A MODEL FOR THE PUPILLARY LIGHT REFLEX

SIMEON WONG, CINDY BUI

PREPARED FOR PROF. YOO (BME344)
OUTLINE

• Background and existing models
• Our model for the Pupillary Light Reflex
• Validation
• Advances, limitations, and future steps
**BACKGROUND**

- Main purpose of pupillary light reflex to moderate intensity of lighting entering the eye

- Effected through antagonistic muscle pairs on iris:
  - Constriction - *Circular Sphincter*
  - Dilation - *Radial Dilator*
BACKGROUND: PATHOLOGIES

• Pupil area pathologies are usually caused by defects in the sympathetic or parasympathetic innervation pathways

• Sympathetic defect: Miosis
  • Uncontrollable over-constriction of pupils

• Parasympathetic defect: Mydriasis
  • Uncontrollable dilation of pupils
EXISTING MODELS

**Neuromuscular Reflex**

**Conceptual Diagram of Pupil Dilation**

**Light Response Equation**
EXISTING MODELS
NEUROMUSCULAR REFLEX

EXISTING MODELS

NEUROMUSCULAR REFLEX

M(D) = \text{atanh} \left( \frac{D - 4.9}{3} \right)

\frac{dM}{dD} + 2.3026 \text{atanh} \left( \frac{D - 4.9}{3} \right) = 5.2 - 0.45 \ln \left[ \frac{\Phi(t-\tau)}{4.8118 \times 10^{-10}} \right]

LIGHT RESPONSE EQUATION
EXISTING MODELS
OVERALL PUPILLARY LIGHT REFLEX EQUATION

\[
M(D) = \text{atanh} \left( \frac{D-4.9}{3} \right) \\
\frac{dM}{dD} \frac{dD}{dt} + 2.3026 \text{atanh} \left( \frac{D-4.9}{3} \right) = 5.2 - 0.45 \ln \left[ \frac{\Phi(t-\tau)}{4.8118 \times 10^{-10}} \right]
\]

D: pupil diameter
Φ: luminous intensity (retina)
t: current time
τ: reflex latency

EXISTING MODELS

CONCEPTUAL DIAGRAM
OF PUPIL DILATION

NEUROMUSCULAR REFLEX

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\[ \frac{dM}{dD} \frac{dD}{dt} + 2.3026 \text{atanh} \left( \frac{D-4.9}{3} \right) = 5.2 - 0.45 \ln \left[ \frac{\Phi(t-\tau)}{4.8118 \times 10^{-10}} \right] \]

LIGHT RESPONSE EQUATION
EXISTING MODELS
CONCEPTUAL SCHEMATIC OF PUPILLARY LIGHT REFLEX

OBJECTIVE

A physiologically-relevant, accurate and detailed model of the pupillary light reflex that is easily scalable to include pathologies and external influences.
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SPOILER ALERT: We succeeded.
OUR MODEL FOR PLR
LIGHTING CONDITIONS

- Fundamental reason for PLR
- Model accepts ambient lighting of room as input
EYE OPTICS

• Pupil acts as aperture for optics of the eye
• Resulting light on retina proportional to pupil area
• Feedback from pupil diameter output
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Nervous System

- Afferent and efferent neurons modelled by delays
- Light reflex controller in the brain
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MUSCLE EFFECTOR

Net muscle movement

• Contraction - *circular sphinctor*
• Dilation - *radial dilator*
OUR MODEL FOR PLR
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PATHOLOGY AND DRUGS

- Drugs or a pinched nerve prevent oculomotor nerve from stimulating the constriction of the pupils
- Results in uncontrollable dilation
PATHOLOGY AND DRUGS

• Drugs or a pinched nerve prevent oculomotor nerve from stimulating the constriction of the pupils

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approximated by delta function (1 sample)
PATHOLOGY AND DRUGS

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Diagram:
- Entering body system: Drug not yet in system
  - Slowly entering system
  - Input
  - 1/s
- Activation and binding:
  - Drug in system
  - Drug being activated
  - 1/s
  - 0.004
- Exiting system:
  - Active Drug
  - 1/s
  - 0.00006
  - Excretion
  - Active in system
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% receptors not blocked
PATHOLOGY AND DRUGS

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% of receptors not blocked = max function as % of normal
**PATHOLOGY AND DRUGS**

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% of remaining function
OUR MODEL FOR PLR

