Pupillometry
(with a focus on children and language)

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Basics

Pupillometry… looking back

- Connection between cognitive processing and pupillary dilation noticed at the end of the 19th century
- "*Every active intellectual process, every psychological effort, every exertion of attention, every active mental image, regardless of content, particularly every affect just as truly produces pupil enlargement as does every sensory stimulus.“*
  Oswald Bumke in 1911, cited from Hess (1975, p. 23–24)
- Pupillometry pioneer: Otto Lowenstein (Thompson, 2005)
- Irene E. Loewenfeld (1993) *The Pupil: Anatomy, Physiology and Clinical Applications*. Iowa State University Press.
  - The book comprises the work of Lowenstein and Loewenfeld
  - A standard reference on pupil research

Image source: Thompson, H. S. (2005). Otto Lowenstein, Pioneer Pupillographer. *Journal of Neuro-Ophthalmology, 25*(1), 44-49.

FIG. 12. Loewenfeld and Lowenstein in the central yard at Columbia University in the late 1950s.

Pupillometry… not so new but much easier now

1920 →

2020 ←

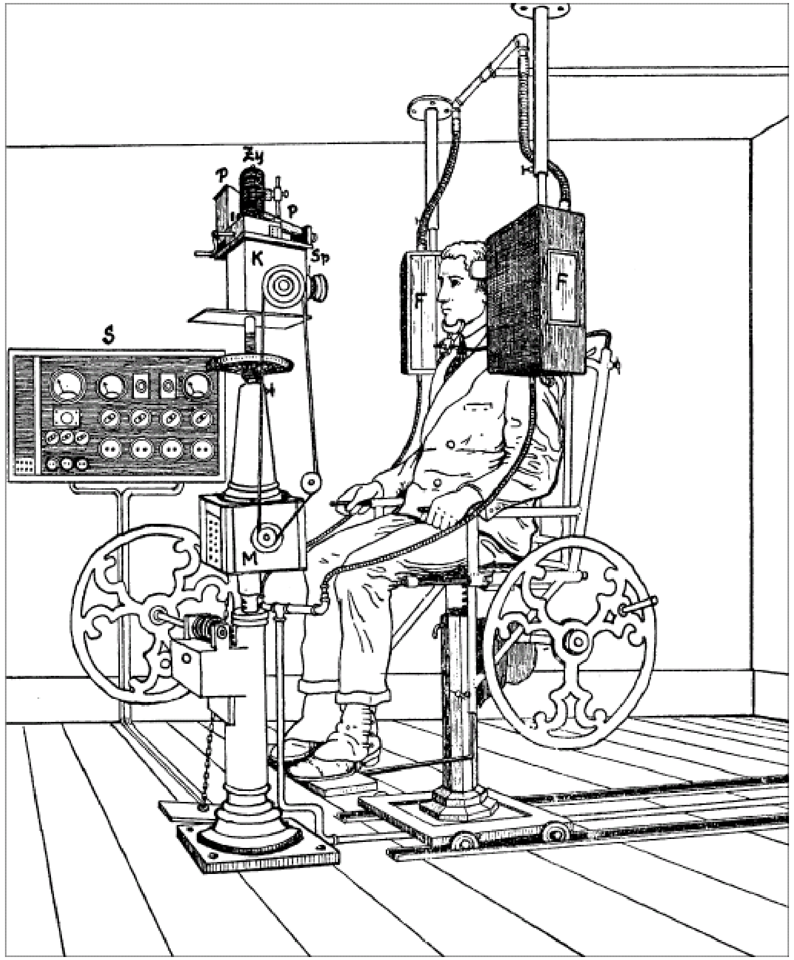


FIG. 6. Recording pupil movements (late 1920s). This is one of Lowenstein's early arrangements. The lights were still very hot and had to be cooled by circulating water.

Image sources: BabyLAB Potsdam/Thomas Hölzel
Thompson, H. S. (2005). Otto Lowenstein, Pioneer Pupillographer. *Journal of Neuro-Ophthalmology, 25*(1), 44-49.

What is pupillometry?

- Pupil: the hole in the middle of the iris, adjusting the light level that reaches the retina
  - Size is controlled by two opposing muscles connected to the parasympathetic (constrictor/sphincter) and sympathetic (dilator) nervous system
  - Typical size: 3-5 mm(range: 1-9 mm) gets smaller by .04 per year
- The measure of pupil size across time, 2 dimensions:
  - Amplitude (diameter or area)
  - Temporal info (onset, duration, latency)
  - Comparable to a single-channel EEG

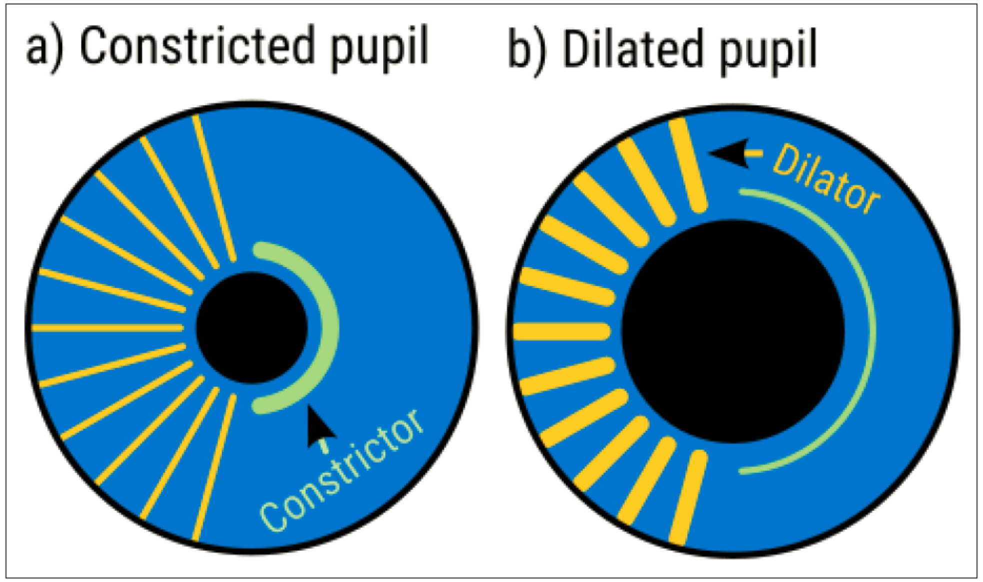


Image source: Mathôt (2018, p. 2)

Pupil size changes constantly

- Pupil Oscillations
  - Pupillary Hippus: Rhythmic but irregular (usually <0.04 Hz) constrictions and dilations independent of eye movements or luminance changes
  - Spontaneous oscillations (especially in the dark/sleepiness waves), usually < 0.5 Hz
- Pupillary Light Reflex
  - Increase in light: constriction, with a latency of ~200 ms and a peak at 500–1000 ms
  - Indicator of neurological status
- Pupil Near Response
  - Constriction in response to looking at a nearby object, dilation for far-away objects
- Psychosensory Pupil Response
  - [Next slide]

Psychosensory Pupil Response

"Any sensory occurrence - whether tactile, auditory, gustatory, olfactory, or noxious - evokes a pupillary reflex dilation." (Beatty & Lucero-Wagoner, 2000, p. 145)

- Not only external sensory events, but also internal (hence PSYCHOsensory):
  - Emotions
  - Mental processes
  - Increases in intentional efforts
  - Motor output preparation
  - ...

!

Time scales of pupil size changes

The pupil is *slow* when compared to eye movements (gaze) or electrophysiological responses.
Changes occur on the scale of seconds rather than on a millisecond scale

- Phasic
  - Rapid (relatively) and transient / time-locked
  - In response to an (external or internal) event (i.e. psychosensory responses)
- Tonic
  - Slow and long lasting / continuous
  - State of arousal/emotion or mode of processing information
  - Influence of medical conditions/illnesses, pharmacological effects (i.e. drugs)
- Rhythmic
  - Frequency-based / oscillations, fluctuations
  - Related to mental states (sleepiness), external stimuli (entrainment > Alan Langus) or cognitive processing (Index of Cognitive Activity/ICA, Demberg et al., 2013)

Task-Evoked Pupillary Response (TEPR)

- Term taken from Beatty & Lucero-Wagoner (2000, p. 147)
  other (more general) term: Pupil Dilation Response (PDR)
- A non-reflexive phasic pupillary movement
- TEPRs serve as “empirically based reporter indicators for brain processes that underlie the dynamic, intensive aspects of human cognition”
- General properties:
  - Response delay: 200–300 ms
  - Peak at about 1200 ms (500–2000 ms)
  - Amplitude is small (less than .5 mm) compared to pupillary light reflex
  - These values vary with task, modality, age, …

TEPR as an index of cognitive load

- Arithmetic problems (Hess & Polt ,1964)
- Memory
  - STM load (Kahneman & Beatty, 1966)
  - LTM retrieval (Beatty & Kahneman, 1966)
- Perception, e.g. pitch discrimination (Kahneman & Beatty, 1967)
- Language
  - Syntactic complexity (Schluroff, 1982; Just & Carpenter, 1993)
  - Grammaticality violations (Gutiérrez & Shapiro, 2010)
  - Sentence comprehension (Wright & Kahneman, 1971)
  - Context integration (Engelhardt et al., 2010)
- Attention (Beatty, 1982, 1988)
- Responding (similar to ERP components - CNV or RP)
- Standard tests of “concentration”

Influences and interpretations of pupil size

Emotion

Task

Response

Repetitions

Fatigue

Attention

Mental capacity

Arousal

Interest

Difficulty

Proficiency

There is no causal link to specific cognitive functions

Mental workload

Cognitive effort

Surprisal

Attention allocation

Emotional arousal

Memory load

Intensity of processing

Our first study

(as an example)

Mispronunciation detection in children

Study	Age (months)	Language	Method	Manipulation	Mispro Detection?
Swingley, 2005	11	Dutch	HPP	onset or offset	onset: ✓ offset: ✗
Yoshida et al., 2009	14	Englsih	Habituation + Preferential looking	novel words: 1st consonant	✓
Ballem & Plunkett, 2005	14	English	Learning + Preferential looking	novel & familiar words: 1st consonant (1 feature)	✓
Mani et al., 2012	14	English	ERP	vowels (1 feature)	✓
Swingley, 2003	19	Dutch	Preferential looking	first or medial consonant	✓
Swingley & Aslin, 2000	18-23	English	Preferential looking	1st segment or vowel	✓
Höhle et al., 2006	19	German	Preferential looking	1st consonant	✓
White & Morgan, 2008	19	English	Preferential looking	1st consonant (1-3 features)	✓
Mani & Plunkett, 2011	18 24	English	Preferential looking	vowels (1-3 features)	✗ ✓

Why pupillometry?

- Preferential looking
  - Two referents are needed to induce a selection process based on how auditory and visual information match or mismatch
  - Referent for the distractor is theoretically not of interest but may influence the results
- EEG & pupillometry
  - Only one picture is shown:
the influence of finding a referent or lexical selection/competition is avoided
> reduction of task demands
- Pupillometry vs. EEG
  - Easier to administer than EEG
  - Good temporal resolution (50-60 Hz), not as good as EEG
  - Pupillary changes are slower than EEG waves

Method & Participants

Method

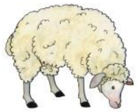
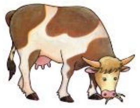
- Materials from Höhle et al., 2006 (preferential looking)
  - Pictures slightly adjusted
- Apparatus
  - Tobii 1750 (50 Hz)

Participants

- Children (N=25)
  - Age range: 29-31 months
  - 12 girls, 13 boys
- Adults (N=28)
  - Mean age: 24 years (18-38)
  - 20 women, 8 men

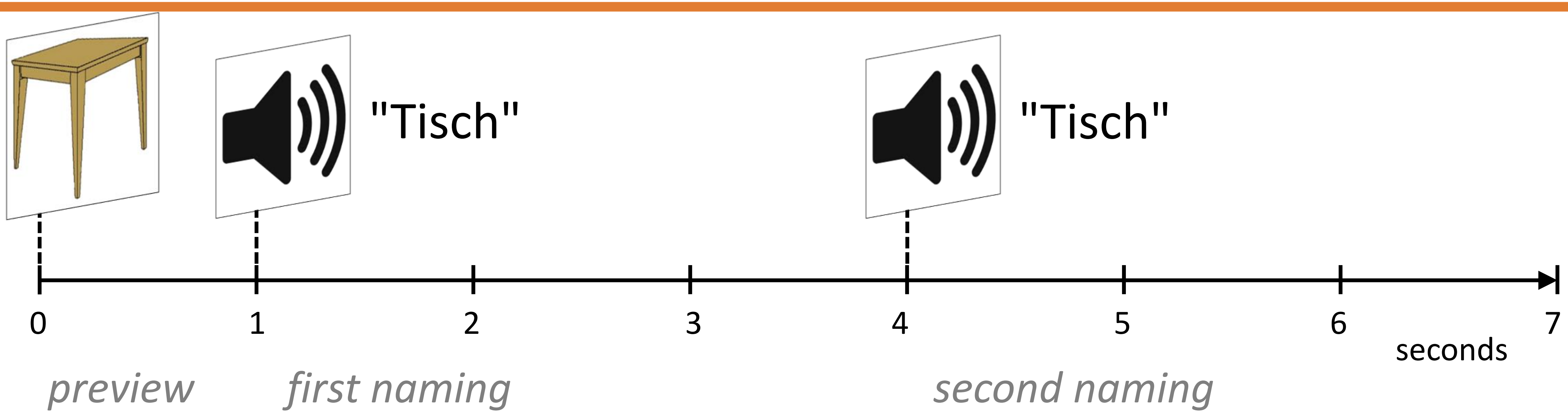
Fritzsche & Höhle (2015). Phonological and lexical mismatch detection in 30-month-olds and adults measured by pupillometry. *ICPhS.*

