Fan, et al. (2009). Abnormal transient pupillary light reflex in individuals with autism spectrum disorders. *Journal of autism and developmental disorders*, 39(11), 1499-1508.



**Fig. 2** a The distribution of pupillary light reflex (PLR) latency data and b the statistics of the mean latencies in the ASD and control groups. Data shown here were from 43 typically developing participants and 24 participants with ASDs. The error bars in b indicate the standard deviation. LA light adaptation; DA dark adaptation



**Fig. 3** a The constriction velocity (mm/s) and b recovery velocity (mm/s) in the ASD and control groups. Data shown here were from 43 typically developing children and 24 children with ASDs. The error bars indicate the standard deviation. LA light adaptation; DA dark adaptation

# Psychiatry Neuropsychology : a marker of mental disorders

In: E. Usdin and I. Hanin (Eds.), Biological markers in psychiatry and neurology. Oxford: Pergamon Press, 1982, 371-385.

## VULNERABILITY TO SCHIZOPHRENIA: INFORMATION PROCESSING IN THE PUPIL AND EVENT-RELATED POTENTIAL

S. Steinhauer and J. Zubin

### PUPILLARY DILATION RESPONSE EVENT-RELATED POTENTIAL

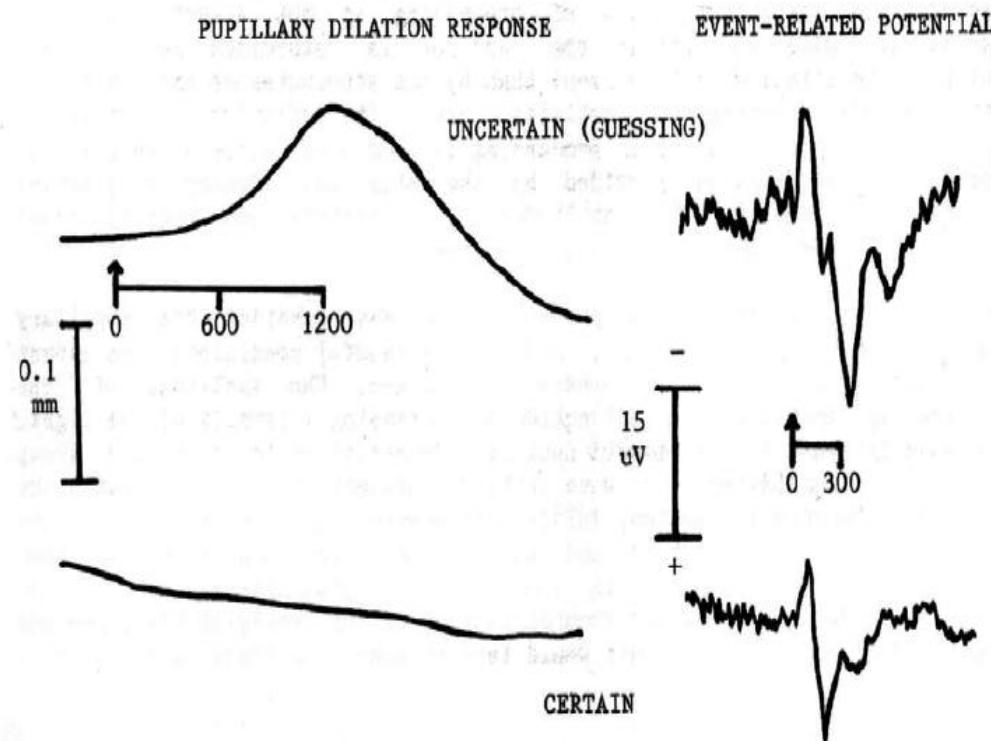


Fig. 1. Pupillary dilation response and vertex event-related potential recorded from a normal subject under conditions of Uncertainty and Certainty.

## Control

### PUPILLARY DILATION RESPONSE

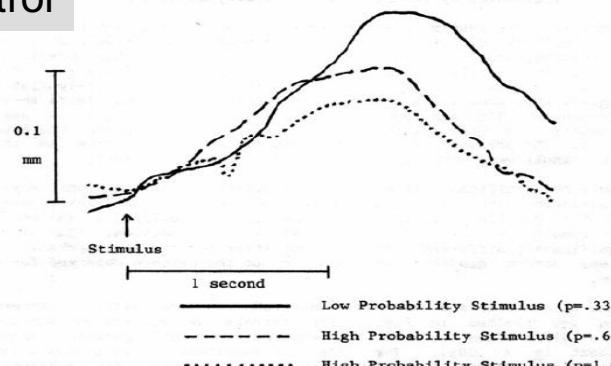


Fig. 2. Representative data for one control subject in the counting task.

## Depressive

### PUPILLARY DILATION RESPONSE

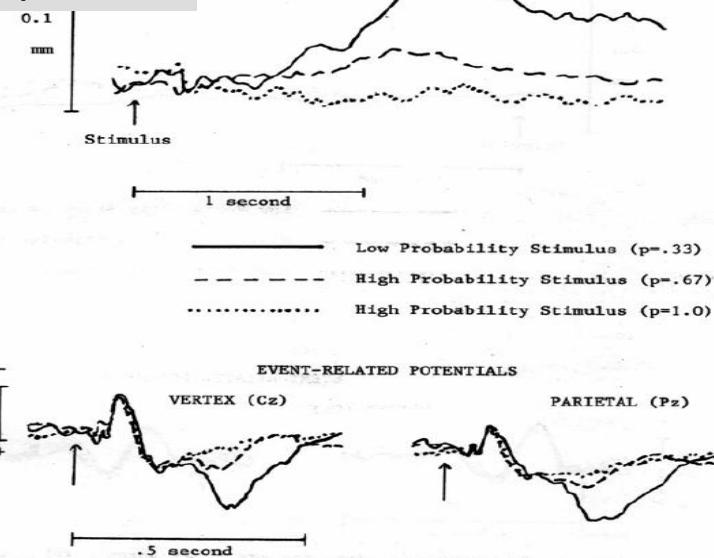


Fig. 3. Representative data for one depressive subject in the counting task.

## Schizophrenic

### PUPILLARY DILATION RESPONSE

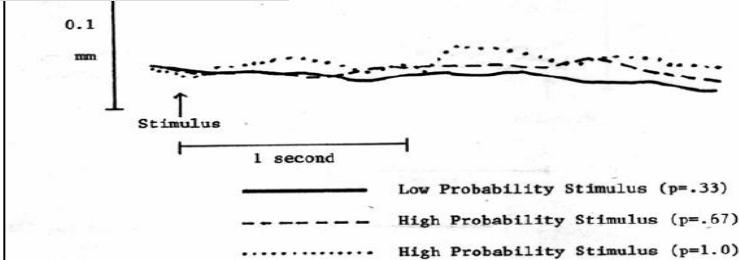


Fig. 4. Representative data for one schizophrenic subject in the counting task.

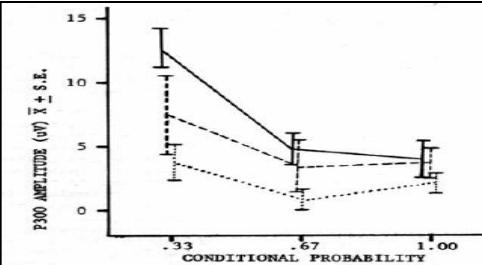


Fig. 5. Pupillary Dilation vs. conditional probability for controls, depressives and schizophrenics.

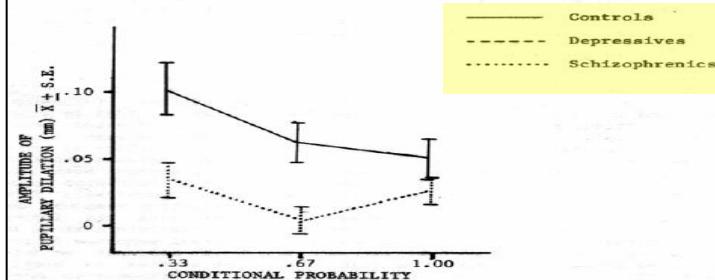


Fig. 6. P300 at Pz vs. conditional probability for controls and schizophrenics.

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# Pupil & Cognition

: marker of detection, memory load, attention, emotion

Hakerem & Sutton. Pupillary Response At Visual Threshold. Nature. Vol 212(5061), 1966, 485-486.

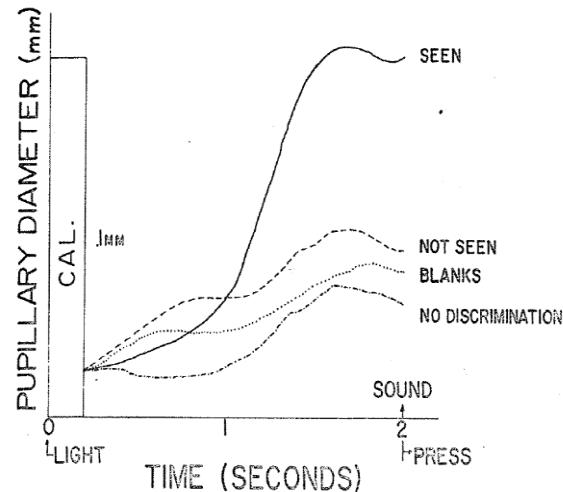
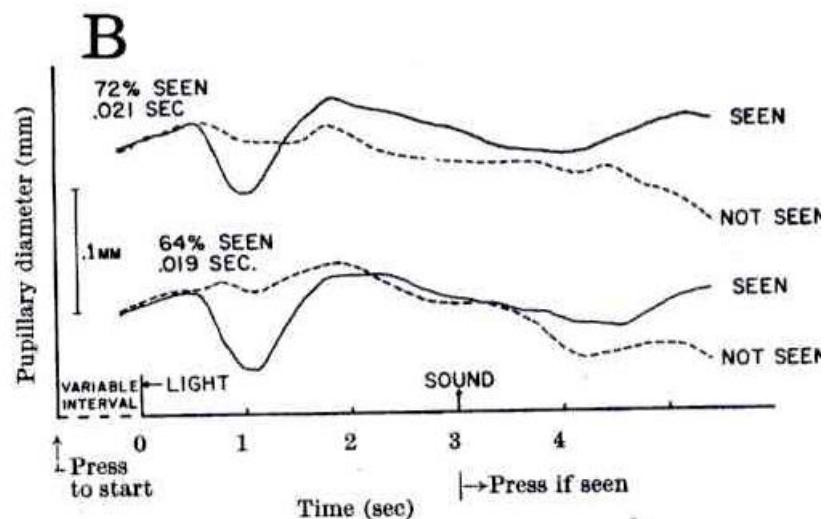
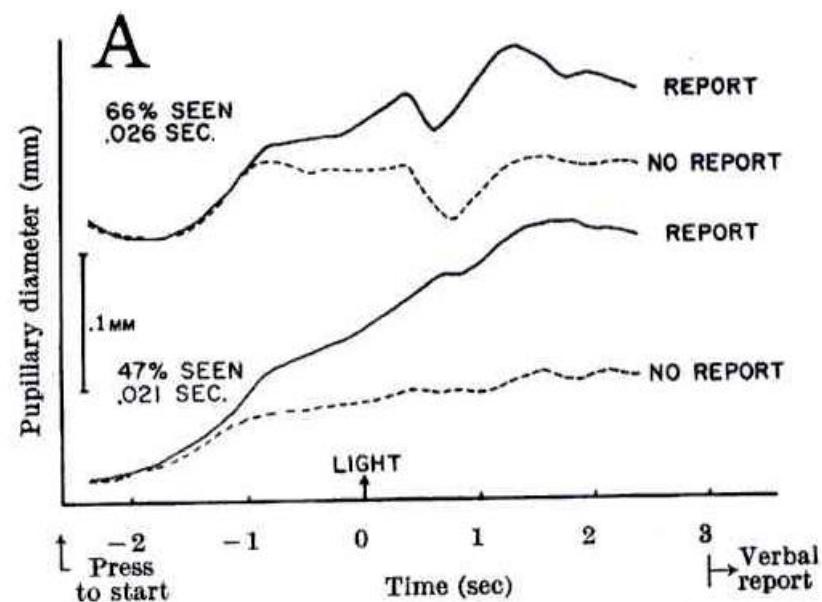


Figure 3-26. Pupillary responses at the visual threshold. A: Average curves of relative pupillary diameter for "report" and "no report" conditions when the eye was stimulated at two different energy levels (0.026 second and 0.021 second at  $6 \times 10^{-5}$  mL). The curves were arbitrarily superimposed at the onset of the trial to help comparison. Both "seen" and "not seen" trials were included in the average curves. (From G. Hakerem and S. Sutton, *Ann. N.Y. Acad. Sci.*, 156 [1969]:951) B: Average curves of relative pupillary diameter as a function of whether or not the light stimulus was reported as seen. The curves were arbitrarily superimposed at light onset, and the first period of dilation after initiating the trials was discarded. The energy levels were 0.21 second and 0.019 second at  $6 \times 10^{-5}$  mL. (From G. Hakerem and S. Sutton, *Nature, London*, 212 [1966]:485; reprinted by permission from *Nature*, © 1966 Macmillan Magazines Ltd.)



