Tuning the senses

How pupils shape vision

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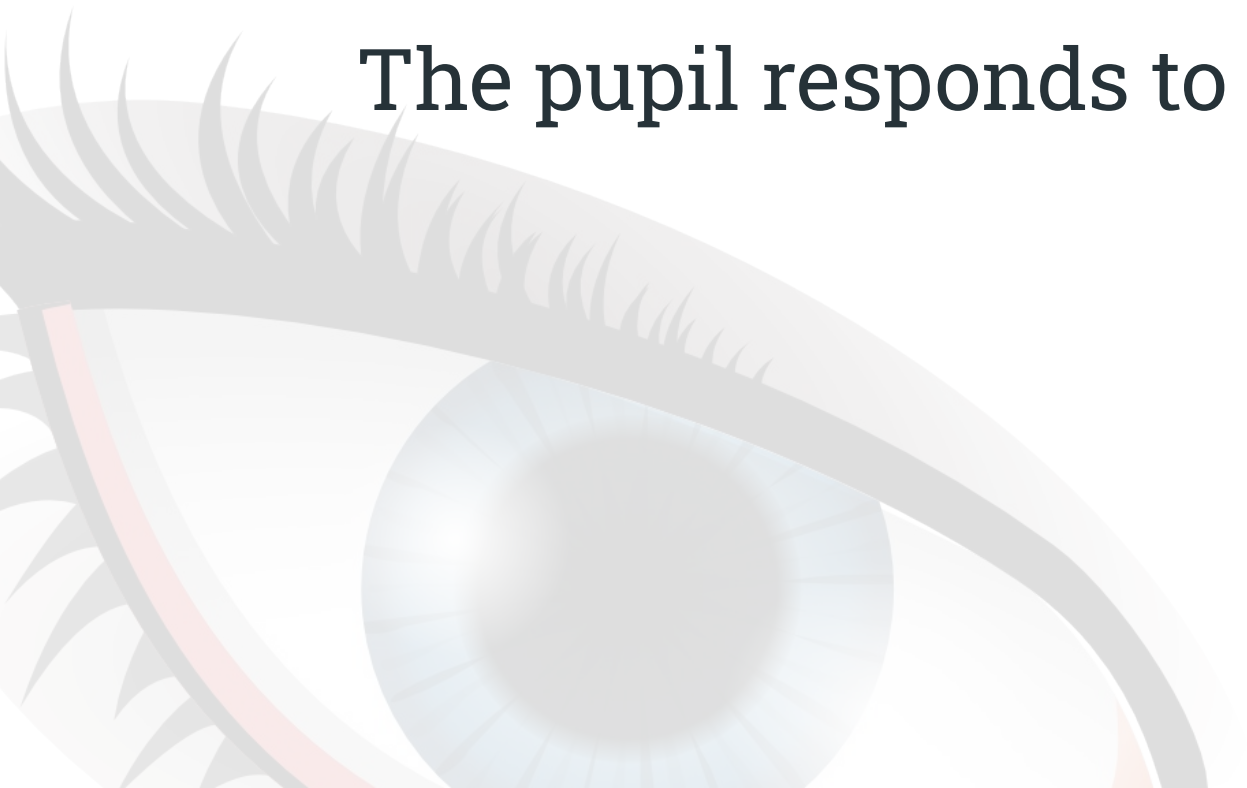
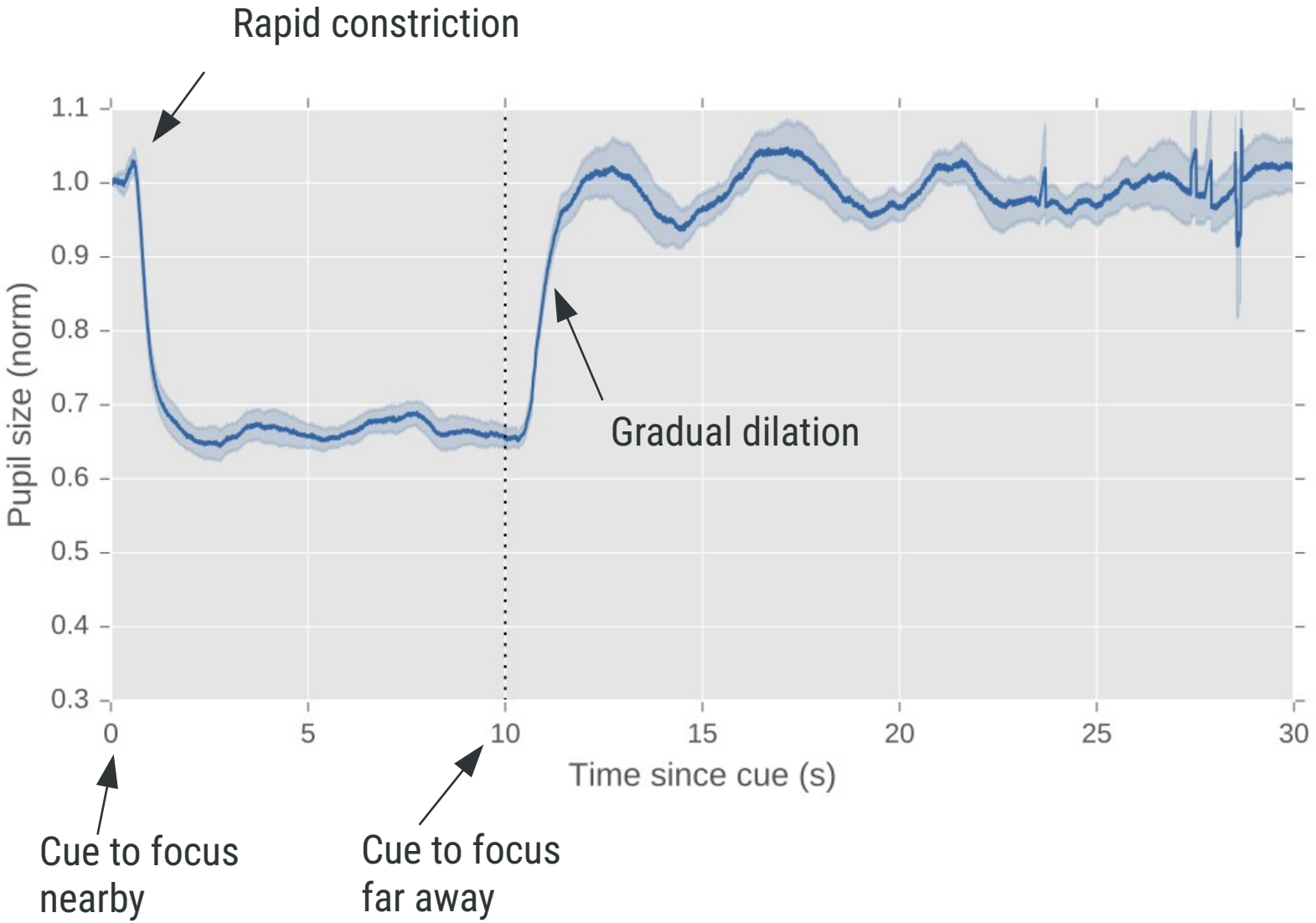
The pupil 101


Anatomy

The pupil responds to three things.

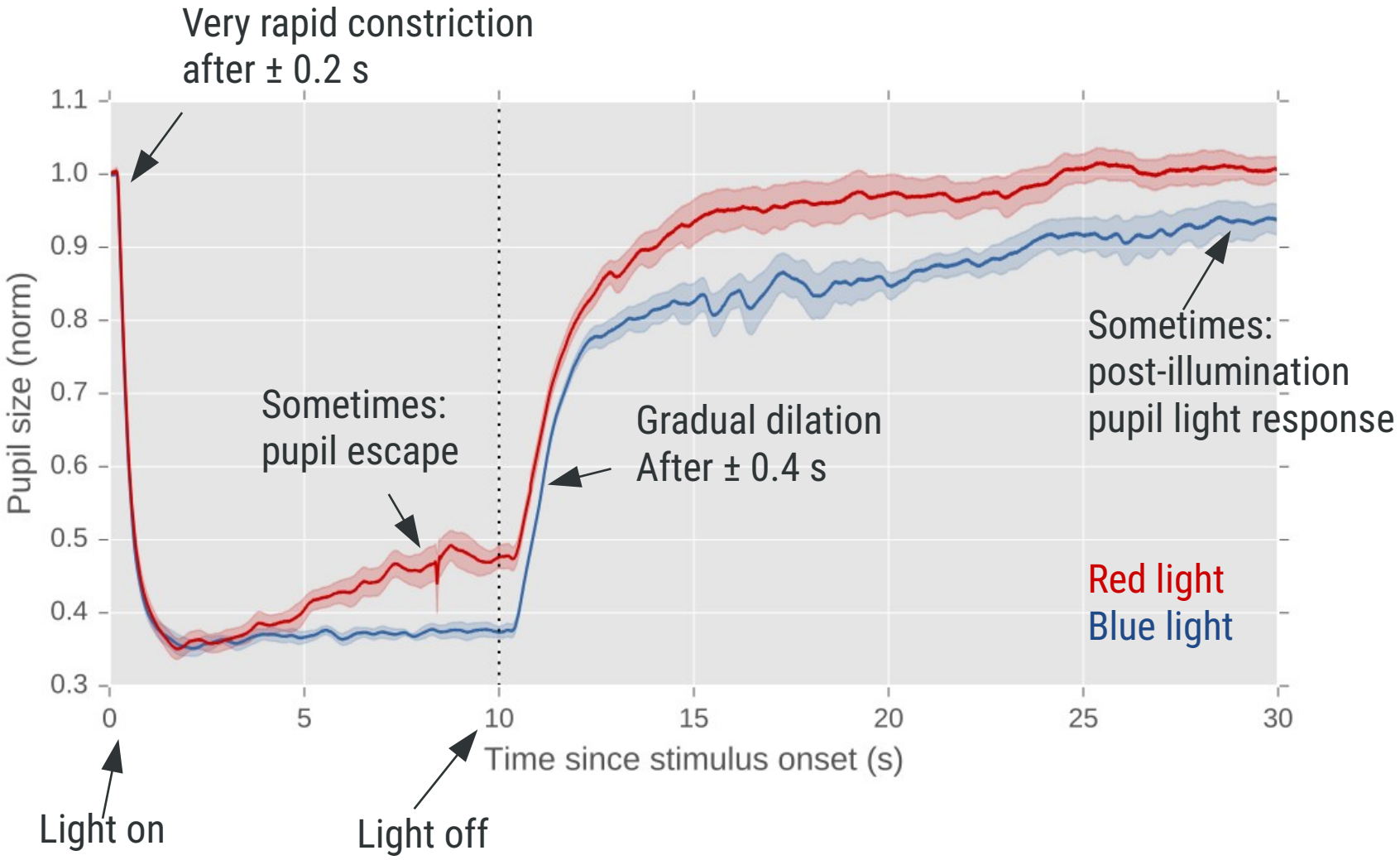



Distance.