Stimulus design: Experimental items

Picture	Correct	Mispronunciation	Unrelated	
			Word	Nonword
	Tisch	Kisch	Kamm	Tamm
	Kamm	Tamm	Tisch	Kisch
	Po	Ko	Schaf	Saaf
	Schaf	Saaf	Po	Ko
	Kuh	Puh	Fisch	Sisch
	Fisch	Sisch	Kuh	Puh

Fillers	
	Bett
	Huhn
	Reh
	Maus

Time course of a trial



- No inter-stimulus interval, after 4 trials an attention-getting stimulus
- 3 blocks of 10 items (6 test items, 4 fillers)
- Combined with another study that was unrelated to this

Predictions

- Larger pupils for mispronunciations vs. correct labels
  - Discovering the relation between a mispronounced word and a picture requires more effort than for correct labels
    (reconstructing the correct phonological form or accessing the matching lexical entry)
- Larger pupils for unrelated words vs. correct labels
- Differences between unrelated words and non words

Data Management

(1) Inclusion of participants who saw all trials

(2) Replacement of missing data
  - Linear interpolation for missing data of max. 400 ms (blinks)
  - Exclusion of trials with more than 400 ms data missing
  - Trials with less than 50% of eye-tracking data were removed

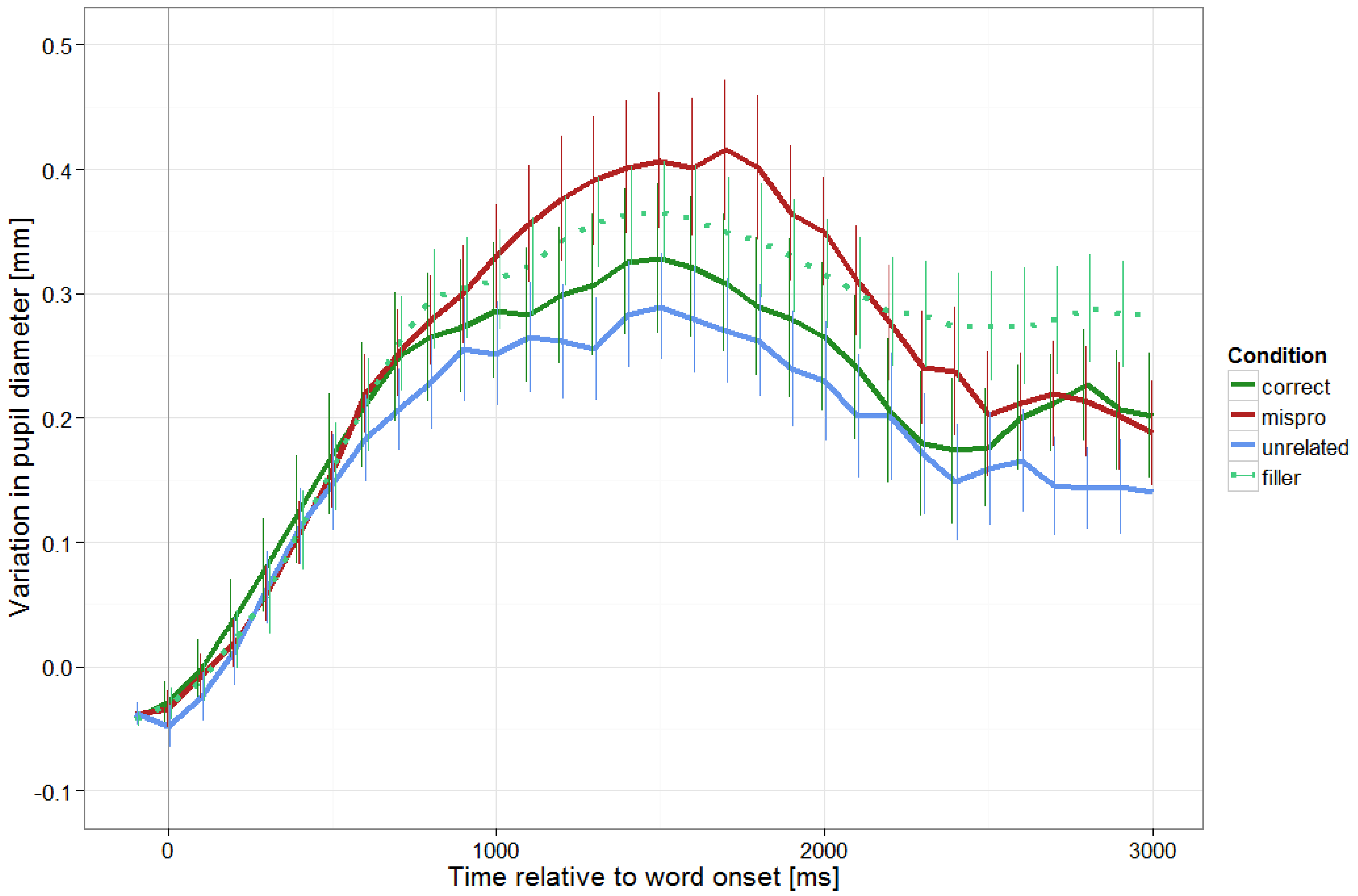
(3) Averaging both pupil size values

(4) Baseline adjustment
  - Baseline of 500 ms before onset of the word
  - Calculation of baseline-corrected pupil change measure
  - Removal of trials without baseline data

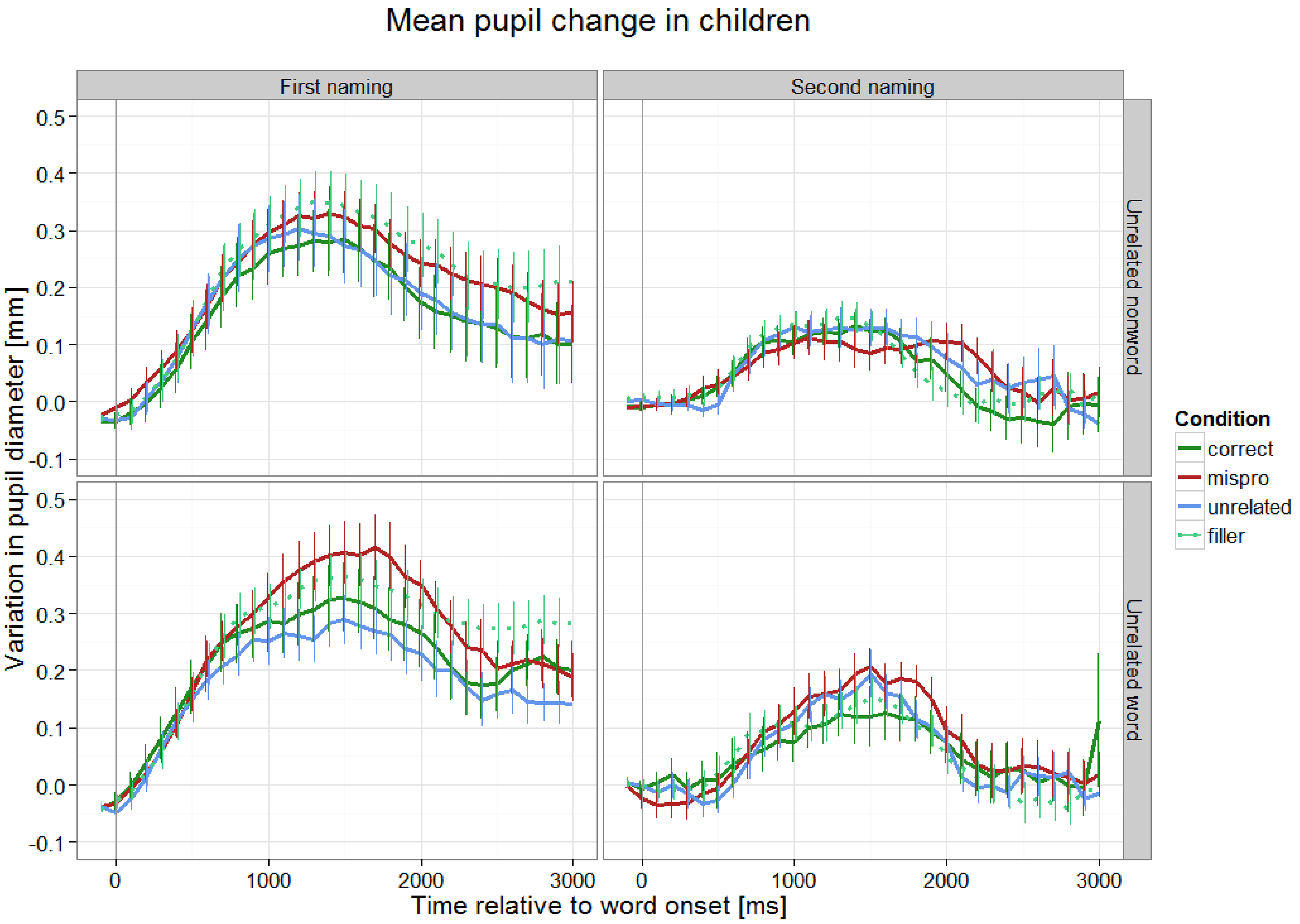
- Mean no. of trials per condition (after removing data)
  - Children: 4.8–5.2 (of 6)
  - Adults: 5.6–5.8

Results: Children 1

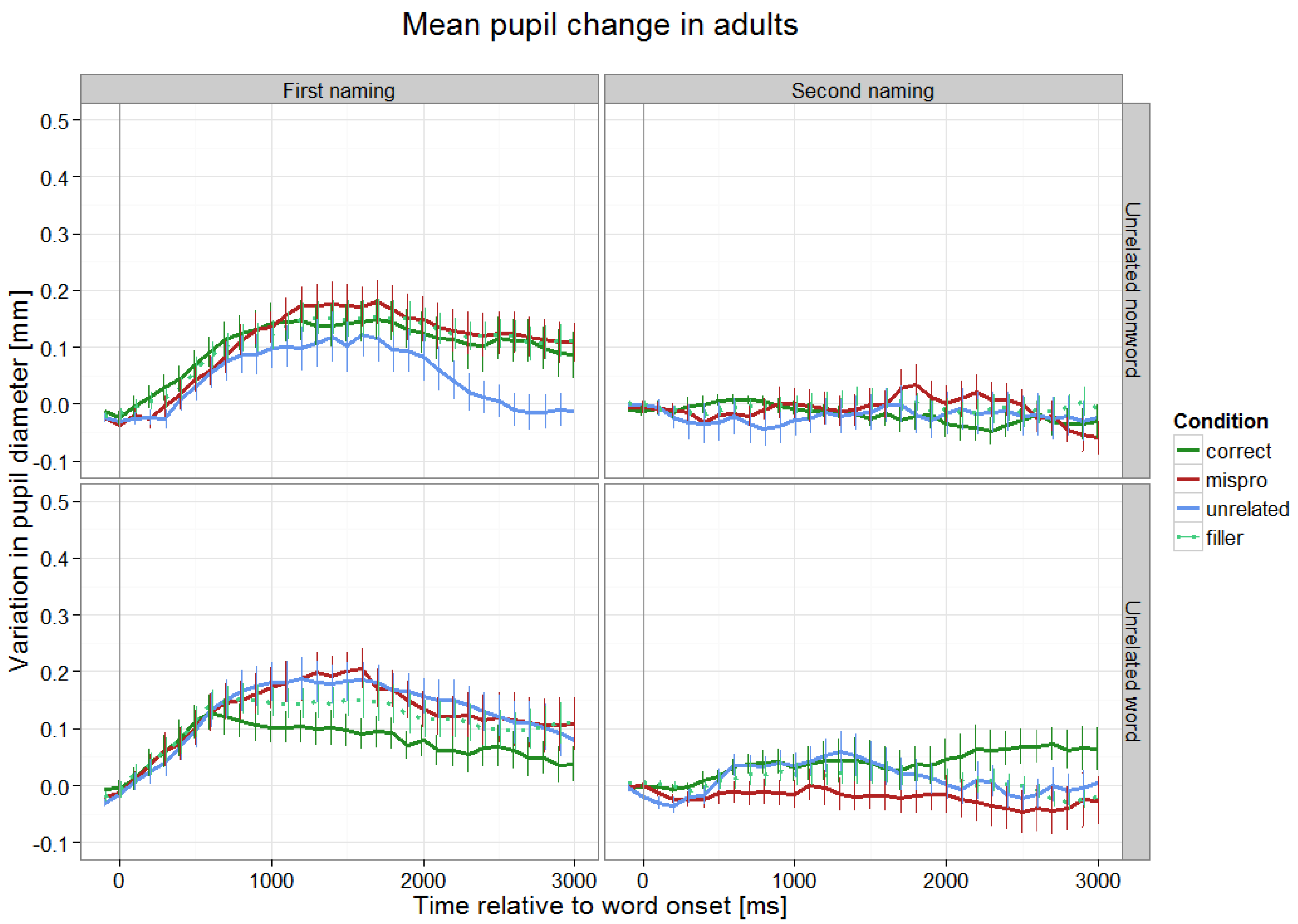
Mean pupil change in children after first naming in the word group



