Beyond a fixation on fixations

What can we learn from eye-movement behavior?

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Department: Human Perception, Cognition, and Action

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut
für biologische Kybernetik

Overview

- Why do we move our eyes?
- Why do we tend to study fixations?
- Why should we look at eye-movements? [15]
  - *scene and task: saccade amplitude dynamics*
  - *decision-making: saccade and smooth pursuit*
  - *user state: eye-movement planning*
- Should we and how do we start studying eye-movements?

Why do I study eye-movements?

Introduction

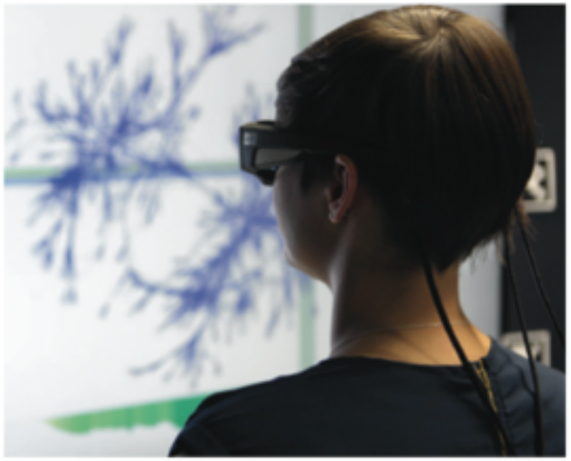
Cognition & Control in Human-Machine Systems

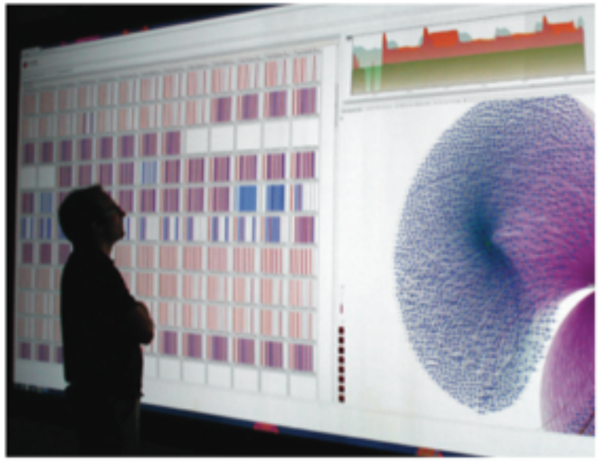
Introduction

SFB-TRR161: Quantitative Methods to Visual Computing

2nd Workshop on Eyetracking and Visualization, IEEE-Vis
www.etvis.org

We are hiring: Postdoc.
PhD Exchange programs.





University of Stuttgart
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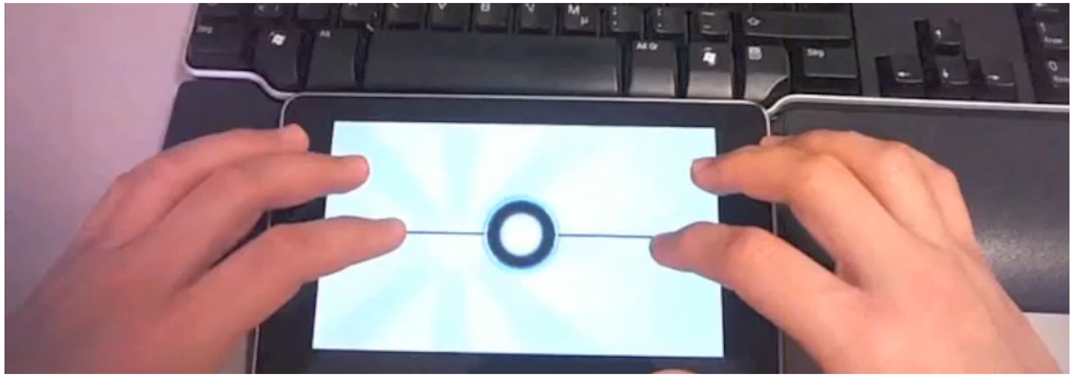
Introduction

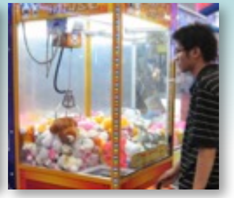
Non-interruptive evaluation of human-in-the-loop

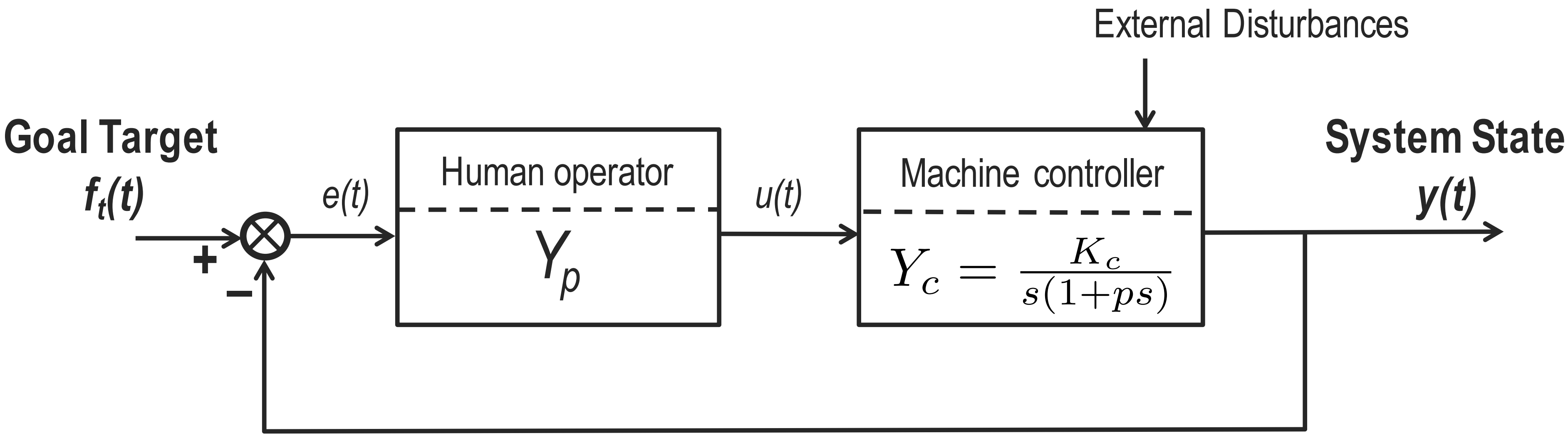
with Prof. Harald Reiterer
BW-FIT



Introduction

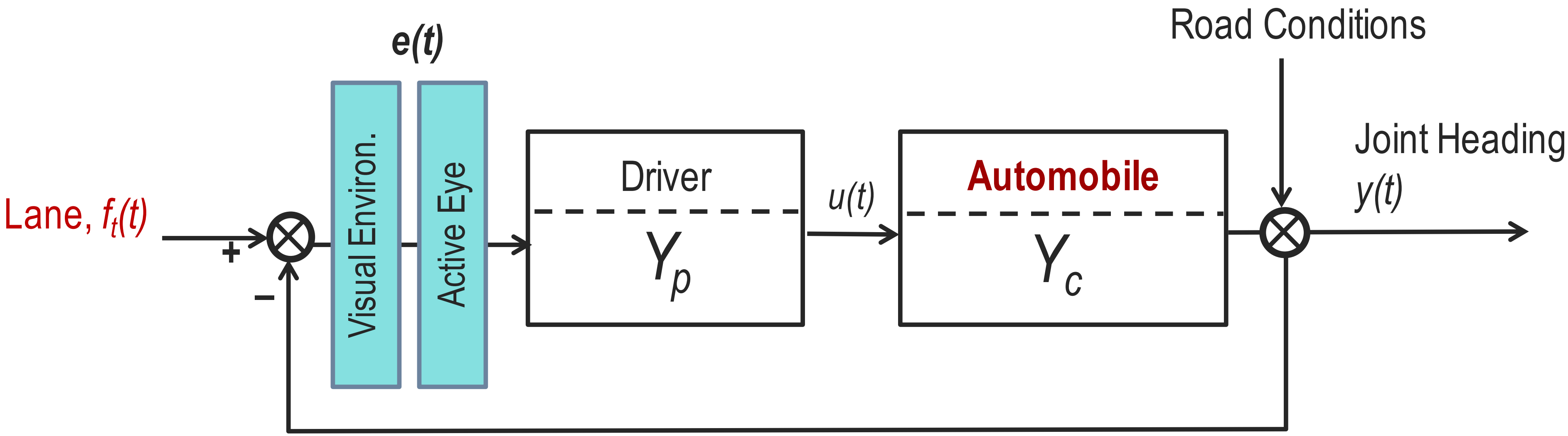
Research Framework: Human-in-the-Loop





Introduction

Research Framework: Human-in-the-Loop



Visual information is physiological limited

Rosenholtz, R. (2011). What your visual system sees where you are not looking. *Proc SPIE Human Vision and Electronic Imaging*, 7(1), 786510-786510–14. http://doi.org/10.1117/12.876659

Eye-movements

control the rate of information sampling

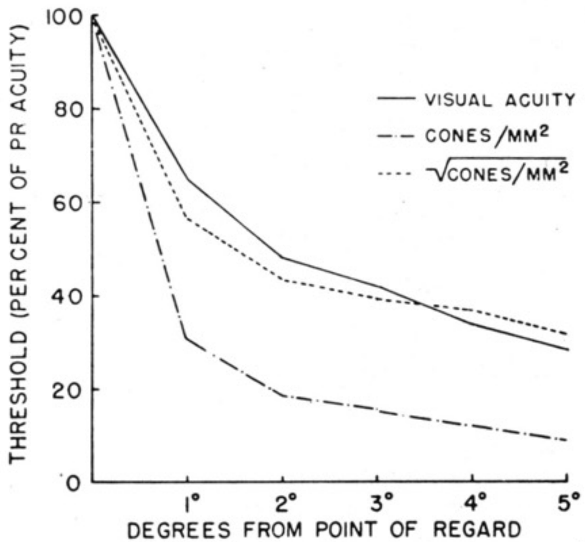


Fig. 11. Visual Acuity Compared with Distribution of Retinal Cones (27) (N = 5)

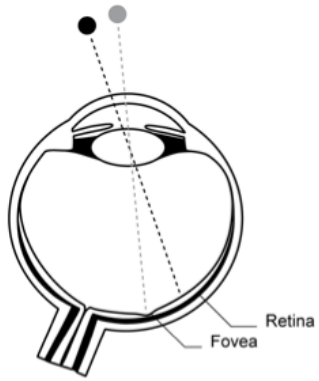


TABLE I

PERIPHERAL VISUAL ACUITY

Distance from Fovea	Visual Acuity
1°	20/30
2°	20/35
3°	20/50
4°	20/60
5°	20/70

Korte W (1923). Über die Gestaltauffassung im indirekten Sehen. *Zeitschrift für Psychologie*, 93, 17–82. In Walton H.N. (1957)

Walton, H. N. (1957). Vision & Rapid Reading*. *Optometry & Vision Science*, *34*(2), 73-82.