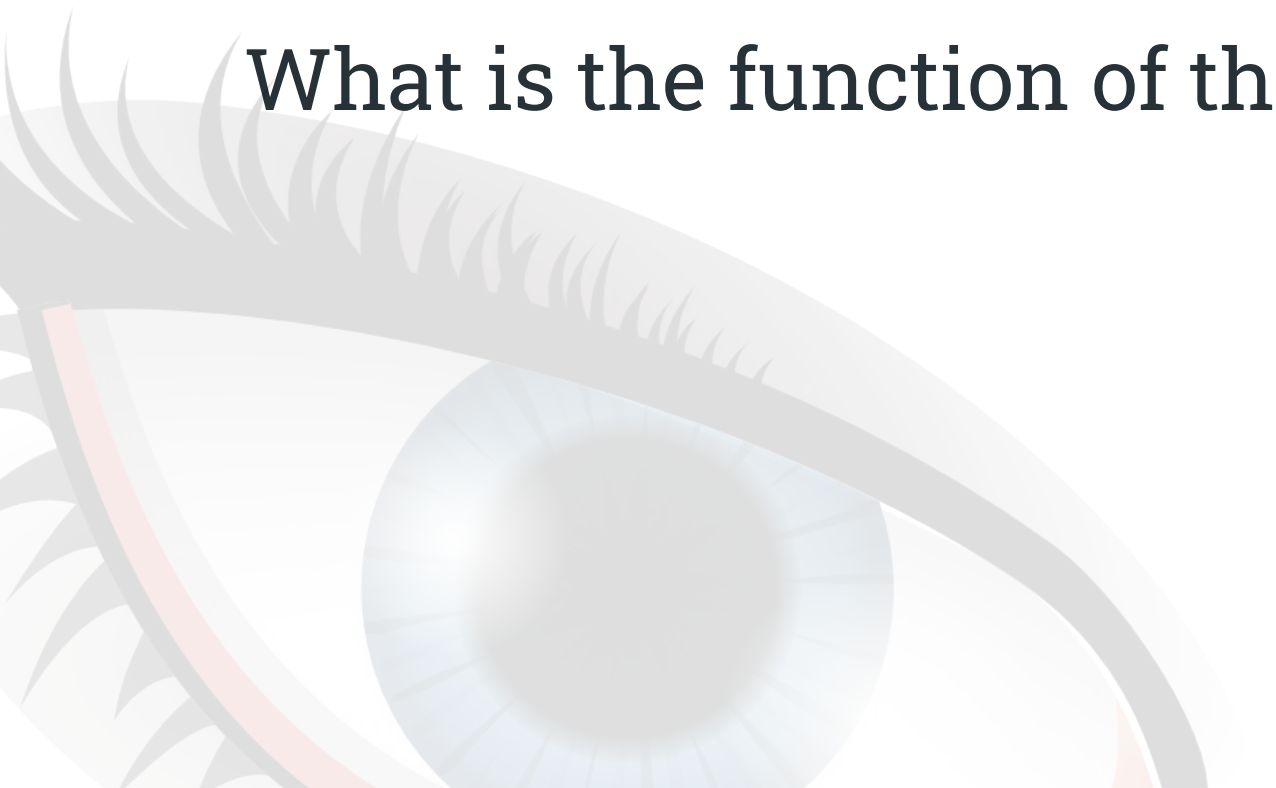
Data from Mathôt (2018)

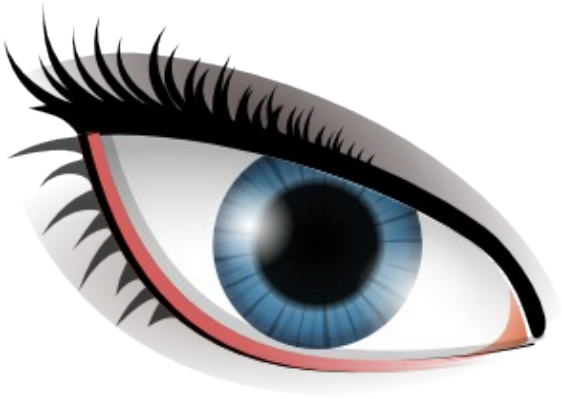

Light.

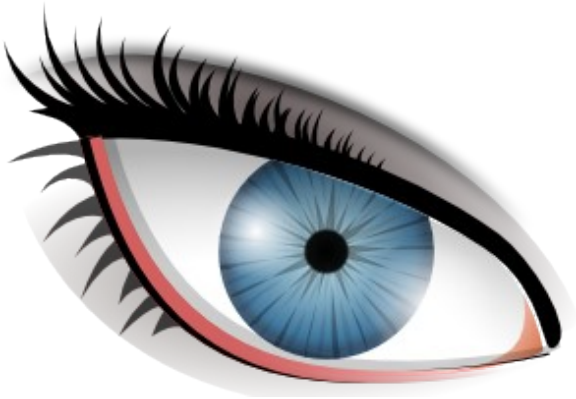


Data from Mathôt (2018)

What is the function of these responses?







Captures lots of light

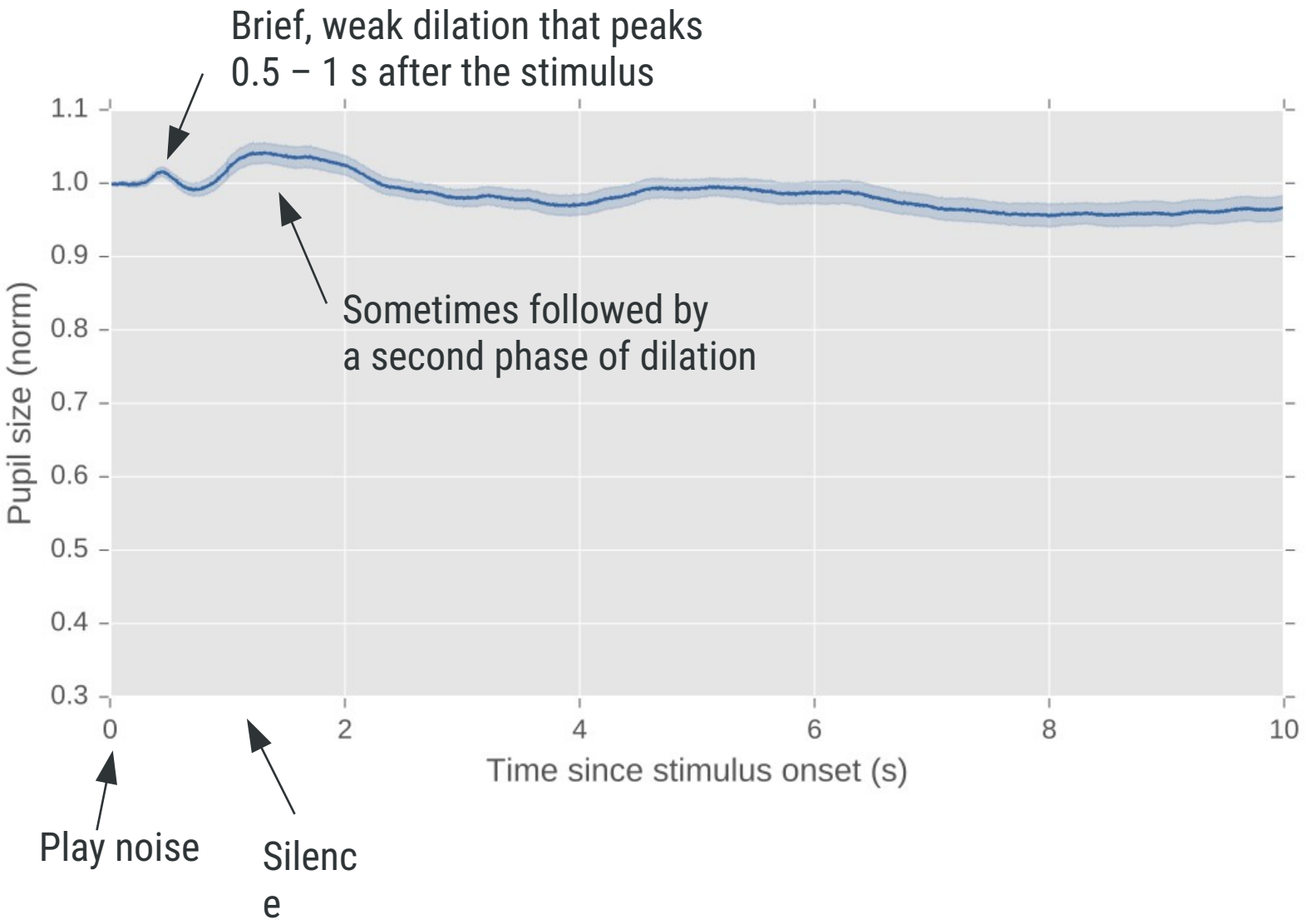
Has lots of optical distortions

Captures less light

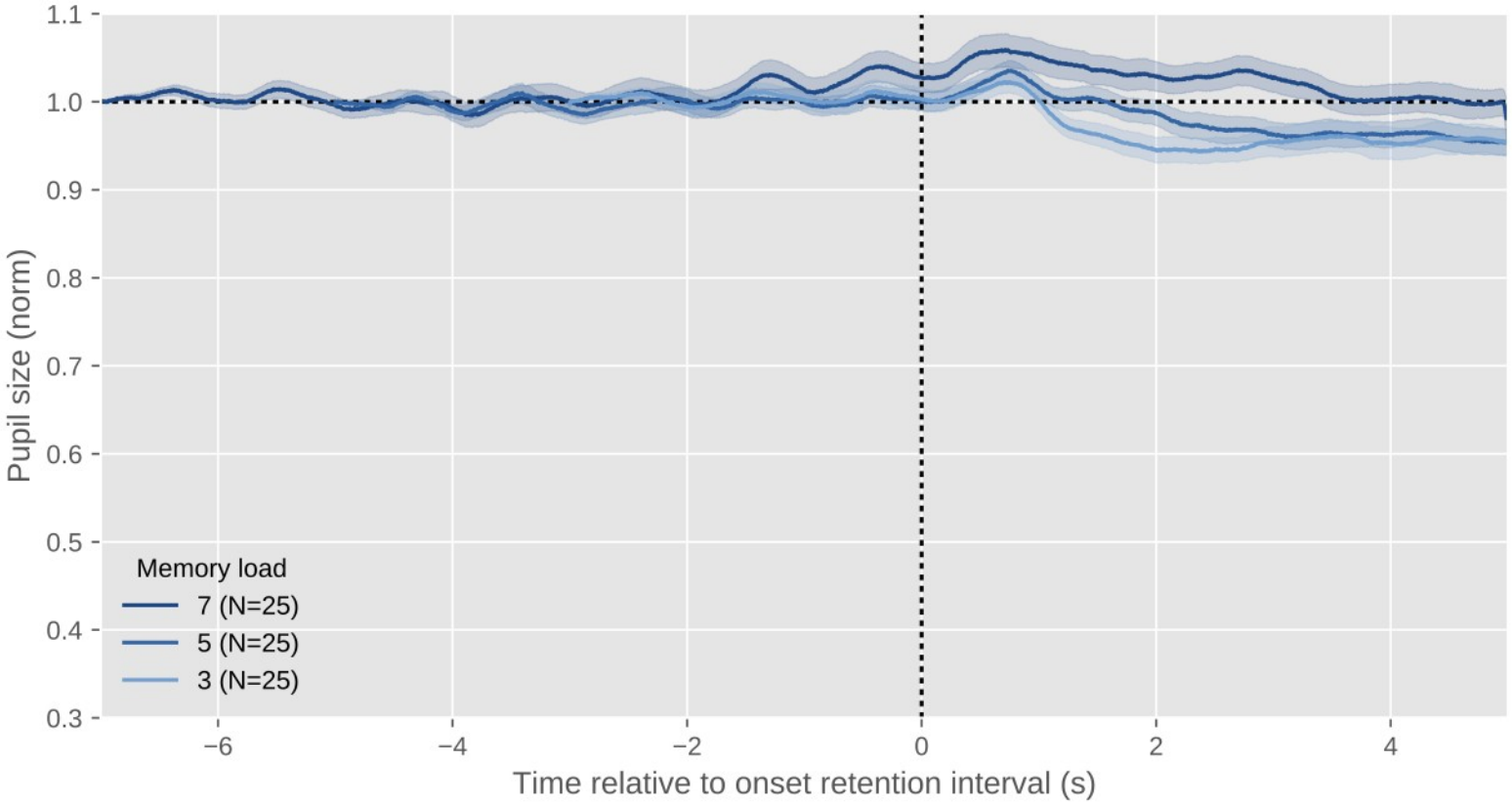
Has less optical distortions

The pupil responds to **three** things.
(So far I've mentioned two.)