Results: Children 2



Results: Adults



ANOVA: Significant effects

ANOVA

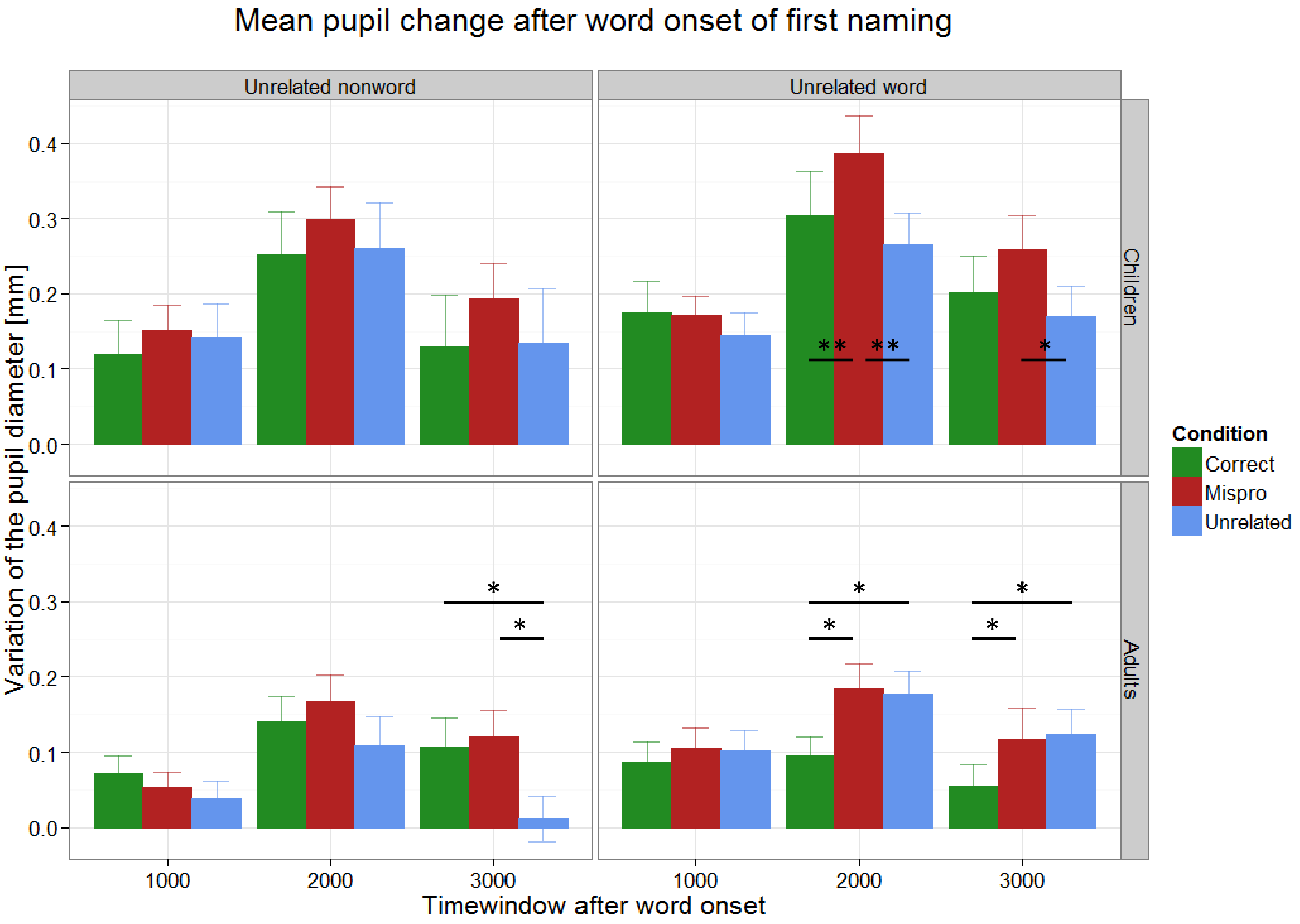
Factors: age, unrel, win, cond

- Age *p*<.01
- Cond *p*<.01
- Win *p*<.001
- Age x Win *p*<.01
- Cond x Win *p*<.001
- Age x Unrel x Cond *p*<.05

Single comparisons with *t*-tests

* p<.05

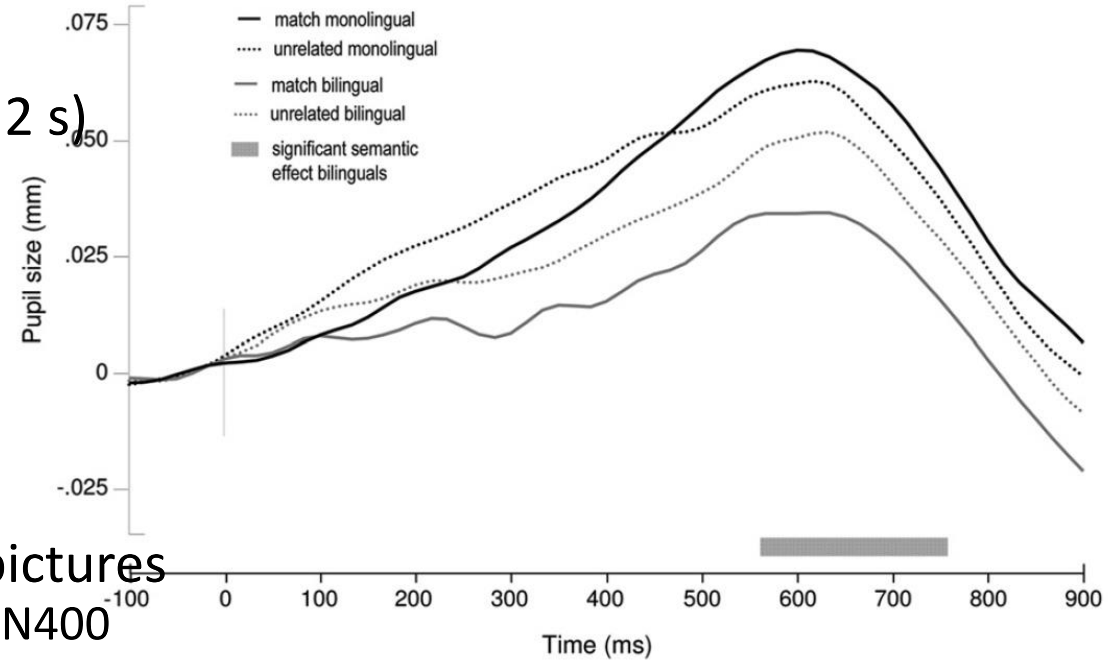
** p<.01



Interpretation

- Mispronunciation detection is visible in pupil responses after approx. 1000 ms of word onset
- This might indicate higher processing costs of reconstructing/or activating the correct form or integrating information
- Larger pupils do not seem to reflect a surprise for an unexpected word form because unrelated items (in children) did not lead to this response
- In the presence of a non word condition makes a differences in adults (but not in children
  - Here the effect is significant later, perhaps the effort to process correct and mispronounced labels (=words) seems to be higher (relative to the non words)

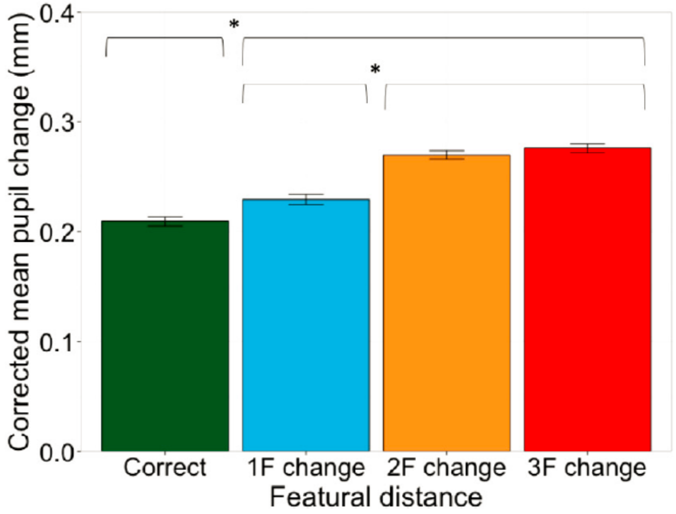
Audio-visual word (mis)match (Kuipers & Thierry, 2013)

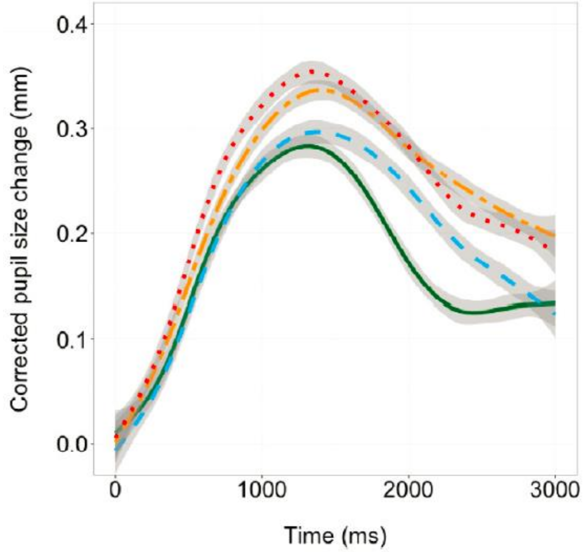


- Word – Picture pairs
  - Presentation order: word, 100 ms silence, image (1.2 s)
  - No task
  - 2 conditions: matching or non-matching pictures
  - 13 bilingual & 13 monolingual children (mean age: 31 months) + 7 drop outs
  - Tobii X60 (60Hz) + EEG
- Results
  - Bilinguals: larger pupils for unrelated vs. matching pictures
    - Negative correlation with N400: larger pupil ~ smaller N400
  - Monolinguals no difference in pupil measures
    - Positive correlation with N400: larger pupil ~ larger N400
- Interpretation
  - Pupil size = attention (more attention to unexpected stimuli)
  - More efficient stimulus processing in bilinguals

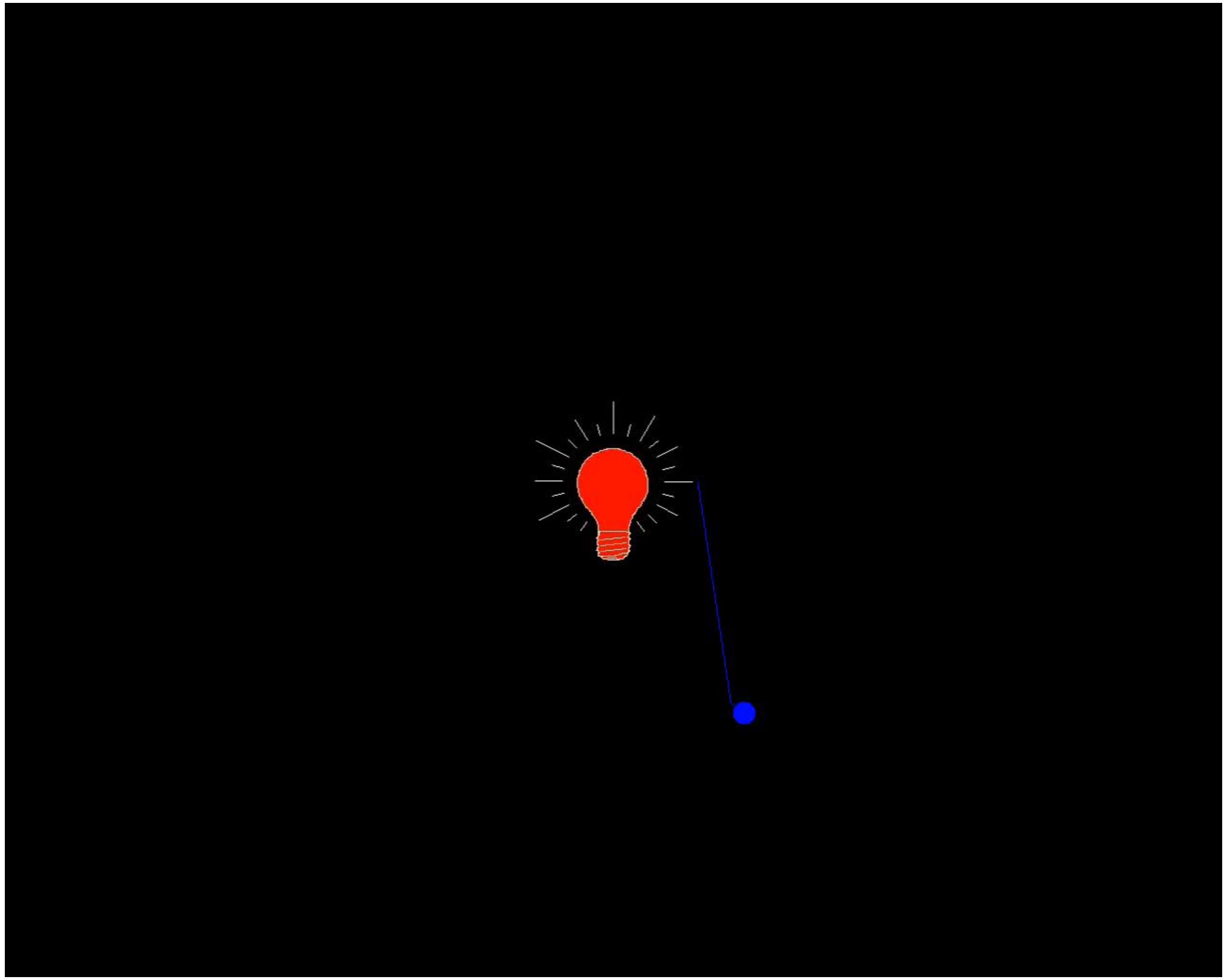
Mispronunciation detection (Tamási et al., 2017)