# Pupil & Cognition: marker of memory load, attention, emotion

Privitera, et al. The pupil dilation response to visual detection. Human Vision and Electronic Imaging XIII, edited by Bernice E. Rogowitz, Thrasivoulos N. Pappas, Proc. of SPIE-IS&T Electronic Imaging, SPIE Vol. 6806, 68060T, © 2008 SPIE-IS&T

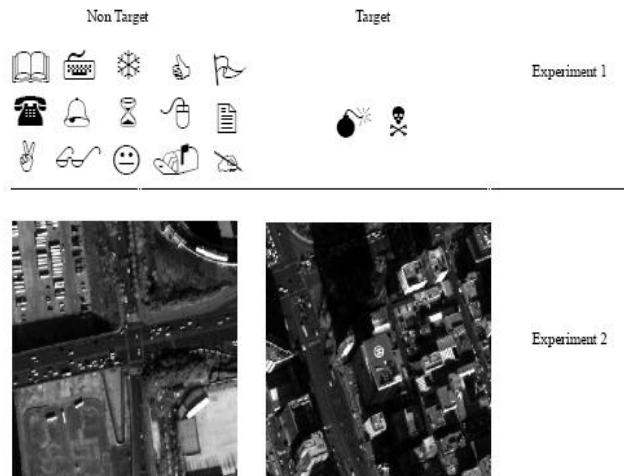


Figure 1. Examples of target (right) and non-target (left) visual stimuli for the two experiments; note the helipad sign in the center of the satellite photo for the second experiment (Experiment 2 imagery is © DigitalGlobe). The locus of eye fixation was maintained at the center of the computer stimulus monitor and stimuli were rapidly alternated at 10 Hz. Subjects were asked to detect objects that could be associated to a meaning of *threat* or *danger* in the first experiment and to detect helipads in the second experiment.

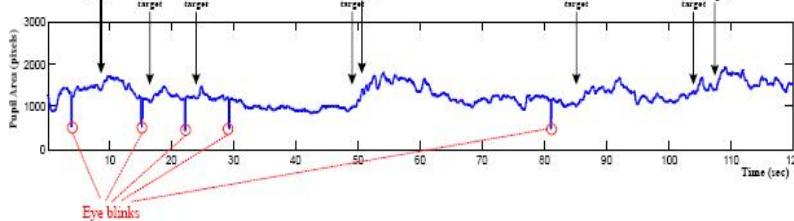


Figure 2. Example of pupil fluctuation during a single viewing session; eye blinks were easily detected by the eye-tracker software and removed in our analysis. Target presentations elicited pupil dilation; see arrows and the associated pupil area expansion.

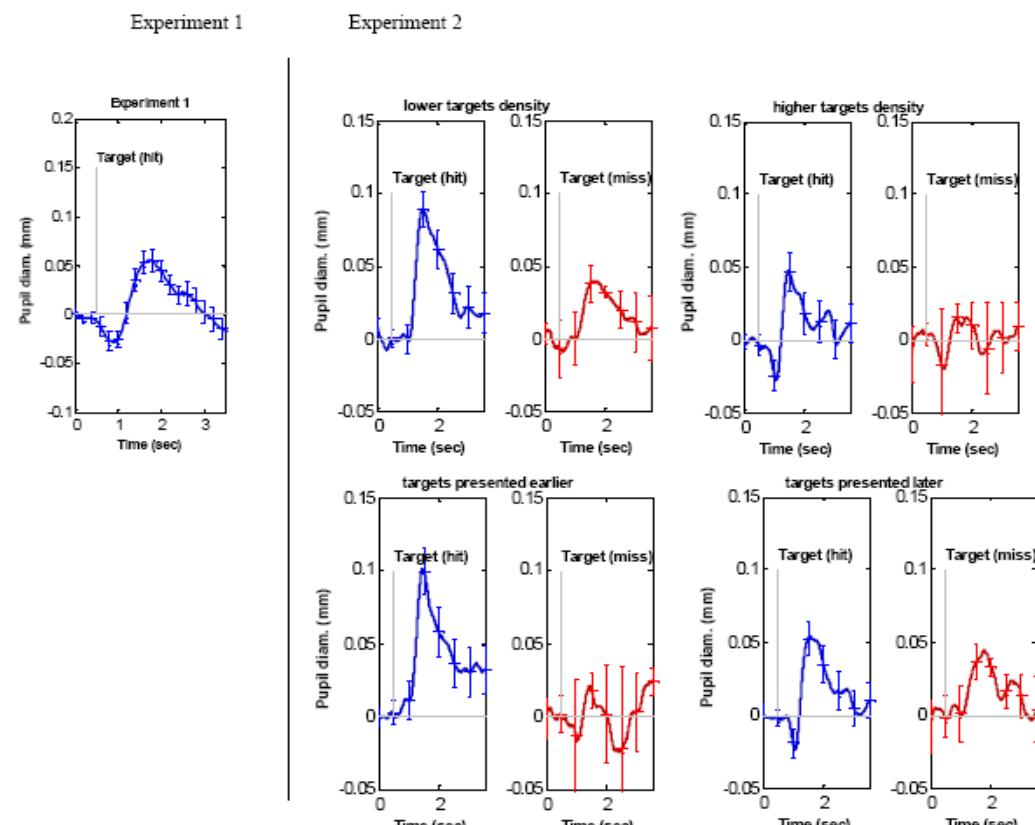
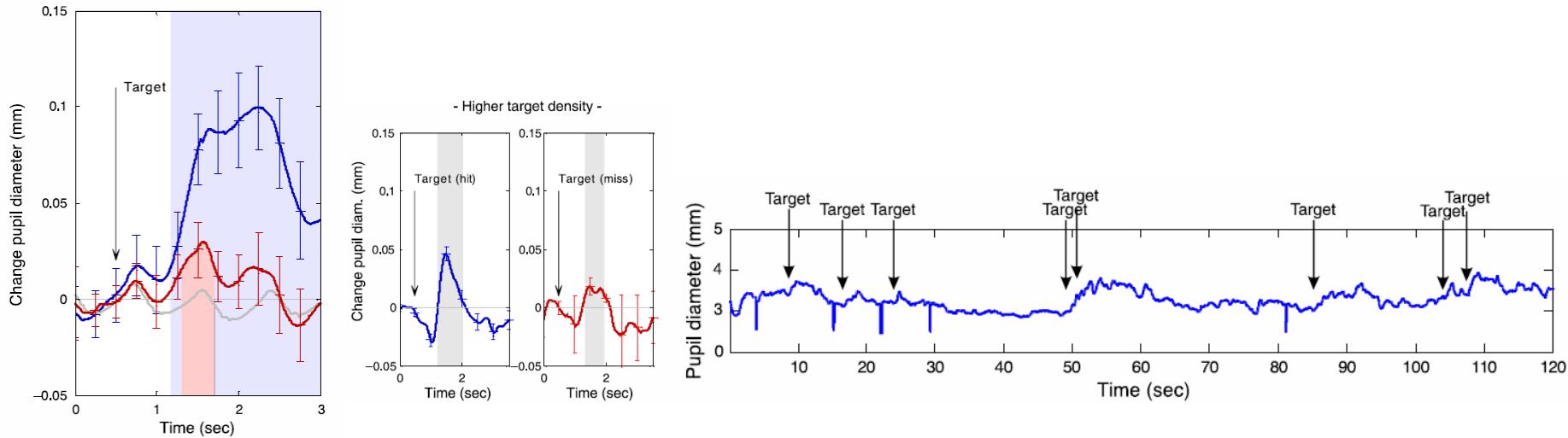


Figure 3. Average of pupil responses for Experiment 1 (left) and Experiment 2 (right). The vertical gray line indicates time of target presentation. Error bars correspond to CIs at  $\alpha=0.01$ . Pupil dilation onset occurs around 500ms after target presentation in both experiments. For Experiment 2 (right), the data are divided into two groups. In the upper panels, one is for lower targets density (few targets per run) and one for higher targets density (many targets per run). *Hit*, (blue line) are pupil profiles when the corresponding target was detected by means of a button press and *miss*, (red line) are the pupil profiles when the target was missed. Pupil dilation is evidenced by a positive peak of the pupil diameter after the target presentation and it is more pronounced in those runs with fewer targets. In the lower panels, data are divided based on the time of target presentation within the run. Targets viewed earlier generated larger dilations.

Pupil dilation during visual target detection Claudio M. Privitera,  
Laura W. Renninger, Thom Carney, Stanley Klein, and Mario Aguilar. <http://www.journalofvision.org/content/10/10/3>

-Experiment 1 : Semantic target detection



# Pupil & Cognition: marker of memory load

Van Gerven & al: Memory load and the cognitive pupillary response in aging. Psychophysiology, 41 (2004), 167–174.  
*Sternberg task : a: encode digits (1 to 6) and b: determine whether a digit belongs to the series (search)*

## Encoding

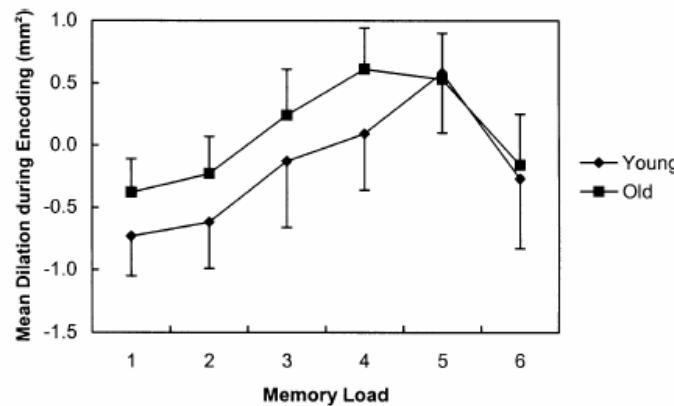


Figure 1. Mean pupil dilation (in square millimeters) during encoding as a function of memory load. Values are change scores relative to baseline. Bars indicate one standard error of the mean.

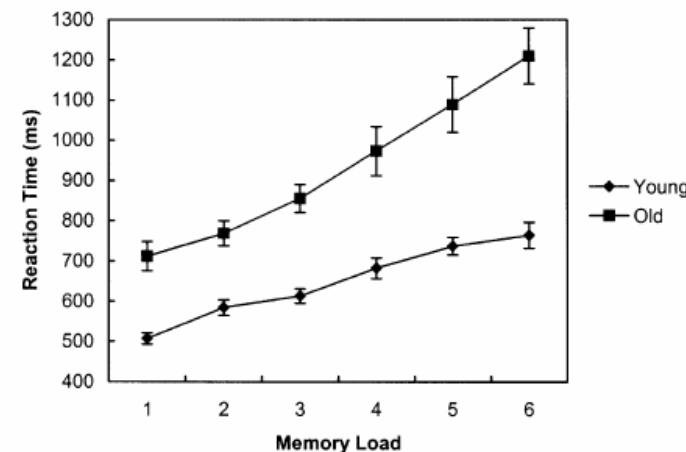


Figure 2. Reaction time (in milliseconds) as a function of memory set. Bars indicate one standard error of the mean.

## Search phase

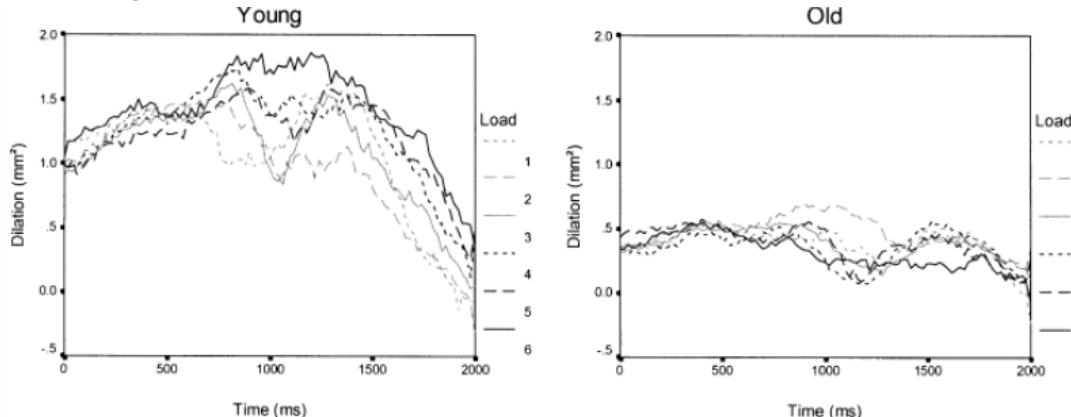


Figure 3. Mean pupil dilation (in square millimeters) as a function of time (in milliseconds after probe onset) in the search phase. Values are change scores relative to baseline. The left panel shows the mean values of the 16 young participants; the right panel shows the mean values of the 16 elderly participants.