[Diagram of a model for PLR with various nodes and connections, including:
- drug_tropicamide
- Input
- Pharmacokinetics (Tropicamide)
- f(u)
- tropicamide_levels
- tropicamide_effects
- tropicamide_effects_out
- retina_lumination
- retina_lumination_out
- sym_action
- para_action
- Sym Stimulation
- ANS
- Slower Dilation
- Combined Effect of Muscles
- muscle state
- Pupil Diameter Output]
MAJOR RESULTS:
STEP CHANGE IN LIGHTING
MAJOR RESULTS:
TOPICAL TROPICAMIDE
MAJOR RESULTS: PINCHED NERVE VS. CONTROL
COMPARED TO THE LITERATURE

V. F. Pamplona et al.

Fig. 8. Comparison between our simulated results and measurements from real video sequences using light emitted by a lightbulb as stimulus. The “x” and “+” marks represent the pupil diameter measurements for the blue-eye (left), and for the green-eye (right) subjects, respectively. Top row: values obtained for all frames along 56- and 50-second-long video sequences, respectively. The solid and dashed lines are the pupil diameters predicted by our physiologically-based model with and without hippus, respectively. The vertical lines delimit the intervals in which the incandescent light bulb was kept on and off for each subject. The predicted values match the actual measurements well. The bottom row shows zoomed versions of the graphs shown on the top.

—When comparing the 100-watt lightbulb and the flashlight experiments, both the lighting and the pupil sizes varied for the on and off states of the light sources. For instance, for the green-eye subject, the pupil diameters were approximately 4.3mm and 5.7mm for the on and off states of the flashlight, respectively (Figure 7). This resulted in a $r_I$ index of 0.92. In the case of the 100-watt lightbulb experiment, these values were approximately 4.3mm and 6.0mm, respectively (Figure 8), with $r_I = 1$. These two indices are relatively close and reflect the difference in the maximum pupil diameters between the two experiments. The difference in the $r_I$ indices for the blue-eye subject were considerably larger, from 0.54 to 0.9. Again, this can be explained by comparing the measured pupil diameters in the two experiments. These values went from approximately 3.2mm and 4.2mm in the on and off states of the flashlight (Figure 7) to 4.4mm and 5.2mm in the on and off states of the 100-watt lightbulb (Figure 8).

An important point to note is that by using an average of the estimated $r_I$ indices for the on and off states of the light source, our model is capable of realistically simulating the pupil behavior of individuals with considerable differences in PLR responses under different and variable lighting conditions.

6. MODELING THE IRIS DEFORMATION

Although the iris is a well-known structure [Freddo 1996], there is no general agreement about a model of its behavior. Rohen [1951] seems to have been the first researcher to study the form of the collagen structure of the iris. He suggested that the collagen fibers are arranged in a series of parallel arcs, connecting the iris root with the pupil border, clockwise and counterclockwise in an angle of 90 degrees oriented by the center of the pupil. These fibers would be interwoven with other iris components, such as blood vessels. Based on Rohen’s fiber arrangement, Wyatt [2000] proposed a 2D nonlinear model for iris deformation. Such a model has been validated on canine, porcine, and monkey irises, but so far not on human irises [Wyatt private communication].

We derived our model for iridal pattern deformation by analyzing sets of photographs taken from five volunteers under controlled conditions. In our experiments, an eye doctor dilated their pupils with some mydriatic drug and we photographed their irises at several stages during the pupil dilatation process using a Canon PowerShot SD 400 camera with macro lens. The images were taken...
ADVANCES

• To the best of our knowledge, our model is the first to combine:
  
  • Models of individual components of the reflex and their interaction to form the PLR
  
  • Acetylcholine antagonist effects of tropicamide on oculomotor nerve function and pupil diameter
  
  • Effect of a pinched oculomotor nerve
ADVANCES

• Easy to add other neuromuscular blocking drugs
• Can sample system state of all subcomponents
• Customizable to various individuals by changing constants
LIMITATIONS

• Cause of hippus unclear

• Pharmacokinetics could be more rigorous

• Pupillary light reflex reaction assumed to be instantaneous

• Ideal light on retina assumed to be constant
FUTURE STEPS

- More pathologies, drugs
- Model effect of other stimuli
  - Hormones
  - Mental Activity
  - Serotonin
REFERENCES

Sources

Images
THANKS.

QUESTIONS?