Arousal
and effort.

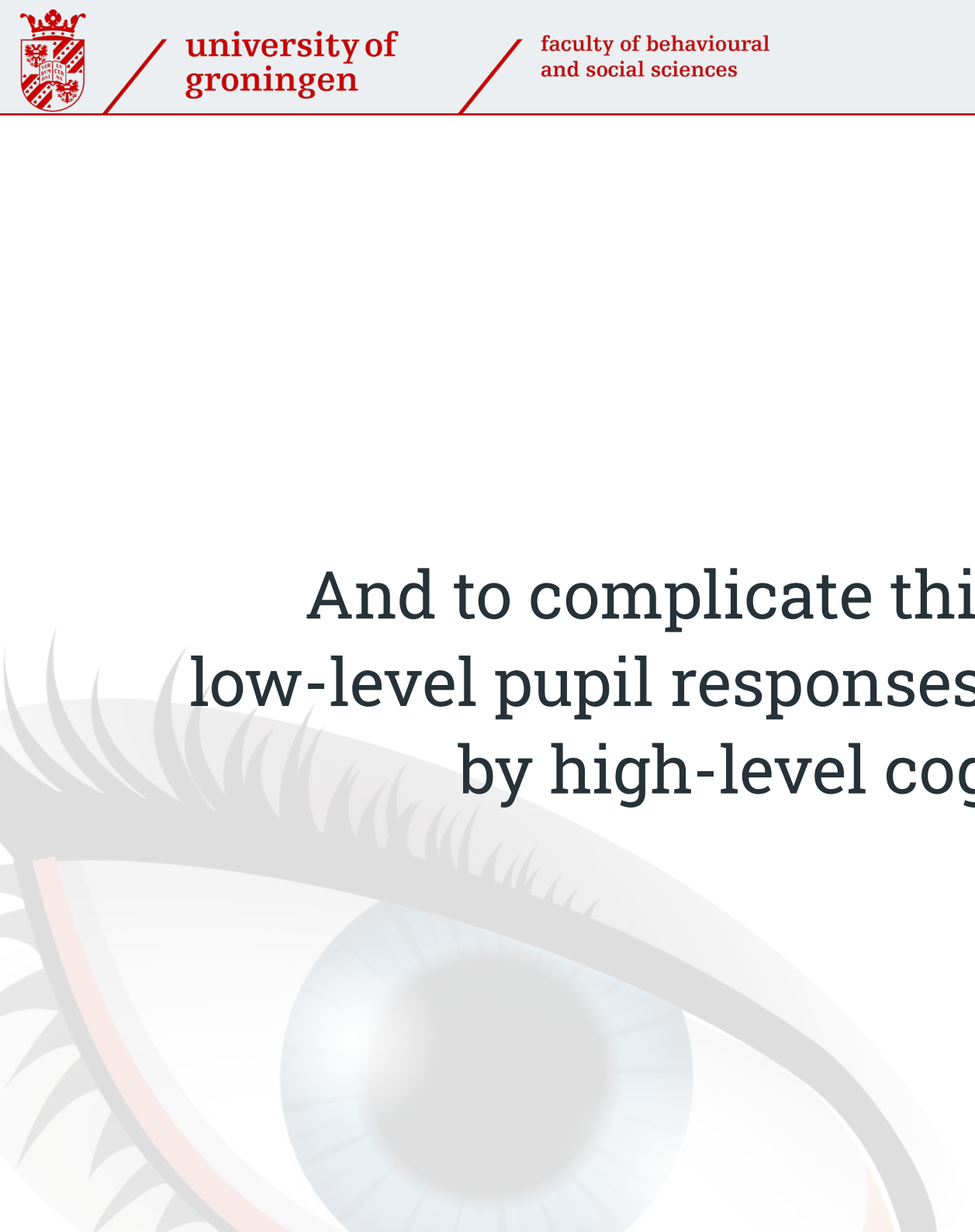


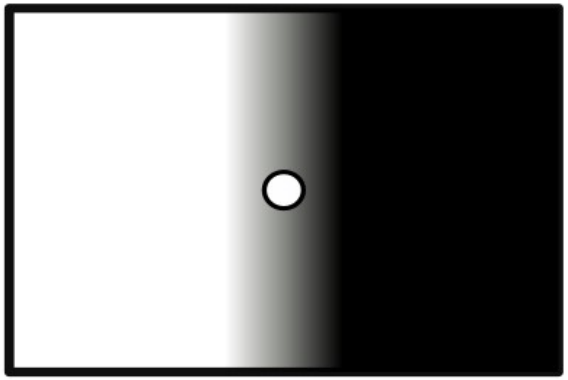
Data from Mathôt (2018)



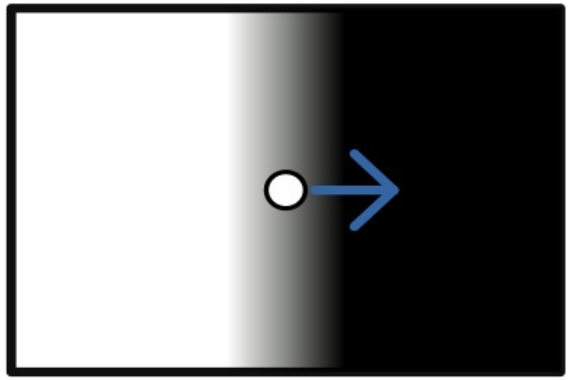
Data from [1] Mathôt (2018), based on [2] Kahneman & Beatty (1966)

And to complicate things further, low-level pupil responses are modulated by high-level cognition





Mathôt et al. (2013) https://doi.org/10.1371/journal.pone.0078168



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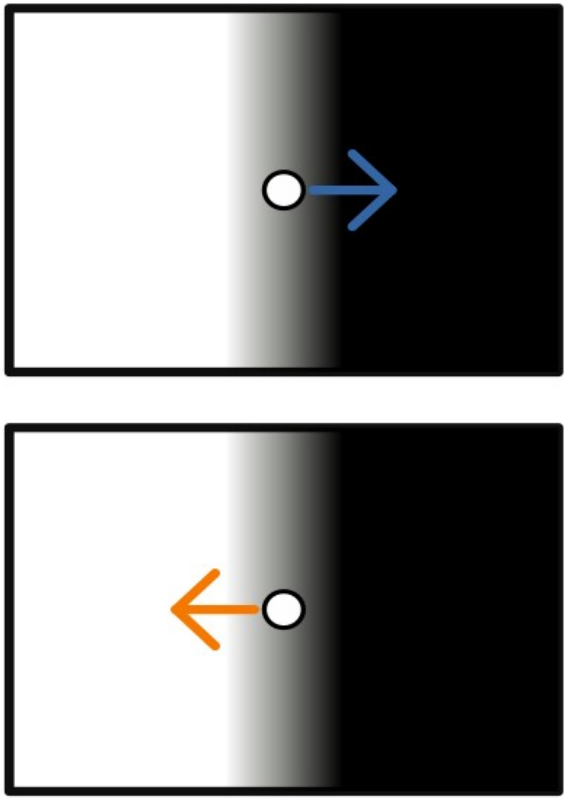

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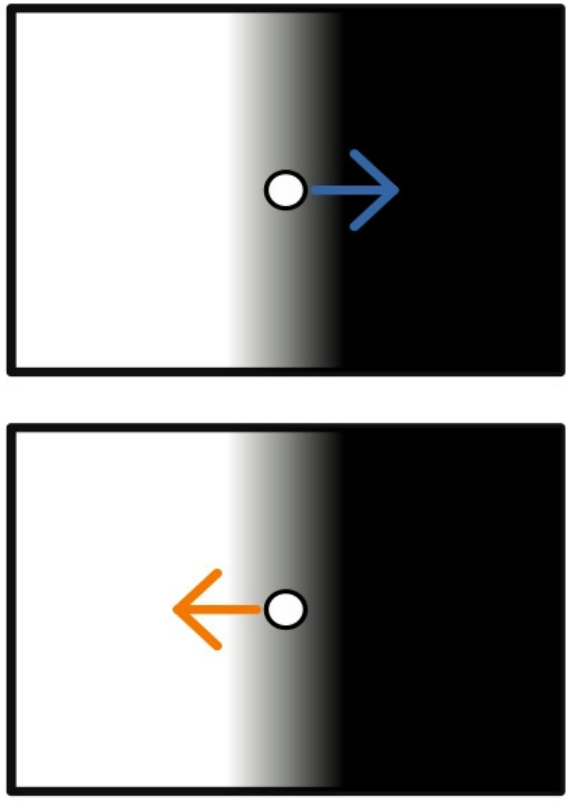