- Picture – Word pairs
  - Presentation order: image (1 s), then word
  - No task
  - 4 conditions: correct pronunciations + 3 mismatches (number of phonological features varied: e.g. ***baby*** – ***daby*** – ***faby*** – ***shaby***)
  - 20 experimental trials +20 fillers, 20 from another study, 35 correct items (no items were repeated!)
  - 43 monolingual children (mean age: 30 months) + 5 drop outs
  - Tobii 1750 (50Hz)
- Results
  - Gradient increase of pupil size with "larger" mispronunciations
- Interpretation
  - Pupil size = cognitive effort to establish a link between stimulus and lexical representation; the pupil response is not completely graded
- Follow-up: Tamási et al. (2019)
  - Implementation as a preferential looking study
  - Same results, target looking proportions is inversely related to pupil size





Gaze replay



Practical issues

Why pupillometry?

- What is the age group?
- What is the research question?
- What are the stimuli
  - Visual or audio only
  - Audio-visual
  - Single words, phrases, sentences
- What is the task or is there one at all?
- Is pupil size the primary dependent variable?
  - Only pupil size
    - For previously unexplored phenomena:
      Add a condition for which pupil size effects have been reported
  - Pupil size in addition to other measures (gaze data, responses, EEG, etc.)

Paradigms

- Pupillometry has been done with a variety of eye-tracking/testing paradigms:
  - Violation of Expectation
  - Single Screen Fixation
  - (Intermodal) Preferential Looking / Picture Selection
  - Habituation/Familiarisation procedures
  - Anticipatory Eye Movements
  - Reading
- A visual stimulus is not required, but for infants and children a fixation cross is too boring
- Complex scenes (Visual World Paradigm) or video clips are *not* recommended
- Design: If possible vary conditions *within* participants

Task

- Passive participation (watching and/or listening)
  - Depending on the research question this might be suitable but can get boring
  - It needs to made sure that the information is processed to obtain processing effects (this seems to be more relevant to pupillometry than to eye tracking / gaze measures), especially if non-reflexive processing effects are investigated
- Overt tasks requiring some kind of response, i.e. answers, judgements, button presses, etc.
  - Helps in engaging in the task (avoid boredom) and provides additional information
  - Might affect pupil size:
    - Response preparation is likely to increase and prolong pupil size (Winn et al., 2018, p. 7)
    - Difficult task > pupil dilation
    - Pressure/stress/emotions will affect pupil size

Luminance

- Pupillary light reflex (initial constriction) is much bigger and masks cognitive effects/TEPRs

💣Control for

  - Luminance of stimuli
  - Different colours of the same luminosity are perceived differently (Corney et al., 2009)
    - Helmholtz-Kohlrausch effect:
      Red and blue appear brighter than
      equiluminant yellow and green
  - Lighting of room
    - Natural light varies > challenge for testing not in the lab

- Choosing a good baseline window might reduce or even eliminate the effects

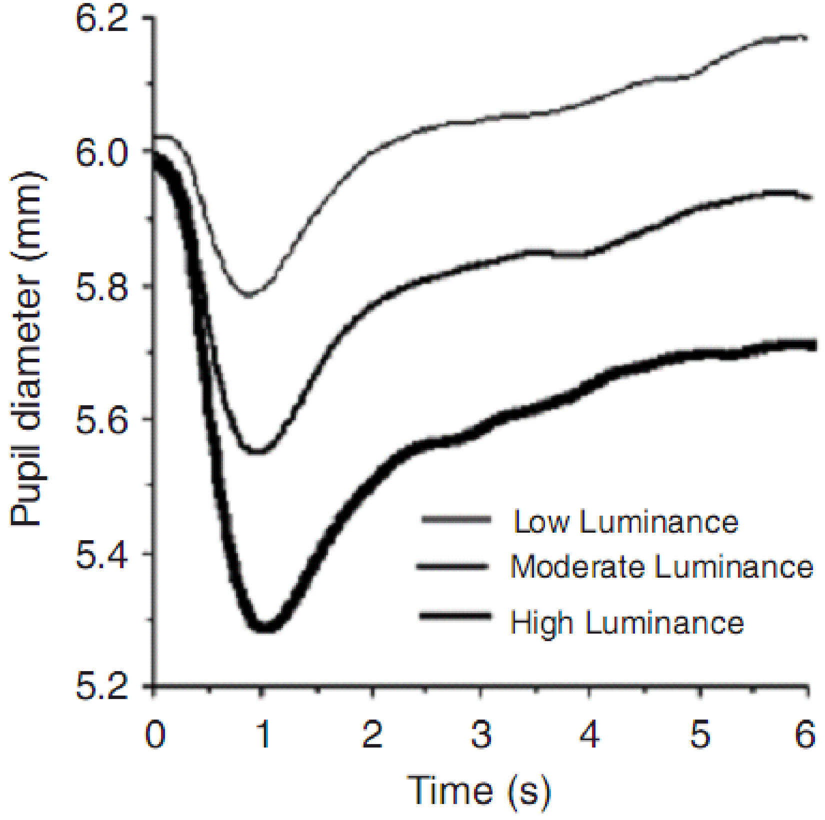


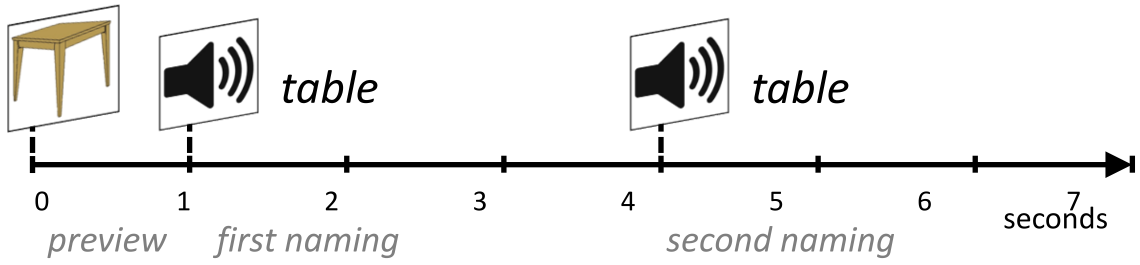
Image source: Bradley et al. (2008, p. 603)

Stimuli

- Visual stimuli
  - Make sure your expected effects can not be explained by differences in luminance (this is often the first question of a reviewer)
    - If possible: Use the same images for different conditions
    - Adjust luminance levels
  - Image size should be as small as possible
    - Reduces eye movements and thereby gaze position effects on pupil size measurement
    - Reduces effects of luminance and colour in different parts of the image
- Number of trials
  - Power analysis (interacts with number of participants)
  - Winn et al. (2018) recommend 16-18 “good” trials per condition
  - Fatigue effects: will result in smaller pupil responses

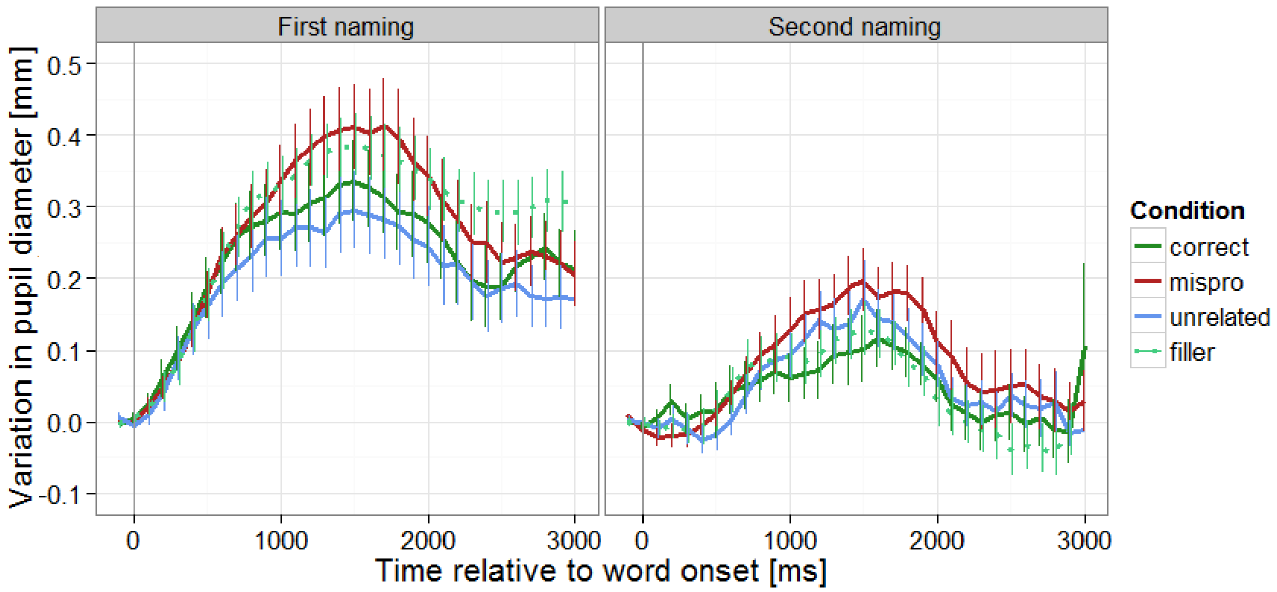
Stimulus repetitions

- Repetitions are likely to influence the effects
- *“Reliable habituation of the PDR across multiple presentations of task-irrelevant stimuli”* (adults for orienting responses, cited from Nieuwenhuis et al., 2011, p. 166)
- From a mispronunciation detection task with children and adults (Fritzsche & Höhle. 2015):



  - Effects disappeared in the second naming

Mean pupil change in children



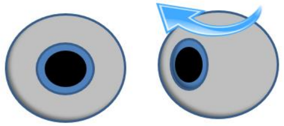
Timing

- Like in any eye-tracking study, timing is crucial!
- Pupillometry-specific considerations:
  - Time for the baseline (prior to the critical information)
  - Time for the pupillary effect (needs more time than gaze shifts to a target)
  - Time for the pupil to recover
  - 💣 It is not advisable to just add pupillometry to an existing design
- Timing largely depends on the phenomenon investigated, there are no recommendations that fit all situations

Devices

Devices: How is pupil size measured?