Eye-tracking
reveals(?) information sampling

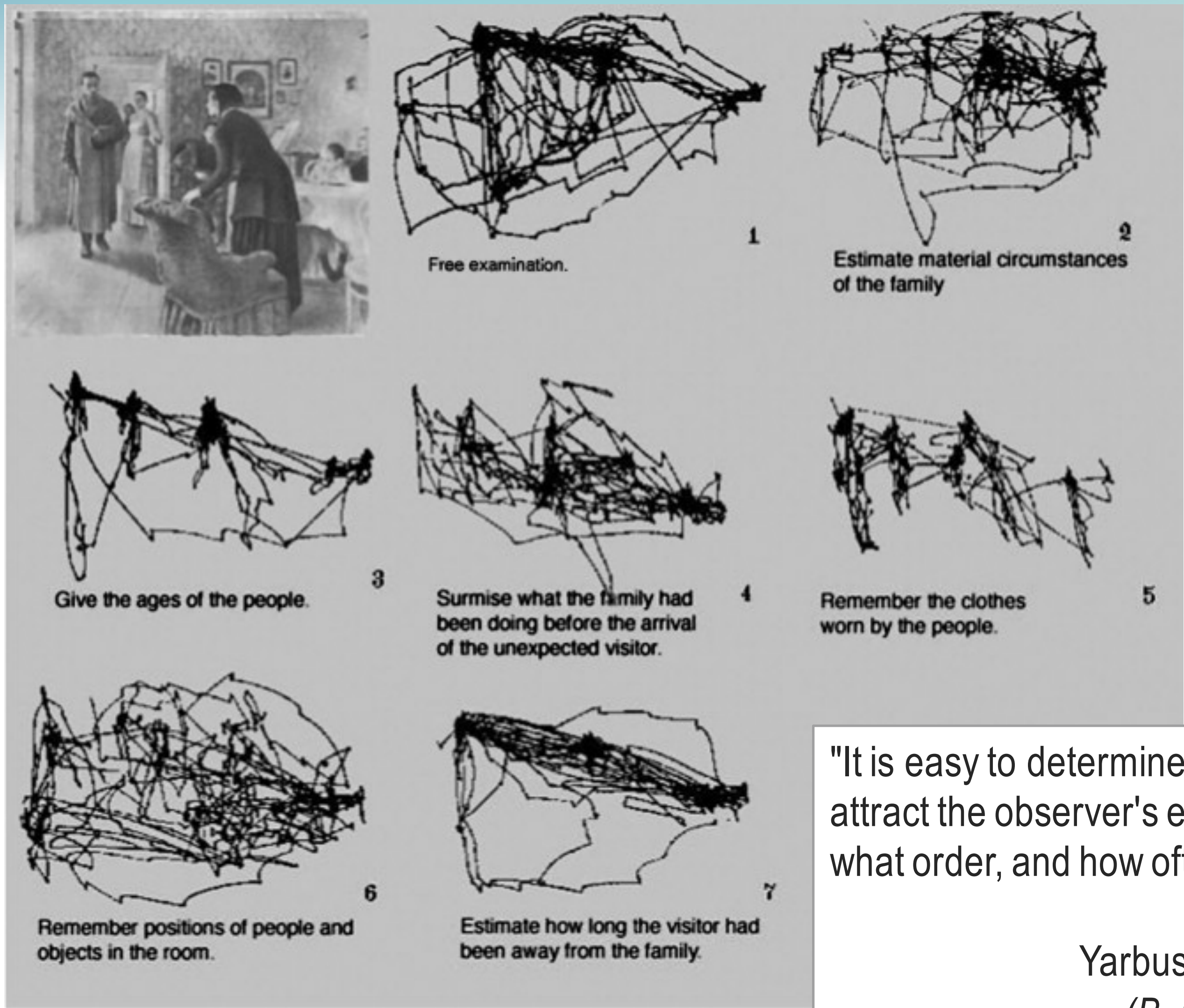
Subtasks:
- Observe oncoming traffic
- Drive curve
- Read traffic signs
- Search pedestrian
- Mirror check
- Check speed
- Regulate distance

Credit: SMI

Why do we study fixations?

Fixations indicate Cognition

Yarbus, 1967



"It is easy to determine from these records which elements attract the observer's eye (and, consequently, his thought), in what order, and how often."

Yarbus, A. L. (1967) *Eye movements and vision (B. Haigh, Trans.)*, New York: Plenum Press.

Do Fixations indicate Cognition?

2012-present

1. Determine the decade in which the picture was taken (*decade*).
2. Determine the wealth of the people in the picture (*wealth*).
3. Memorize the picture (*memory*).
4. Determine how well the people in the picture know each other (*people*).

Greene, M. R., Liu, T., & Wolfe, J. M. (2012). Reconsidering Yarbus: A failure to predict observers' task from eye movement patterns. *Vision research*, *62*, 1-8.

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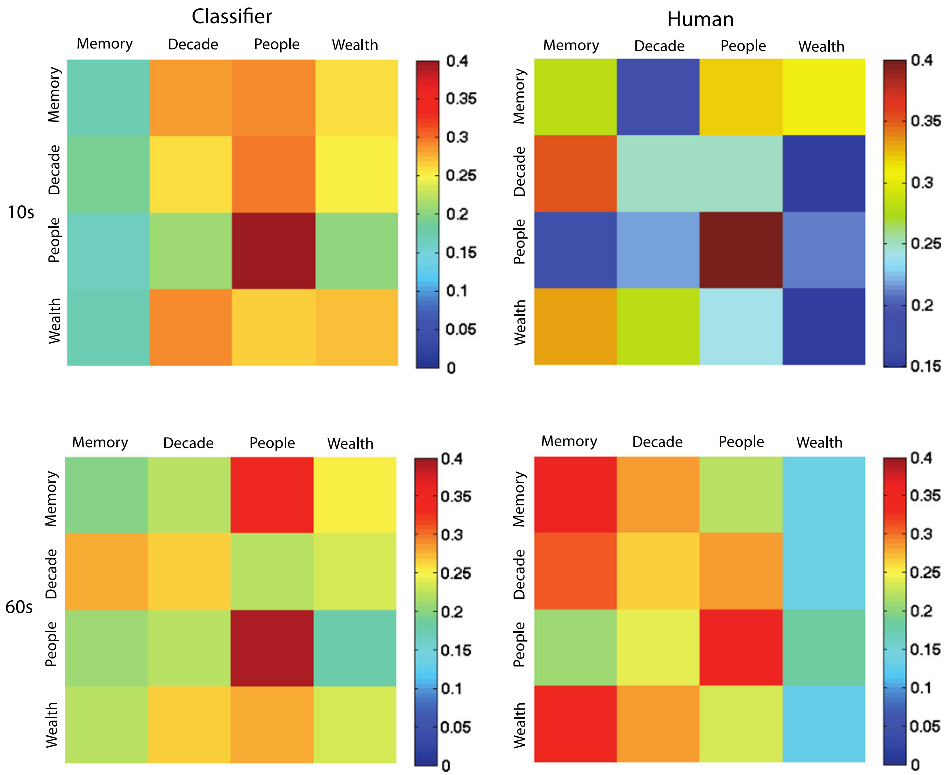

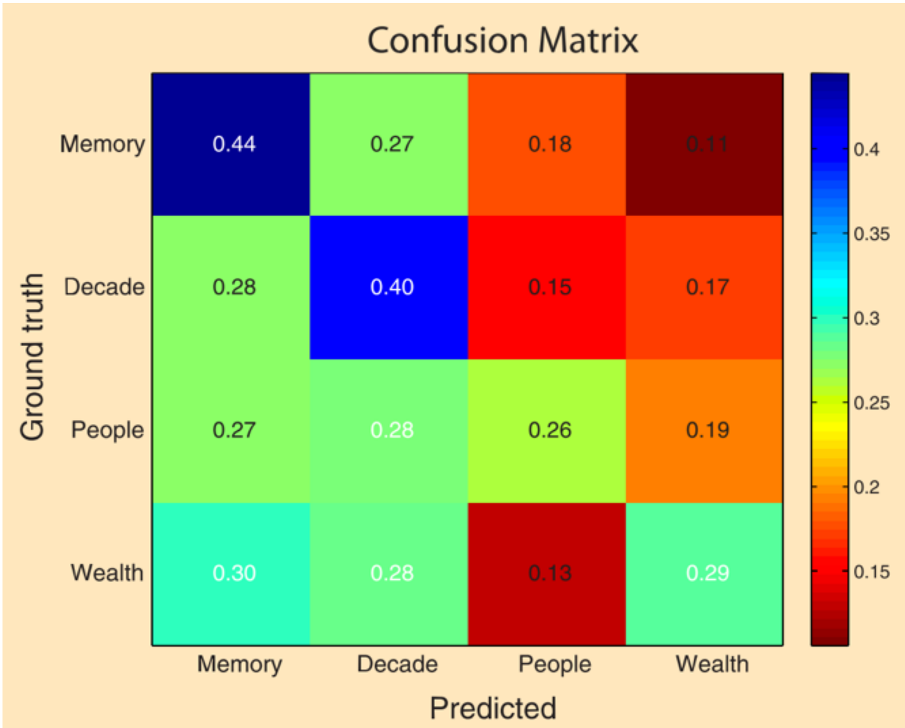

[1] Greene, M. R., Liu, T., & Wolfe, J. M. (2012). Reconsidering Yarbus: A failure to predict observers' task from eye movement patterns. *Vision research*, *62*, 1-8.
[2] Borji, A., & Itti, L. (2014). Defending Yarbus: Eye movements reveal observers' task. *Journal of Vision*, *14*(3), 29–29. http://doi.org/10.1167/14.3.29

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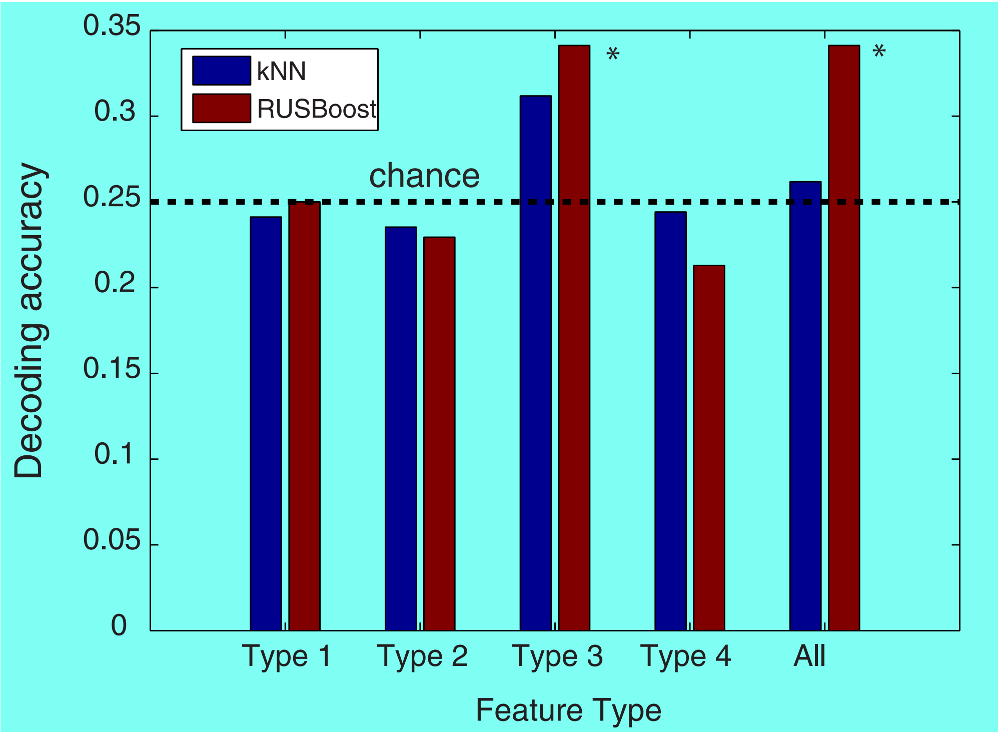