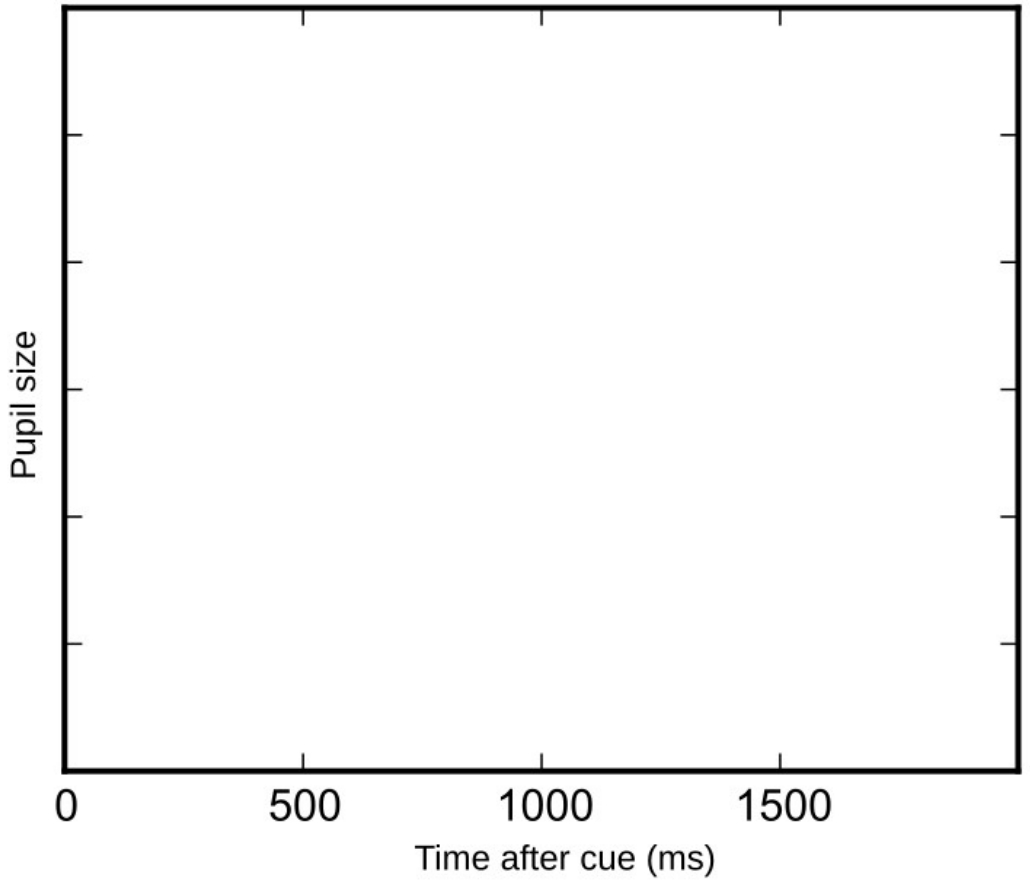

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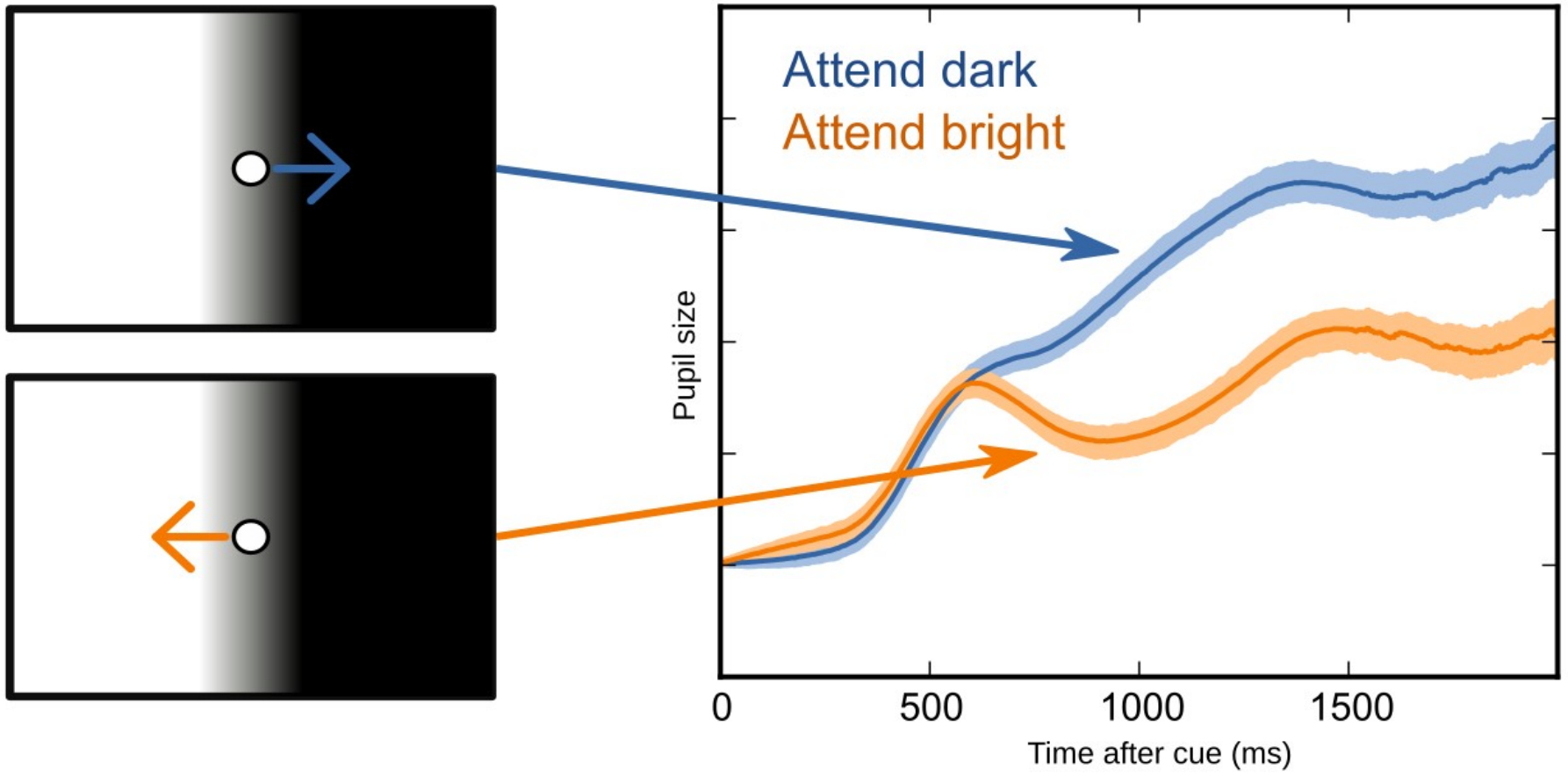

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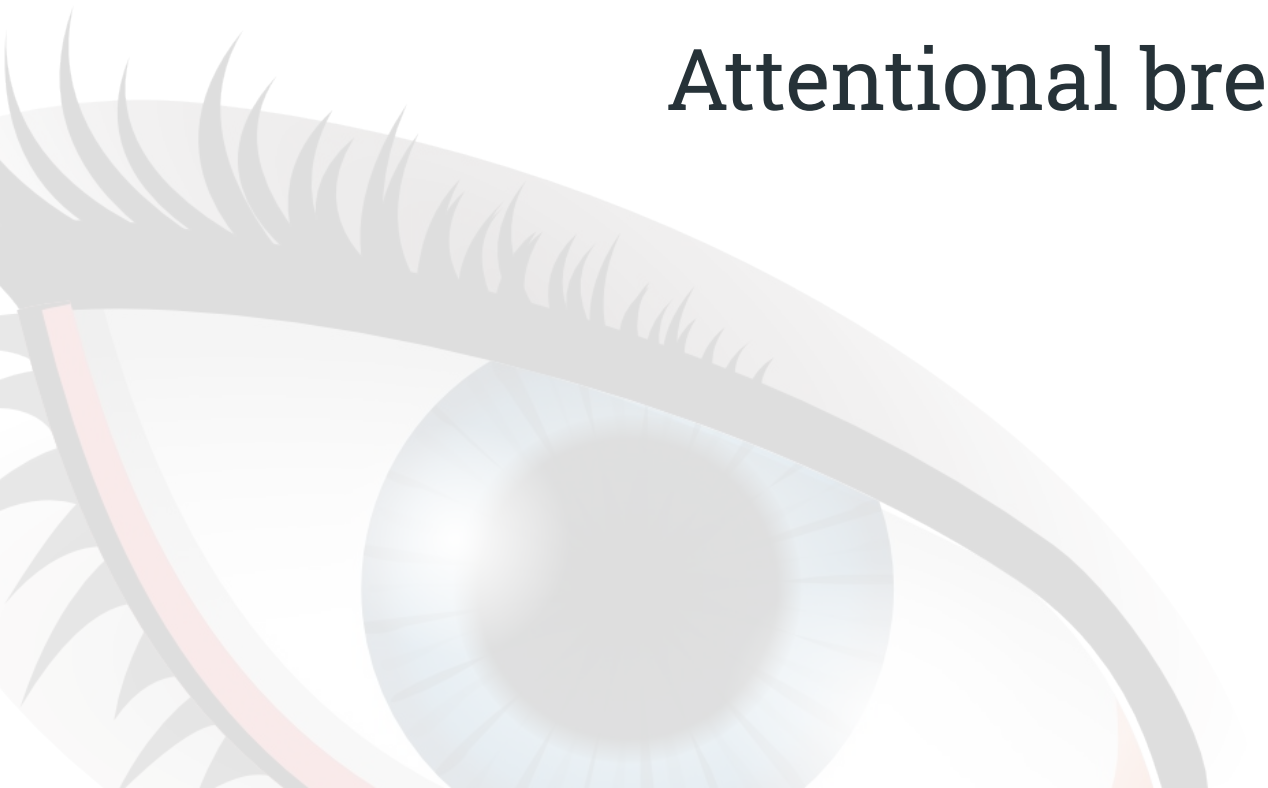
What (if any) function do cognitively driven pupil responses serve?

