Investigating Development of Cognitive and Affective Processes with Pupillometry Methods

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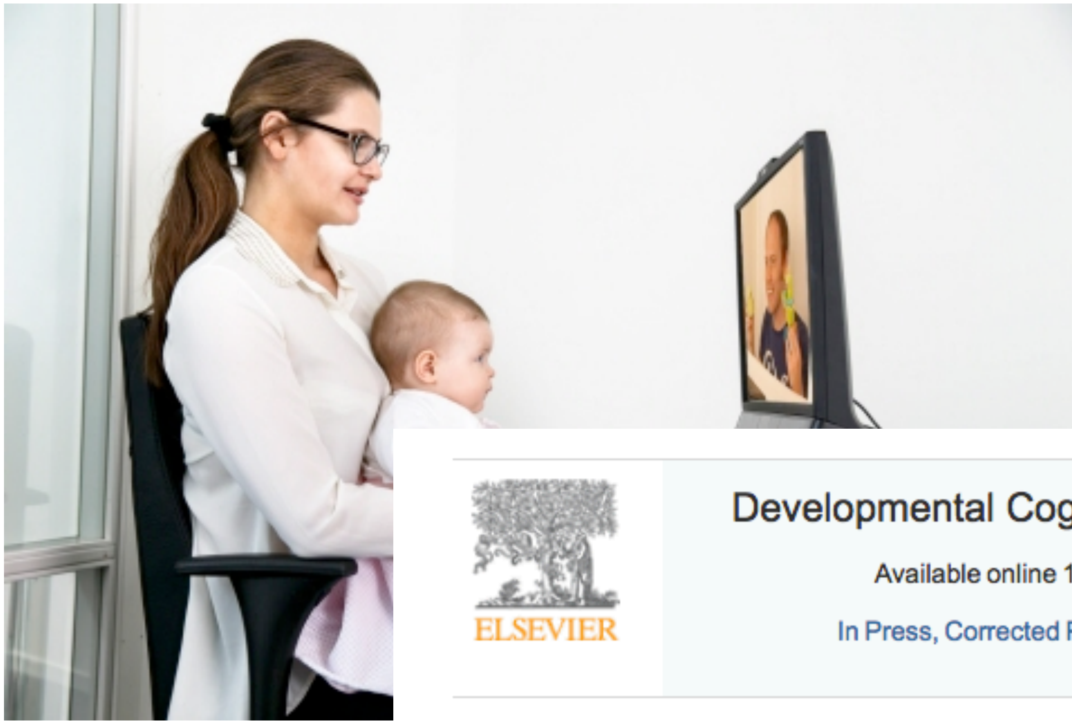
Talk Outline

- Physiological basis of pupil signal
- What can the pupil tell us about cognitive and affective processes?
  - Example data
  - Developmental considerations
- Collection and analysis of pupillometric data
- In-progress: analyzing pupil data using FieldTrip (open-source toolbox)



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Developmental Cognitive Neuroscience

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In Press, Corrected Proof — Note to users

Open Access

Beyond eye gaze: What else can eyetracking reveal about cognition and cognitive development?

Maria K. Eckstein[a], Belén Guerra-Carrillo[a], Alison T. Miller Singley[a], Silvia A. Bunge[a, b]

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http://dx.doi.org/10.1016/j.dcn.2016.11.001

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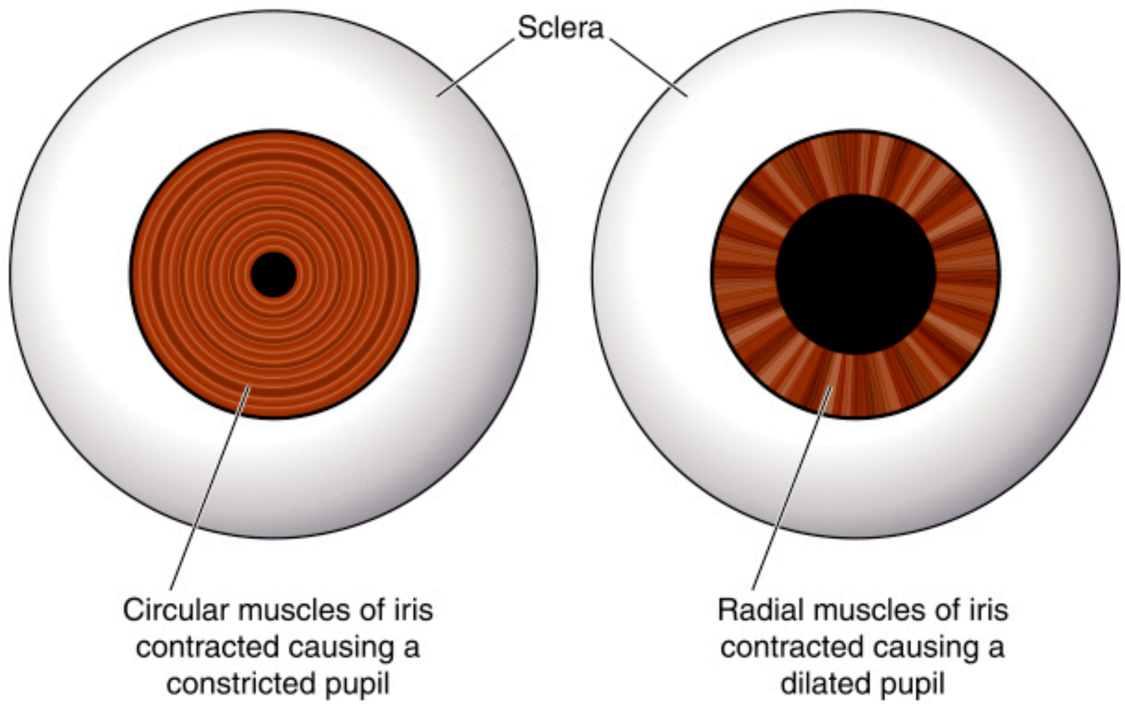
Pupil Signal: Physiology

- Pupil diameter: determined by relative contraction of two opposing sets of muscles within the iris of the eye (Beatty & Lucero-Wagoner, 2000)
  - Sensitive to sympathetic & parasympathetic nervous system activity (Steinhauer et al., 2004)
- Changes in pupil diameter are primarily determined by light and accommodation reflexes