Feature Type 1: fixation positions
Feature Type 2: saliency of fixated regions

Feature Type 3

- number of fixations
- mean fixation duration
- mean saccade amplitude
- percent of the image area covered by fixations

[2] Borji, A., & Itti, L. (2014). Defending Yarbus: Eye movements reveal observers' task. *Journal of Vision*, *14*(3), 29–29. http://doi.org/10.1167/14.3.29

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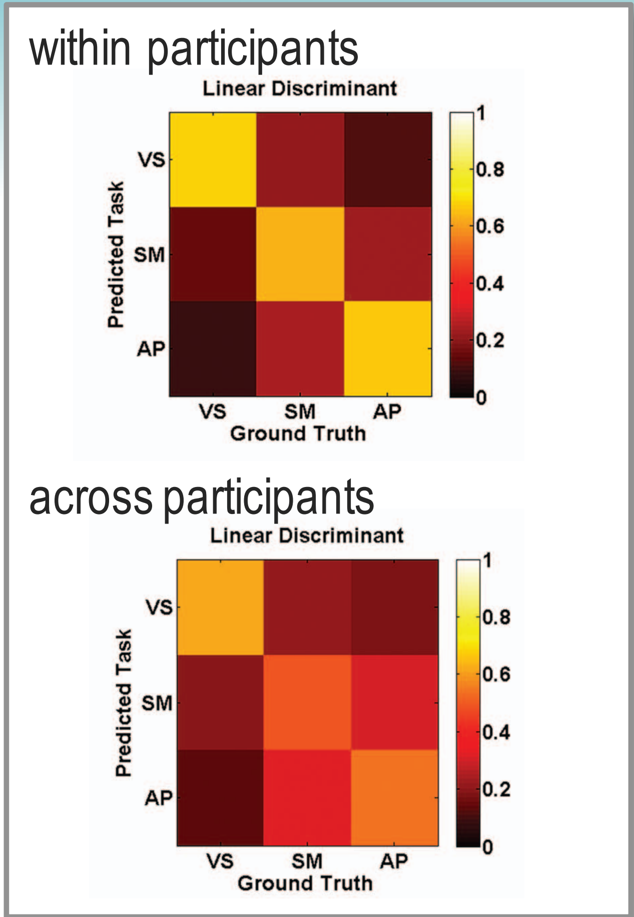
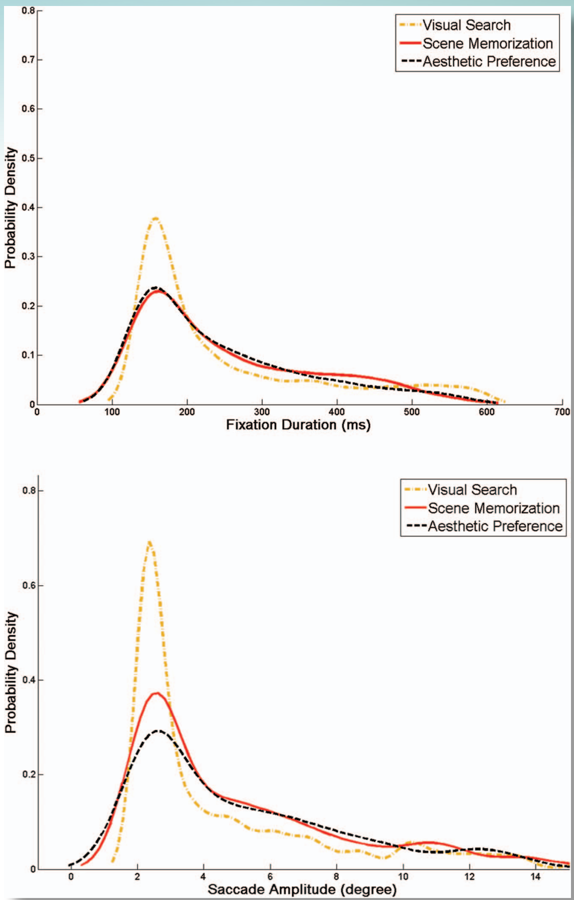




[1] Kardan, O., Berman, M. G., Yourganov, G., Schmidt, J., & Henderson, J. M. (2015). Classifying mental states from eye movements during scene viewing. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(6), 1502–1514. http://doi.org/10.1037/a0039673

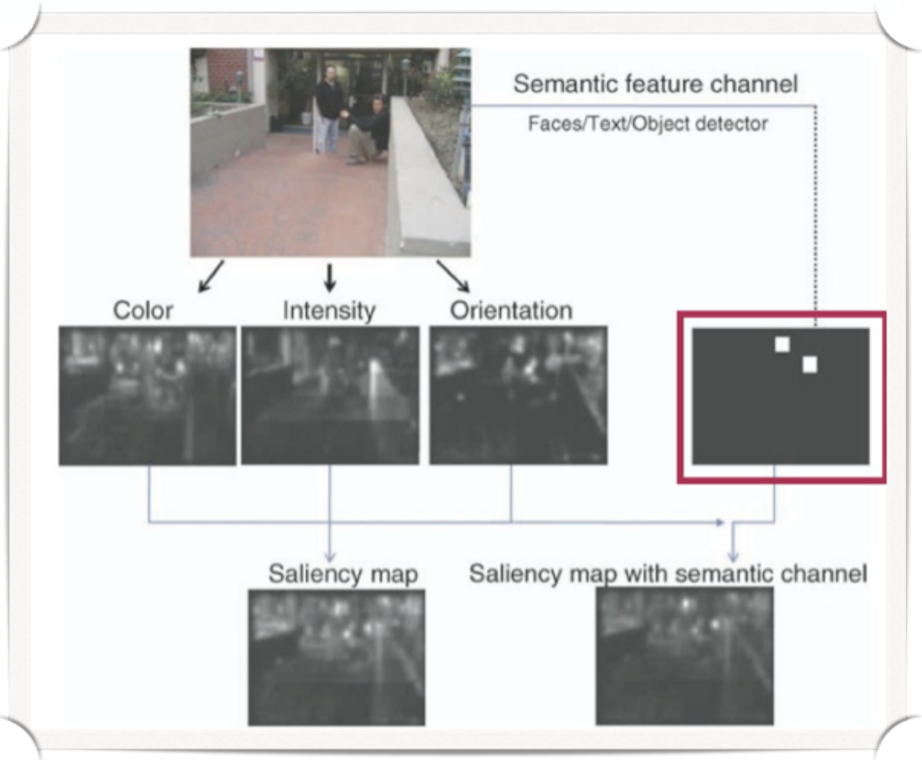
I'm sorry, but...

fixations are not eye-movements

- Fixations/Dwells
  - *measurable by 30Hz cameras*
  - *algorithms discard all movement (blinks, saccades...)*

Task and Scene properties influence saccade amplitude dynamics

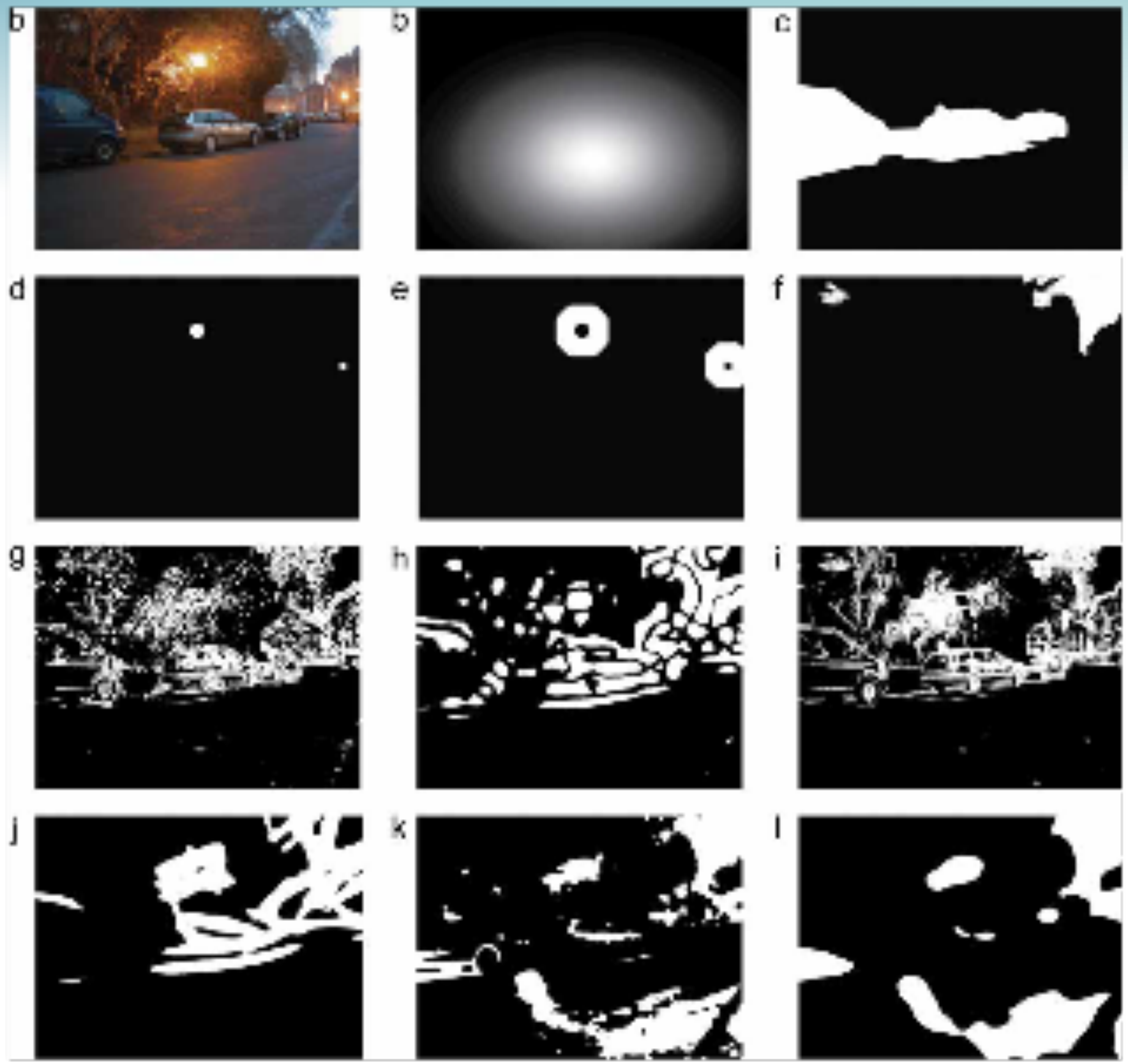
Bottom-up visual saliency



Itti, L., & Koch, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision Research*, *40*(10–12), 1489–1506. http://doi.org/10.1016/S0042-6989(99)00163-7

Borji, A., & Itti, L. (2013). State-of-the-art in visual attention modeling. *IEEE transactions on pattern analysis and machine intelligence*, *35*(1), 185-207.

Quick word about saliency models



Do we look at lights?

b) central bias
c) foreground (ie., objects)
d) lights
e) around lights
f) sky
g) contrast (high spat. freq.)
h) contrast (low spat. freq.)
i) edges (high spat. freq.)
j) edges (low spat. freq.)
k) contrast (high spat. freq.)
l) contrast (low spat. freq.)

Vincent, Baddeley, Correani, Troscianko & Leonards, 2009.