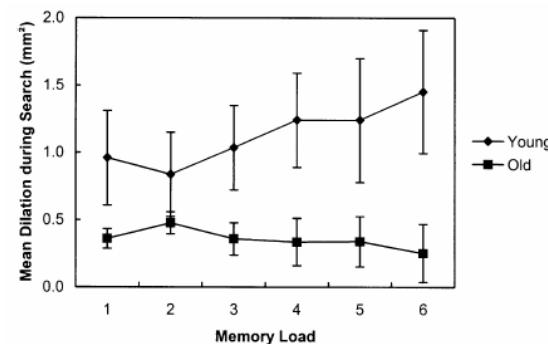


Figure 4. Mean pupil dilation (in square millimeters) during memory search as a function of memory load. Values are change scores relative to baseline. Bars indicate one standard error of the mean.

## Pupil size variation as an indication of affective processing

Timo Partala<sup>a</sup>, Veikko Surakka<sup>a,b,\*</sup>

Thirty stimuli, 10 per category were selected from the IADS. The IADS mean rating values of two dimensions, valence and arousal, were used as criteria for stimulus selection (Bradley and Lang, 1999). The categories were negative highly arousing (e.g. a couple fighting), neutral (e.g. background office noise), and positive highly arousing (e.g. a baby laughing) stimuli. Erotic stimuli were not used. The respective means for valence and arousal for the different categories were for negative (2.6 and 6.8), neutral (5.1 and 4.2), and positive (7.4 and 6.6). All the stimuli were about 6 s long.

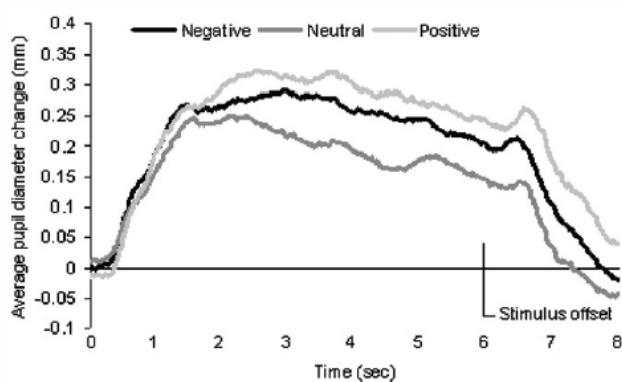


Fig. 2. Averaged pupil diameter timelines for the different stimulus categories for female subjects.

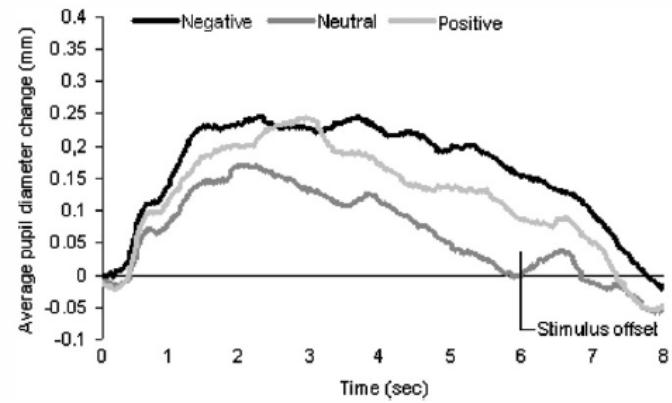
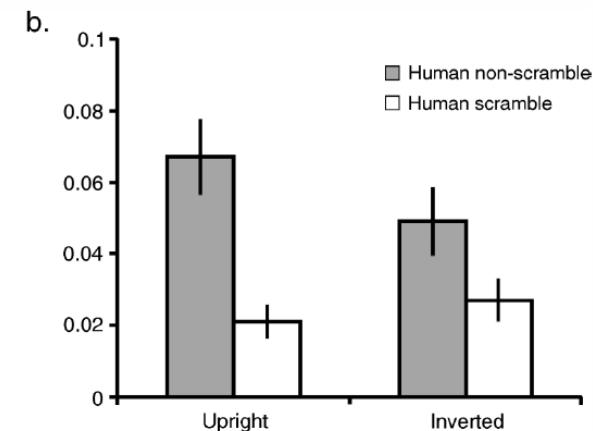
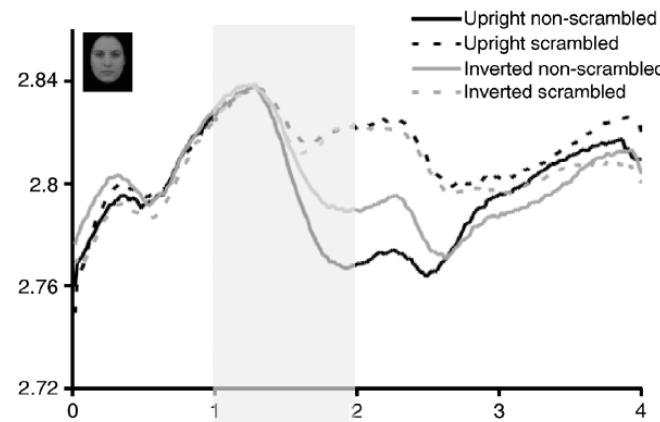
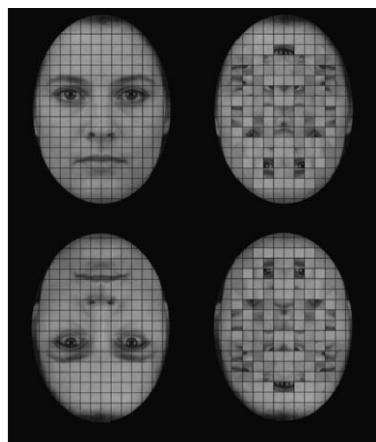


Fig. 3. Averaged pupil diameter timelines for the different stimulus categories for male subjects.

# Pupil & Cognition: marker of emotion processing

Transient pupil constrictions to faces are sensitive to orientation and species

Conway et al. Journal of Vision (2008) 8(3):17, 1–11 <http://journalofvision.org/8/3/17/>



Cerebral Cortex  
doi:10.1093/cercor/bhn034

## Human Amygdala Sensitivity to the Pupil Size of Others

K.E. Demos, W.M. Kelley, S.L. Ryan, F.C. Davis and P.J. Whalen

Department of Psychological and Brain Sciences, Center for Cognitive Neuroscience, Dartmouth College, Hanover, NH 03755, USA

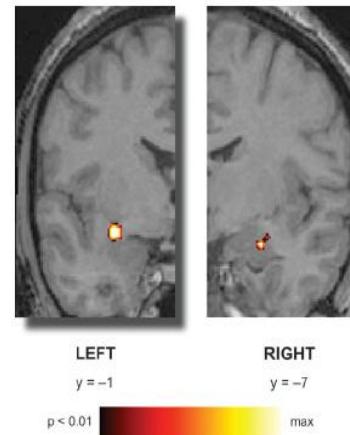
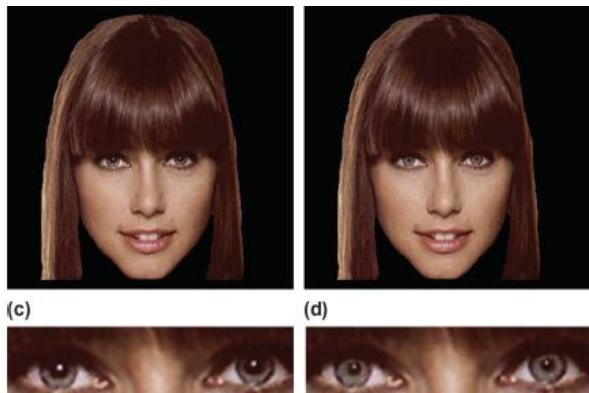
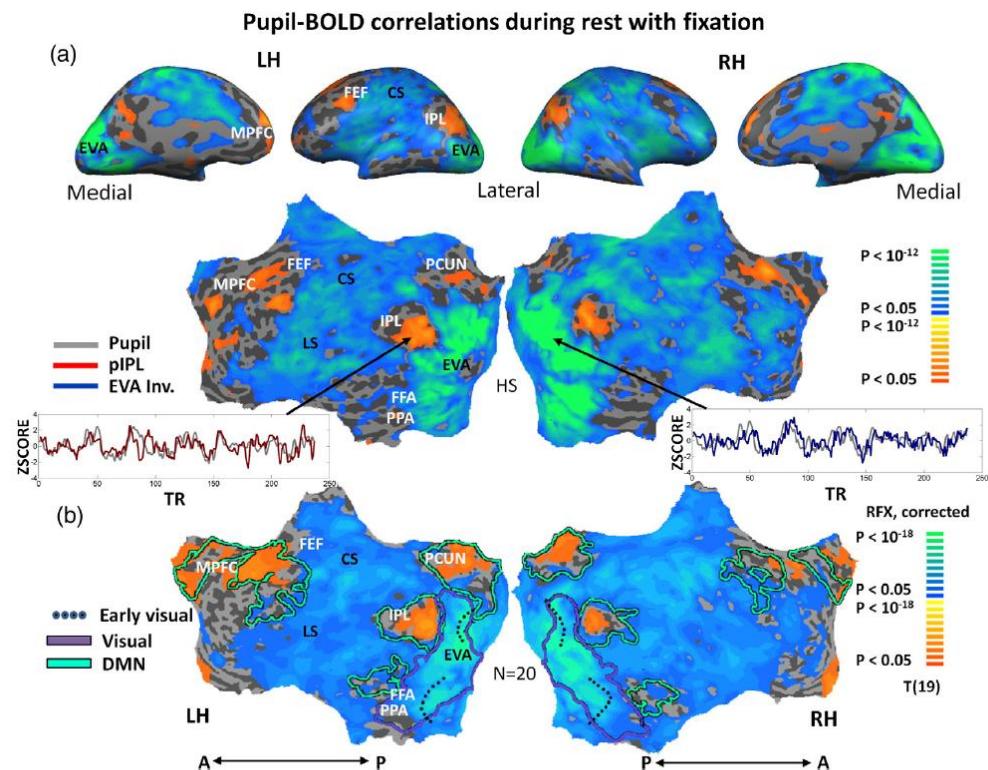
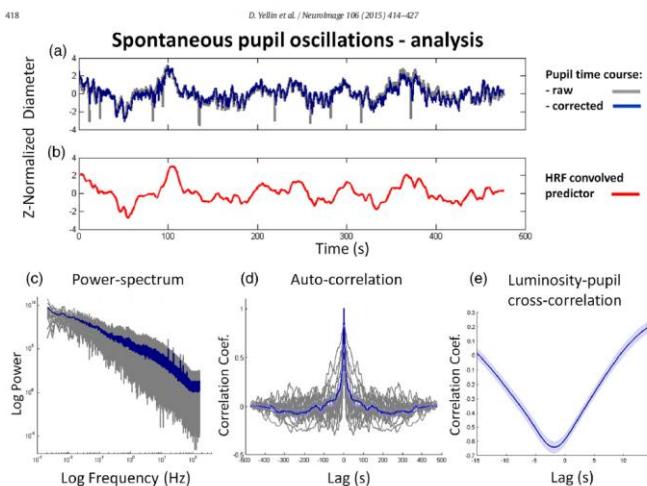


Figure 2. Amygdala responses during passive viewing of big- and small-pupil faces. Coronal sections show greater activity for big- versus small-pupil faces. Images are coronal sections in Talairach and Tournoux (1988) atlas space. Colored pixels exceed the statistical threshold ( $P < 0.01$ , uncorrected, minimum cluster size = 5 voxels) and are superimposed on corresponding anatomy images. The left side of the image corresponds to the left hemisphere at a  $y$  coordinate of  $-1$  and the right side of the image corresponds to a  $y$  coordinate of  $-7$ . Greater activity to BIG versus SMALL pupils was observed in both the right amygdala ( $27 -7 -15$ ) and the left amygdala extending into the substantia innominata within the ventral basal forebrain ( $-30 -1 -10$ ).