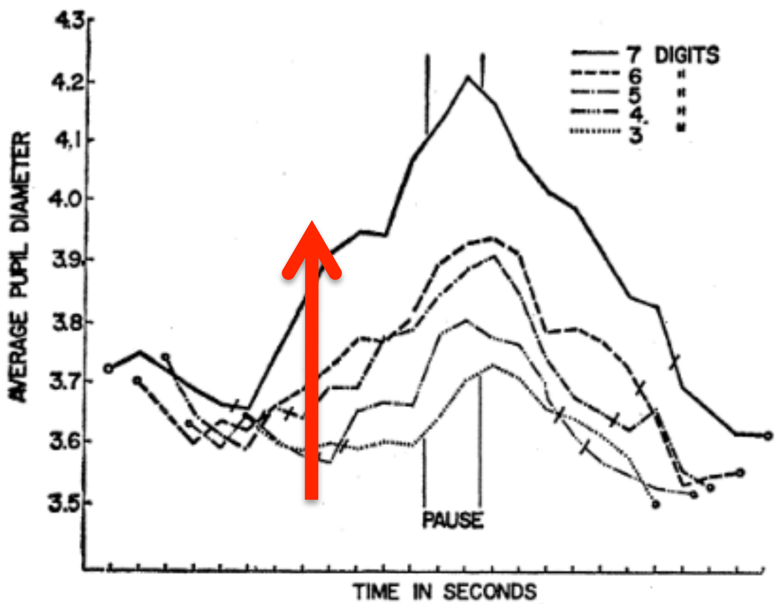
Pupil Signal: Physiology



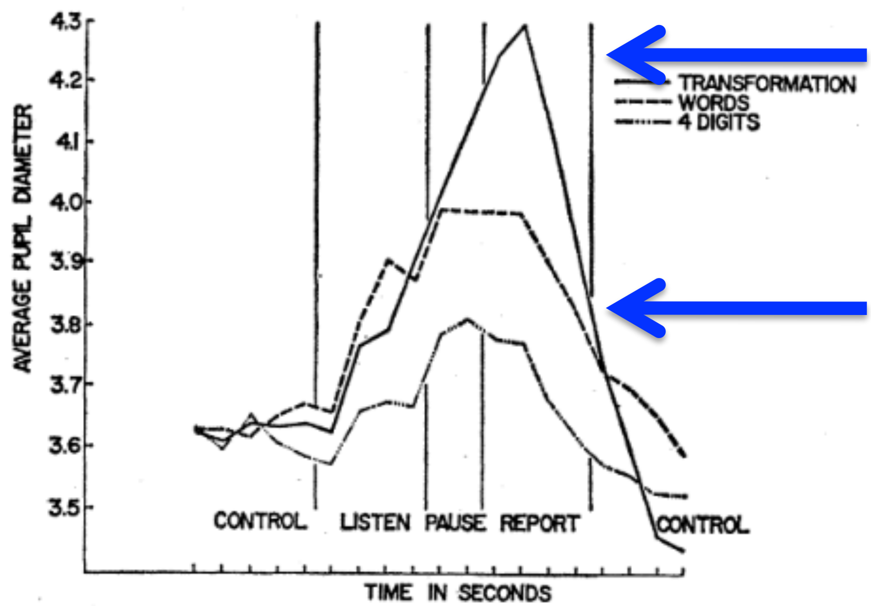
Pupil and Cognitive Processing

- Pupil demonstrates cognitively-related fluctuations in pupil diameter independent of visual luminance levels
- Responds to specific changes in cognitive demand, effort, and fatigue

- Increased pupil dilation with increased working memory demand



Increased dilation with WM maintenance of more information



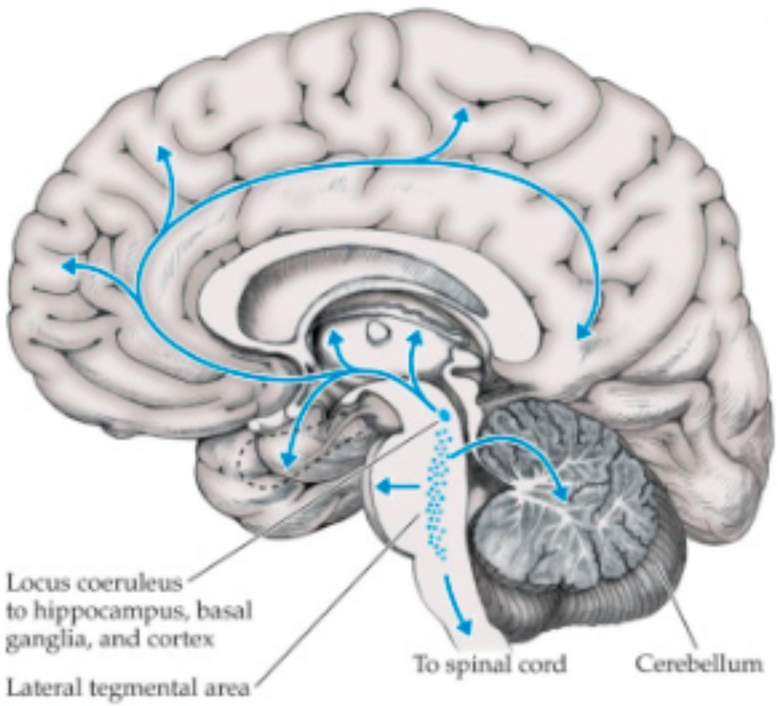
Increased dilation with transformation vs. maintenance

(Kahneman & Beatty, 1966)

Pupil: Neuromodulatory Activity

- Pupil dilation considered a proxy for norepinephrine activity in CNS
  - NE: projected to cortex from locus coeruleus
  - Pupils dilate during autonomic arousal
  - Primate neurophys studies: coupling between pupil diameter and LC neuron firing (Rajkowski et al. 1993)

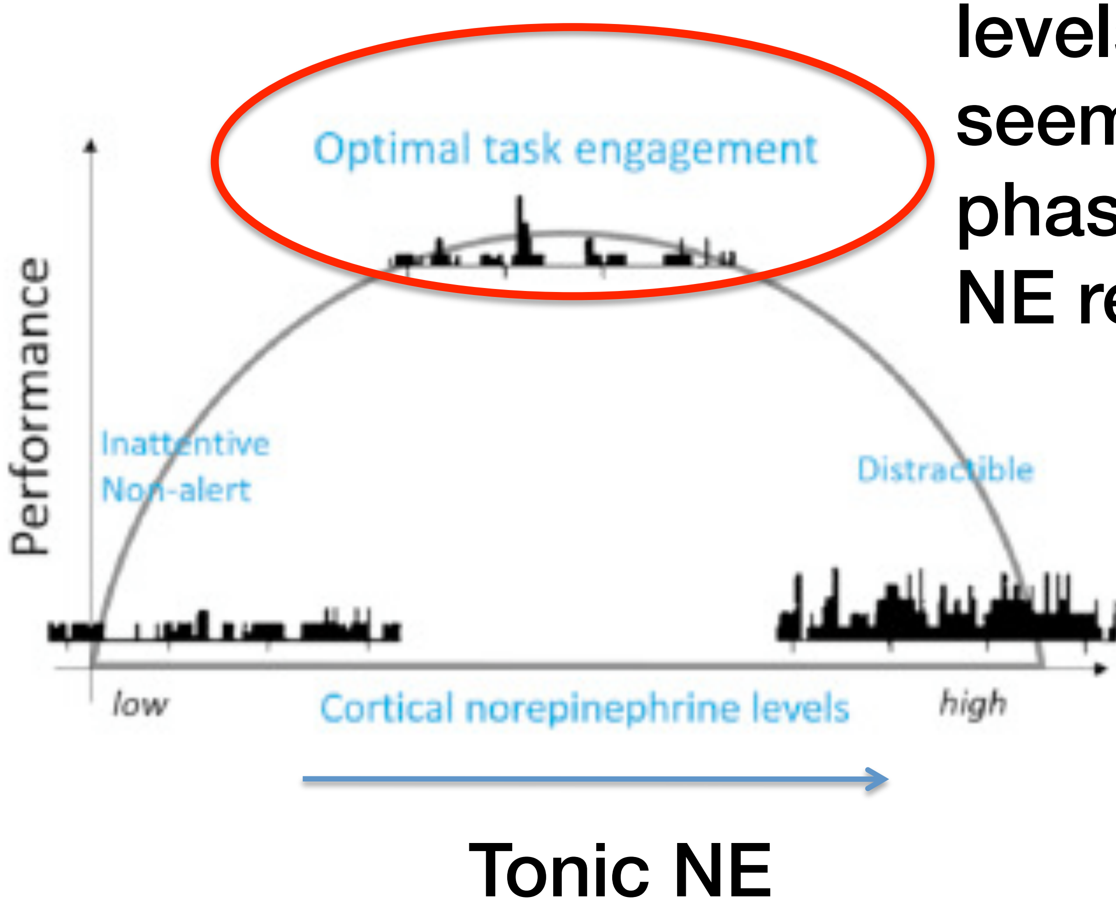
LC-NE Modulatory System



- Global influence on cortical processing
- <u>Tonic</u> background activity
- Task-evoked <u>phasic</u> responses