Let’s review several findings …

Attentional breadth

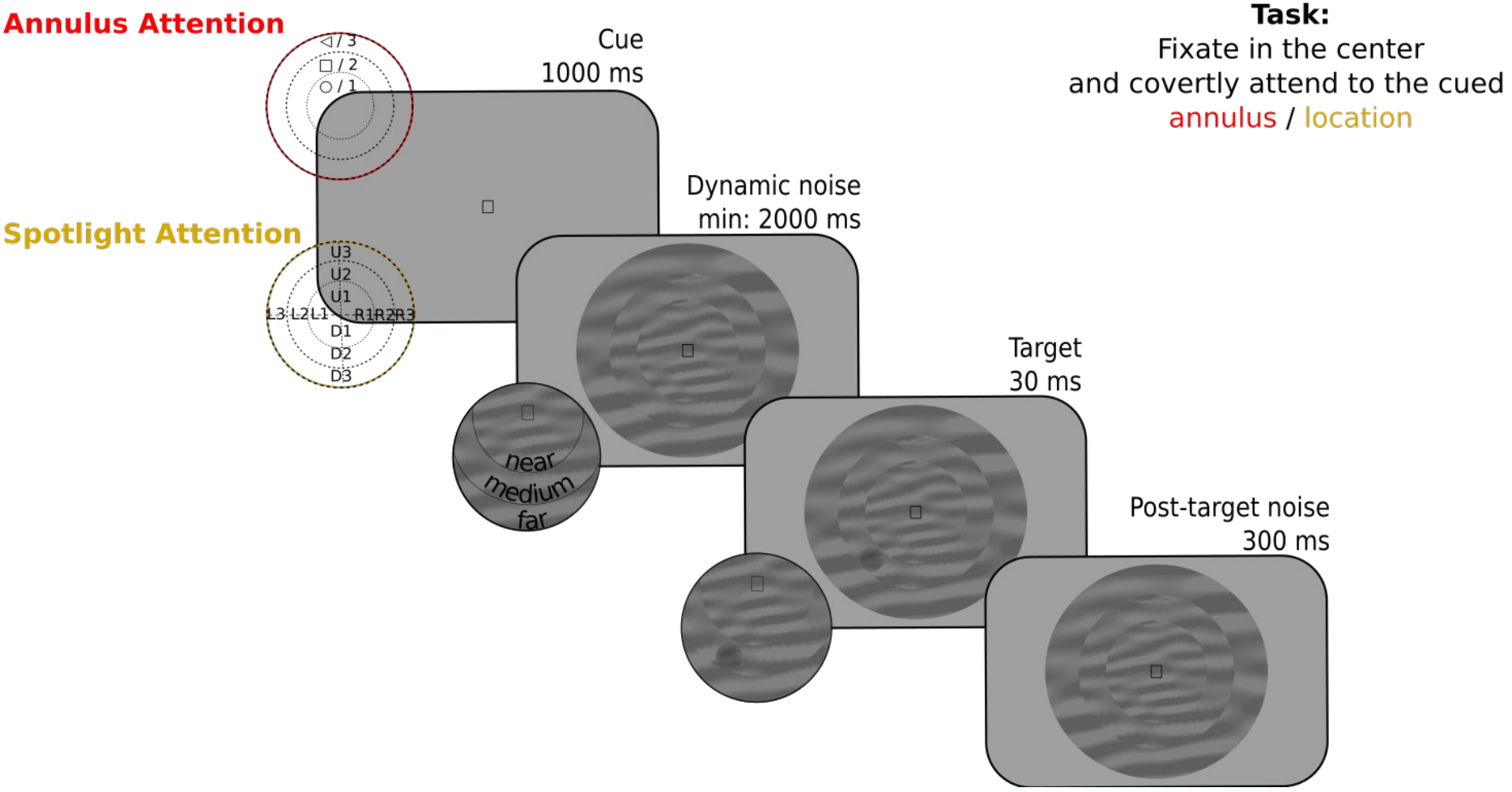


Attentional breadth

- You can focus attention
  - Narrowly → on central vision
  - Broadly → diffusely over a large part of the visual field, including peripheral vision
- How does this affect pupil size?

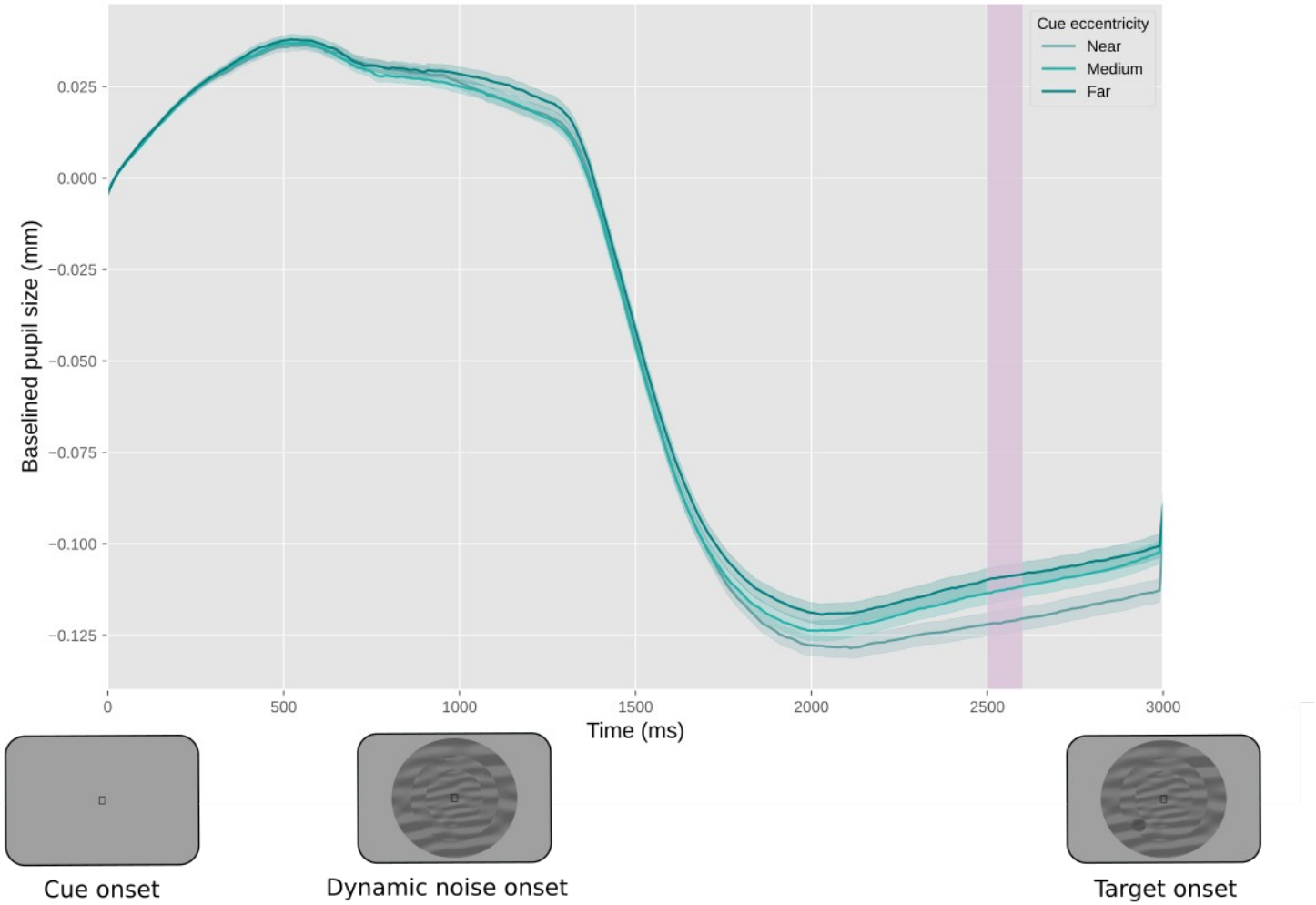
https://www.deviantart.com/jordanowen/art/Tunnel-Vision-116456839

Attentional breadth



Vilotijević & Mathôt (2023a)
http://dx.doi.org/10.3758/s13423-023-02283-5

Attentional breadth



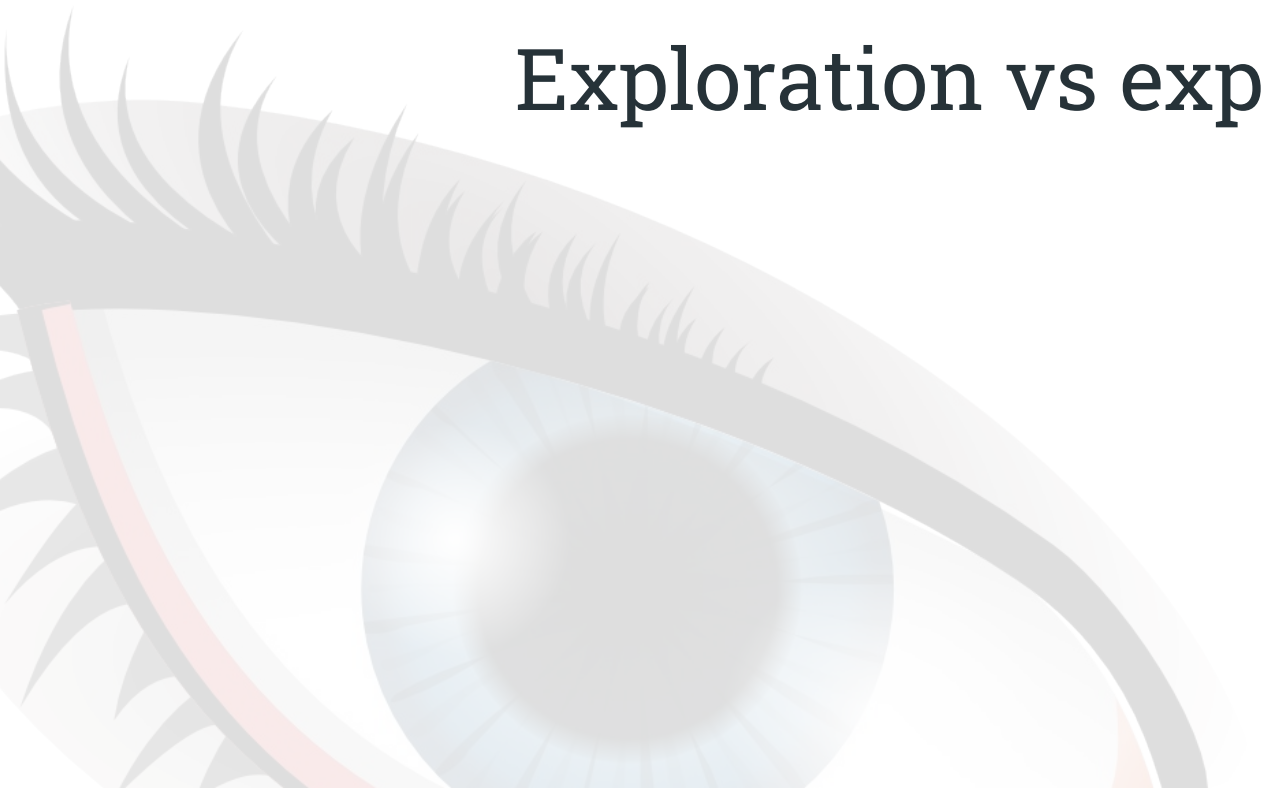
Vilotijević & Mathôt (2023a)
http://dx.doi.org/10.3758/s13423-023-02283-5

Attentional breadth

- Observation
  - Broad focus → large pupils
  - Narrow focus → small pupils
- Possible function
  - Small pupils enhance acuity by decreasing lens aperture
  - Mostly beneficial for central vision, where acuity is highest due to increased cone density on the retina

Reviewed in Vilotjević & Mathôt (2023b, http://dx.doi.org/10.1002/wcs.1672)
See also Ivanov & Mathôt (unpublished data), Daniels et al. (2012), Brocher et al. (2018), Kolnes et al. (2023)