- Diameter
  - Units: mm (Tobii, SMI), pixels, arbitrary units (EyeLink)
  - Horizontal, vertical or average diameter?
  - Left eye, right eye, averaged?
- Area
  - Units: pixels or arbitrary units (EyeLink, ranges between 100 and 1000)
- Pupil size is affected by gaze position
  - Up to 10% (EyeLink 1000 User Manual 1.5.0, p. 95)
  - Tobii claims (info at a Tobii workshop) that TobiiStudio uses a 3D model of the eye to estimate pupil size (which should reduce position effects)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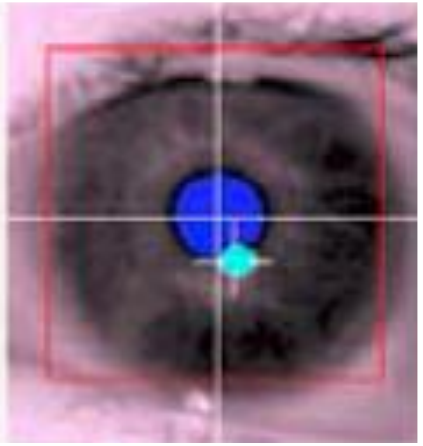


Image source: EyeLink 1000 User Manual 1.5.0, p. 23

💣 "Arbitrary" really means that: it is specific and unique to each participant (depending on the calibration) and therefore not comparable

* Source: https://www.sr-research.com/eye-tracking-blog/background/pupillometry-research/

Measures

- Mean pupil dilation
  - Average pupil size in a specified time window
  - Choice of window is crucial
- Peak dilation
  - Amplitude: maximum dilation after a critical time point
  - Latency: time of max. peak dilation
- Pupil size dynamics (changes)
  - Linear: Slope of the change in a specified time window
    - Example in Engelhardt et al. (2010, p. 642)
  - Analysis of the curves that describe the pupil size changes
    - Growth curve analysis
    - Functional data analysis:
      Sylvain Sirois: https://oraprdnt.uqtr.uquebec.ca/pls/public/gscw031?owa_no_site=314&owa_no_fiche=3
    - Generalised Additive Mixed Models (GAMMs): van Rij et al. (2019)

Data processing steps

Pipeline (inspired from: Kret & Sjak-Shie, 2019, Mathôt et al., 2018)

1. **Preparing** the raw output for processing
   - How are missing data marked? (e.g. Tobii 1750: -1, SMI: 0), recommendation: convert them to 'NaN'
   - Convert to a readable format (e.g. edf files from EyeLink to txt files)
2. **Cleaning** the raw data to extract the valid samples subset
   - Outlier and artifact removal
   - Check/correct gaze position artifacts
   - Quantify & document corrections and missing data
3. **Up-sampling** and **smoothing** the valid samples
   - Averaging both eyes (if available and desired)
   - Interpolation of missing data
   - Smoothing/filtering/up-sampling
4. **Splitting** the data into the relevant segments
   - Based the relevant timepoints and windows
5. **Baseline** calculation

6. **Analysis**

Data management: Missing data

- Keep the full (continuous) recording
- Unlike gaze data, pupillometry data can be recovered

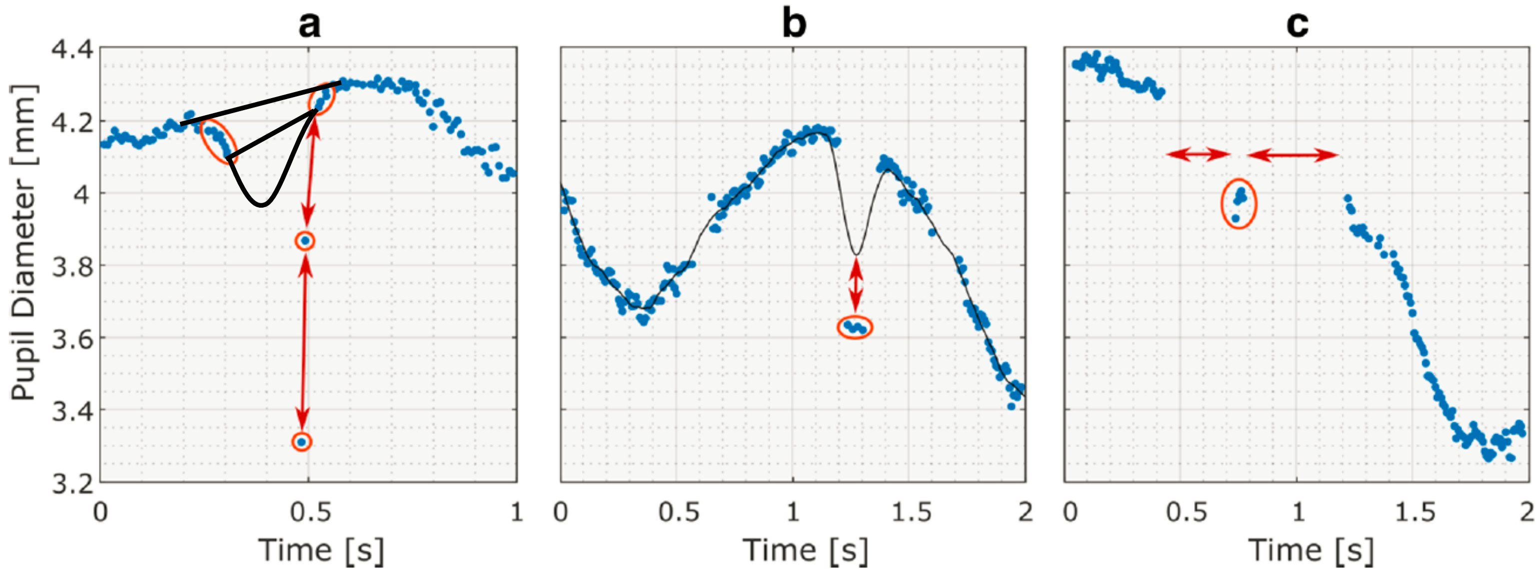


Image source: Kret & Sjak-Shie (2019, p. 1338)

a. **Blink**
b. **Erroneous data points**
c. **Spurious samples**

- Short missing stretches (from blinks ~250 ms) can be interpolated
- Interpolation procedures: linear, nonlinear (splines)
- Check that missing data/blinks do not vary systematically (with condition)

Data management: Baseline & Normalising

- The baseline ensures that the change is time-locked to a task/event
- Different ways
  - Subtractive baseline: Most commonly applied baseline
  - Divisive baseline (baseline + normalisation): This is sensitive to the baseline value, This may distort the effects, especially with large fluctuations in baseline values
  - Some analyses might not require a baseline (e.g. GAMMs, van Rij et al., 2019)

Subtractive baseline: data – baseline

Divisive baseline: $\frac{\text{data} - \text{baseline}}{\text{baseline}}$

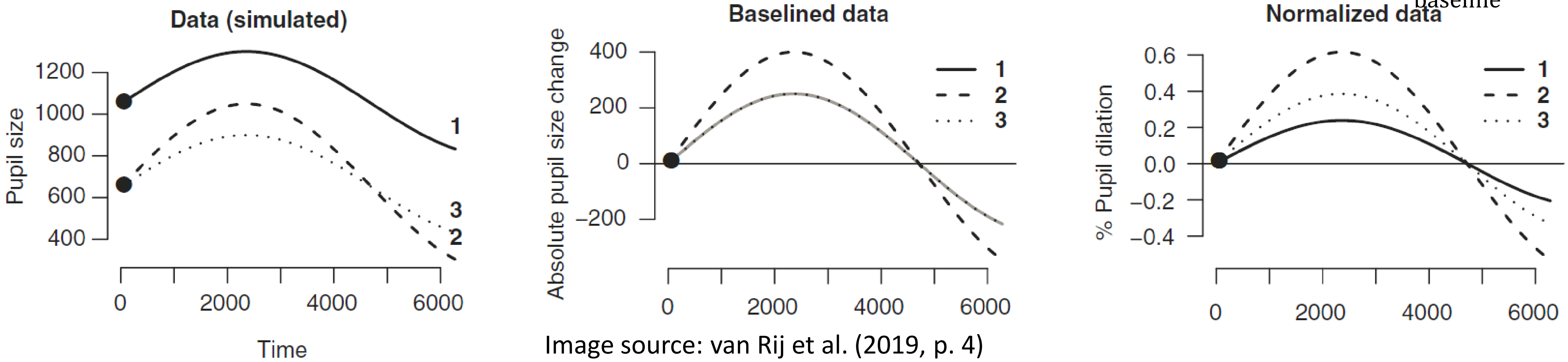


Image source: van Rij et al. (2019, p. 4)

Data management: Baseline size

- Baseline size should be related to
  - What is presented during the baseline (blank screen, fixation, other material)
  - Size of the analysis window
  - Duration of the effect
- Baselines sizes in studies
  - Up to 1000 ms (or longer9
  - Some prefer short baselines (Mathôt et al., 2018)

Analysis

- ANOVA
  - Hochman & Papeo (2014)
  - Wetzel et al. (2016)
- Linear mixed models (LME)
  - Hepach & Westermann (2013)
  - Tamási et al. (2017, 2019)
- Functional data analysis
  - Jackson & Sirois (2009)
- Generalised Additive Mixed Models (GAMMs)
  - van Rij et al. (2019)
  - Porretta & Tucker (2019)
- Growth Curve Analysis (GCA)
  - Wagner et al. (2019)
- Principal Components Analysis (PCA)
  - Wetzel et al. (2020)
- Permutation analysis
  - Csink et al. (2021)

Software packages & online resources

- PupilPre: https://cran.r-project.org/web/packages/PupilPre/index.html
  - Kyröläinen, Porretta, van Rij, & Järvikivi (2020)
  - Pipeline for preprocessing data collected with SR Research EyeLink eye trackers
- PupillometryR: https://cran.r-project.org/web/packages/PupillometryR/index.html
  - Forbes & Robinson (2020)
  - Clean, prepare, plot, and run basic analyses on pupillometry experiments for all eye tracker types
  - Presentation from the CLEAR workshop 2019 in Potsdam: https://www.uni-potsdam.de/wild2019/assets/Forbes_PupillometryR.html
- CHAP: https://in.bgu.ac.il/en/Labs/CNL/chap/default.aspx
  - Hershman, Henik, & Cohen (2019)
  - Processing and analysing pupillometry data for different eye trackers (EyeLink, Tobii, ASL, Eye Tribe)
- Paper and scripts: https://github.com/smathot/baseline-pupil-size-study
  - Mathôt, Fabius, van Heusden, & Van der Stigchel (2018)
  - Preprocessing and baseline-correction of eye-tracking data
- Paper and scripts: https://github.com/ElioS-S/pupil-size
  - Kret & Sjak-Shie (2019)
  - Preprocessing pupil size data for all eye tracker types
- Info: Eye tracking for pupillometry - SR Research
  https://www.sr-research.com/eye-tracking-blog/background/pupillometry-research/

Literature suggestions with links (articles)

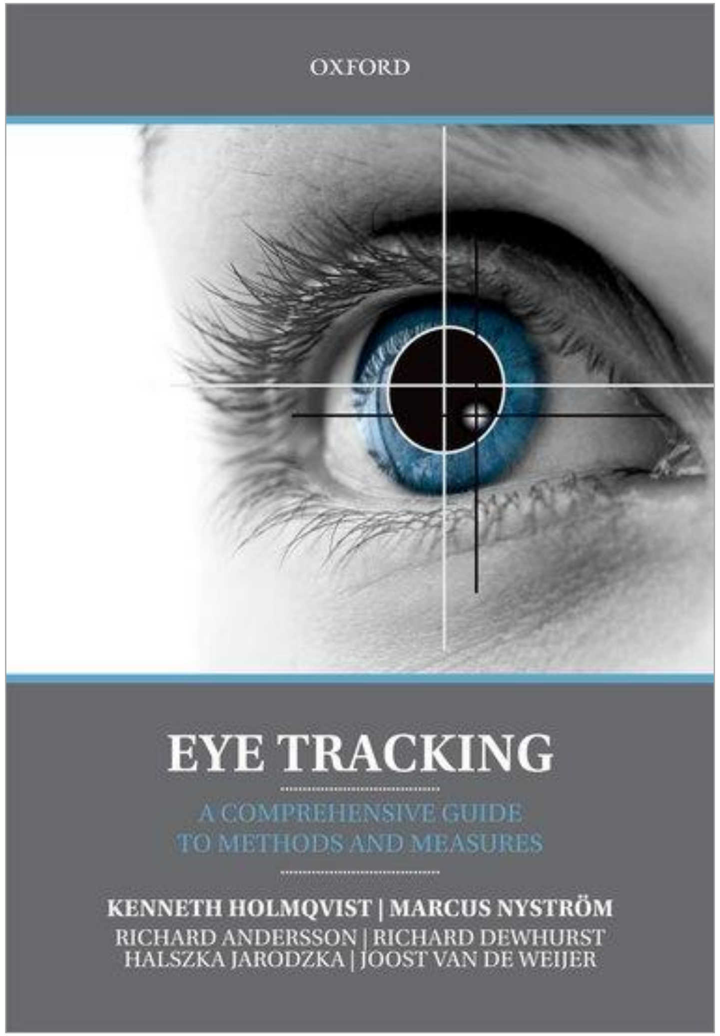
- [Beatty & Lucero-Wagoner (2000) The pupillary system]
  - A bit older but very nice overview and starting point
- Hepach & Westermann (2016) Pupillometry in infancy research
  - Good intro for pupillometry with infants
- Winn et al. (2018) Best practices and advice for using pupillometry to measure listening effort
  - Very practical and detailed guide, focused on auditory studies, contains information for testing children
- Nieuwenhuis et al. (2011) P3 and autonomic components of the orienting response
  - Focus is *not* on pupillometry but contains lots of information about pupil responses and their relation to different tasks and other measures (ERP components and skin conductance), also looks at habituation effects
- Sirois & Brisson (2014) Pupillometry
  - Nice intro and some information on data processing and analysis (adults)
- Laeng et al. (2012) Pupillometry
  - Good overview, relation to brain activity, a section on development
- Zekveld et al. (2018) The pupil dilation response to auditory stimuli
  - Comprehensive review of 146 studies on auditory processing, some with children, evaluation of the method
- Schmidtke (2018) Pupillometry in linguistic research
  - Reviews papers with linguistic research using pupillometry (adults and a few child studies)

Literature suggestion (book)

Extremely comprehensive, thorough and detailed book on all kinds of eye-tracking methods and measures (but just a few pages on pupillometry)

“Choice of methods and measures should be tailored to your research question and experimental design” (p. 464)