(from Eckstein et al., 2016)

Arousal, Tonic NE, and Task Engagement



Only intermediate levels of tonic NE seem to allow for phasic task-evoked NE responses

(from Eckstein et al., 2016)

Pupil and Brain Activity

- Examine with fMRI
- Pupil dilation and BOLD activity coupled:
  - In locus coeruleus (oddball task) (Murphy et al., 2014)
  - In PFC (digit-sorting task) (Siegel et al., 2003)
  - In default-mode network (during rest) (Yellen et al., 2015)
- In general, pupil seems to correlate with activity in task-relevant brain areas
  - Index of adaptive gain (Eldar et al., 2013)

Pupil and Cognitive Dynamics

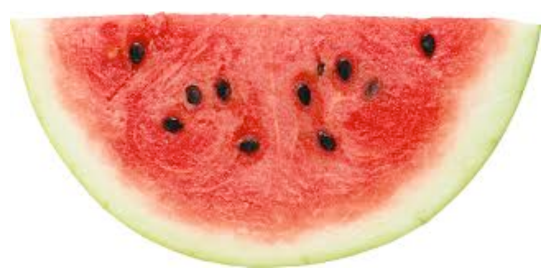
- Development of cognitive control (Chatham et al., 2009)
  - Hypothesis: top-down/proactive control improves over childhood
  - Use pupillometry to examine timing of control deployment in a cognitive control task
  - Contrast performance and pupil dilation in 3.5 year olds and 8 year olds on an adapted AX Continuous Performance Task (AX-CPT)

Child AX-CPT

"Sponge Bob likes watermelon, so press the happy face when you see Sponge Bob and then watermelon."

cue

probe



response

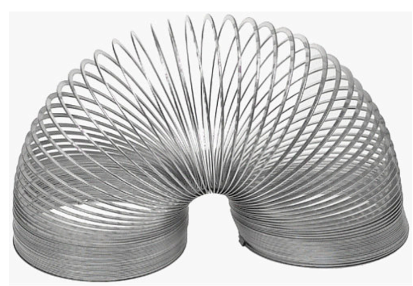
(Chatham et al., 2009)

Child AX-CPT

"Blue doesn't like the Slinky, so press the happy face when you see Sponge Bob and then watermelon."

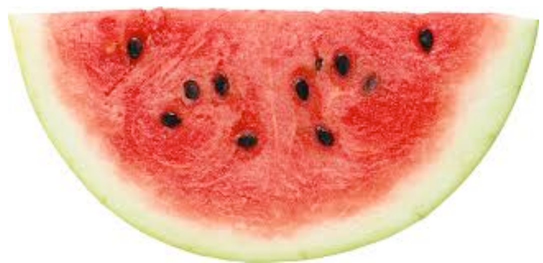
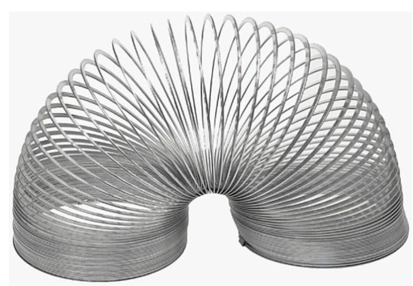
cue

probe

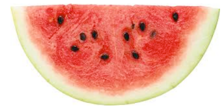


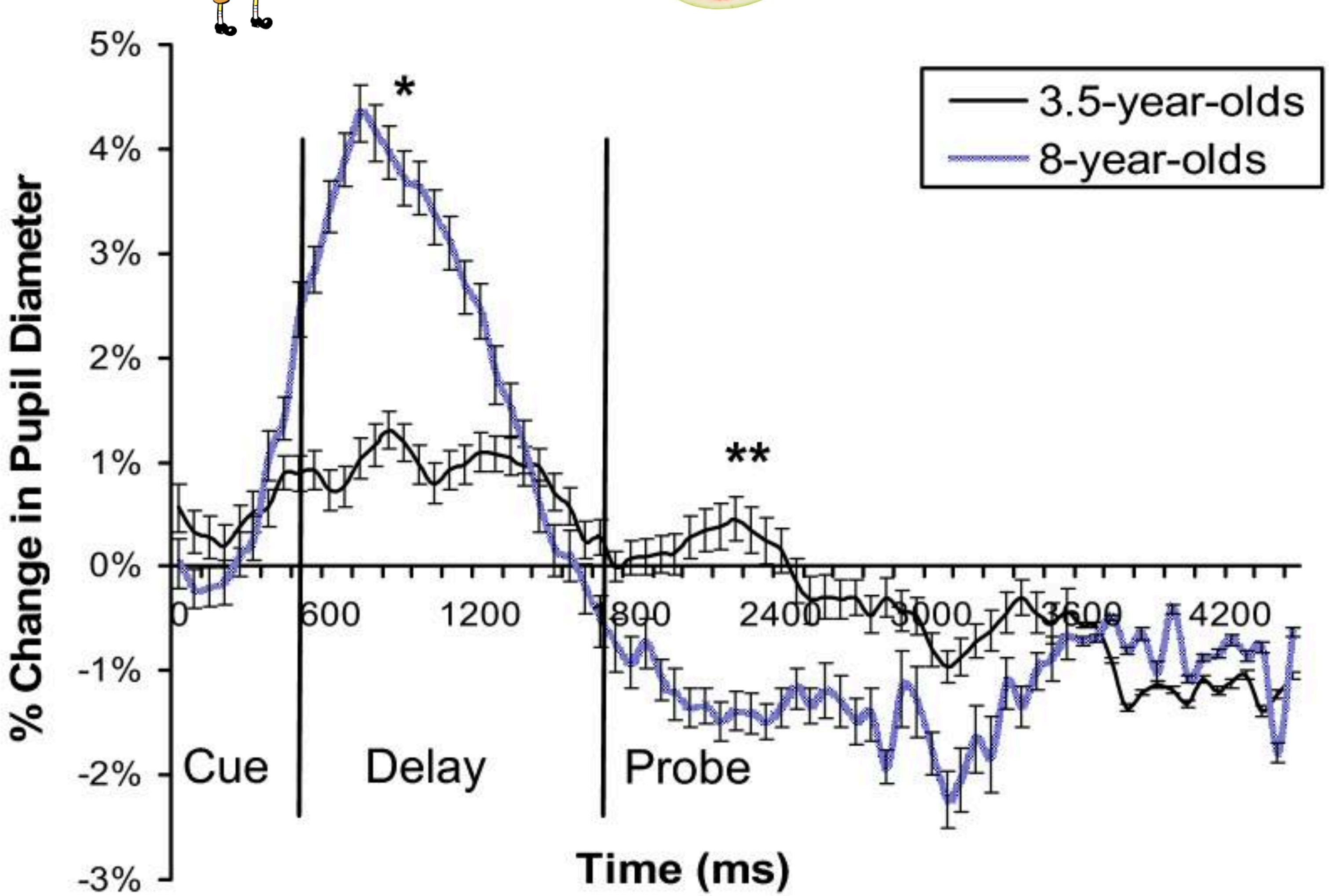
response

Child AX-CPT

cue	probe	response
		☺
		☹

(Chatham et al., 2009)