Exploration vs exploitation



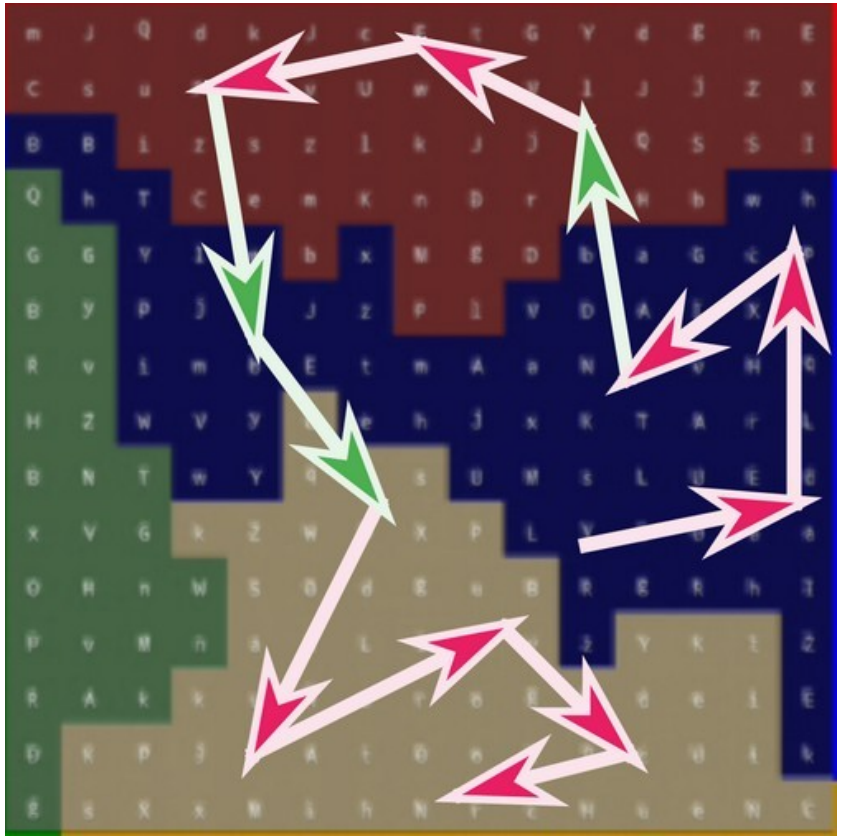
Exploration vs exploitation

- Two modes of behavior
  - Exploration → prone to distraction, frequent task switching
  - Exploitation → focus on a single task
- The adaptive-gain theory links this to pupil size
  - Exploration → large pupils (and not very reactive)
  - Exploitation → medium-small pupils (and highly reactive)

Aston-Jones & Cohen (2005), Jepma & Nieuwenhuis (2011)

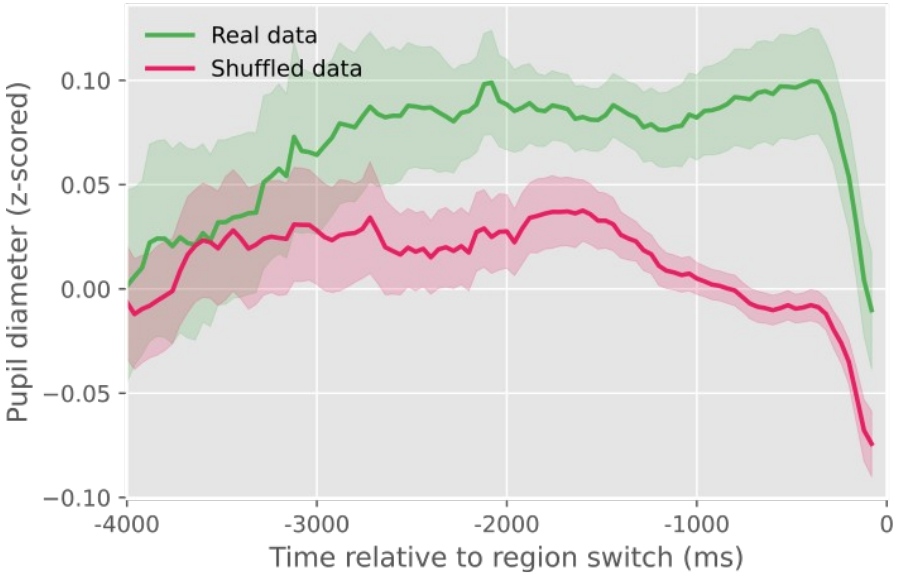
Exploration vs exploitation

- Most studies on the link between exploration/ exploitation and pupil size have focused on game-like tasks
- We recently tested whether this link also holds for eye movements



Regnath & Mathôt (2021, preprint), Jepma & Nieuwenhuis (2011), Pajkossy et al. (2017)

a) Pupil size before region switches



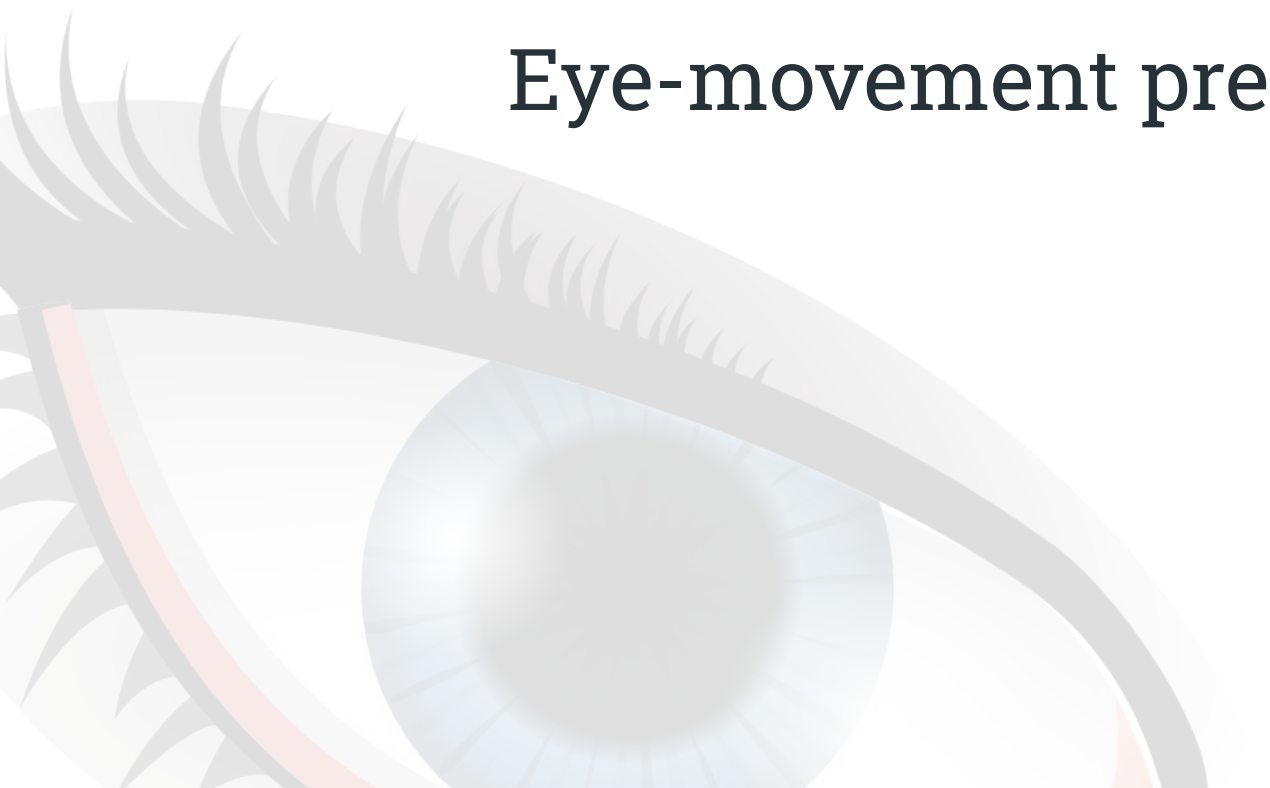
Regnath & Mathôt (2021, preprint)

Exploration v exploitation

- Observation
  - Exploration (gaze shifts between regions) → large pupils
  - Exploitation (gaze shifts within regions) → small pupils
- Possible function
  - Exploitation is accompanied by a narrow focus
  - … and therefore benefits more from the increased visual acuity offered by small pupils
  - Analogous to the attentional-breadth interpretation
- May underlie
  - Pupil dilation linked to arousal and mental effort

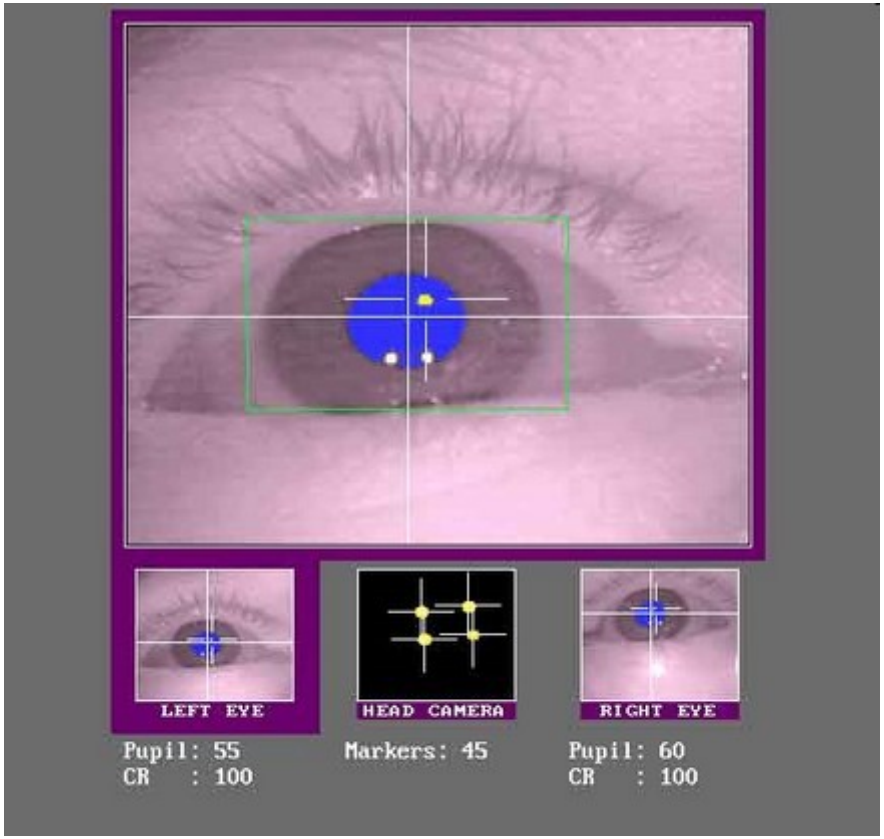
Regnath & Mathôt (2021, preprint), Jepma & Nieuwenhuis (2011), Pajkossy et al. (2017)