# Pupil & Imaging

Dov Yellin, Aviva Berkovich-Ohana, Rafael Malach (2015). Coupling between pupil fluctuations and resting-state fMRI uncovers a slow build-up of antagonistic responses in the human cortex. *NeuroImage* 106 (2015) 414–427.



## Conclusion

To summarize, our findings reveal a spontaneously emerging antagonism between fundamental networks of the human cortex that is correlated to pupil dilatations during rest. Thus, our results reveal a link between behavior – indexed by pupil diameter fluctuations – and spontaneous network activations and deactivations during the resting state.

But also ..... !! And many other papers!

*Brain* (1998), 121, 1065–1072

## Learning from the pupil: a spatial visual channel in the absence of V1 in monkey and human

Lawrence Weiskrantz, Alan Cowey and Carolyne Le Mare

### Task-Evoked Pupillary Response to Mental Workload in Human-Computer Interaction

Shamsi T. Iqbal<sup>\*</sup>, Xianjun Sam Zheng<sup>†</sup> and Brian P. Bailey<sup>\*</sup>

Department of Computer Science<sup>\*</sup> and Beckman Institute<sup>†</sup>

University of Illinois

Urbana, IL 61801, USA

(siqb@uiuc.edu, xzheng, bpbailey@uiuc.edu)

### THE PUPILLARY RESPONSE IN COGNITIVE PSYCHOPHYSIOLOGY AND SCHIZOPHRENIA<sup>a</sup>

Stuart R. Steinhauer<sup>b</sup> and Gad Hakerman<sup>c</sup>

## A Pupillometric Correlate of Scotopic Visual Acuity

ROCKEFELLER S. L. YOUNG,<sup>\*†</sup> EIJI KIMURA,<sup>\*</sup> PATRICIA R. DELUCIA<sup>‡</sup>

Received 28 April 1994; in revised form 5 September 1994

*Behavior Research Methods, Instruments, & Computers*  
1993, 25 (1), 16–26

### Pupillary dilation as a measure of attention: A quantitative system analysis

BERT HOEKS and WILLEM J. M. LEVELT

Max Planck Institute for Psycholinguistics, Nijmegen, The Netherlands

It has long been known that the pupil dilates as a consequence of attentional effort. But the function that relates attentional input to pupillary output has never been the subject of quantitative analysis. We present a system analysis of the pupillary response to attentional input. Attentional input is modeled as a string of attentional pulses. We show that the system is linear; the effects of input pulses on the pupillary response are additive. The impulse response has essentially a gamma distribution with two free parameters. These parameters are estimated; they are fairly constant over tasks and subjects. The paper presents a method of estimating the string of attentional input pulses, given some average pupillary output. The method involves the technique of deconvolution; it can be implemented with a public-domain software package, PUPIL.

### Voluntary Pupil Size Change as Control in Eyes Only Interaction

Inger Ekman<sup>1</sup>, Antti Poikola<sup>1</sup>, Meeri Mäkäräinen<sup>1</sup>, Tapio Takala<sup>1</sup> and Perttu Hämäläinen<sup>2</sup>

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Copyright © 2005 Society for Psychophysiological Research  
DOI: 10.1111/j.1469-8986.2005.00306.x

Absolute pitch and pupillary response: Effects of timbre and key color

KATHRIN B. SCHLEMMER, FRANZiska KULKE, LARS KUCHINKE,  
AND ELKE VAN DER MEER  
Department of Psychology, Humboldt University at Berlin, Germany

## A Chromatic-cancellation Property of Human Pupillary Responses

EIJI KIMURA,<sup>\*</sup> ROCKEFELLER S. L. YOUNG<sup>\*†</sup>

Received 21 February 1995; in revised form 22 August 1995

# Conclusions

- Pupil dynamics :
  - Underlies a variety of “functions”
  - Is regulated by a rich set of cortical and sub-cortical structures,
  - coupled to a complex set of cortical and sub-cortical structures involved in attention, emotion, cognitive load, awareness, etc..
- May offer a tool to “measure” cognitive states and psychological processes
- However, pupil dynamics results from multiplexed signals, is sensitive to a variety of stimuli, depends upon eye-movements, is modulated by idiosyncratic factors.

According to Loewenfeld (1999, p. 319), *“Any sensory stimulation (with the exception of light), can elicit pupillary dilation; and spontaneous thoughts and emotions have the same effect as sensory stimuli.”*
- *Thus, devising experiments to tackle/identifiy/evaluate cognitive processes should carefully consider the many factors that influence pupil reactivity: stimuli (luminance, spatial frequency, color..), distance (acomodation, vergence), lighting conditions (scotopic, photopic), population involved (elderly, young), day time, etc...*

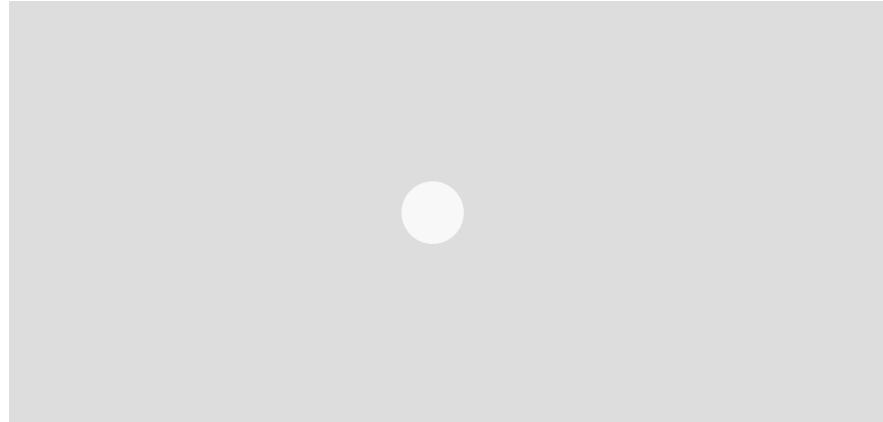
# Some recent findings

- Simple reaction time experiment
- Pupil dynamics during bistable vision
- Pupil dynamics during RSVP

# Reaction time & Pupil

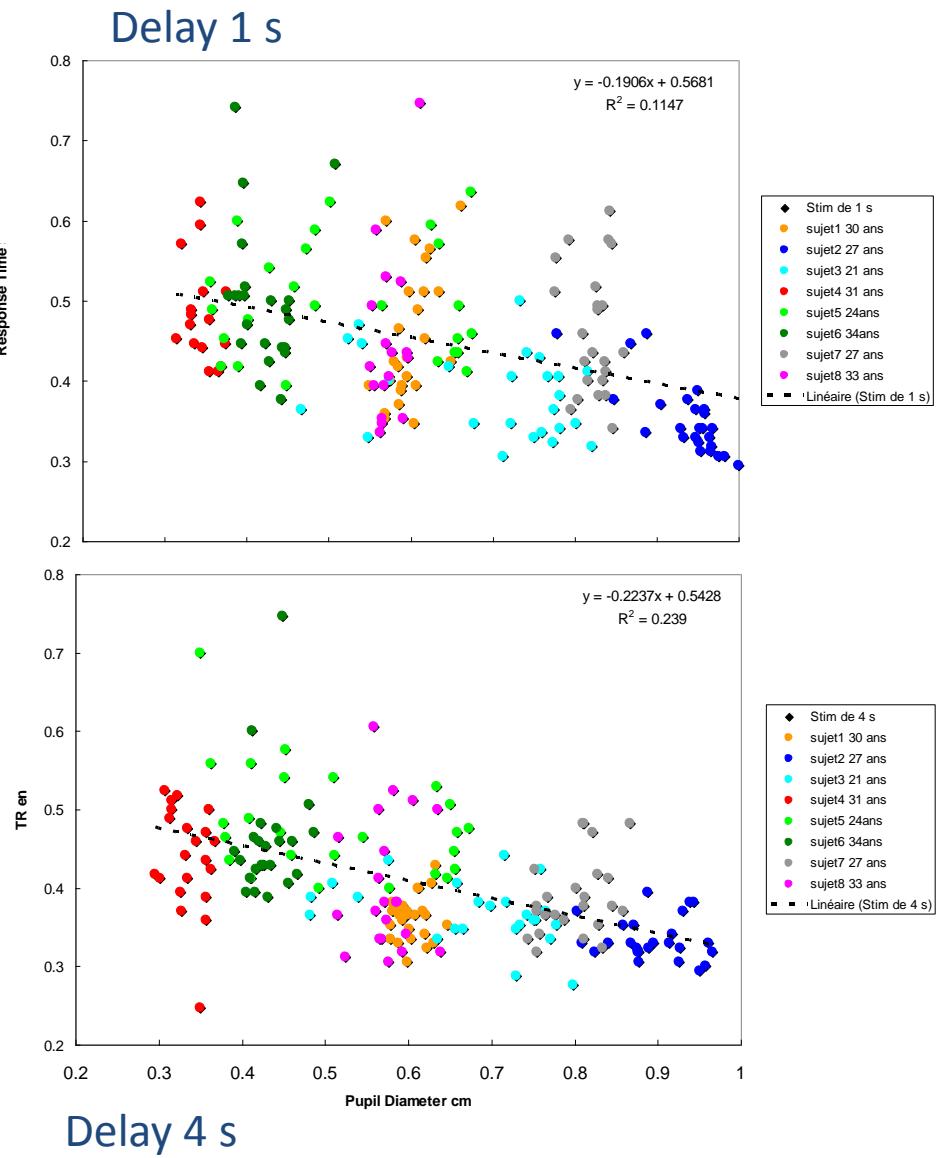
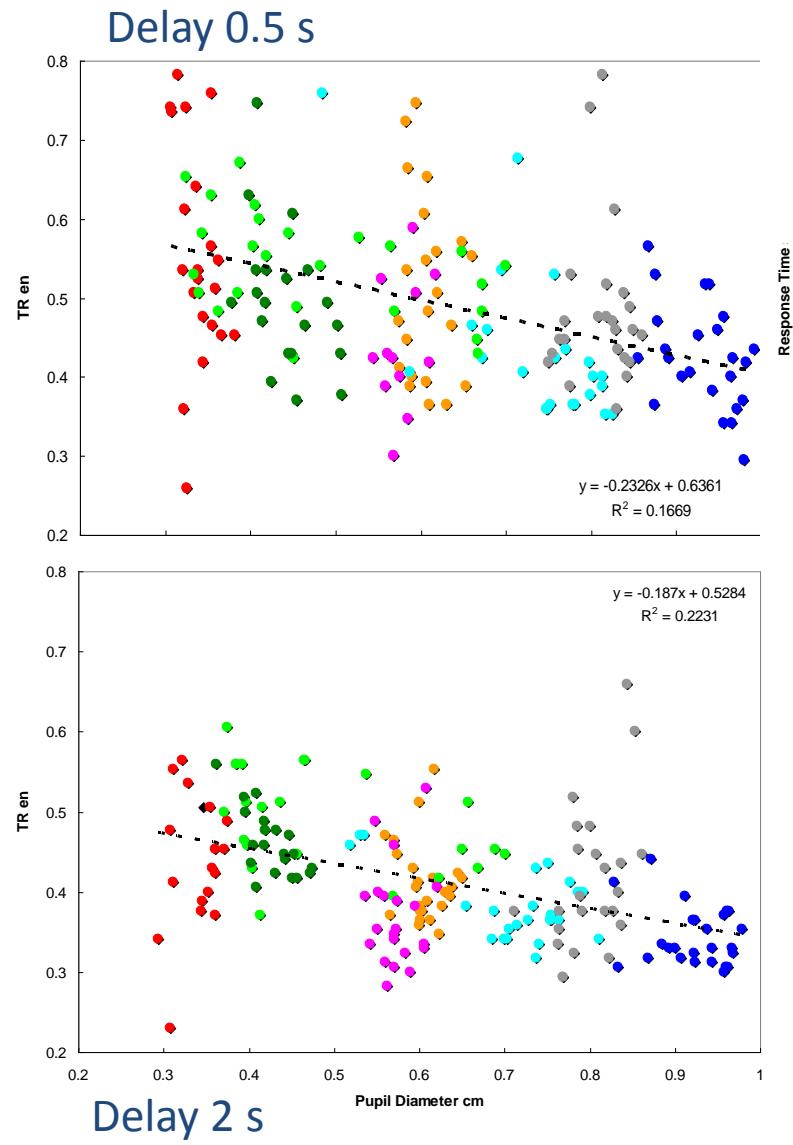
Cédric Lamirel, Jean Lorenceau (unpublished results)