(Chatham et al., 2009)

Development of Cognitive Control

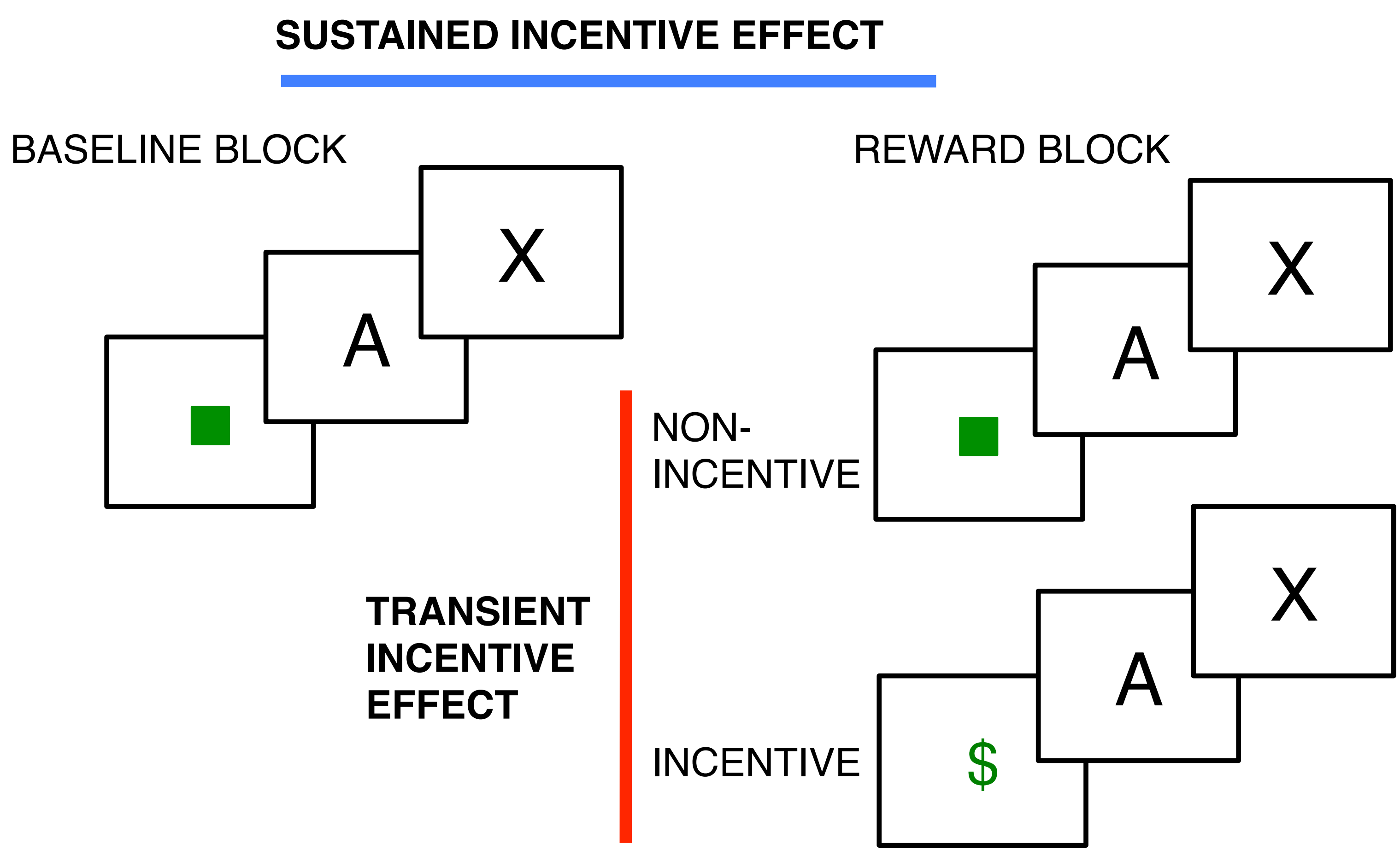
- Control changes qualitatively over the course of development
- Transitions from reactive, probe-based form control to a more anticipatory, proactive form of control
- Pupil data complements behavioral performance – illustrating how control unfolds

Reward and Control Dynamics

- Reward incentives might also change dynamics of cognitive control
- Reward might enhance top-down control and lead to similar dynamic effects
- Also associated with affective changes
- Examine with pupillometry

(Chiew & Braver, 2013)

Reward and Control Dynamics



N=33 healthy young adults

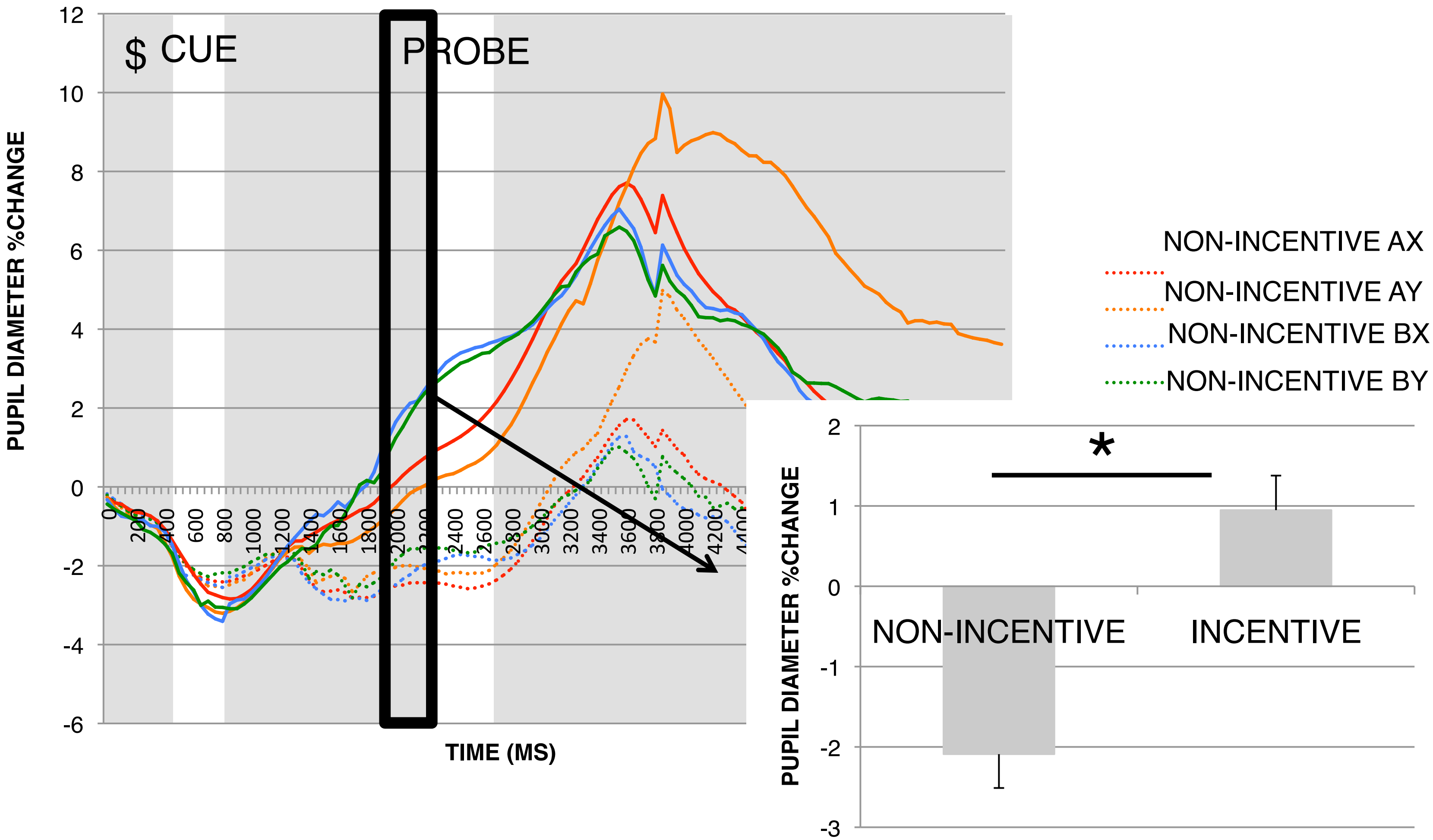
(Chiew & Braver, 2013)