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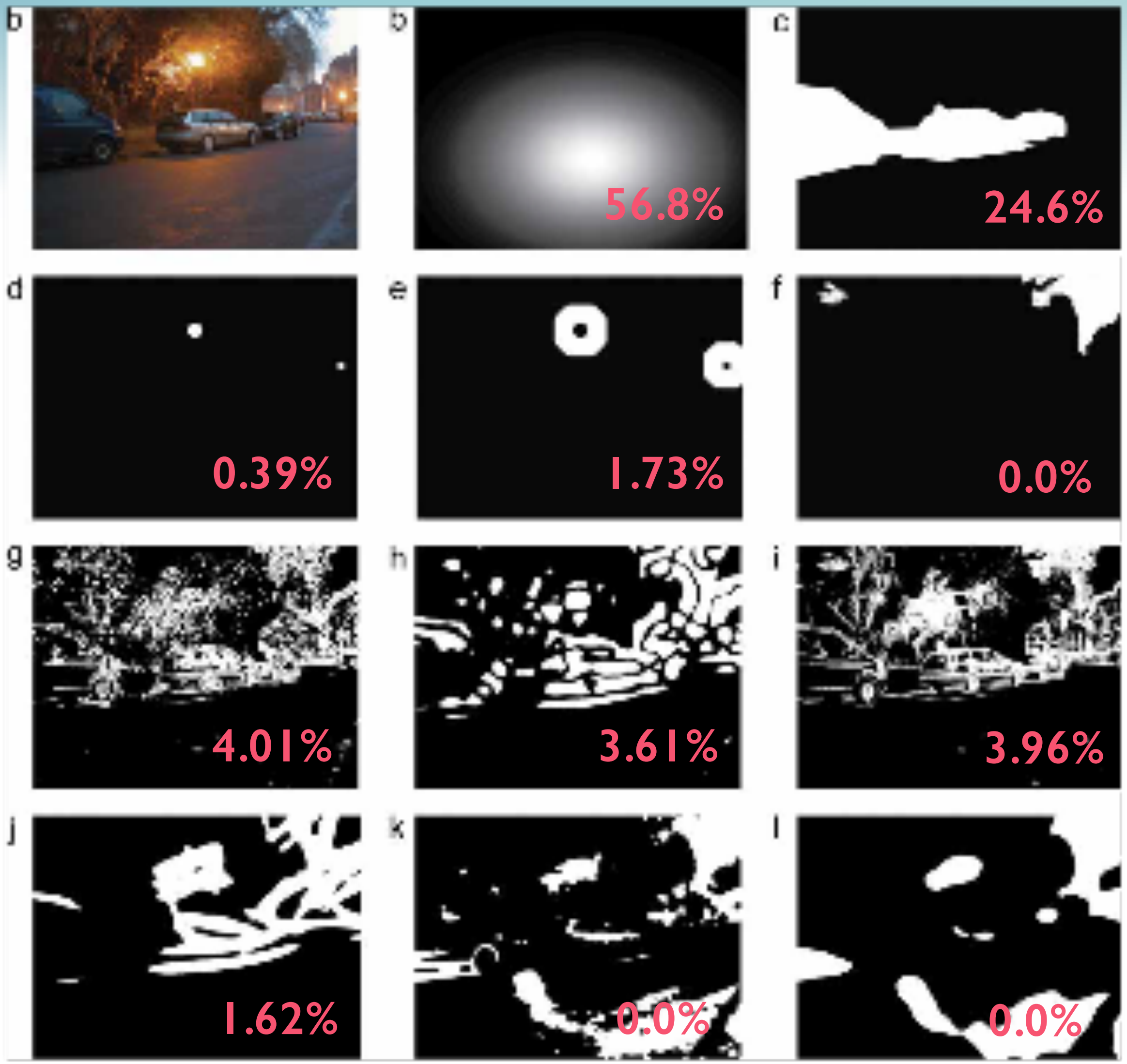

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Central Bias

Most naturally occurring human saccades have magnitudes of 15 degrees or less.
A. TERRY BAHILL, DEBORAH ADLER, AND LAWRENCE STARK.

Normal human saccadic eye movements are seldom larger than 15 degrees. In an outdoor environment, 86 per cent of the saccades of three subjects were 15 degrees or less in magnitude.

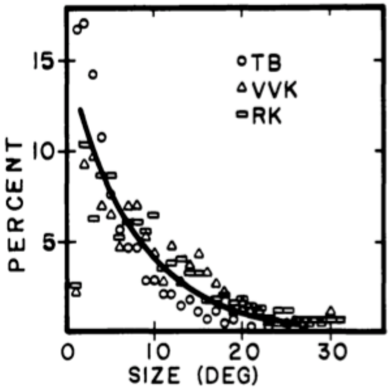
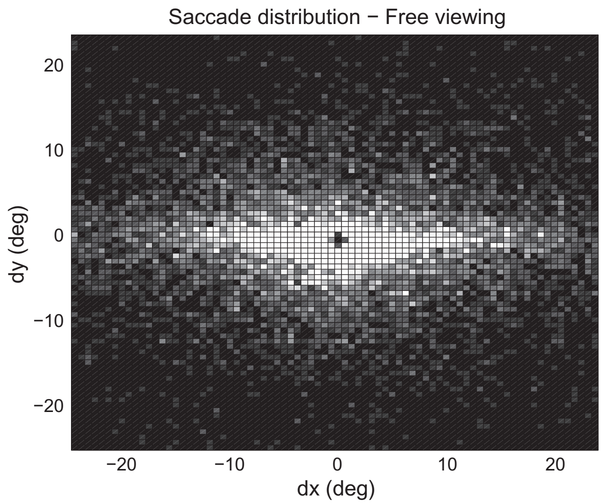
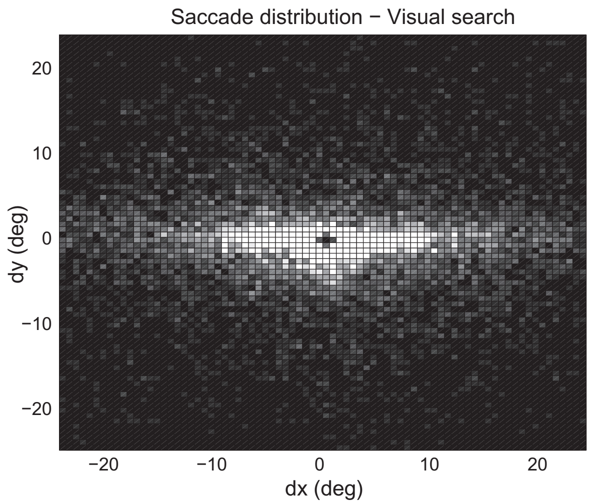


Fig. 1. Frequency of occurrence of various sized saccades for three normal subjects. The solid line representing the equation Y = 15 exp(−X/7.6), where Y is the per cent occurrence, and X is size of the saccade in degrees, was derived by the method of least squares from all of the data.

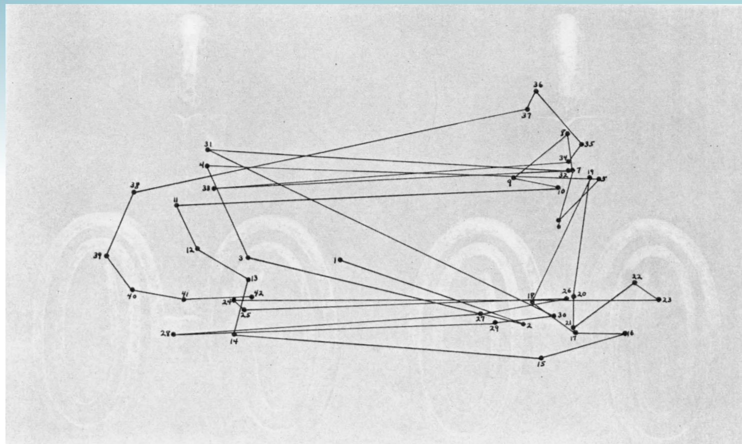




[1] Bahill, A. T., Adler, D., & Stark, L. (1975). Most naturally occurring human saccades have magnitudes of 15 degrees or less. *Investigative Ophthalmology*, *14*, 468–469.

[2] Bonev, B., Chuang, L. L., & Escolano, F. (2013). How do image complexity, task demands and looking biases influence human gaze behavior? *Pattern Recognition Letters*, *34*(7), 723–730. http://doi.org/10.1016/j.patrec.2012.05.007

Model for two modes of Looking



Ambient mode (look): *short fixations and long saccades*
processes scene gist and spatial orientation

Focal mode (see): *long fixations and short saccades*
processes object identities and memory encoding

Buswell, G. T. G. T. (1935). *How people look at pictures*. *Social Science Research* (1st ed.). Chicago, Illinois: The University of Chicago Press.

Unema, P. J. A., Pannasch, S., Joos, M., & Velichkovsky, B. M. (2005). Time course of information processing during scene perception: The relationship between saccade amplitude and fixation duration. Visual Cognition, 12, 473–494, doi:10. 1080/13506280444000409.

Pannasch, S., & Velichkovsky, B. M. (2009). Distractor effect and saccade amplitudes: Further evidence on different modes of processing in free exploration of visual images. *Visual Cognition*, *17*(6-7), 1109-1131.

Eisenberg, M. L., & Zacks, J. M. (2016). Ambient and focal visual processing of naturalistic activity. *Journal of Vision*, *16*(2), 5.

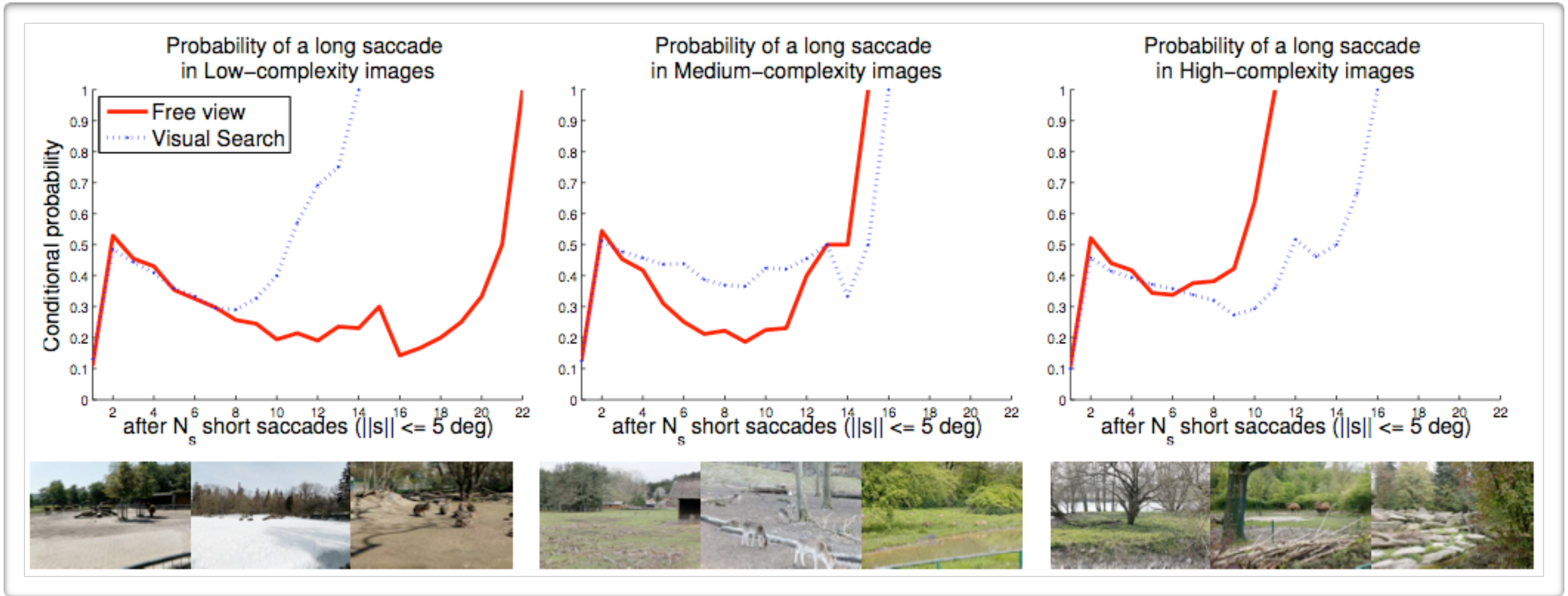
Looking modes and Scene complexity

Modes of looking (ambient & focal; Pannasch & Velichovsky, 2009):

- In general: patterns of a long saccade after several short saccades.