- Stimuli : a simple white disk moving to the right after 0.5, 1, 2, or 4 sec.  
-> Trial start signaled by a beep.
- Task: press a key as fast as possible at motion onset
- 8 participants



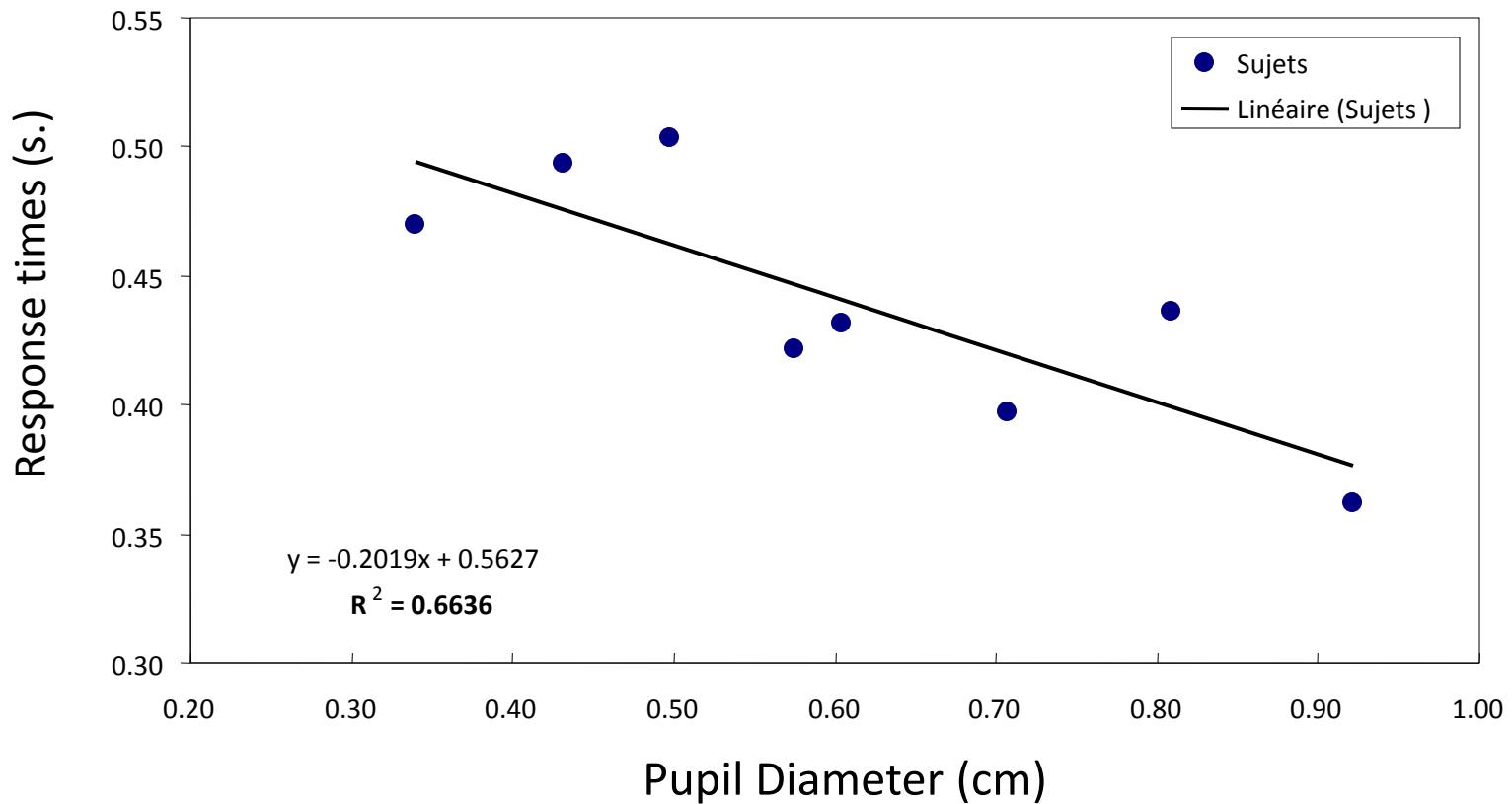
- Pupil diameter measured as averaged size during 500 ms **before** a button press. (Other measures : e.g. averaged pupil size from -500 ms to -400 ms give similar results)
- Response times decrease with longer delay between stimulus onset & stimulus movement

# Pupil size predicts response time

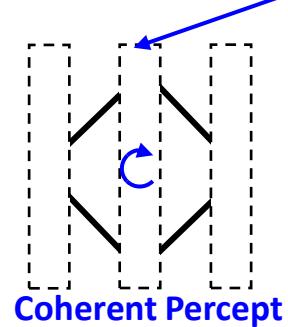
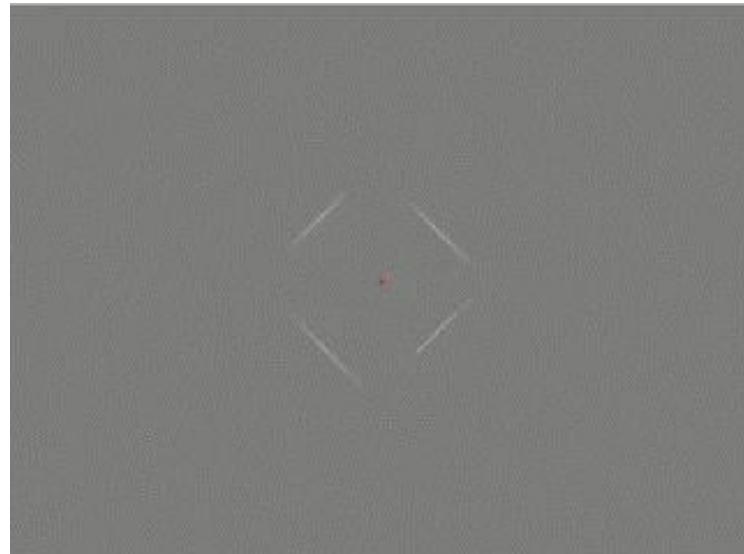
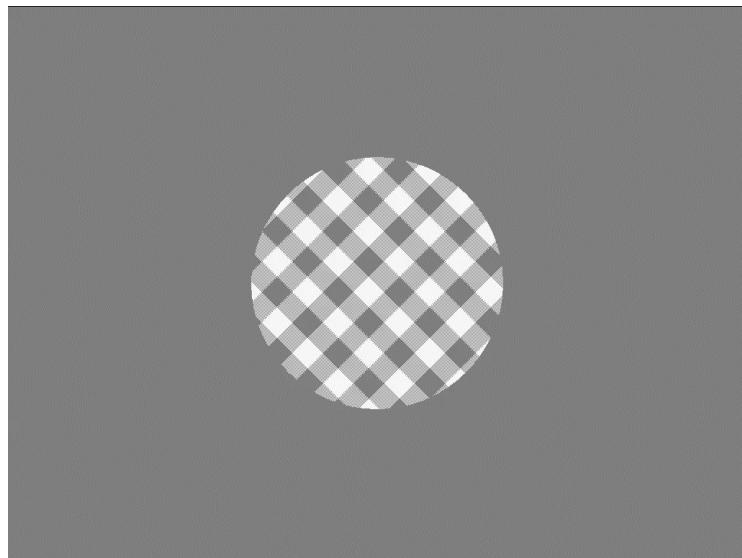


# Pupil size predicts response time

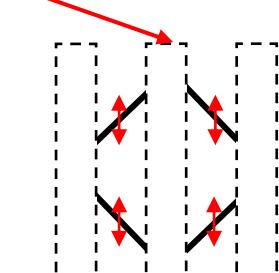
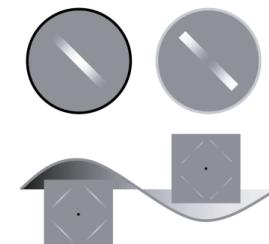
## All subjects, all conditions



Hupé, Lamirel & Lorenceau, (2009). Pupil dynamics during bistable motion perception.  
Journal of Vision (2009) 0(0):1, 1–19

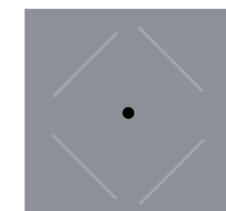


A Induced



Incoherent Percept

B Spontaneous



## Blink & Pupil Dynamics

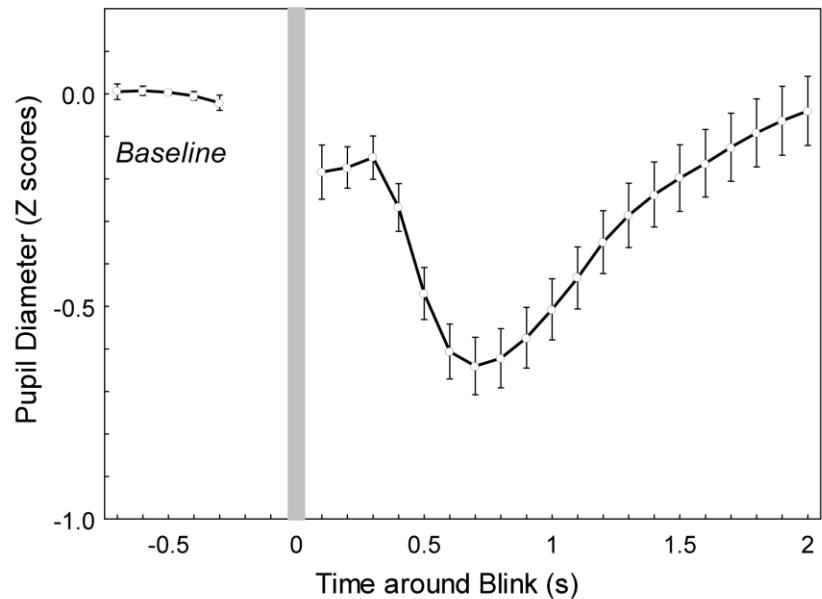
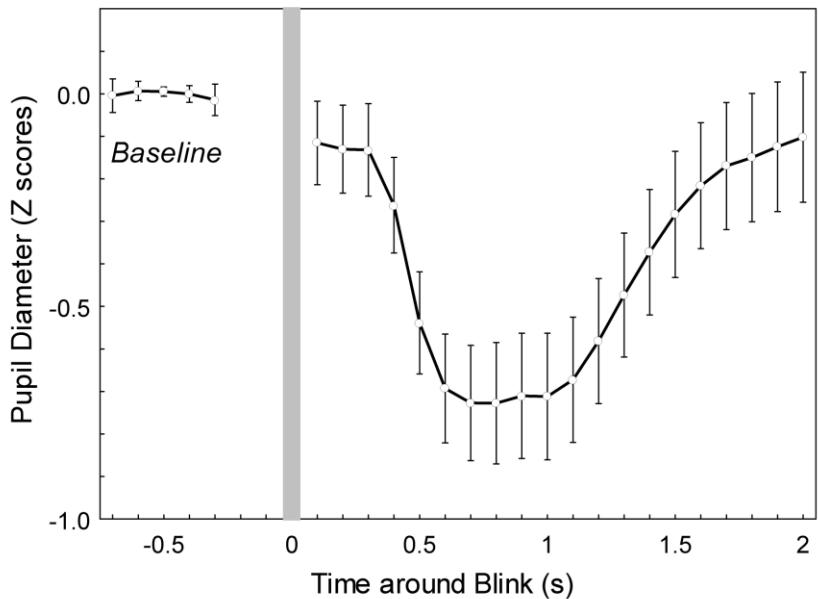


Figure 2. **Left.** Pupil response around blinks in the **plaid** experiment (mean +/- SEM). Data from 14 subjects, N = 417. The total number of blinks was 2267. Average pupil diameter was computed for the period [-0.7 -0.3] s before the beginning of each blink and subtracted to each trace. Blinks were excluded from the analysis if another blink or a button press occurred within 2.2 s before (i.e. 1.5 s before baseline) the beginning of the blink or 1.5 s after its end. Pupil diameter was significantly ( $p < .03$ ) below zero between 400 ms and 1.5 s after the end of the blink. **Right.** Pupil response around blinks in the **diamond** experiment. Data from 10 subjects, N = 492. The total number of blinks was 1980. Pupil diameter was significantly ( $p < .03$ ) below zero between 400 ms and 1.5 s after the end of the blink.