Reward and Control Dynamics: Behaviour

- Comparing trial-by-trial effects
  - Non-incentivized vs. incentivized trials within reward block
- Comparing sustained/block-level effects
  - Baseline block vs. non-incentivized trials within reward block
- Behavioural performance shows a shift towards more proactive / top-down control on both transient and sustained timescales

(Chiew & Braver, 2013)

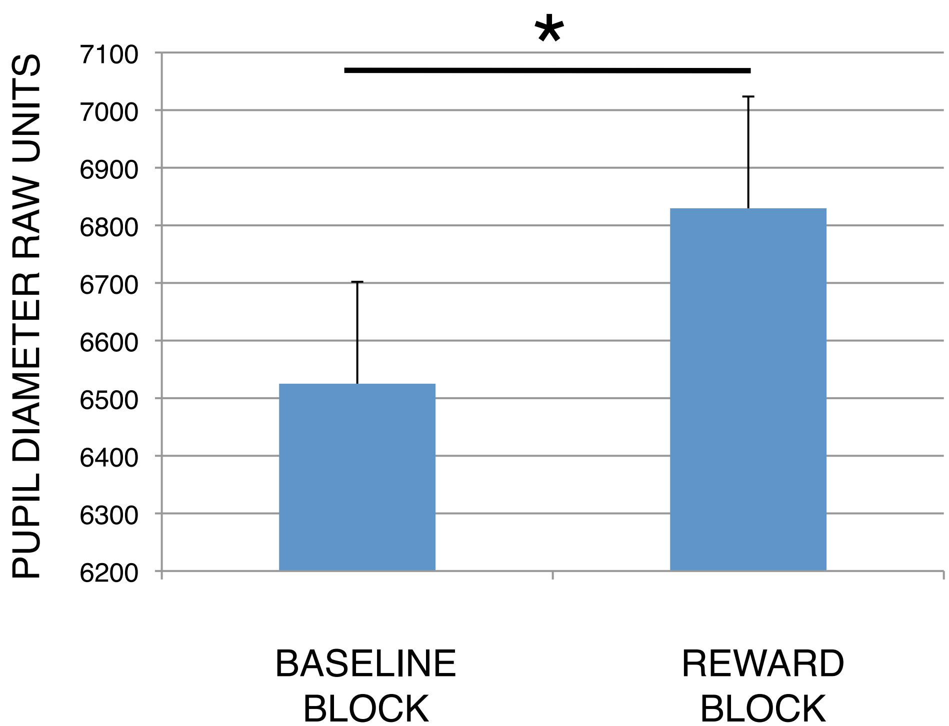
Reward and Control Dynamics: Trial-by-Trial Pupil Dilation



*p < .05

Chiew & Braver (2013)