Model the short (S) and long (L) saccades (x_i) as a Markov process of

- P(L|S,S,...,S)
- Estimate the likelihood of a long saccade after *n* short saccades



Bonev, B., Chuang, L. L., & Escolano, F. (2013). How do image complexity, task demands and looking biases influence human gaze behavior? *Pattern Recognition Letters*, *34*(7), 723–730. http://doi.org/10.1016/j.patrec.2012.05.007

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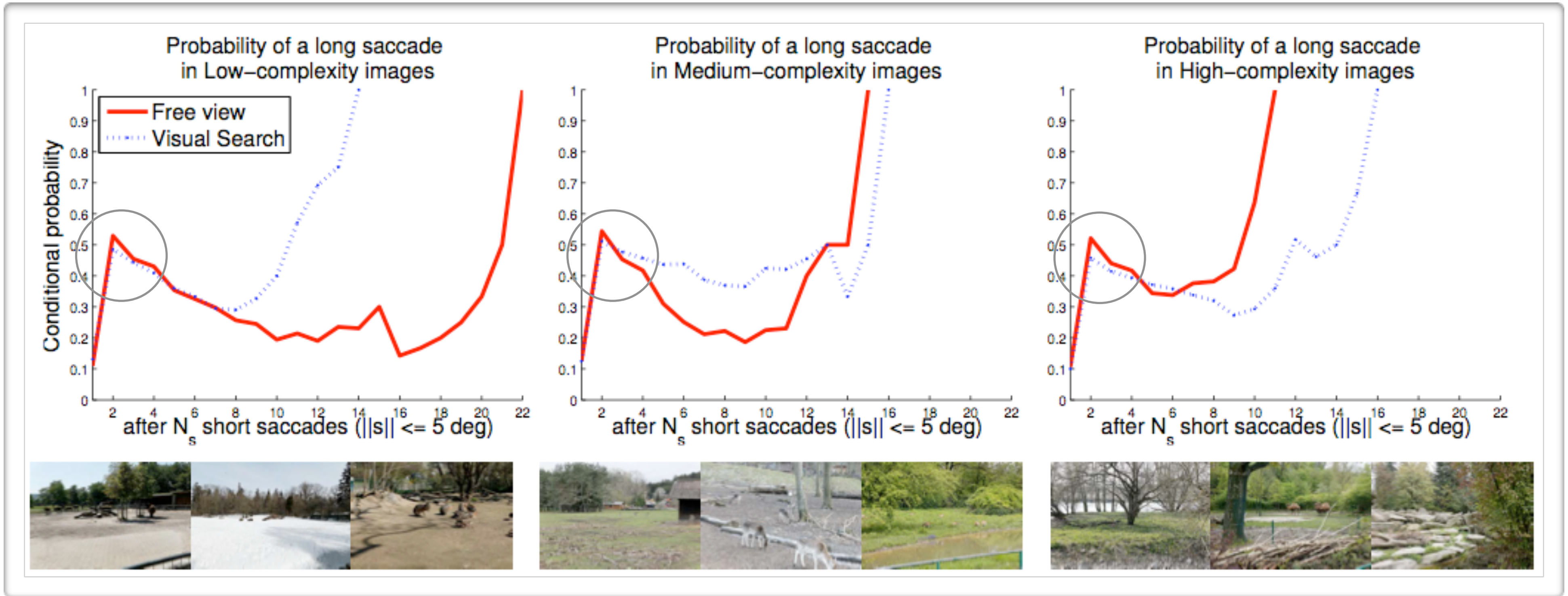

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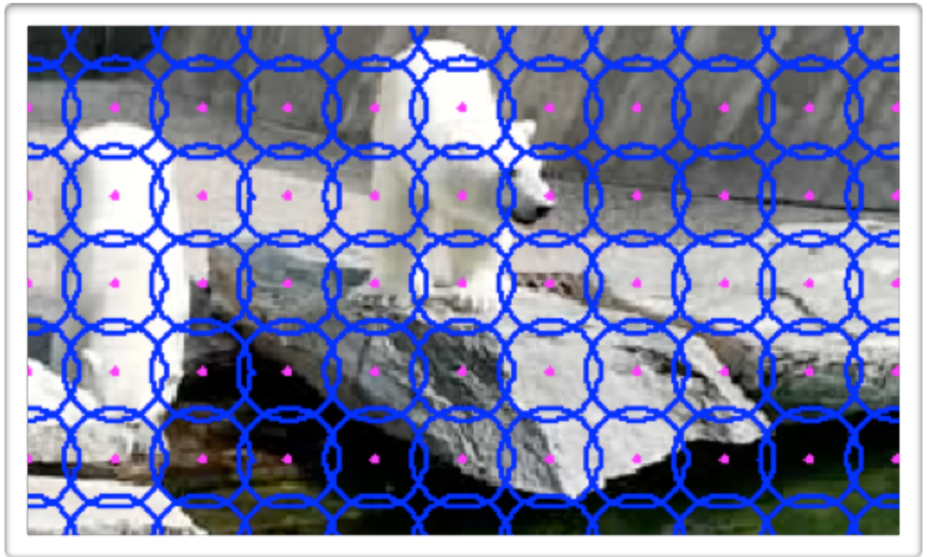
Describing a scene in terms of gaze behavior

Describing a scene in terms of looking modes



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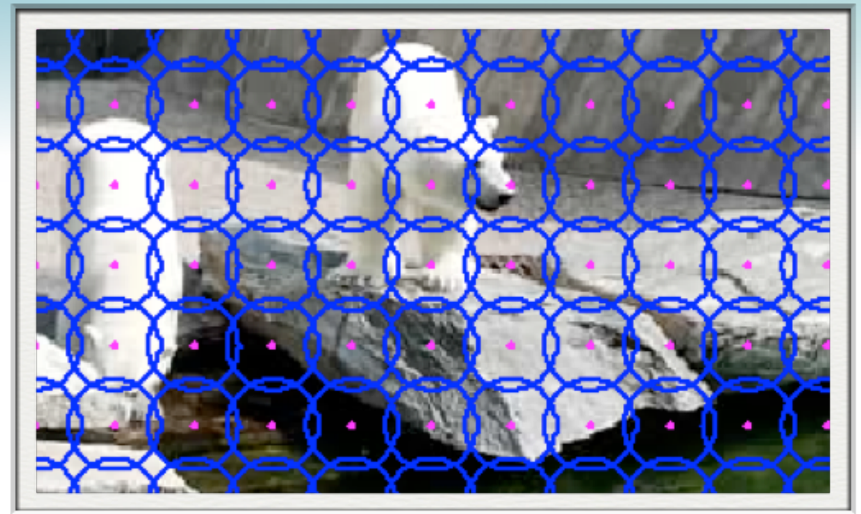
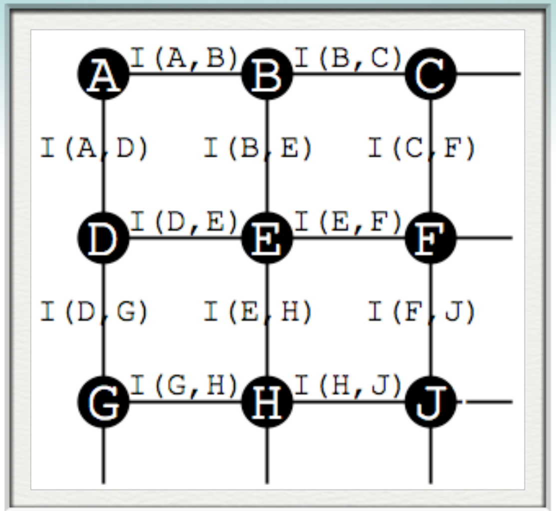


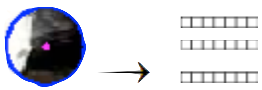


Four-connected grid graph

- Fixed node positions (1650 nodes per image)
- Characterize node regions R of diameter 2 deg
- Edges weighted by $I(R(v_i),R(v_j))$

"Information" within region

- Feature vector for each pixel *p*

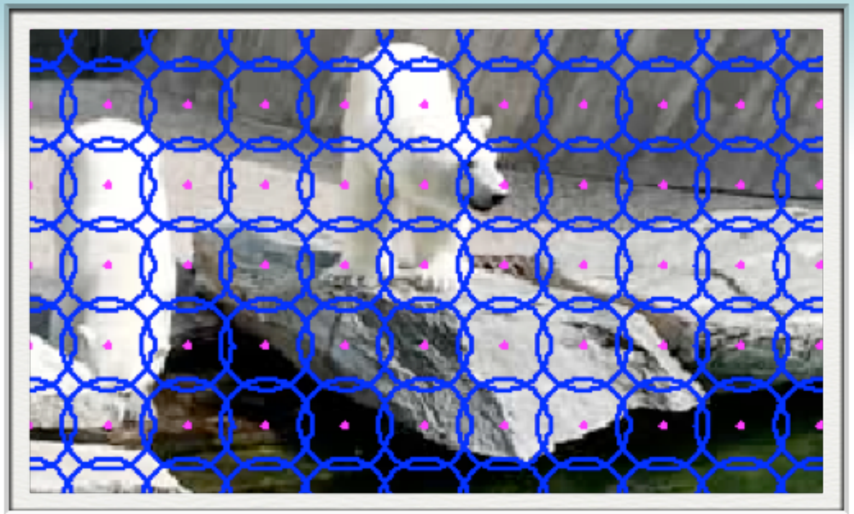


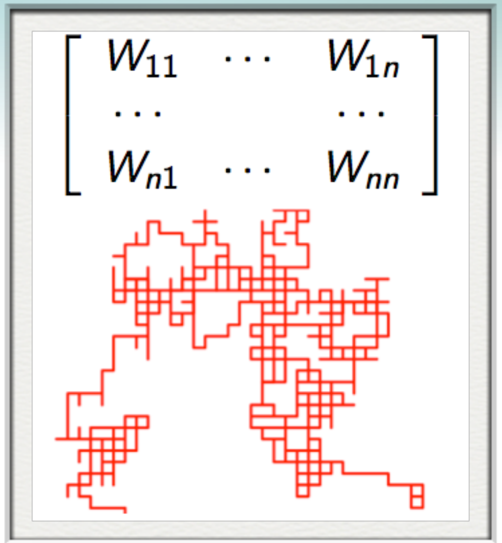
- $f_m(p)$: R,G,B, ∇x, ∇y, $\nabla 2xx$, $\nabla 2yy$
- Assuming d-dimensional Gaussianity with mean Φi and covariance $\Sigma\Phi i$