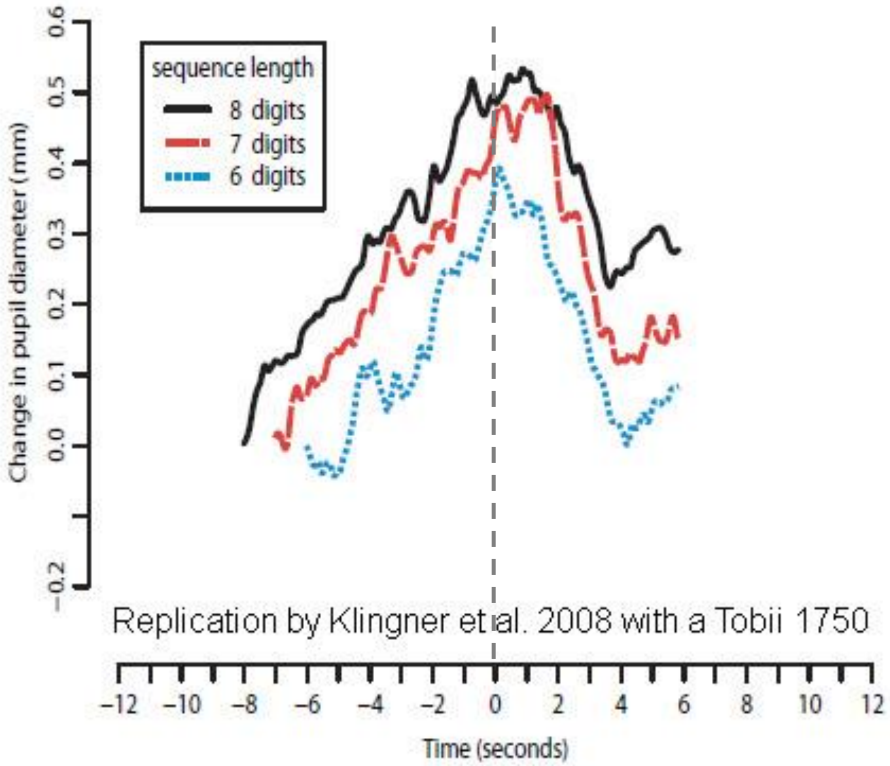
Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., & van de Weijer, J. (2011). Eye Tracking: A Comprehensive Guide to Methods and Measures. Oxford University Press.



More studies

Memory load (Kahneman & Beatty, 1966)

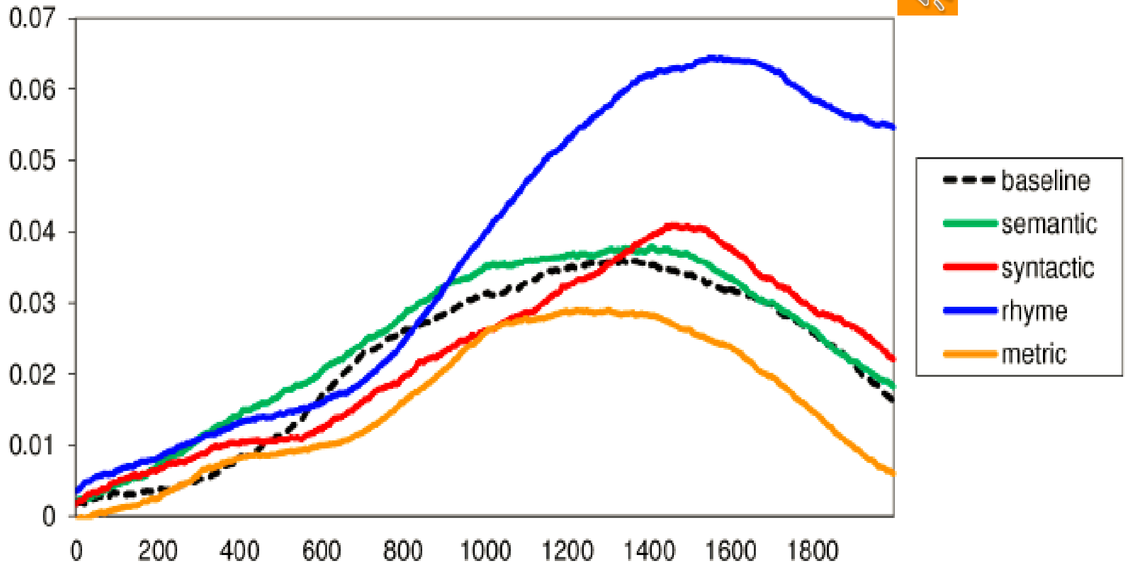
- Digit memory task (3-7 digits)
  - Remembering digits
    store one digit/second, then recall 1 per second
  - 5 adult participants
  - Original: camera, replication Tobii 1750 (50Hz)
- Results
  - Memorisation: Dilation
  - Recall: Constriction
- Interpretation
  - Pupil size = memory load
  - Practise effects: reduction in repetition



Expectancy violations (Scheepers et al., 2013)

- Listening to Limericks while fixating a cross
  - Different limericks:
    18 without and 20 with violations
  - 40 adult participants
  - Head-mounted EyeLink II 500Hz
- Results
  - Larger pupils for violations of rhyme only
  - Additional offline task
    - All violations were detected
    - Rhyme violations were rated as most anomalous
- Interpretation
  - Conflict between expectation and input
  - Pupil size = emotional arousal,
    NOT: processing load or surprisal

There once was a dashing young mouse
Who was bored with only one spouse.
"I think one more wife,
Would add spice to my life,
And be nicer to have round the house."
And be nicer to have round the blouse."
And be nicer to have the round house."
And be nicer to have round the flat."
And be nicer to have around the house."

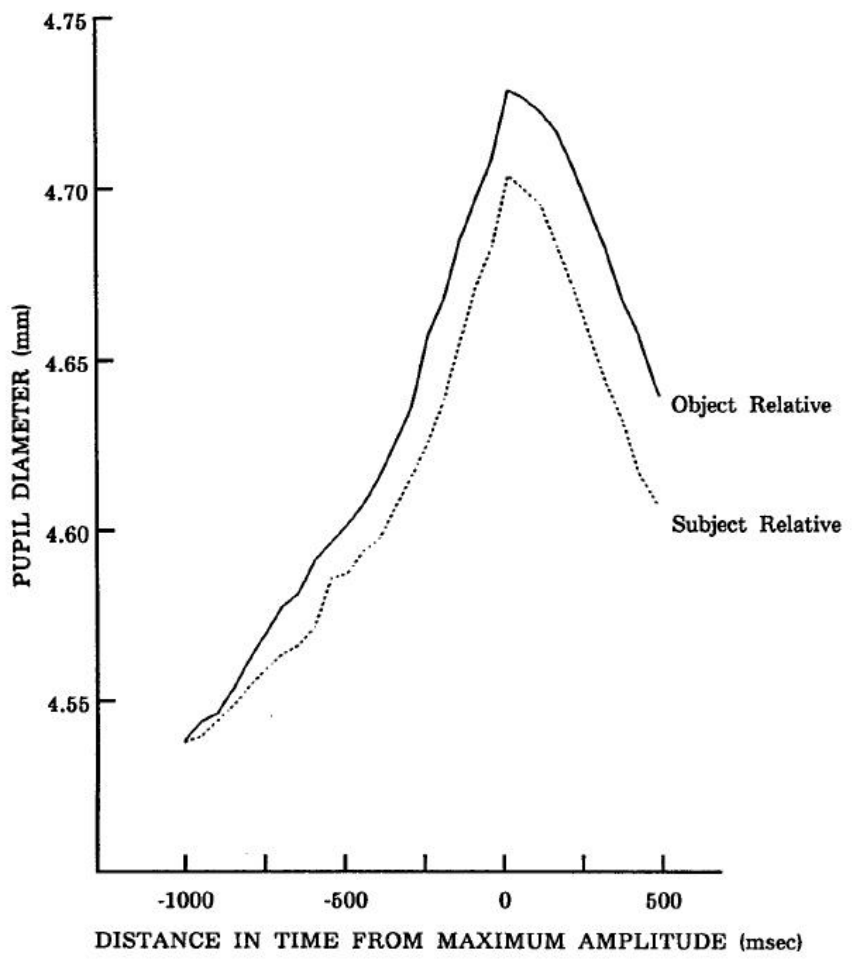


Syntactic complexity (Just & Carpenter, 1993)

- Reading subject and object relatives
  - Exp.1: SRC/ORC, 36 trials + 24 fillers

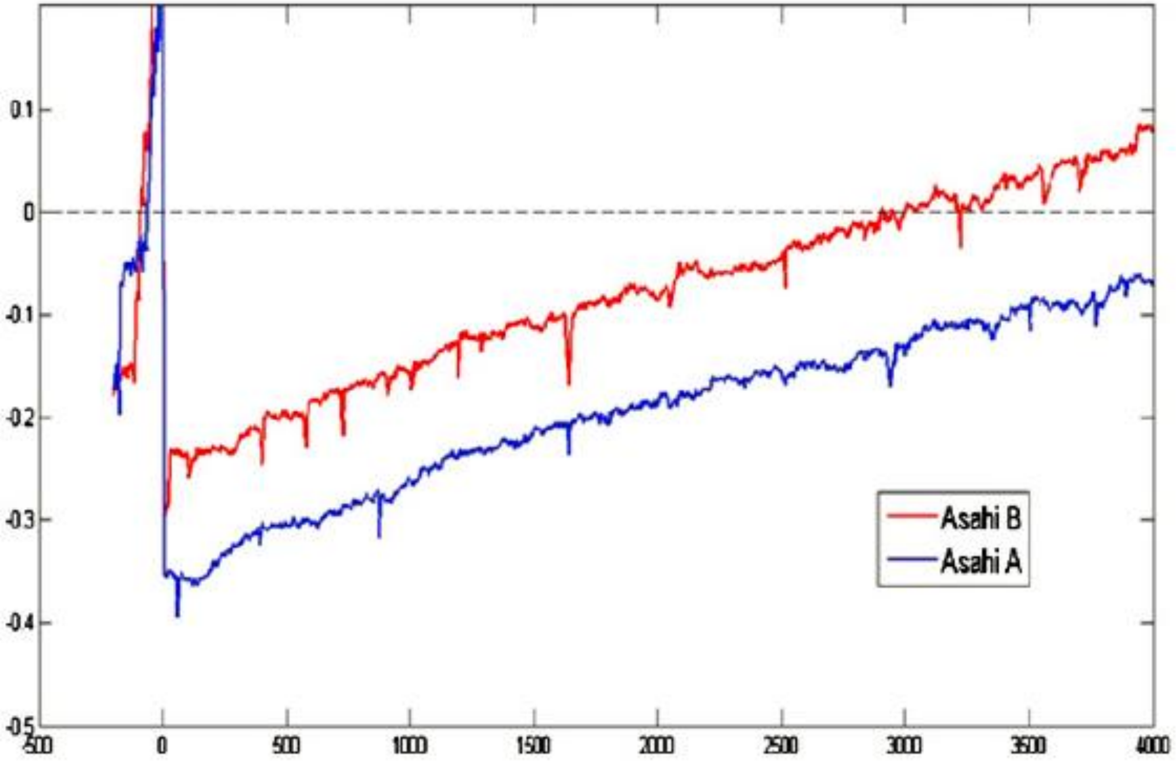
The reporter that ... attacked the senator / the senator attacked ... admitted the error publicly after the hearing.