## Pupil dilation around a button press

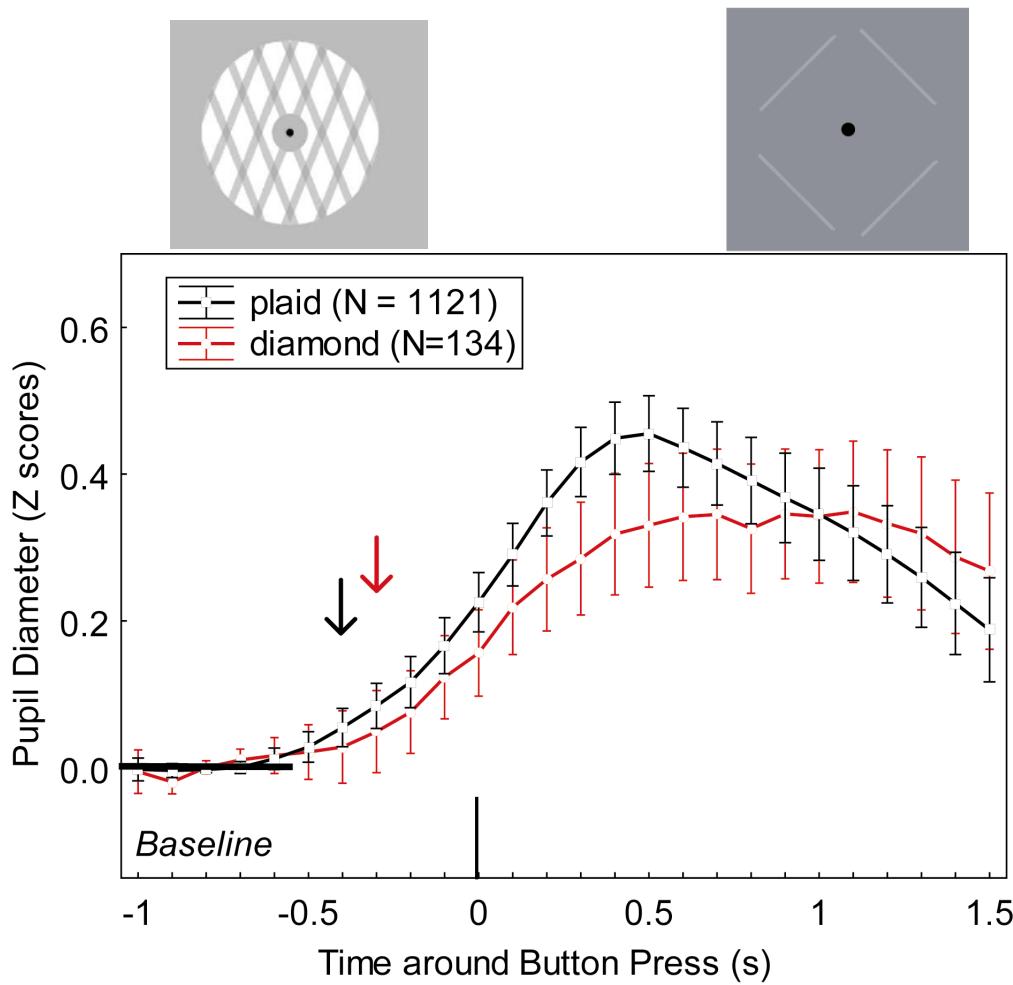


Figure 4. Pupil response around perceptual switches of ambiguous plaids and diamonds (mean +/- SEM). Plaids: data from 14 subjects, N = 1121 (10 outliers removed. The total number of transitions was 3390). Diamonds: data from 10 subjects, N = 134 (9 outliers removed. The total number of transitions was 332). Subjects indicated percept changes by releasing and pressing mouse buttons. Since pupil response to blinks last on average 1.5 s, button presses were excluded if a blink occurred within 2.5 s before (i.e. 1.5 s before baseline) or 1.5 s after the button press. In order to avoid between events contamination, button presses were excluded if following another press by less than 2.5 s or preceding another press by less than 2 s. Average pupil diameter was computed for the period [-1 -0.6] s before each button press and subtracted. For plaids, pupil diameter started to increase significantly above zero 400 ms before button press (Black curve.  $F(1, 1093) = 6.6, p = .021$ ). The increase was significant for 13 out of the 14 subjects. For diamonds it started 300 ms before button press (Red curve.  $F(1, 114) = 5.3, p = .026$ ). The increase was significant for 8 out of the 10 subjects.

## Pupil dilation around a button press

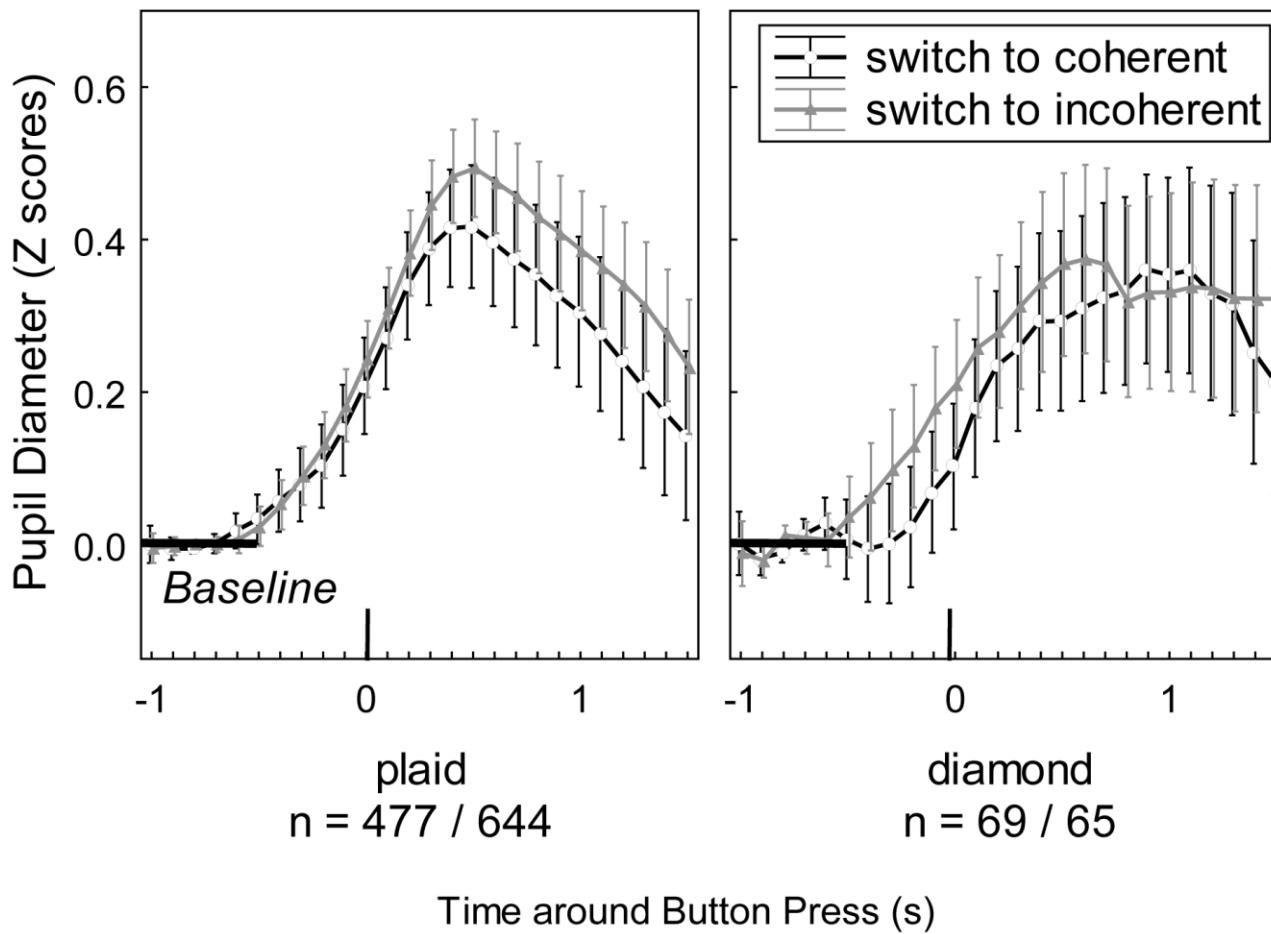


Figure 5. Percept type has no or little effect on the amplitude or timing of pupil responses (mean +/- SEM). Same data set as in figure 4. For spontaneous diamonds, we observed a tendency for the pupil response to start earlier for switches to incoherent percepts. However, amplitude difference between both traces did not reach significance: the stronger difference occurred at the time of button press ( $F(1, 114) = 3.02, p = .098$ ). Inspection of data of individual subjects confirmed that this latency difference was not reliable in our data set.

# Pupil dilation control experiments: effect of button press!!

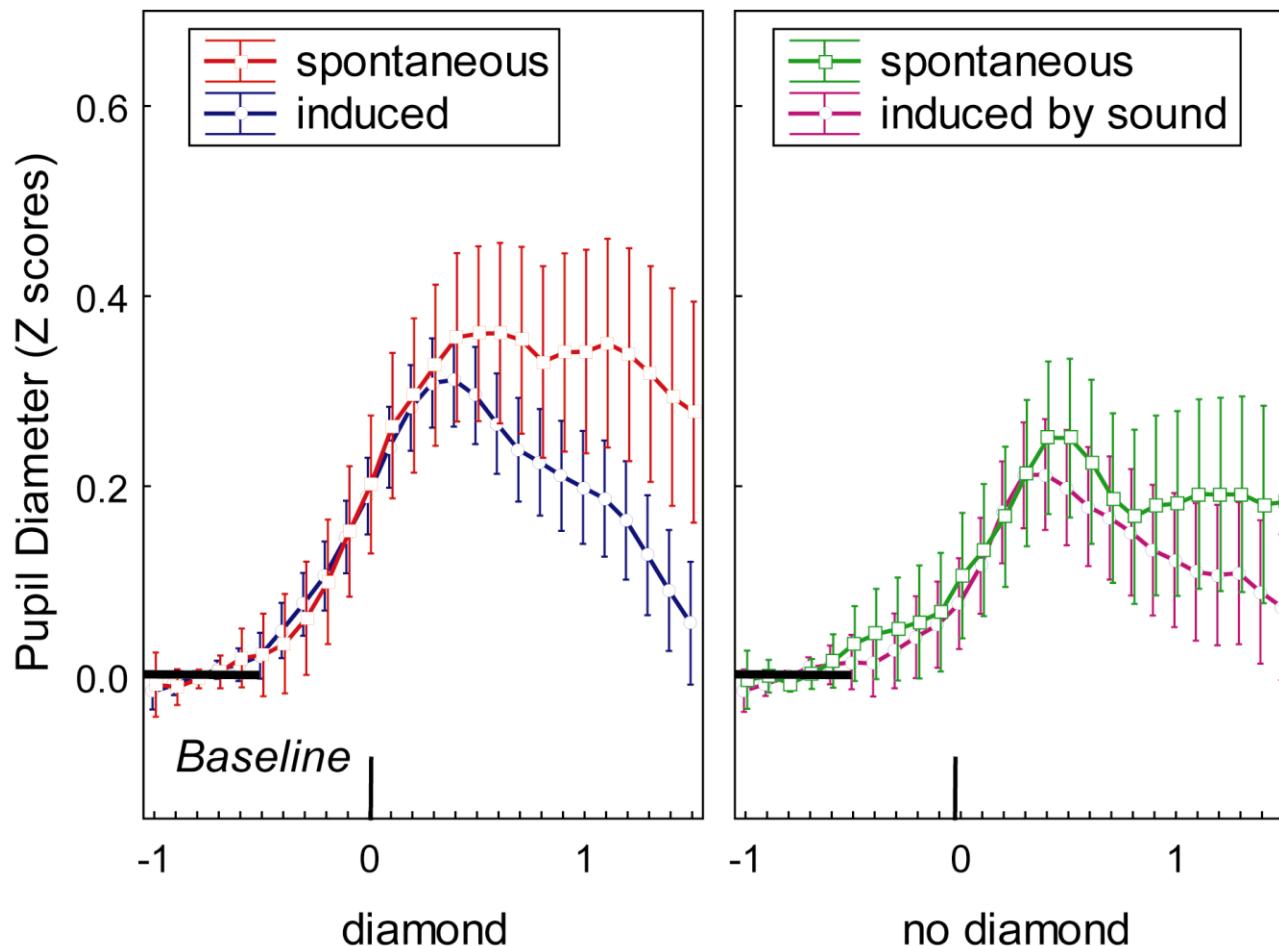


Figure 6. Pupil response for different tasks. The same 9 subjects ran all four experiments (subject 5 had too many blinks in the 'green' condition, and was therefore excluded for this graph). Red lines: **Condition 1**, diamonds were ambiguous and subjects experienced spontaneous changes of percept (same data set as in figures 4-5). Blue lines: **Condition 2**, perceptual transitions were induced by stimulus manipulations. Purple lines: **Condition 3**, subjects were asked to switch of mouse button each time there was a sound. Green lines: **Condition 4**, subjects were asked to press the mouse buttons randomly. In those two conditions subjects were required to keep fixating a small disk at the center of a static occluded diamond (static version of the stimulus of Condition 1). Total number of events used for the computation of each PSTH was, respectively, 138, 320, 164 and 303 (20 outliers were removed). Pupil response was stronger in the presence of rotating diamonds from 100 ms before until 500 ms after button press (comparison between the curves of the left and those of the right panel; maximum effect of stimulus 100 ms after button press,  $F(1,889) = 15.7$ ,  $p = .003$ ). A trend for more sustained pupil dilation is visible for both 'spontaneous' conditions, compared to the 'induced' conditions, but the difference was not significant (comparison of the curves across both panels; maximum effect 1.5 s after button press,  $F(1,889) = 1.77$ ,  $p = .22$ ).