Edge-weights

- $I(R(v_i),R(v_j)) = 0.5 * \log_2(|\Sigma\Phi i|\,|\Sigma\Phi j|)/|\Sigma\Phi|)$

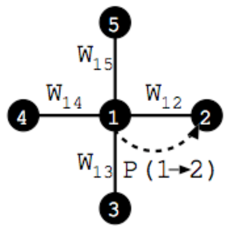
Describing a scene in terms of gaze behavior





Random Walk

- P_{ij} : probability to go from v_i to an adjacent node v_j , proportional to the edge weight



$$P_{ij} = \frac{W_{ij}}{W_i}, \quad W_i = \sum_{k=1}^{n} W_{ik}$$

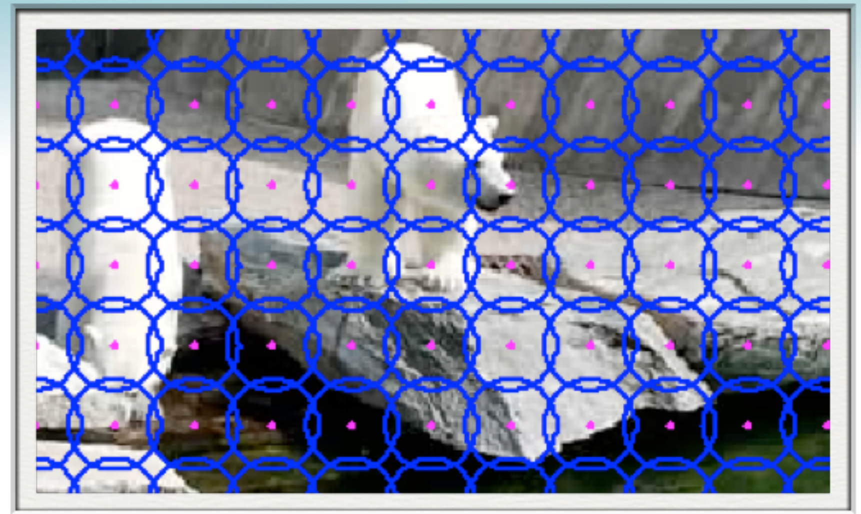
- Weights for n nodes, $W_{ij} = I(R(v_i),R(v_j))$ with $W_{ij} = W_{ji}$ (undirected graph)
- Convergence to a Markov chain's stationary distribution μ which has to satisfy $\mu P = \mu$

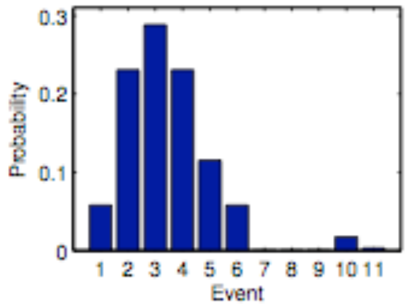
$$\mu_1 P_{11} + \mu_2 P_{21} + \cdots + \mu_n P_{n1} = \mu_1$$

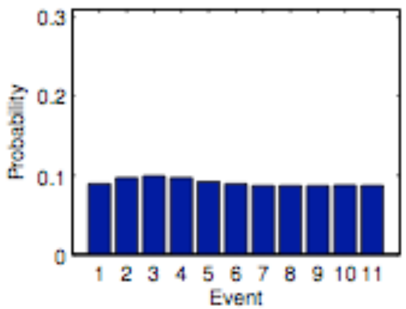
$$\cdots$$

$$\mu_1 P_{1j} + \mu_2 P_{2j} + \cdots + \mu_n P_{nj} = \mu_j$$

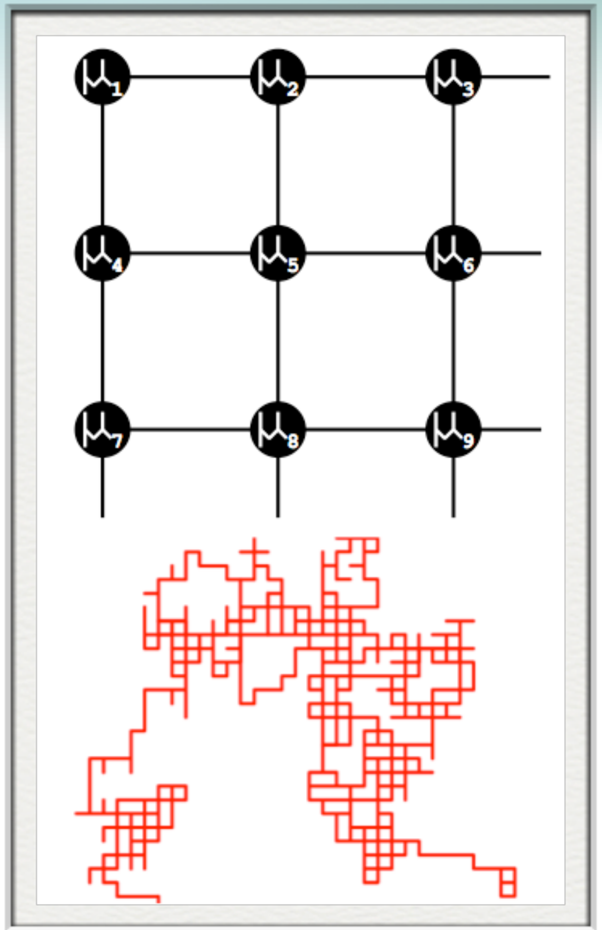
Describing a scene in terms of gaze behavior







$$H(\mu) = -\sum_{i=1}^{n} \mu_i \log_2 \mu_i$$



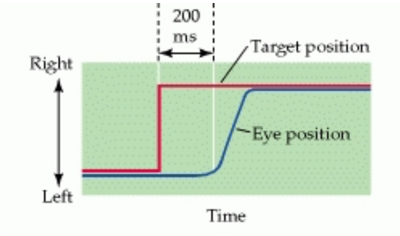
Scene complexity as information search

- probabilistic distribution of long saccades, given short saccades, describe modes of looking
- this also depends on the scene
- a computational metric for scene complexity can be developed, based on search behavior for visual information

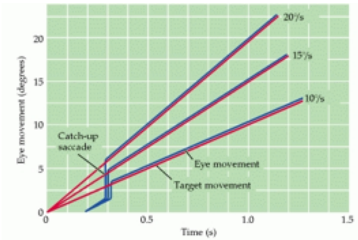
Classes of Eye-Movement Behavior

- Fixations/Dwells
  - *measurable by 30Hz cameras*
  - *algorithms discard all movement (blinks, saccades...)*

- Saccades
  - *~300°/s*



- Smooth-Pursuits
  - *~< 30°/s*



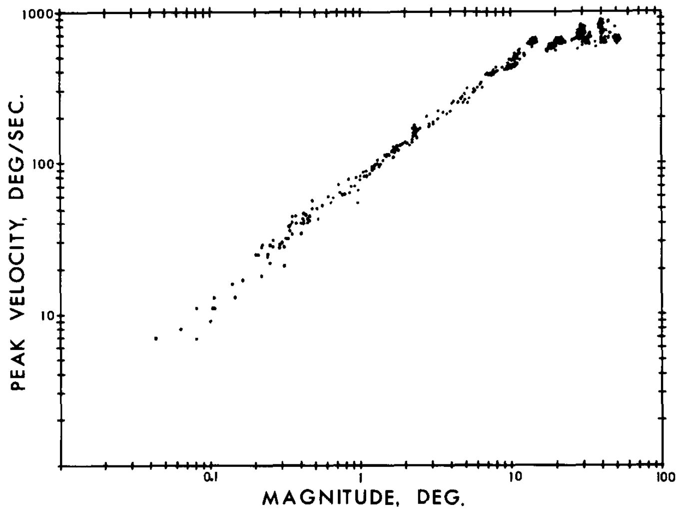


Fig. 3. Peak velocity versus magnitude of human saccadic eye movements.

Purves D, Augustine GJ, Fitzpatrick D, et al., editors. Sunderland (MA): Sinauer Associates; 2001.

Bahill, A. T. T., Clark, M. R., & Stark, L. (1975). The main sequence, a tool for studying human eye movements. *Mathematical Biosciences*, *24*(3–4), 191–204. http://doi.org/10.1016/0025-5564(75)90075-9

Top-down decisions that underlie saccade and smooth pursuit

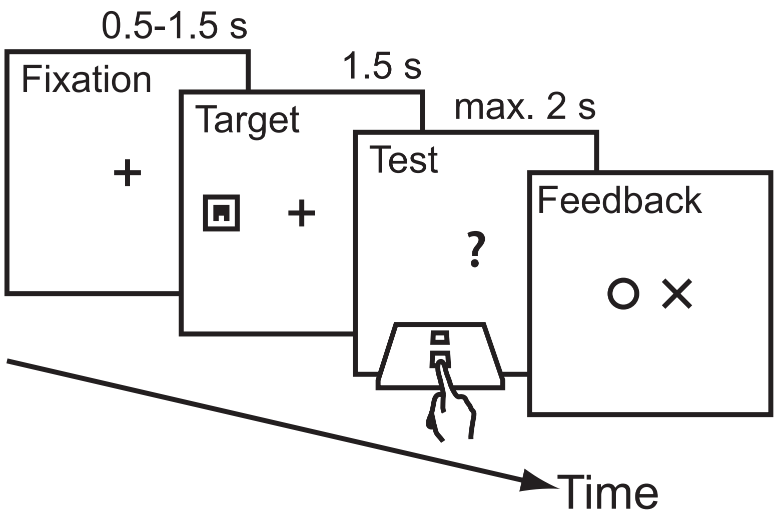
Looking and Seeing

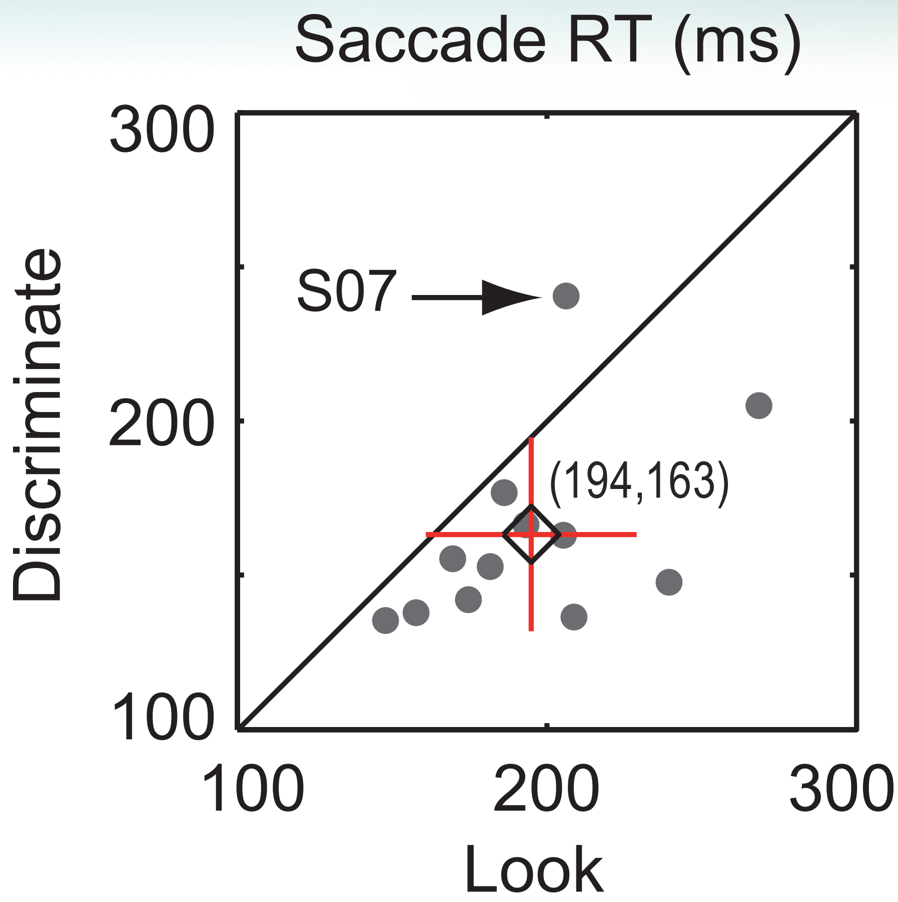
Saccade response times are earlier for seeing