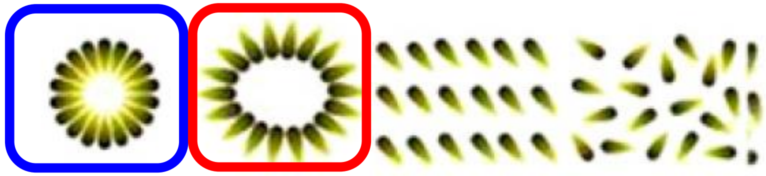
  - 35 adult participants
  - ISCAN RK-426 (60Hz)
- Results
  - Larger pupil size for ORC vs. SRC
  - Later peak in ORC vs. SRC (116 ms)
  - Pupil size is proportional to reading time and error rate (of probe questions)
- Interpretation
  - Processing intensity



Brightness illusions (Laeng & Endestad, 2012)

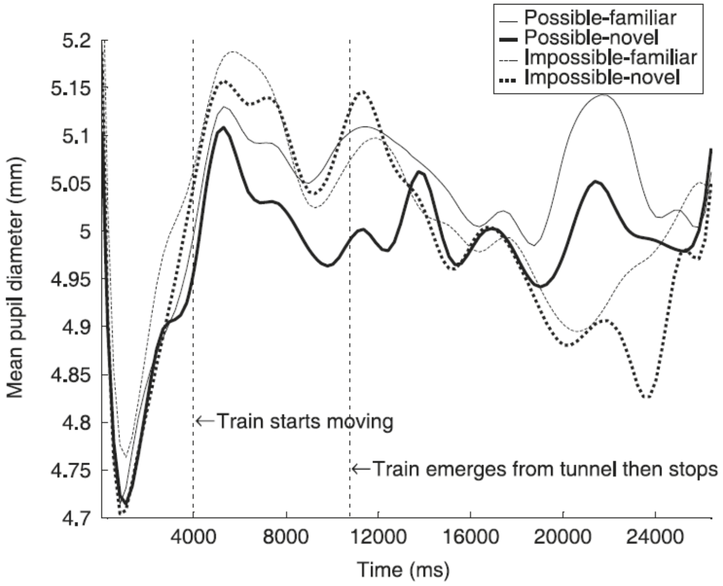
- Visual illusions with equiluminant images
  - Looking at images (32 trials) without a task: 500 ms blank screen, 4 s image
  - 15 adult participants (students)
  - Remote SMI eye tracker (500Hz)
- Results
  - Brightness illusions: Constriction
- Interpretation
  - The pupillary light reflex is influenced by cortical processing (see also Mathôt, 2018, p. 7), i.e. interpretation not mere perception





Violation of expectation (Jackson & Sirois, 2009)

- Impossible events: Change of colour of the train re-emerging
  - Videos of a train going through a tunnel, familiarisation with 2 colours
  - Familiarisation (6 videos) : 2 colours
  - Test (3 videos): impossible-novel, possible-novel, impossible-familiar, (possible-familiar = last familiarisation trial)
  - 21 children (mean age: 8.5 months) + 6 drop outs
  - Tobii x50 (50Hz) + looking times (LTs)
- Results
  - Larger dilations for impossible vs. possible only with novel
  - LTs: longer impossible vs. possible for novel (reversed for familiar)
  - No correlation of pupil size and LTs
- Interpretation
  - Pupil size = violation of expectation
  - Pupil size (dynamic) might be more sensitive than LTs (cumulative)



Violation of expectation (Gredebäck & Melinder, 2010)

- Rationality of action goals
  - 6 videos of a feeding event
  - Between-subject design: rational/irrational
  - 2 age groups: 6 and 12 months
  - 56 infants (14 in each age/condition) + 6 drop outs
  - Tobii 1750 (50Hz) + eye gaze (anticipations)
- Results
  - Pupil size increases after irrational goal (hand) and decreases after rational goal (both age groups)
  - Long analysis window (4 s) and "late" baseline (after spoon reaches goal)
  - Follow-up control condition
- Interpretation
  - Pupil size = violation of expectation in action goal interpretation, NOT a novelty response

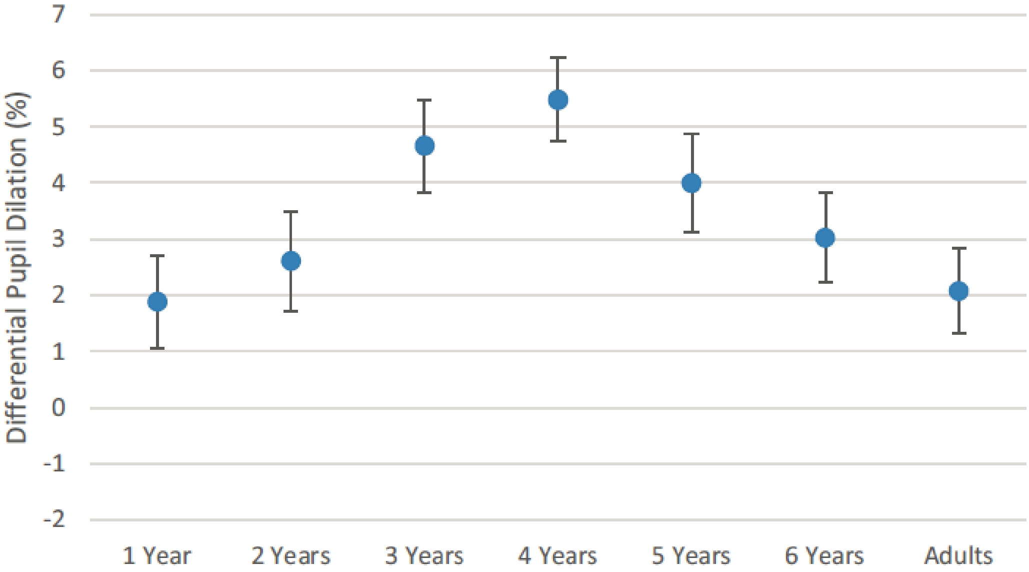
Rational **Irrational**

Violation of expectation (Krüger et al., 2019)

- Animals & animal sounds
  - Presentation: image (2 s), then sound (3 s), silence (3 s)
  - No task
  - 2 conditions: animal/sound match or mismatch
  - 20 trials (repetitions of 4 animals), 8 trials are relevant
    ~ 4 min in total
  - 279 participants in 7 age groups
  - Tobii T120 (60Hz)
- Results
  - Larger dilations for mismatches vs. matches
- Interpretation
  - Pupil size = violation of expectation
  - Suits all age groups
    while looking time measures do not

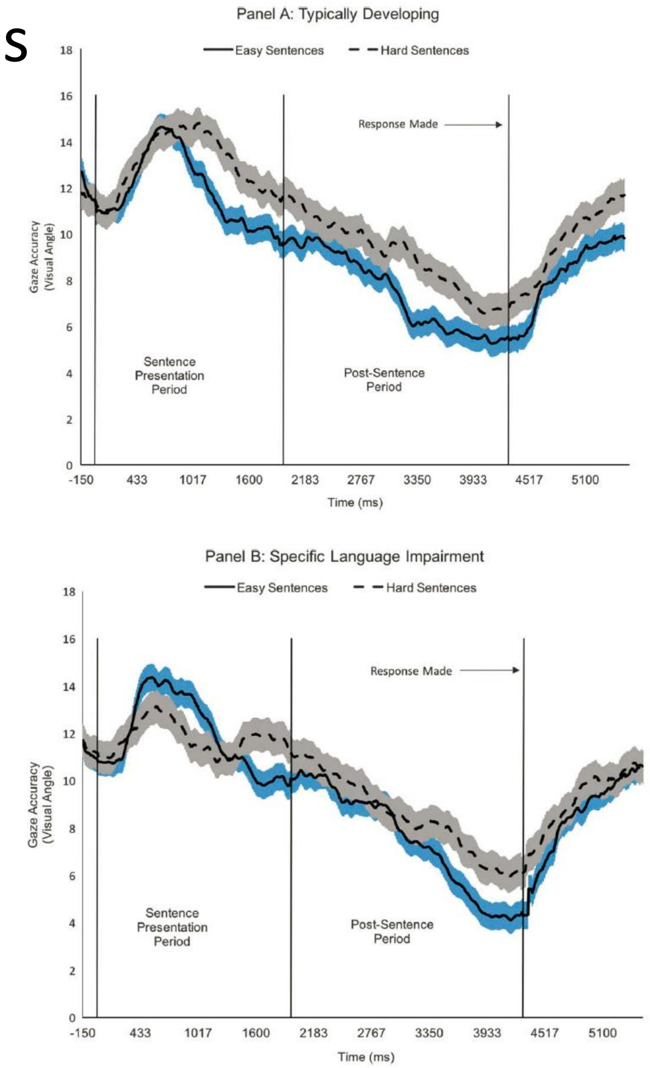
Cat barking

Cow meowing



Sentence comprehension (Lum et al., 2017)

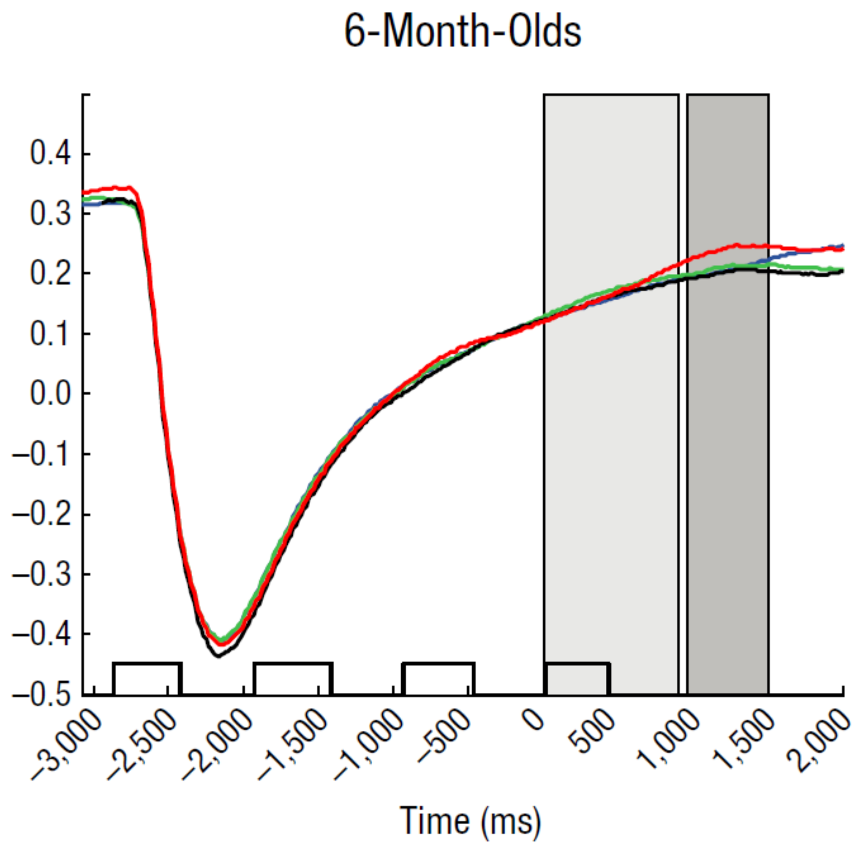
- Sentence - picture matching task with easy and hard sentences
  - 12 easy (SV) and 12 hard (SVO) sentences
  - Presentation of 4 images (target, 3 foils), selection by mouse click
  - 36 children (18 TD and 18 with SLI)
  - Tobii T120 (120Hz) + eye gaze + picture selection responses
- Results
  - TD: larger pupils for hard vs. easy sentences
  - SLI: no differences in pupil size
  - Pupil size of SLI children = TD children for hard sentences
  - The effects align with the looking proportion
- Interpretation
  - Pupil size = attention allocation
  - SLI children need more attention to process the sentences



Speech categorisation (Hochmann & Papeo, 2014, Exp.2)

- Auditory oddball paradigm
  - Visual stimulus: animated cartoon
  - Auditory stimulus: sequences of 4 words
  - 100 trials (at least 24 for inclusion in the analysis)
  - 16 3-month olds and 14 six-month olds + 21 dropouts
  - Tobii T60 (60Hz)
- Result
  - Larger pupil for deviant vs. standard in 6mo 1000–1500 ms after onset of the 4th syllable
- Interpretation
  - Pupil size = expectation violation
  - Infants at 6 but not 3 months form categories based on the first syllable and build expectations

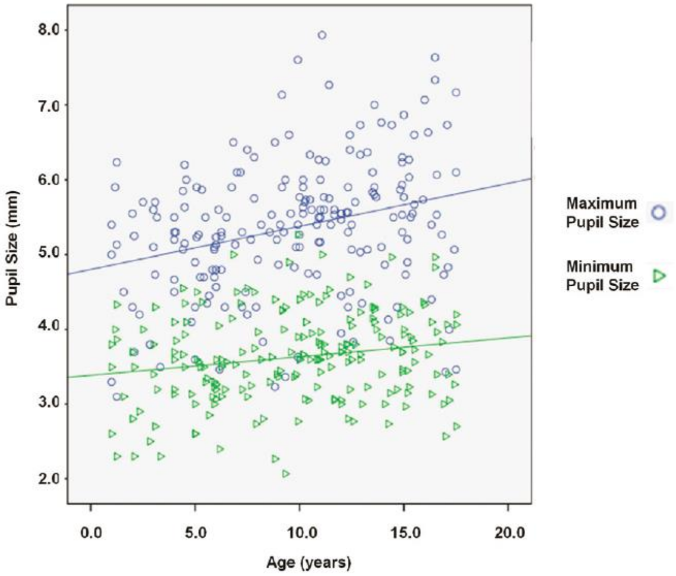
Standard (75%): ***bead bad boat boo***
Deviant (25%): ***bead bad boat due***

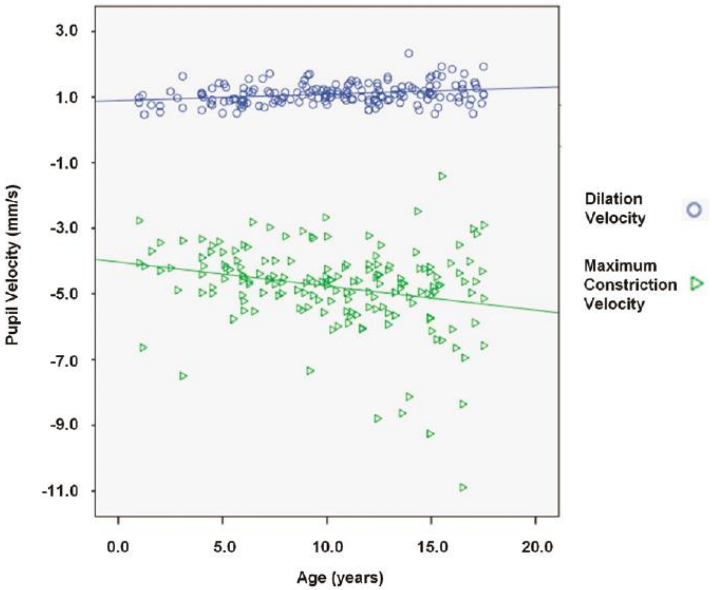


More slides

Pupil size in development (Brown et al., 2015)

- Pupil size and change velocity is stable across 1-18 years (201 participants)





- Weak correlation between age and min/max size was weak (r = .19/r = .29,), this correlates with the size of the eye (r ~ .8)
- No differences between males and females for any of the pupil parameters
- Pupil size larger in white than African Americans (max: 5.56 vs 4.97 mm; min: 3.74 vs 3.40 mm)

References

References – Basics & Overviews

Beatty, J., & Lucero-Wagoner, B. (2000). The pupillary system. In J. T. Cacioppo, L. G. Tassinary, & G. G. Berntson (Eds.), *Handbook of Psychophysiology* (2nd ed., pp. 142–162). Cambridge University Press. http://apps.usd.edu/coglab/schieber/docs/Beatty_Pupillary_System_.pdf

Brown, J. T., Connelly, M., Nickols, C., & Neville, K. A. (2015). Developmental changes of normal pupil size and reactivity in children. *Journal of Pediatric Ophthalmology and Strabismus, 52*(3), 147–151. https://doi.org/10.3928/01913913-20150317-11

Demberg, V., Kiagia, E., & Sayeed, A. (2013). The index of cognitive activity as a measure of linguistic processing. In M. Knauff, M. Pauen, N. Sebanz, & I. Wachsmuth (Eds.), *Cooperative Minds: Social Interaction and Group Dynamics. Proceedings of the 35th Annual Meeting of the Cognitive Science Society* (pp. 2148–2153). Cognitive Science Society.