Reward and Control Dynamics: Sustained Pupil Dilation

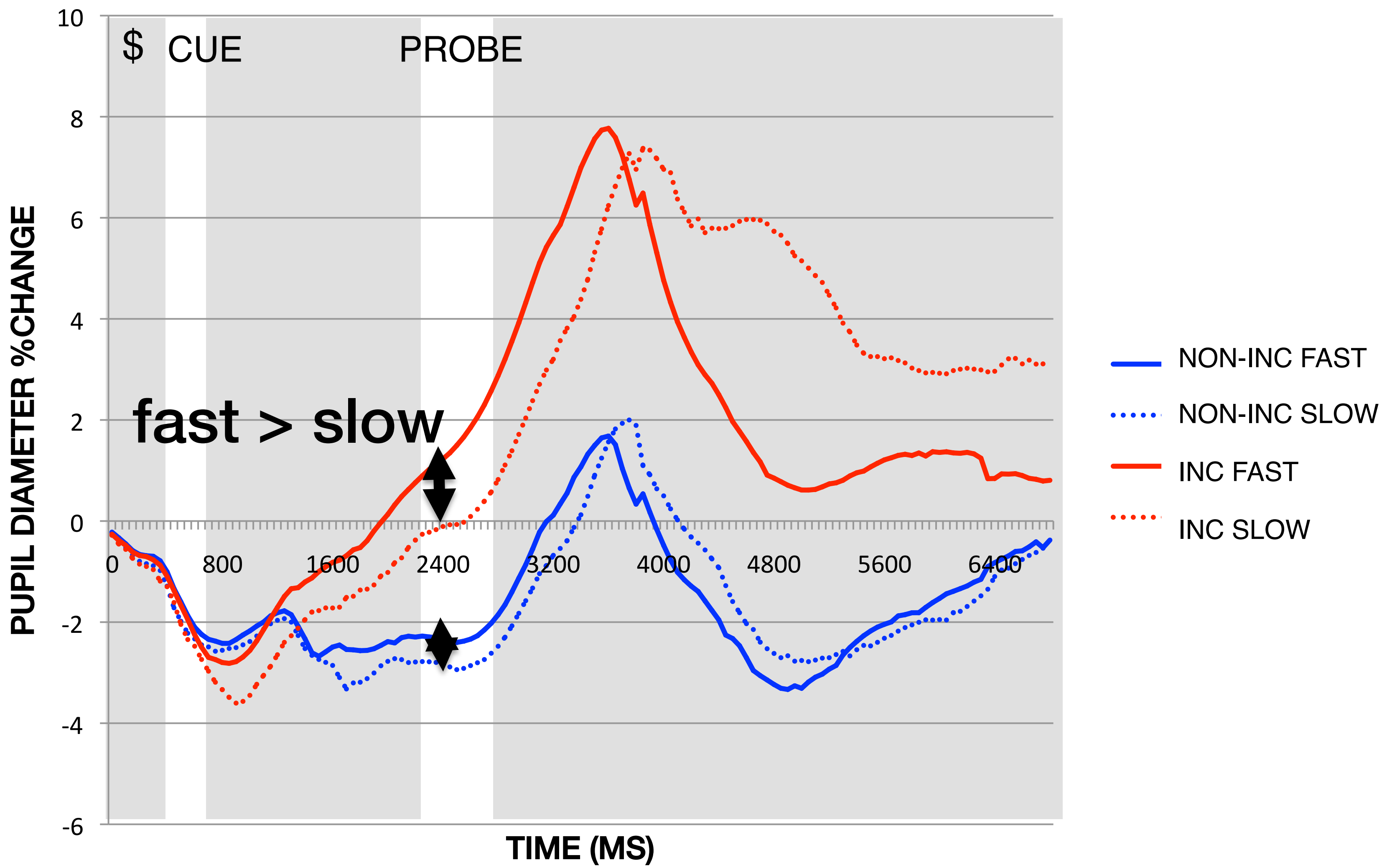


Average pupil dilation during 200ms ITI period

*p < .05

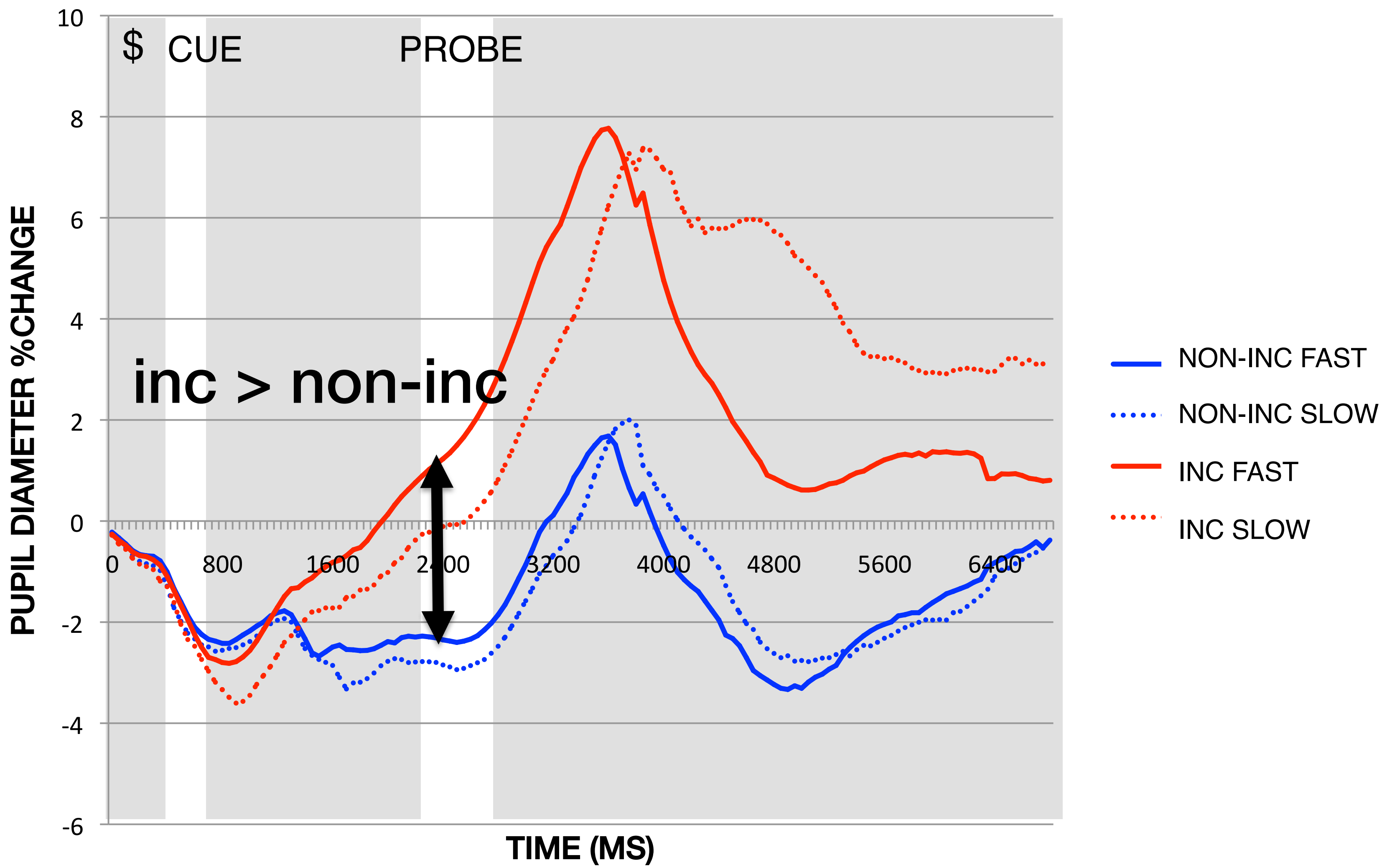
Chiew & Braver (2013)

Pupil Associated With Both Overt Performance and With Incentive Status



Chiew & Braver (2013)

Pupil Associated With Both Overt Performance and With Incentive Status



Chiew & Braver (2013)

Summary of Findings

- Changes in pupil dilation with reward incentive
- On both transient and sustained timescales (corresponding to changes in behaviour)
- Can specifically use to examine preparation *before* response execution
- Pupil dilation scales with both overt performance and incentive status
  - Consistent with idea of pupil as arousal marker
  - More than cognitive effort

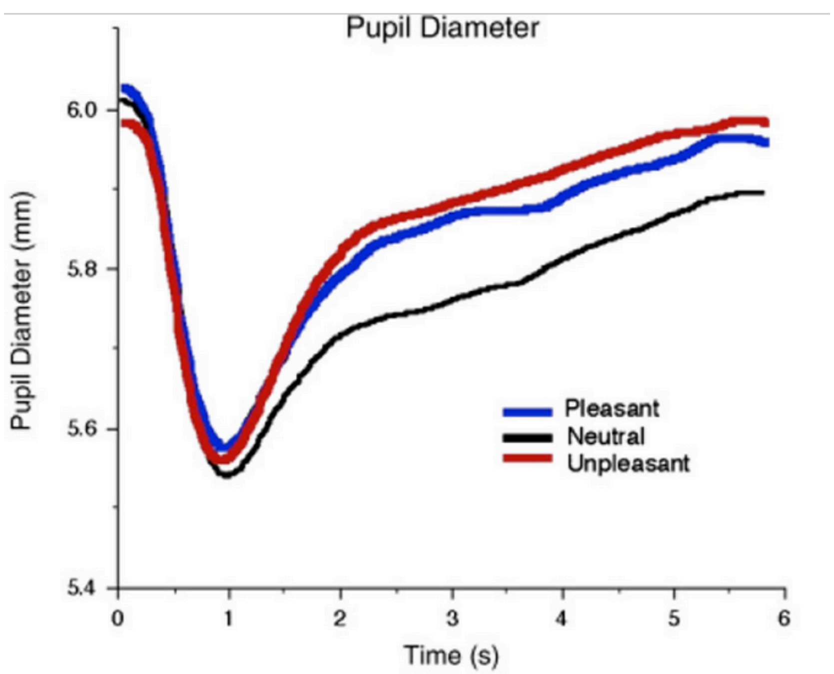
Chiew & Braver (2013)

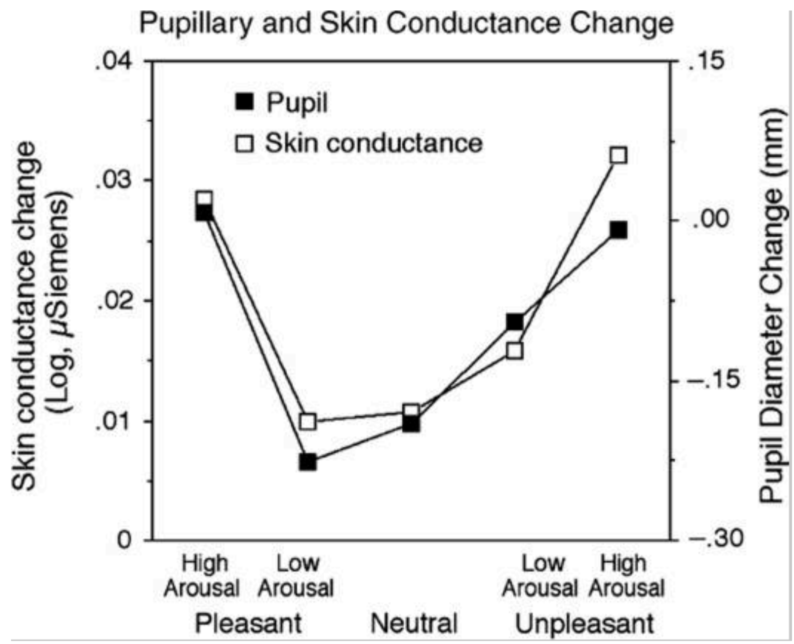
Effort, Arousal, & Efficiency

- Reward incentives → arousal → effort → change in performance
  - These are not 1 to 1 relationships
  - Can think about individual variability at each stage
- Pupil and variability in cognitive processing (Heitz et al., 2008)
  - Low working memory capacity → poorer performance but equivalent pupil activity
  - Low WM capacity individuals trying as hard but less efficient?