## Pupil dilation control experiments: induced perceptual changes only

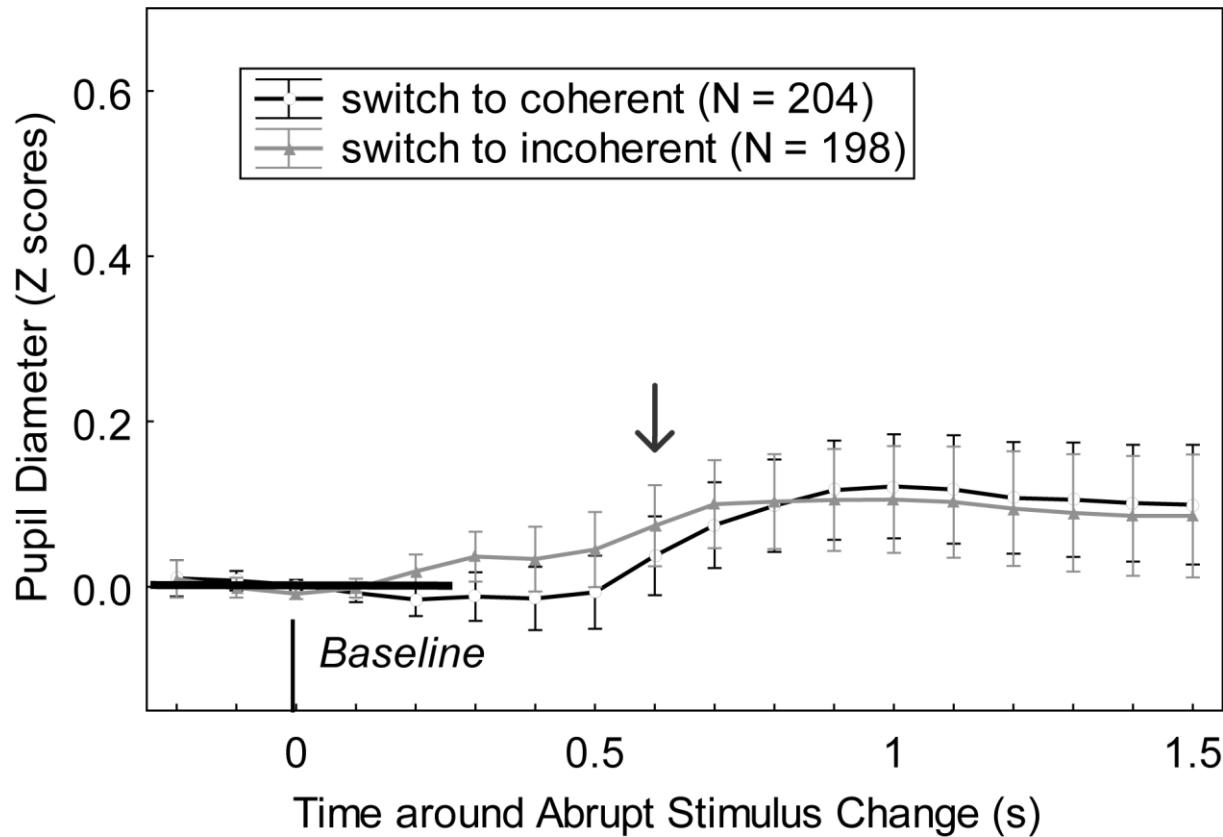


Figure 9. Pupil response after abrupt changes of the diamond stimulus. Each stimulus change was supposed to trigger a perceptual flip. Subjects did not indicate their percepts. Same 10 subjects as previously ( $N = 402$ , 8 outliers excluded). Traces were excluded if a blink occurred within 1.7 s before (i.e. 1.5 s before baseline) or 1.5 s after the stimulus change. Average pupil diameter was computed for the period [-0.2 0.2] s and subtracted. There was no effect of the type of stimulus manipulation: Whether it should induce a switch to coherence or incoherence, there was a small increase of pupil diameter. On average, this increase was just significant 600 ms after the stimulus change and after (maximum significance at 700 ms,  $F(1,382) = 5.83$ ,  $p = .038$ ).

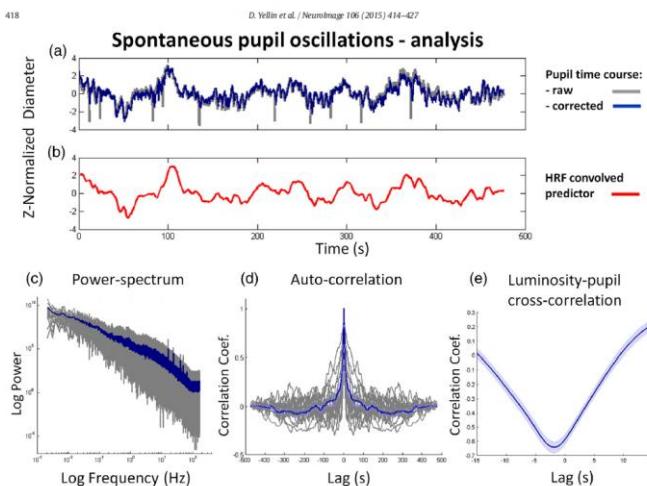
# Conclusions

Pupil dynamics during bistable motion perception:

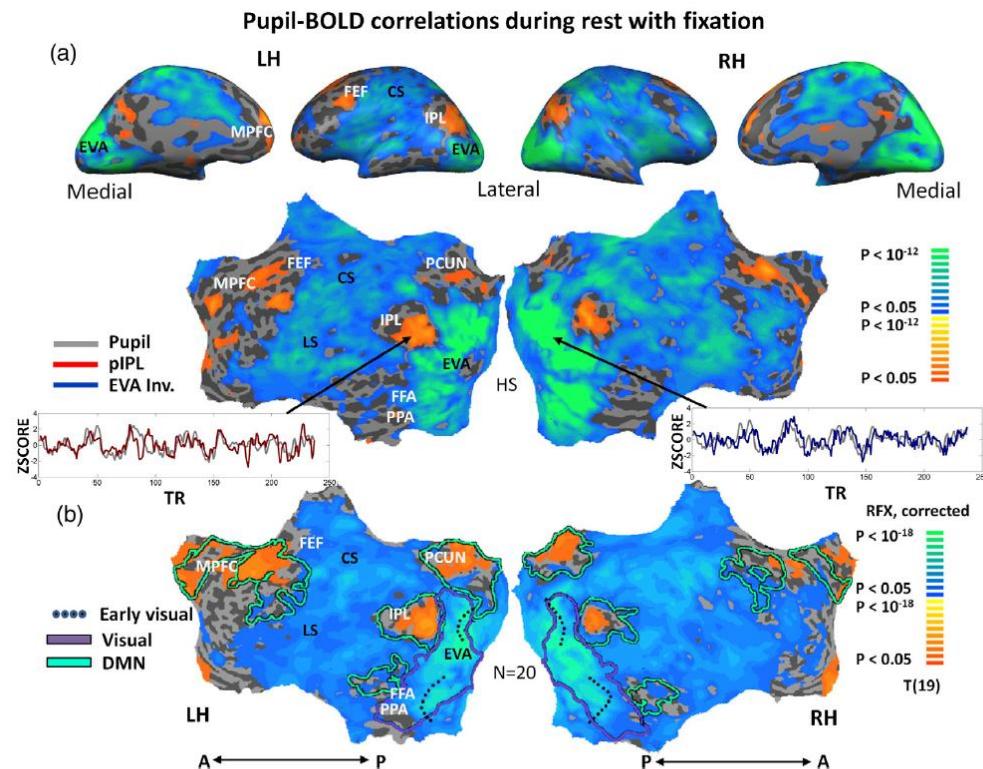
- Small (about 5% of surface change on average) but reliable pupil dilation around (300 ms to 1.5 s) the button presses indicating the changes of percepts.
- 70% of pupil dilation accounted for by the motor response !!
- Remaining perceptual component similar for spontaneously occurring transitions and transitions triggered by physical stimulus manipulations.
- Amplitude of pupil modulation in the spontaneous condition unrelated to the duration of each perceptual state.
- Clear constriction of the pupil after blinks (about 8% of surface change on average).
- Issue : do pupil changes entail retino-cortical activity through changes in eye optics?

# Pupil & Imaging

Dov Yellin, Aviva Berkovich-Ohana, Rafael Malach (2015). Coupling between pupil fluctuations and resting-state fMRI uncovers a slow build-up of antagonistic responses in the human cortex. *NeuroImage* 106 (2015) 414–427.



**Fig. 1.** Rest-fixation experiment – pupil diameter time-course analysis. Example from a single subject's pupil time-course during the main experiment – (a) raw pupil diameter signal in gray and blue-corrected is shown in blue. (b) Same subject's HRF-convolved pupil diameter time-course shown in red. (c) Power spectrum and auto-correlation analysis of pupil diameter changes, respectively ( $N = 20$ ) – average shown in blue overlaid on individual subjects data in gray. (e) Cross-correlation of pupil and luminosity time-courses taken from the alternating luminosity experiment.