Eye-movement preparation



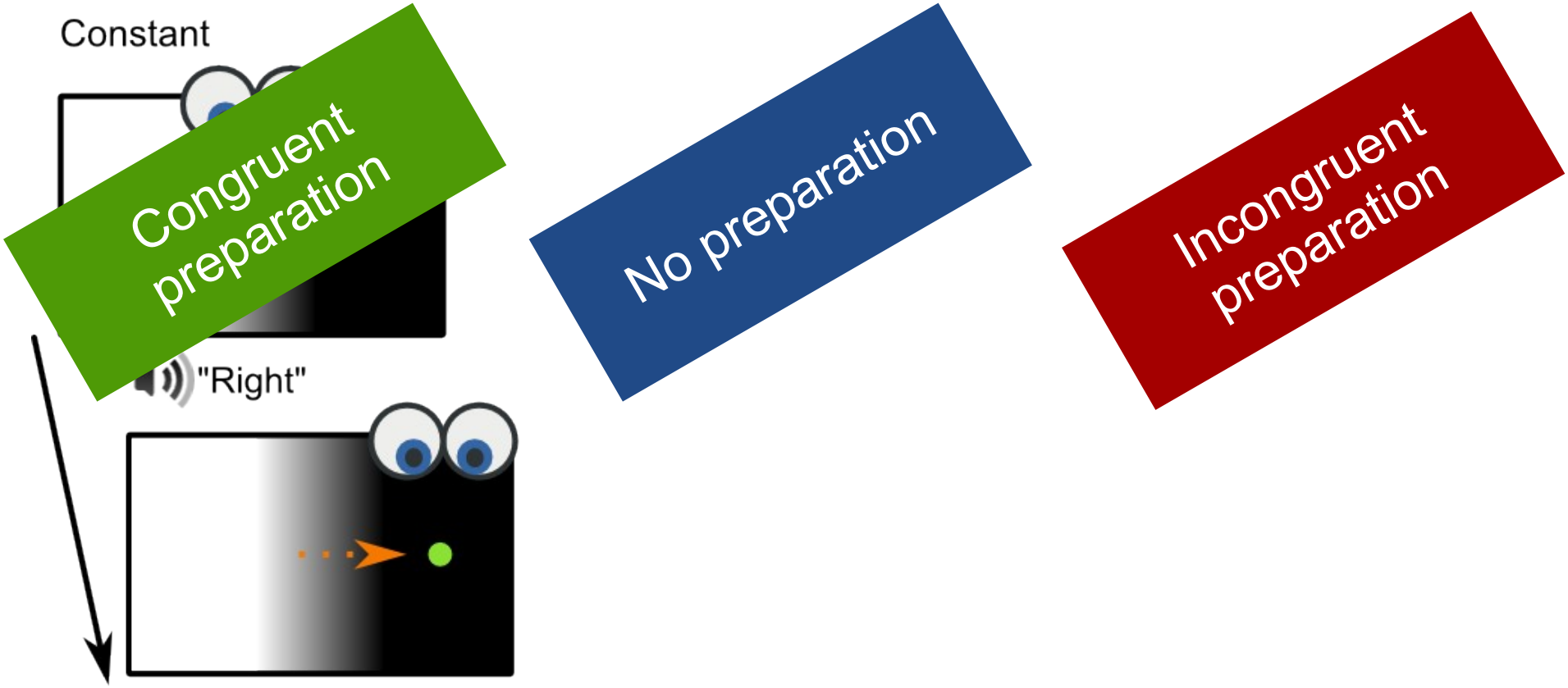
Eye-movement preparation

- Eye movements are preceded by covert shifts of attention
- Covert attention modulates the pupil light response
- Are eye movements to bright/ dark surfaces accompanied by a preparatory pupil light response?



Deubel & Schneider (1996), Mathôt et al. (2013)

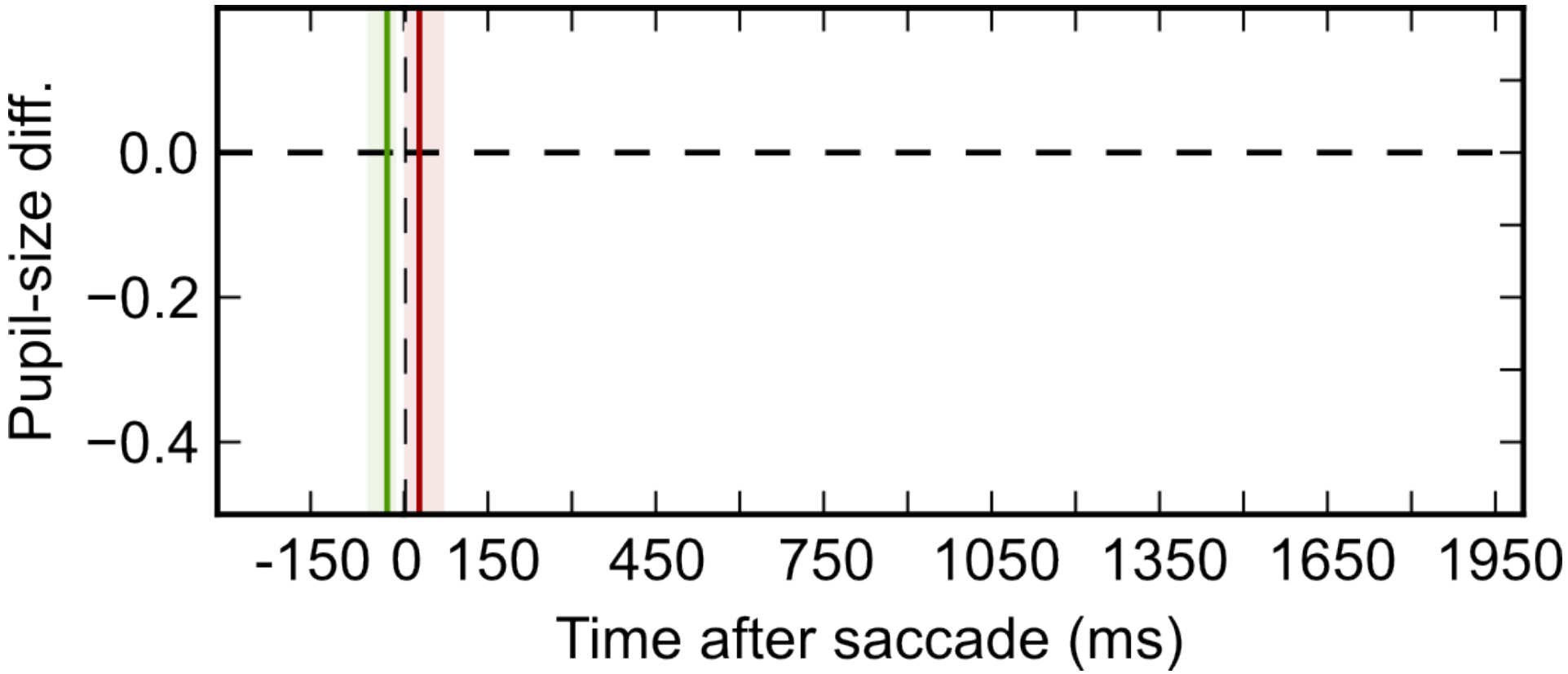
Eye-movement preparation



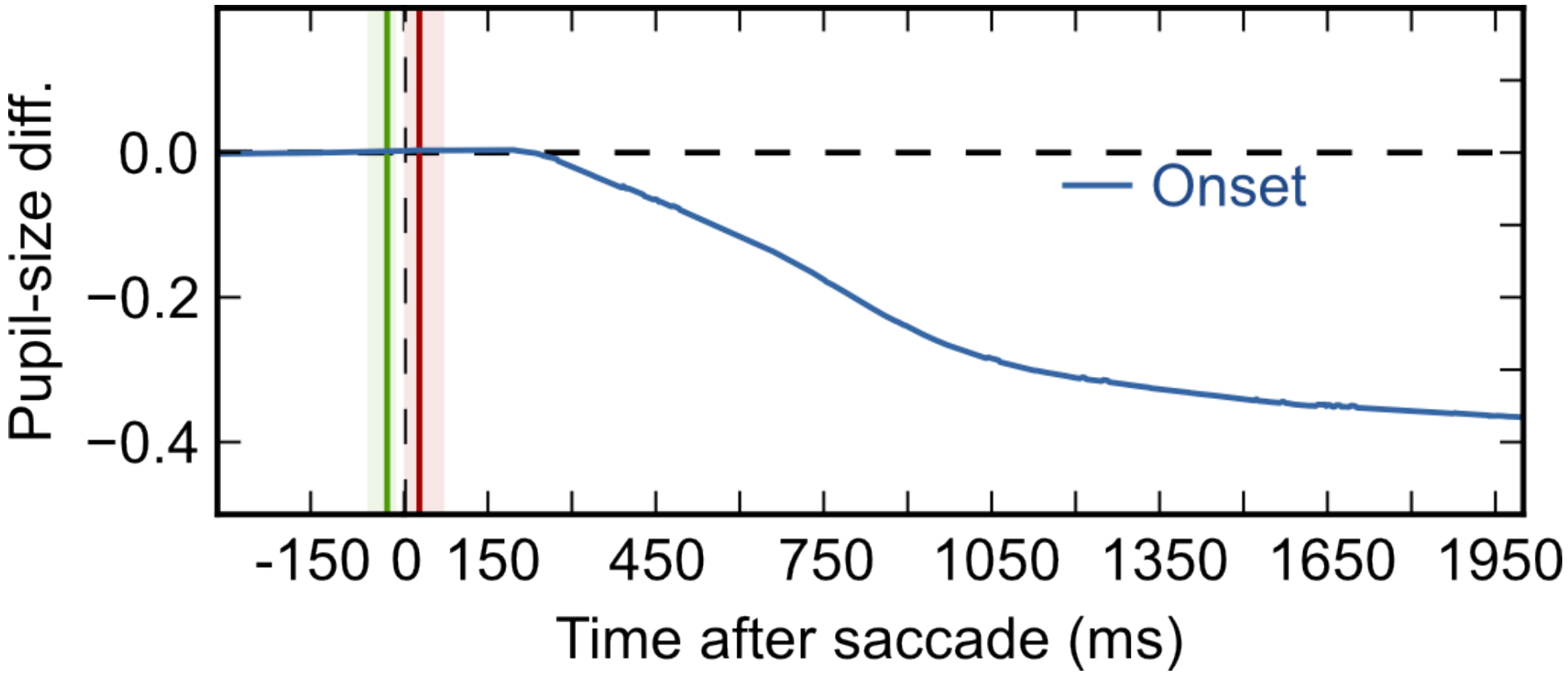
Eye-movement preparation

- Pupil-light-response latency should be reduced
  - If preparation is possible …
    - the Constant condition
  - … relative to when it is not
    - the Onset condition
- Initially (seemingly) inverse light response
  - If preparation is incongruent
    - the Swap condition