Pupil as Index of Emotion

- Independent of cognitive effort
- Passive viewing task





Bradley et al. (2008)

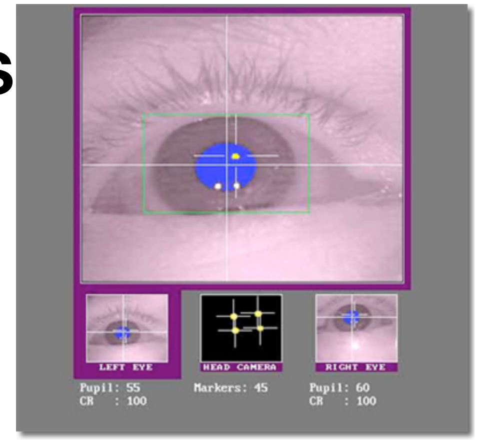
Pupil Activity as Physiological Marker

- Baseline pupil diameter: fluid intelligence (Tsukahara et al., 2016)
- Pupil during digit span: Early risk indicator for Alzheimer's disease (Granholm et al., 2017)
- Tonic/phasic pupil activity: exploration/exploitation (Jepma & Nieuwanhuis, 2011)
- Old/new memory effects (Otero et al., 2011)
  – In 7-month but not 4-month old infants (Hellmer et al., 2016)

Pupil Data: Methodological Issues

- Data Collection
  - Observation
  - Luminance
  - Timing
- Data Analysis
  - Preprocessing
  - Analytical approaches
  - Tools

Data Collection: Observation



- EyeLink control computer shows video of the eye during data collection
  - Does not save this data!
- Worth considering recording the view from control computer screen to time-lock missing pupil data to participant behaviour
- Blink? Movement?

Controlling for Luminance

- Major effect on pupil diameter – control as much as possible
  - No windows in testing room
  - Moderate, constantly-held levels of lighting are best for discerning cognitive changes in pupil diameter (Eckstein et al., 2016)

Controlling for Luminance

- Can use isoluminant colour palette to control for luminance
  - Used in Van Steenbergen & Band (2013)
  - Teufel colours set (RGB) (Teufel & Wehrhahn, 2000):
    - Slate blue (166, 160, 198)
    - Dark cyan (110, 185, 180)
    - Khaki (188, 175, 81)
    - Salmon (217, 152, 158)

Controlling for Luminance

- Luminance effects can be estimated and cleaned from pupil data (Pomplun et al., submitted*)
  - Pupil constriction index
- Controlling for mean luminance level per trial with multi-level modeling
  - Trials nested within subjects
  - Examine average pupil dilation as a function of IVs while regressing out mean luminance level of stimulus
  - Contact me for R script

* http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.219.1130&rep=rep1&type=pdf

Controlling for Luminance

- These luminance controls have been examined in stationary eyetrackers
- Currently unknown if could be used to extract pupil activity from mobile eyetracking data

Data Collection: Timing

- While temporal resolution is high, the pupil response itself is slow
- Can take 1-1.5 seconds to reach max dilation in response to stimulus presentation (Murphy et al., 2011)
- If examining sub-trial events, suggested ISI of 1000ms and ITI of 3000ms (Eckstein et al., 2016)
- However, signal deconvolution makes it possible to examine activity related to faster events (Wierda et al., 2012)

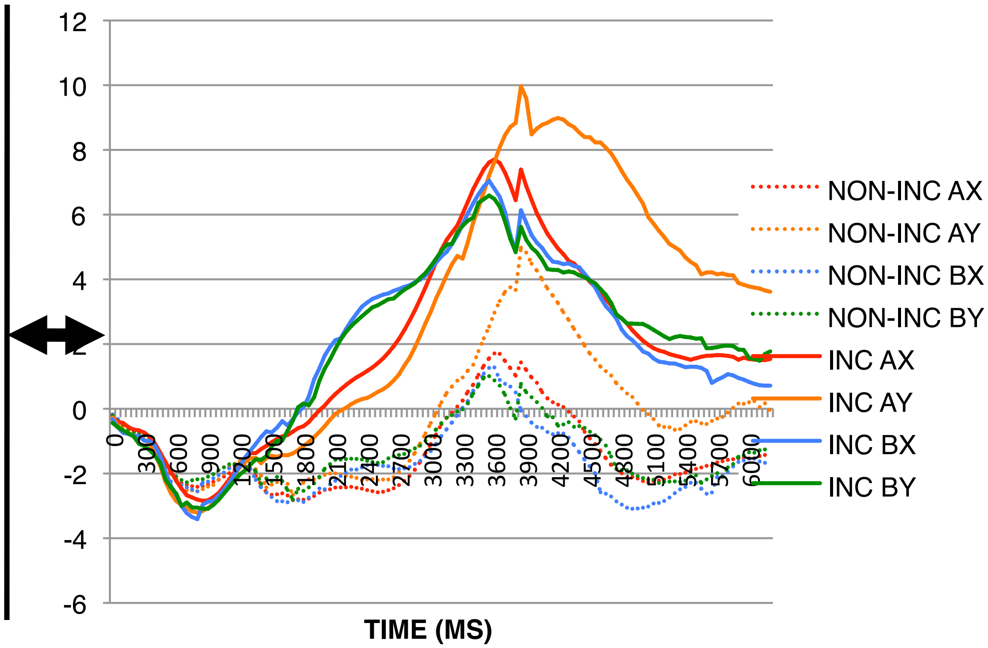
Data Analysis: Preprocessing

- Short gaps of missing data, usually caused by blinking, can be interpolated
  - Or can eliminate trials with blinks but this is not recommended
- A number of blink correction algorithms are currently out there
- Worth examining your data for % “substantial” missing data (too long to be a blink)
  - Chiew & Braver 2013: “substantial” missing data >500ms
  - QA cutoff >20% missing; YMMV with population
- (to my knowledge) signal is not typically filtered

Data Analysis: Characterizing Signal

- Signal measured in relative terms; % change relative to time period before trial-evoked activity