Tasks

Look *at stimulus*

Discriminate *up/down*



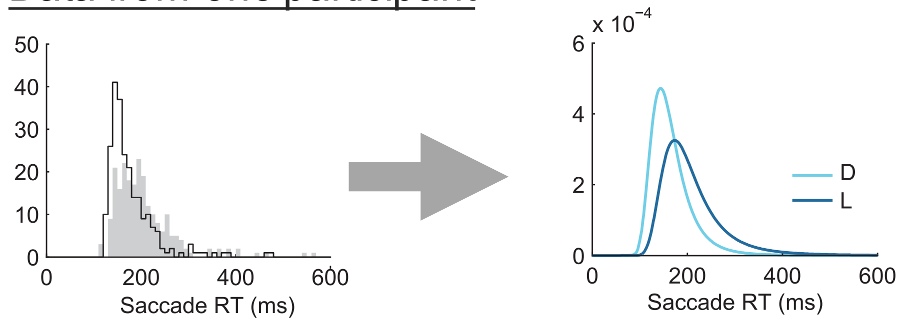


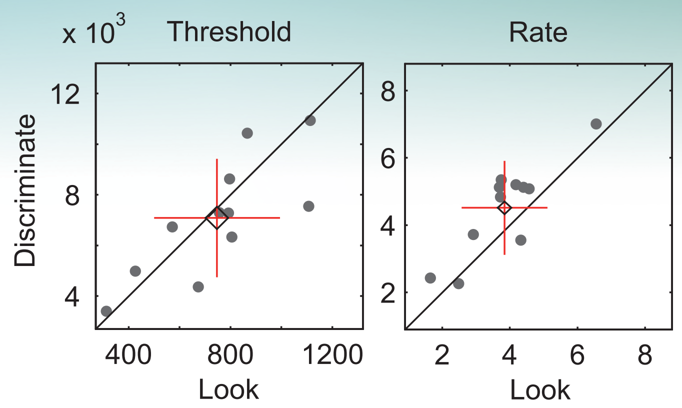
Bieg, H.-J., Bresciani, J.-P., Bülthoff, H. H., & Chuang, L. L. (2012). Looking for Discriminating Is Different from Looking for Looking's Sake. *PLoS ONE*, *7*(9), 1–9. article. http://doi.org/10.1371/journal.pone.0045445

Looking and Seeing

Saccade response time reflects decision-making

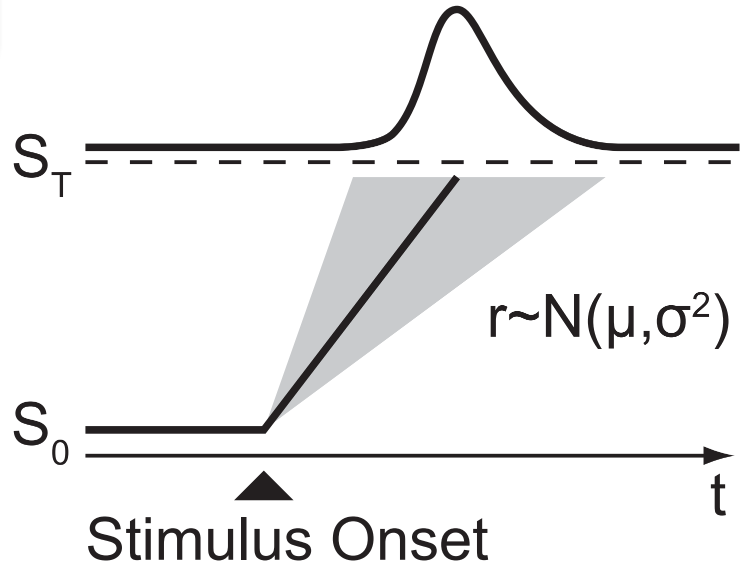
Data from one participant





LATER model

- decision model for saccades
- a saccade occurs when brain activity passes a decision threshold:
  - *threshold*
  - *rate of brain activity*



Bieg, H.-J., Bresciani, J.-P., Bülthoff, H. H., & Chuang, L. L. (2012). Looking for Discriminating Is Different from Looking for Looking's Sake. *PLoS ONE*, *7*(9), 1–9. article. http://doi.org/10.1371/journal.pone.0045445

Carpenter RHS, Williams M (1995) Neural computation of log likelihood in control of saccadic eye movements. Nature 377: 59–62.

Looking and Seeing

Saccade response time reflects decision-making

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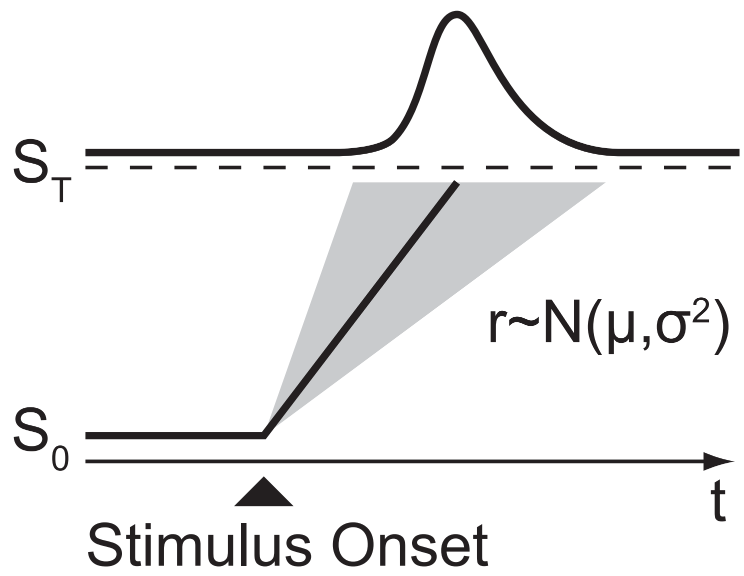
Seeing results in more ”neural activity”, which results in faster saccade response times.

LATER model

- decision model for saccades
- a saccade occurs when brain activity passes a decision threshold:
  - *threshold*
  - *rate of brain activity*



Bieg, H.-J., Bresciani, J.-P., Bülthoff, H. H., & Chuang, L. L. (2012). Looking for Discriminating Is Different from Looking for Looking’s Sake. *PLoS ONE*, *7*(9), 1–9. article. http://doi.org/10.1371/journal.pone.0045445

Carpenter RHS, Williams M (1995) Neural computation of log likelihood in control of saccadic eye movements. Nature 377: 59–62.