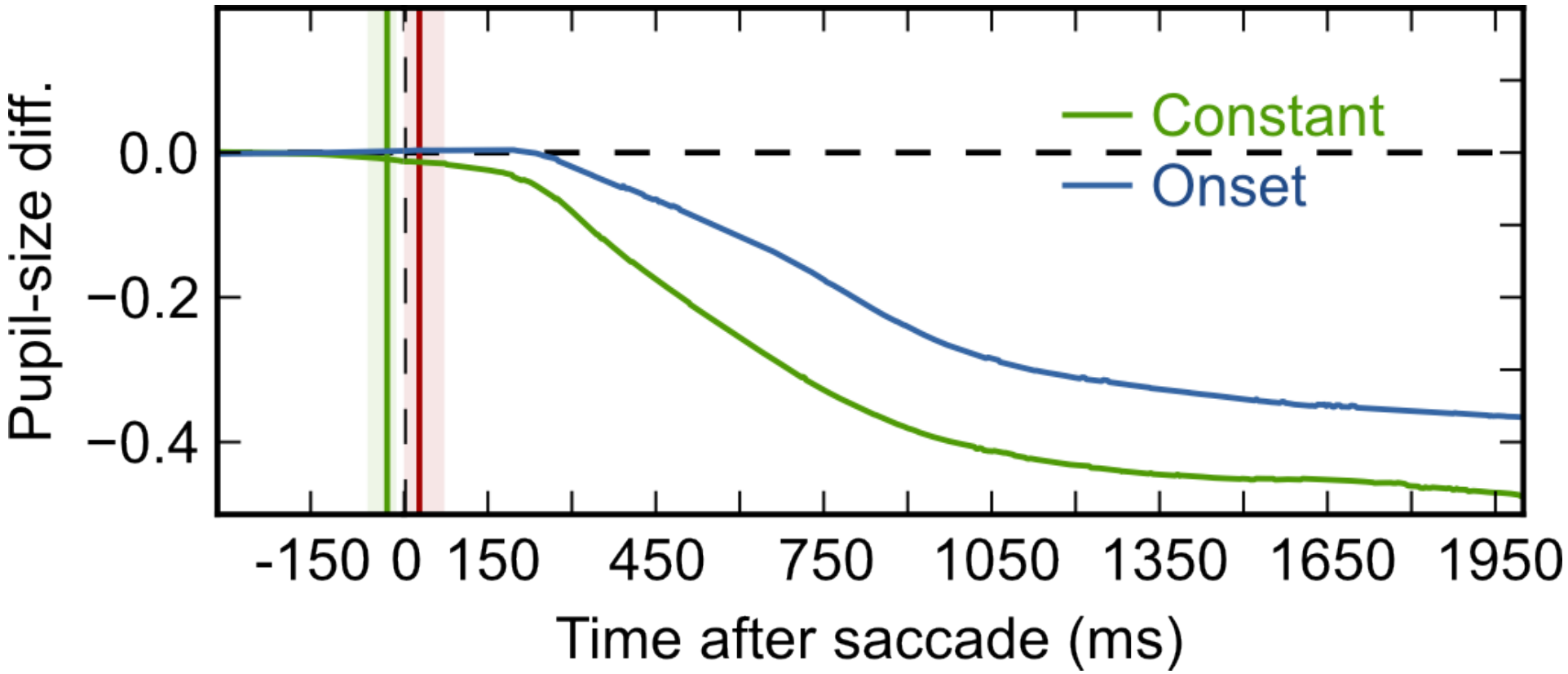
Eye-movement preparation



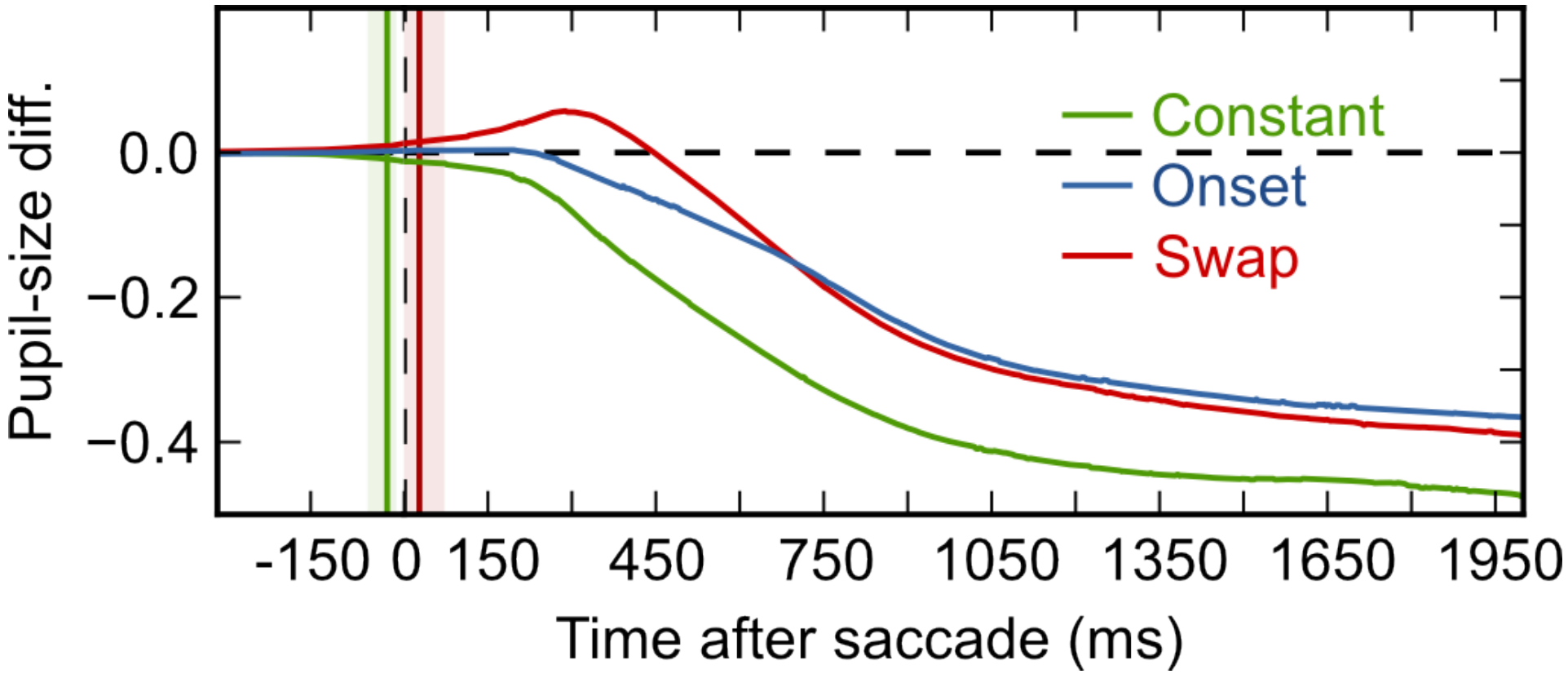
Eye-movement preparation



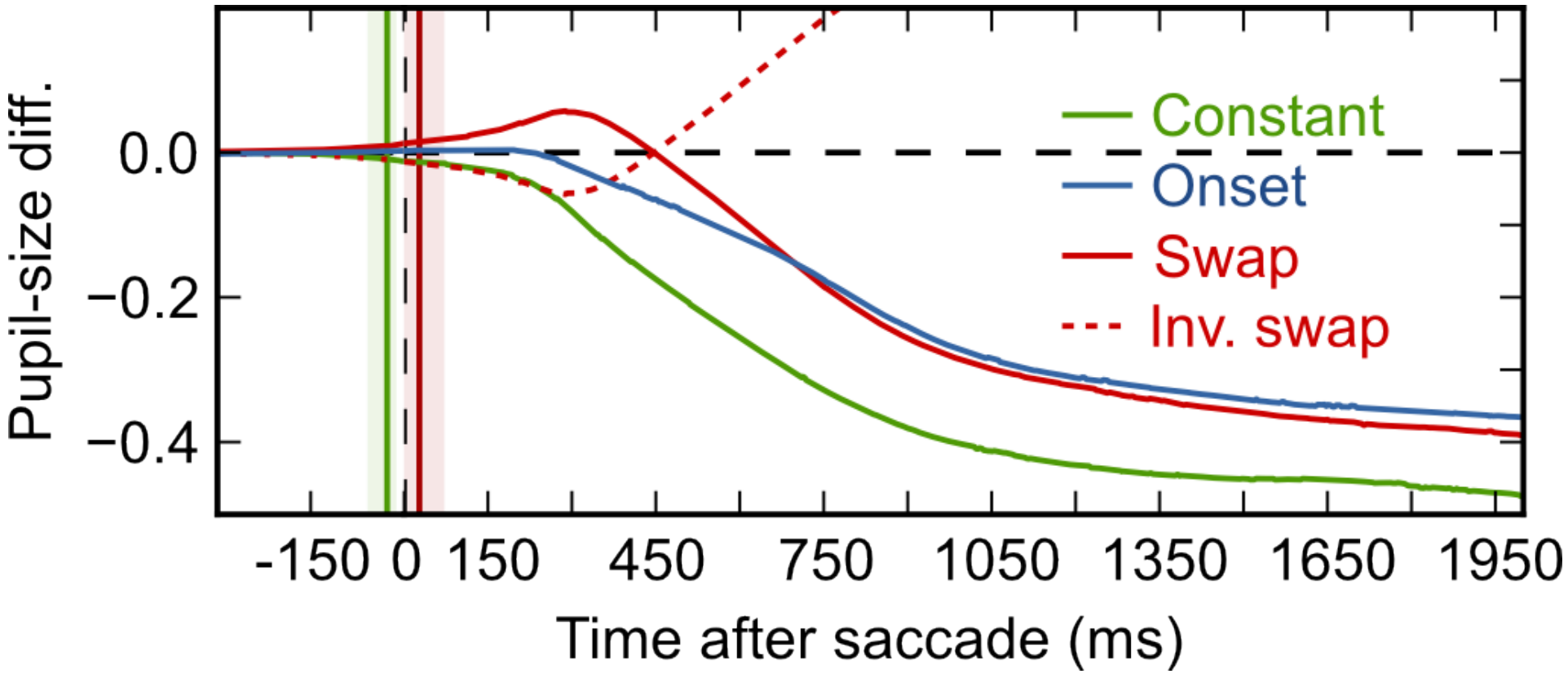
Eye-movement preparation



Eye-movement preparation



Eye-movement preparation



Eye-movement preparation

- Observation
  - Eye-movement preparation is accompanied by preparation of a pupil light response
- Possible function
  - Reduced latency of pupil light response
- May underlie
  - Cognitive modulation of the pupil light response by visual attention, visual working memory, language, etc.

Conclusion

Sensory tuning

- Emphasis on central vision over peripheral vision → pupil constriction
  - Narrow attentional focus
  - Exploitation mode of behavior
- Because central vision benefits most from the increased acuity offered by small pupils

Sensory tuning

- An intention to act with bright stimuli → pupil constriction
  - Eye-movement preparation
  - Covert attention
  - Visual awareness
  - Visual working memory
- Because this reduces the latency of the pupil light response

Sensory tuning

- Cognitively driven pupil responses may be a form of “sensory tuning”
- … a subtle adjustment of the senses to optimize their properties for the current situation and the immediate future

Thank you!

Sebastiaan Mathôt

Mathôt, S. (2018) Pupillometry: psychology, physiology, and function. Journal of Cognition. http://doi.org/10.5334/joc.18
Mathôt, S. (2020) Tuning the senses: How the pupil shapes vision at the earliest stage. Annual Review of Vision Science. https://doi.org/10.1146/annurev-vision-030320-062352
Mathôt, S., & Vilotijević, A. (2023). Methods in pupillometry: design, preprocessing, and statistical analysis. Behavior Research Methods. https://doi.org/10.3758/s13428-022-01957-7
Vilotijević, A. & Mathôt, S. (2023). Functional benefits of cognitively driven pupil-size changes. WIREs Cognitive Science. https://doi.org/10.1002/wcs.1672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