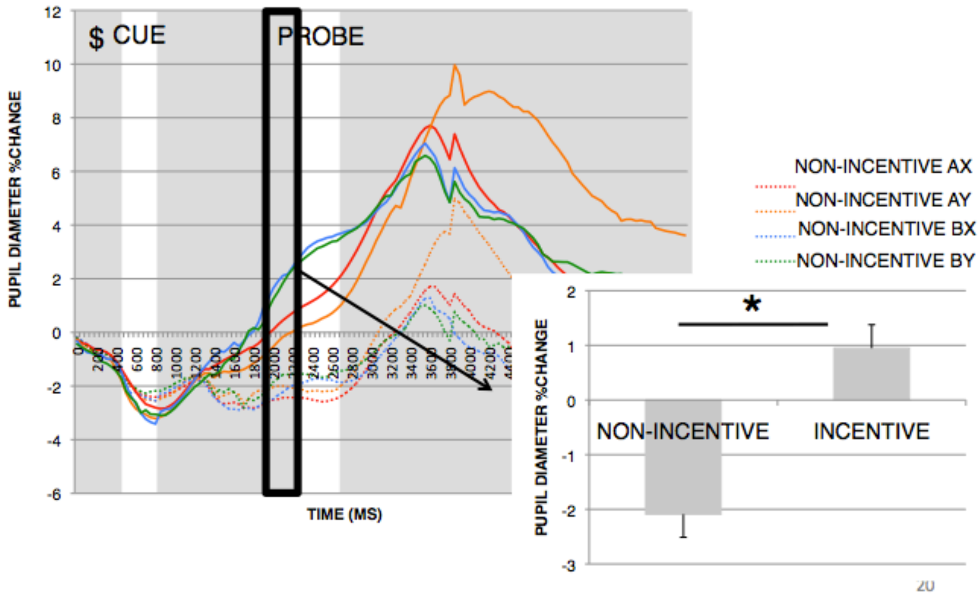
- Transient activity in my data measured in terms of %change relative to mean activity in 200ms ITI period just before next trial begins



Eckstein et al. (2016)

Data Analysis: Characterizing Signal

Chiew & Braver (2013)



- Within period of interest, calculate average pupil dilation and examine as function of IVs

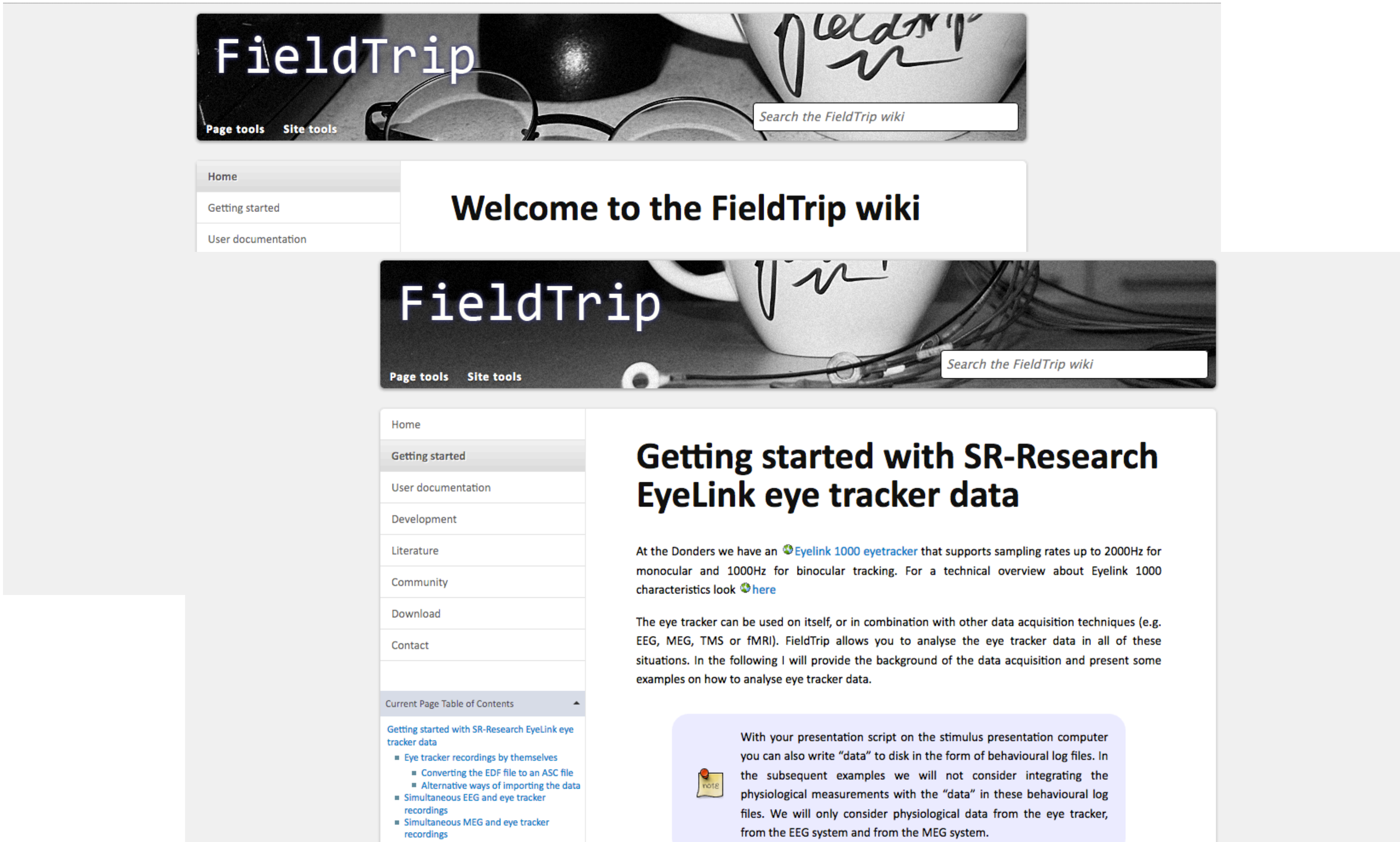
- Can conduct more elaborate analyses using functional data analysis (fitting signal to a mathematical function)

Functional data analysis: http://www.psych.mcgill.ca/misc/fda/index.html

Analytical Tools

- EyeLink Data Viewer
  - Other commercial software packages (e.g., now-defunct BBAS)
- John Pearson's tools
  - https://github.com/pearsonlab/pupil
- FieldTrip
  - www.fieldtriptoolbox.org
  - Freely available MATLAB toolbox for EEG/MEG/pupil data analysis

www.fieldtriptoolbox.org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Getting started with SR-Research EyeLink eye tracker data

At the Donders we have an Eyelink 1000 eyetracker that supports sampling rates up to 2000Hz for monocular and 1000Hz for binocular tracking. For a technical overview about Eyelink 1000 characteristics look here

The eye tracker can be used on itself, or in combination with other data acquisition techniques (e.g. EEG, MEG, TMS or fMRI). FieldTrip allows you to analyse the eye tracker data in all of these situations. In the following I will provide the background of the data acquisition and present some examples on how to analyse eye tracker data.

note

With your presentation script on the stimulus presentation computer you can also write "data" to disk in the form of behavioural log files. In the subsequent examples we will not consider integrating the physiological measurements with the "data" in these behavioural log files. We will only consider physiological data from the eye tracker, from the EEG system and from the MEG system.

FieldTrip Pipeline

- Following Anne Urai's tutorial:
  - http://github.com/anne-urai/PupilPreprocessing
- Steps:
  - Convert data from EDF (eyelink data format) to ASC (ASCII)
  - Set up FieldTrip-format data structure
  - Interpolate blinks
  - Regress out blink- and saccade-linked pupil response
  - Currently working on: define trials
    - Used E-Prime – E-Prime sends a signal to EyeLink computer when sub-trial events happen (cue, probe, response…)

Conclusions…

- Pupillometry is a versatile tool for examining the timecourses of cognitive and affective processes
  - Linked to NE activity
  - Relatively easy to collect measure of CNS function well-suited to developmental research
- Advances in eyetracking technology, signal processing enable more sophisticated analysis
- Correlations between pupil dilation and many other psychologically-meaningful metrics
- This area of research currently rapidly growing