Hepach, R., & Westermann, G. (2016). Pupillometry in infancy research. *Journal of Cognition and Development, 17*(3), 359–377. https://doi.org/10.1080/15248372.2015.1135801

Hess, E. (1975) . *The Tell-Tale Eye*. New York: Van Nostrand.

Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., & van de Weijer, J. (2011). *Eye Tracking: A Comprehensive Guide to Methods and Measures*. Oxford University Press.

Laeng, B., Sirois, S., & Gredebäck, G. (2012). Pupillometry: A window to the preconscious? *Perspectives on Psychological Science, 7*(1), 18–27. https://doi.org/10.1177/1745691611427305

Loewenfeld, I. E. (1993) *The Pupil: Anatomy, Physiology and Clinical Applications*. Iowa State University Press.

Mathôt, S. (2018). Pupillometry: Psychology, Physiology, and Function. *Journal of Cognition, 1*(1), 16. https://doi.org/10.5334/joc.18

Nieuwenhuis, S., De Geus, E. J. C., & Aston-Jones, G. (2011). The anatomical and functional relationship between the P3 and autonomic components of the orienting response. *Psychophysiology, 48*(2), 162–175 https://doi.org/10.1111/j.1469-8986.2010.01057.x

Schmidtke, J. (2018). Pupillometry in linguistic research: An introduction and review for second language researchers. *Studies in Second Language Acquisition, 40*(3), 529–549. https://doi.org/10.1017/S0272263117000195

Sirois, S., & Brisson, J. (2014). Pupillometry. *WIREs Cognitive Science, 5*(6), 679–692. https://doi.org/10.1002/wcs.1323

Thompson, H. S. (2005). Otto Lowenstein, Pioneer Pupillographer. *Journal of Neuro-Ophthalmology*, *25*(1), 44–49.

Winn, M. B., Wendt, D., Koelewijn, T., & Kuchinsky, S. E. (2018). Best practices and advice for using pupillometry to measure listening effort: An introduction for those who want to get started. *Trends in Hearing, 22*, 1–32. https://doi.org/10.1177/2331216518800869

Zekveld, A. A., Koelewijn, T., & Kramer, S. E. (2018). The pupil dilation response to auditory stimuli: Current state of knowledge. *Trends in Hearing, 22*, 1–25. https://doi.org/10.1177/2331216518777174

References – Studies

Beatty, J. (1982). Phasic not tonic pupillary responses vary with auditory vigilance performance. *Psychophysiology, 19*(2), 167–172. https://doi.org/10.1111/j.1469-8986.1982.tb02540.x

Beatty, J. (1988). Pupillometric signs of selective attention in man. In G. C. Galbraith, M. L. Kietzman, & E. Donchin (Eds.), *Neurophysiology and Psychophysiology: Experimental and Clinical Applications* (pp. 138–143). Lawrence Erlbaum Associates

Beatty, J., & Kahneman, D. (1966). Pupillary changes in two memory tasks. *Psychonomic Science, 5*, 371–372. https://doi.org/10.3758/BF03328444

Engelhardt, P. E., Ferreira, F., & Patsenko, E. G. (2010). Pupillometry reveals processing load during spoken language comprehension. *Quarterly Journal of Experimental Psychology, 63*(4), 639–645. https://doi.org/10.1080/17470210903469864

Fritzsche, T., & Höhle, B. (2015). Phonological and lexical mismatch detection in 30-month-olds and adults measured by pupillometry. In The Scottish Consortium for ICPhS 2015 (Ed.), *Proceedings of the 18th International Congress of Phonetic Sciences*. University of Glasgow. https://www.internationalphoneticassociation.org/icphs-proceedings/ICPhS2015/Papers/ICPHS0339.pdf

Gredebäck, G., & Melinder, A. (2010). Infants' understanding of everyday social interactions: A dual process account. *Cognition, 114*(2), 197–206. https://doi.org/10.1016/j.cognition.2009.09.004

Gutiérrez, R. S., & Shapiro, L. P. (2010). Measuring the time-course of sentence processing with pupillometry. Poster presented at the CUNY Conference on human sentence processing.

Hess, E. H., & Polt, J. M. (1964). Pupil size in relation to mental activity during simple problem-solving. *Science, 140*, 1190–1192. https://doi.org/10.1126/science.143.3611.1190

Hochmann, J.-R. (2013). Pupillometry in six-month-old infants. In S. Baiz, N. Goldman, & R. Hawkes (Eds.), *Proceedings of the 37th annual Boston University Conference on Language Development* (Vol. 1, pp. 160–164). Cascadilla Press.

Hochmann, J.-R., & Papeo, L. (2014). The invariance problem in infancy: A pupillometry study. *Psychological Science, 25*(11), 2038–2046. https://doi.org/10.1177/0956797614547918

Jackson, I., & Sirois, S. (2009). Infant cognition: Going full factorial with pupil dilation. *Developmental Science, 12*(4), 670–679. https://doi.org/10.1111/j.1467-7687.2008.00805.x

Just, M. A., & Carpenter, P. A. (1993). The intensity dimension of thought: Pupillometric indices of sentence processing. *Canadian Journal of Experimental Psychology, 47*(2), 310-339. https://doi.org/10.1037/h0078820

Kahneman, D., & Beatty, J. (1966). Pupil diameter and load on memory. *Science, 154*(3756), 1583–1585. https://doi.org/10.1126/science.154.3756.1583

Kahneman, D., & Beatty, J. (1967). Pupillary responses in a pitch-discrimination task. *Perception and Psychophysics, 2*, 101–105. https://doi.org/10.3758/BF03210302

Klingner, J., Kumar, R., & Hanrahan, P. (2008). Measuring the task-evoked pupillary response with a remote eye tracker. *Proceedings of the 2008 Symposium on Eye Tracking Research and Applications*, 69–72. http://graphics.stanford.edu/~klingner/publications/MeasuringPupillaryResponse.pdf

Krüger, M., Bartels, W., & Krist, H. (2019). Illuminating the dark ages: Pupil dilation as a measure of expectancy violation across the life span. *Child Development, 91*(6), 2221–2236. https://doi.org/10.1111/cdev.13354

Kuipers, J.-R., & Thierry, G. (2013). ERP-pupil size correlations reveal how bilingualism enhances cognitive flexibility. *Cortex, 49*(10), 2853–2860. https://doi.org/10.1016/j.cortex.2013.01.012

Laeng, B., & Endestad, T. (2012). Bright illusions reduce the eye's pupil. *PNAS, 109*(6), 2162–2167. https://doi.org/10.1073/pnas.1118298109

Lum, J. A. G., Youssef, G. J., & Clark, G. M. (2017). Using pupillometry to investigate sentence comprehension in children with and without Specific Language Impairment. *Journal of Speech, Language, and Hearing Research, 60*(6), 1648–1660. https://doi.org/10.1044/2017_JSLHR-L-16-0158

Scheepers, C., Mohr, S., Fischer, M. H., & Roberts, A. M. (2013). Listening to limericks: A pupillometry investigation of perceivers' expectancy. *PLoS ONE, 8*(9), e74986. https://doi.org/10.1371/journal.pone.0074986

Schluroff, M. (1982). Pupil responses to grammatical complexity of sentences. *Brain and Language, 17*(1), 133–145. https://doi.org/10.1016/0093-934X(82)90010-4

Tamási, K., McKean, C., Gafos, A., Fritzsche, T., & Höhle, B. (2017). Pupillometry registers toddlers' sensitivity to degrees of mispronunciation. *Journal of Experimental Child Psychology, 153*, 140–148. https://doi.org/10.1016/j.jecp.2016.07.014

Tamási, K., McKean, C., Gafos, A., & Höhle, B. (2019). Children's gradient sensitivity to phonological mismatch: Considering the dynamics of looking behavior and pupil dilation. *Journal of Child Language, 46*(1), 1–23. https://doi.org/10.1017/S0305000918000259

Wright, P., & Kahneman, D. (1971). Evidence of alternative strategies of sentence retention. *Quarterly Journal of Experimental Psychology, 23*(2), 197–213. https://doi.org/10.1080/14640747108400240

References – Data processing & analysis

Bradley, M. M., Miccoli, L., Escrig, M. A., & Lang, P. J. (2008). The pupil as a measure of emotional arousal and autonomic activation. *Psychophysiology, 45*(4), 602–607. https://doi.org/10.1111/j.1469-8986.2008.00654.x

Corney, D., Haynes, J.-D., Rees, G., & Lotto, R. B. (2009). The brightness of colour. *PLoS ONE, 4*(3), e5091. https://doi.org/10.1371/journal.pone.0005091

Csink, V., Mareschal, D., & Gliga, T. (2021). Does surprise enhance infant memory? Assessing the impact of the encoding context on subsequent object recognition. *Infancy*. https://doi.org/10.1111/infa.12383

Engelhardt, P. E., Ferreira, F., & Patsenko, E. G. (2010). Pupillometry reveals processing load during spoken language comprehension. *Quarterly Journal of Experimental Psychology, 63*(4), 639–645. https://doi.org/10.1080/17470210903469864

Hepach, R., & Westermann, G. (2013). Infants' sensitivity to the congruence of others' emotions and actions. *Journal of Experimental Child Psychology, 115*(1), 16–29. https://doi.org/10.1016/j.jecp.2012.12.013

Hershman, R., Henik, A., & Cohen, N. (2019). CHAP: Open-source software for processing and analyzing pupillometry data. *Behavior Research Methods, 51*, 1059–1074. https://doi.org/10.3758/s13428-018-01190-1

Kret, M. E., & Sjak-Shie, E. E. (2019). Preprocessing pupil size data: Guidelines and code. *Behavior Research Methods, 51*, 1336–1342. https://doi.org/10.3758/s13428-018-1075-y

Mathôt, S., Fabius, J., van Heusden, E., & Van der Stigchel, S. (2018). Safe and sensible preprocessing and baseline correction of pupil-size data. *Behavior Research Methods, 50*, 94–106. https://doi.org/10.3758/s13428-017-1007-2

Porretta, V., & Tucker, B. V. (2019). Eyes wide open: Pupillary response to a foreign accent varying in intelligibility. *Frontiers in Communication, 4*(8). https://doi.org/10.3389/fcomm.2019.00008

van Rij, J., Hendriks, P., van Rijn, H., Baayen, R. H., & Wood, S. N. (2019). Analyzing the time course of pupillometric data. *Trends in Hearing, 23*, 1–22. https://doi.org/10.1177/2331216519832483

Wagner, A. E., Nagels, L., Toffanin, P., Opie, J. M., & Başkent, D. (2019). Individual variations in effort: Assessing pupillometry for the hearing impaired. *Trends in Hearing, 23*, 1–18. https://doi.org/10.1177/2331216519845596

Wetzel, N., Buttelmann, D., Schieler, A., & Widmann, A. (2016). Infant and adult pupil dilation in response to unexpected sounds. *Developmental Psychobiology, 58*(3), 382–392 https://doi.org/10.1002/dev.21377

Wetzel, N., Einhäuser, W., & Widmann, A. (2020). Picture-evoked changes in pupil size predict learning success in children. *Journal of Experimental Child Psychology, 192*, 104787. https://doi.org/10.1016/j.jecp.2019.104787

Winn, M. B., Wendt, D., Koelewijn, T., & Kuchinsky, S. E. (2018). Best practices and advice for using pupillometry to measure listening effort: An introduction for those who want to get started. *Trends in Hearing, 22*, 1–32. https://doi.org/10.1177/2331216518800869