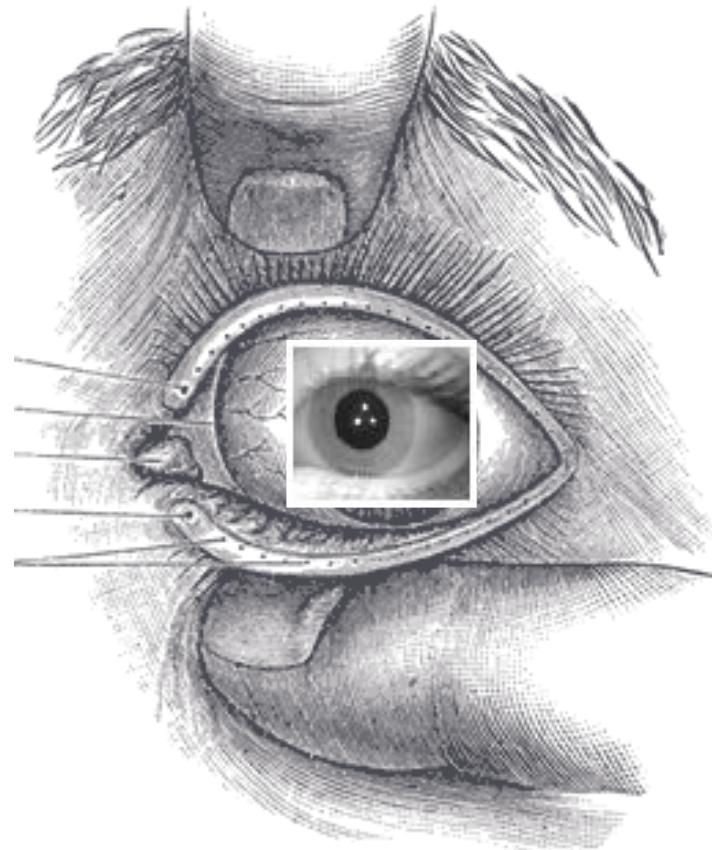


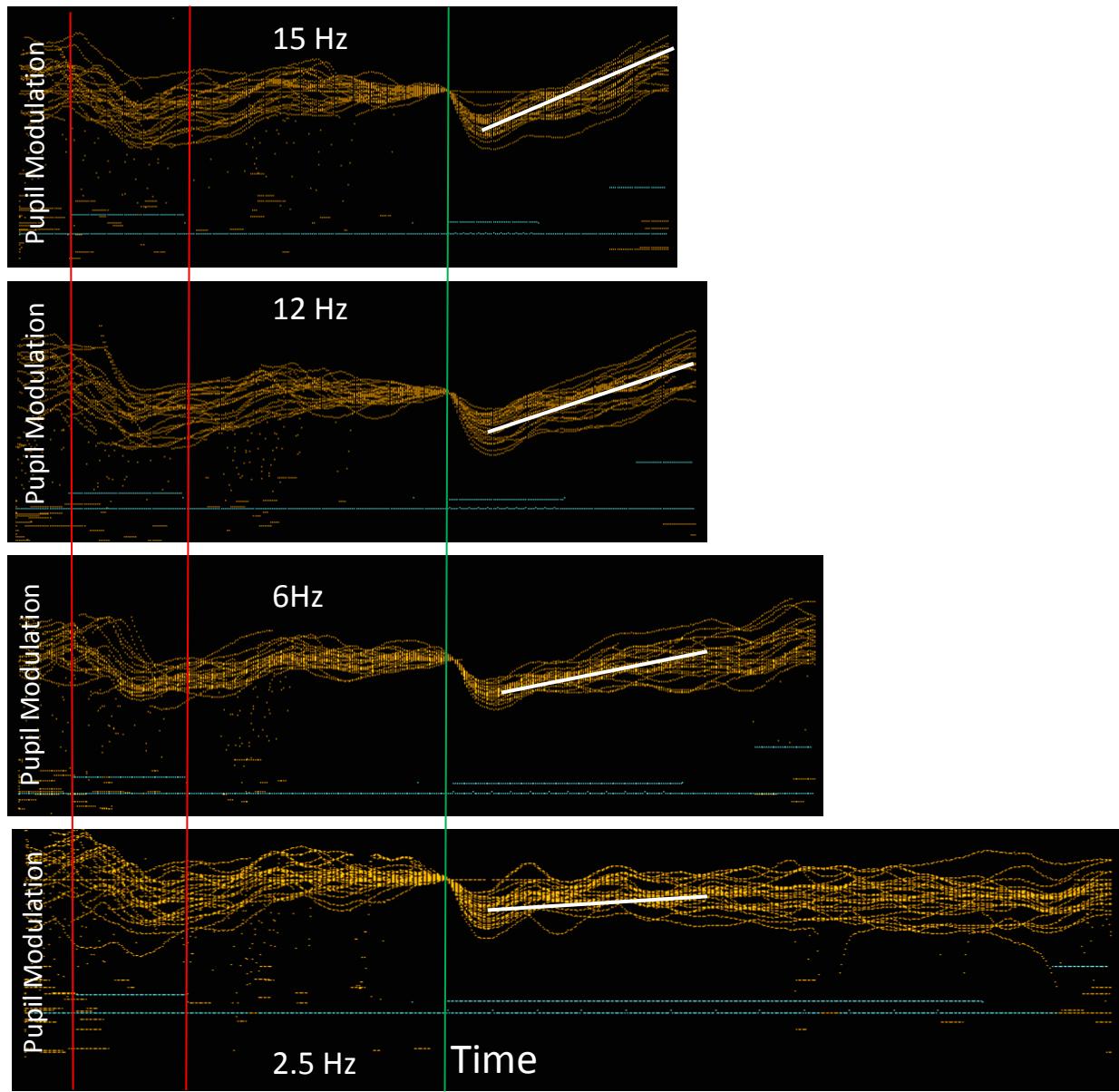
**Fig. 2.** Spatial topography of pupil-BOLD signal correlations in rest-fixation experiment. (a) Single subject correlation map, projected on an inflated (top) and unfolded cortex (below). (b) Multi-subject pupil-BOLD correlations on an unfolded map. Random effects analysis, corrected, on 20 subjects. Note that in both maps, sensorimotor areas are negatively correlated and default mode areas are positively correlated to the pupil diameter predictor. Color scale indicates statistical significance. Yellow-orange regions represent areas for which the BOLD signal was positively correlated to the pupil predictor, whereas blue-green regions indicate negative correlations. Purple and green contours delineate the borders of the visual and default networks, respectively. CS, central sulcus; EVA, early visual cortex; IPL, inferior parietal lobule; IPS, intraparietal sulcus; LS, lateral sulcus; MPFC, medial prefrontal cortex; PCUN, precuneus; LH, left hemisphere; RH, right hemisphere; A, anterior; P, posterior.

## Conclusion

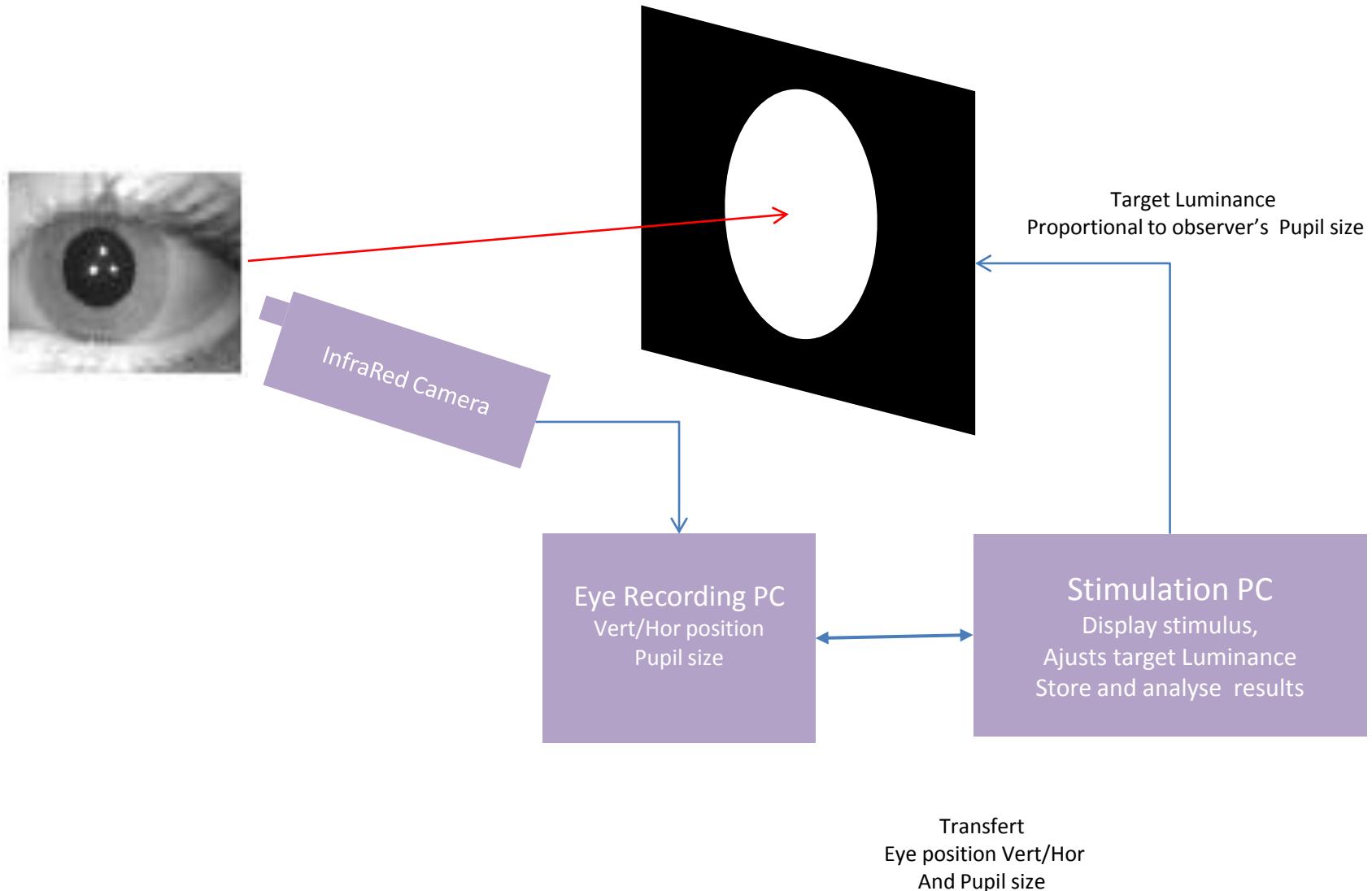
To summarize, our findings reveal a spontaneously emerging antagonism between fundamental networks of the human cortex that is correlated to pupil dilatations during rest. Thus, our results reveal a link between behavior – indexed by pupil diameter fluctuations – and spontaneous network activations and deactivations during the resting state.

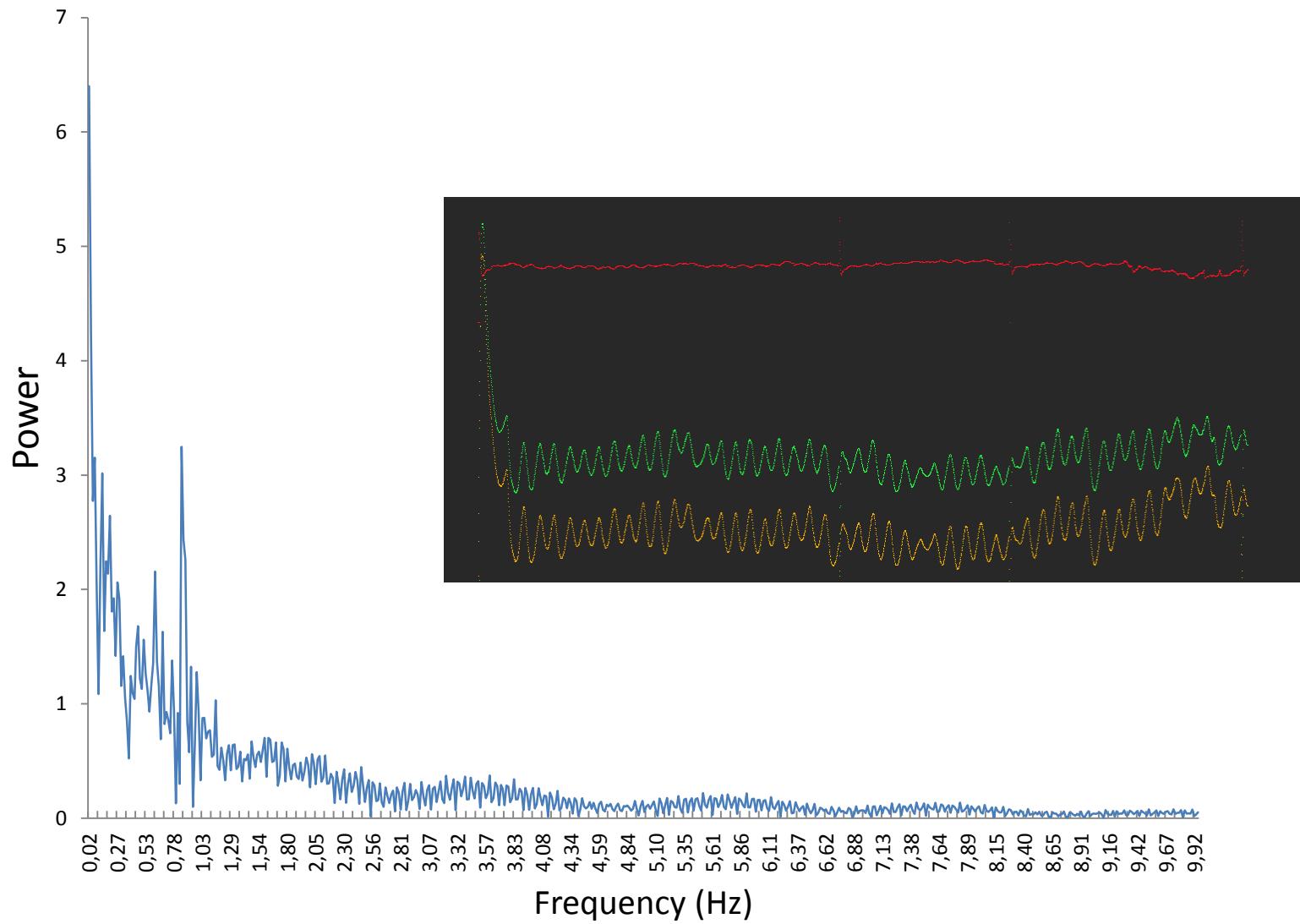
Thanks for your attention !!





# Pupil Cycle Time : Method





# Fixation and smooth pursuit in glaucoma patients