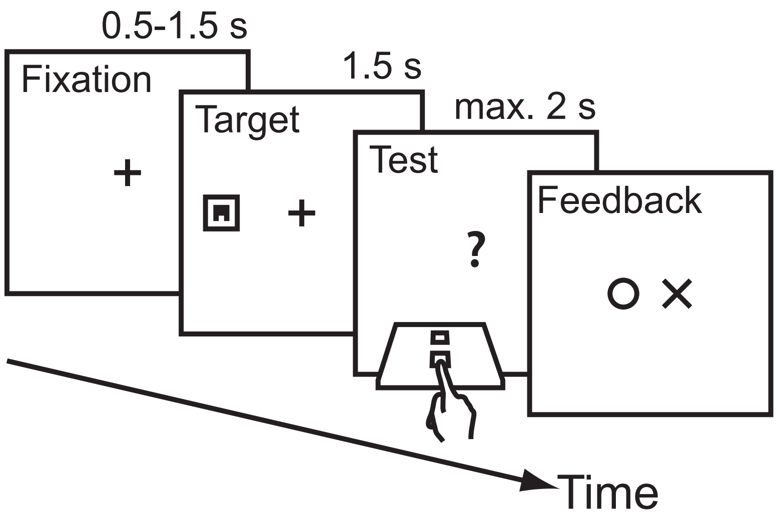
Looking and Seeing

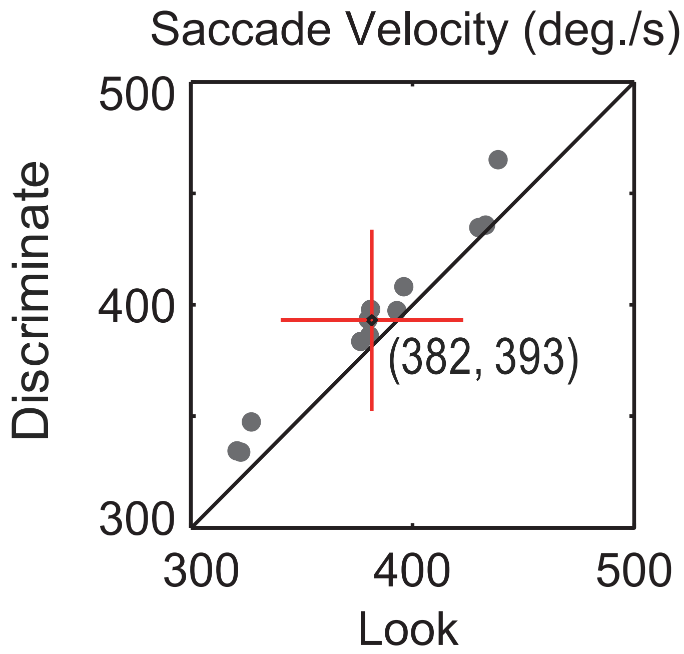
Saccade velocity are higher for seeing

Tasks

Look *at stimulus*

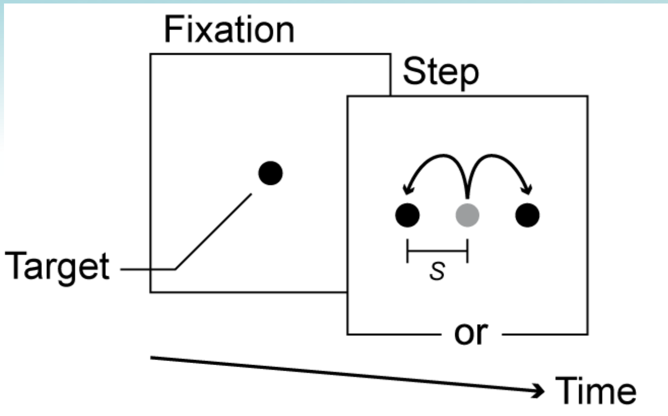
Discriminate *up/down*

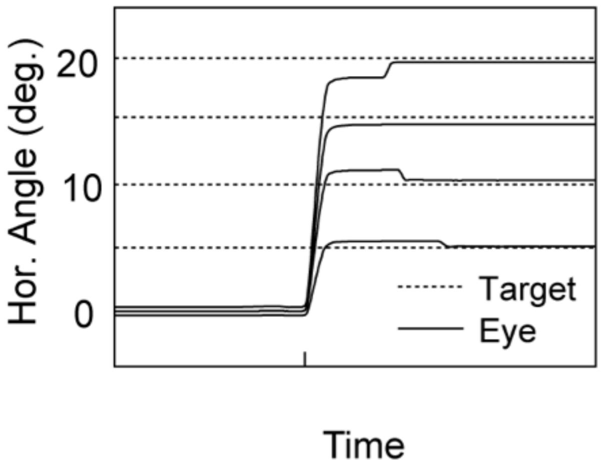


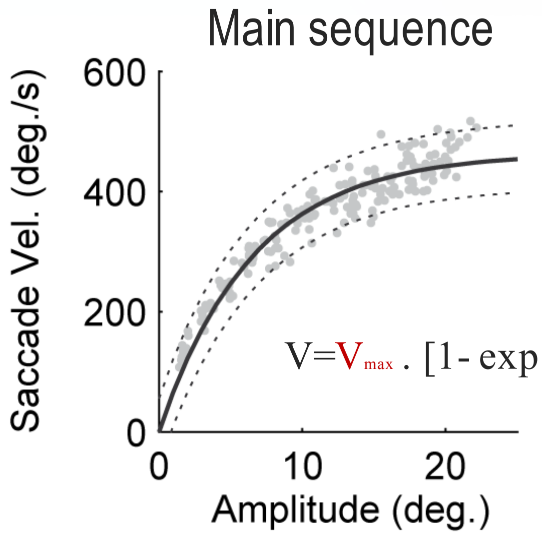


Looking and Seeing

Saccade velocity are higher for seeing







$$V = V_{max} \cdot [1 - \exp(-AMP_{gaze}/C)]$$

V_{max} : saturation velocity

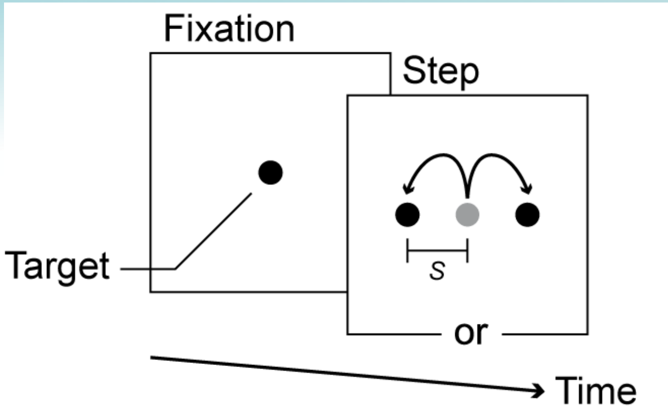
AMP_{gaze} : saccade amplitude

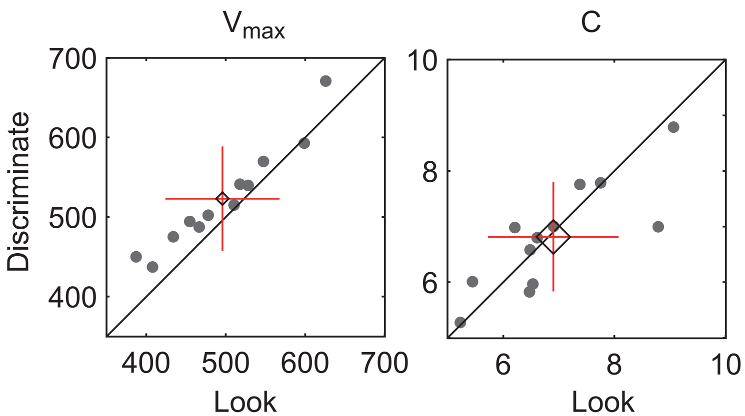
C : constant amplitude (63% V_{max})

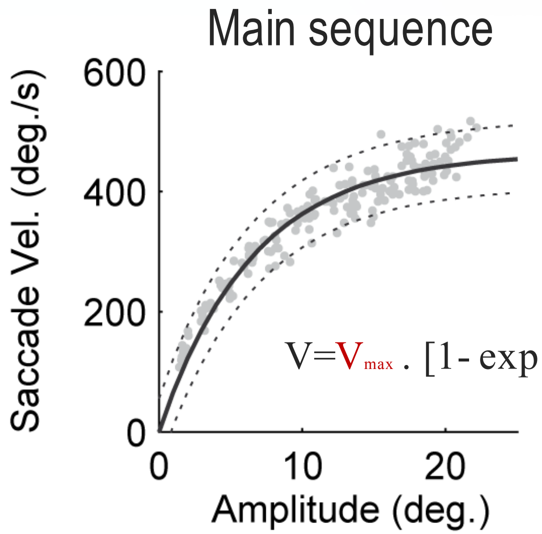
Bahill, A. T. T., Clark, M. R., & Stark, L. (1975). The main sequence, a tool for studying human eye movements. *Mathematical Biosciences*, *24*(3–4), 191–204. http://doi.org/10.1016/0025-5564(75)90075-9

Looking and Seeing

Saccade velocities are higher for seeing







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Looking and Seeing

Eye-movement properties are influenced by the observer’s motivations.

Fixations are a noisy read-out of the observer’s mind.

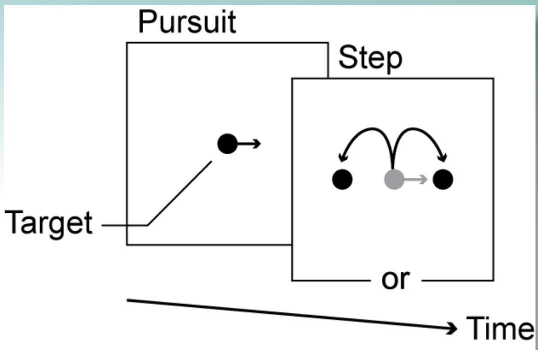
They include relevant and irrelevant information, which have to be subjectively deciphered, which does not necessarily reflect a user’s decision to fixate them in the first place.

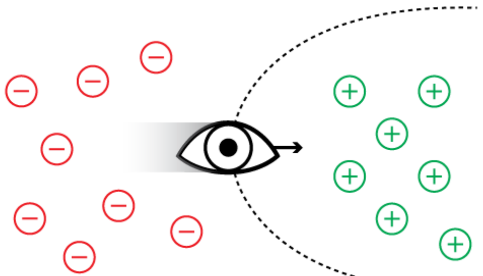
Seeing is influenced by cognition

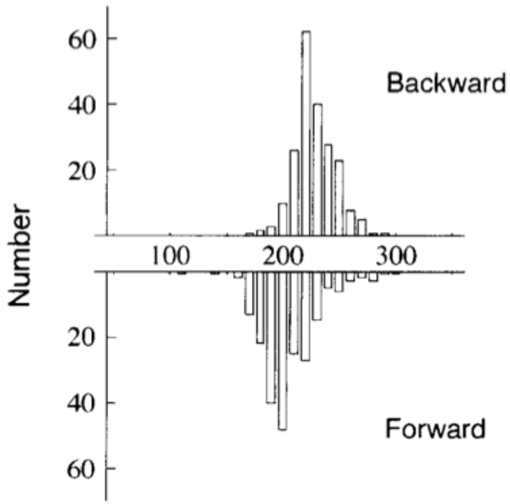
not hard-coded variables

Moving window of attention

attention anticipates eye-movement







Tanaka, M., Yoshida, T., & Fukushima, K. (1998). Latency of saccades during smooth-pursuit eye movement in man: Directional asymmetries. *Experimental Brain Research*, *121*(1), 92-98.

Seya, Y., & Mori, S. (2012). Spatial attention and reaction times during smooth pursuit eye movement. *Attention, Perception, & Psychophysics*, *74*(3), 493-509.

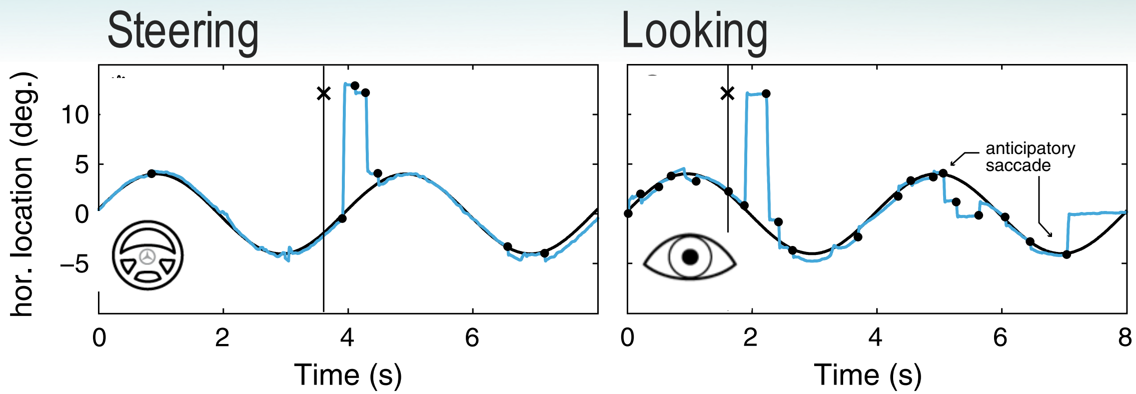
Seeing is influenced by cognition

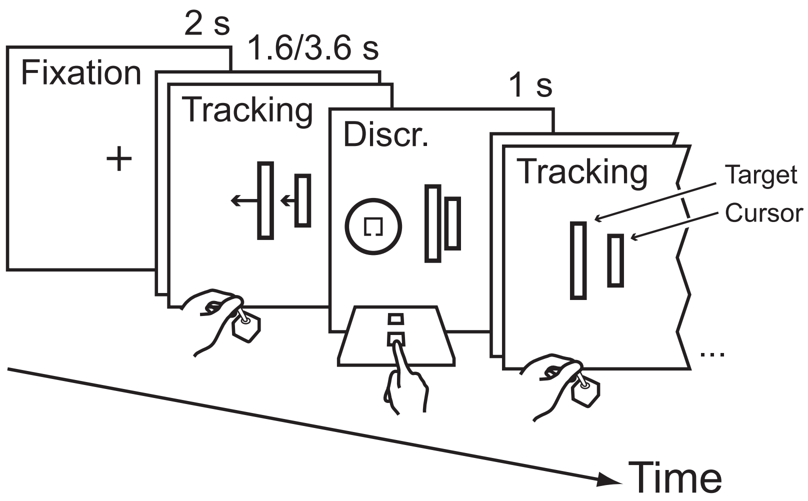
cognition mode results in different characteristics

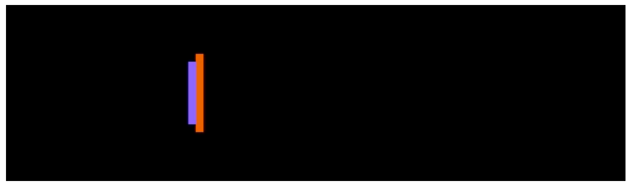
Primary tasks


Steering


Looking







Van Gelder P, Lebedev S, Liu PM, Tsui WH (1995a) Anticipatory saccades in smooth pursuit: task effects and pursuit vector after saccades. Vision Research, 35(5):667–678

Bieg, H. J., Bresciani, J. P., Bülthoff, H. H., & Chuang, L. L. (2013). Saccade reaction time asymmetries during task-switching in pursuit tracking. *Experimental Brain Research*, *230*(3), 271–281. http://doi.org/10.1007/s00221-013-3651-9

Seeing is influenced by cognition

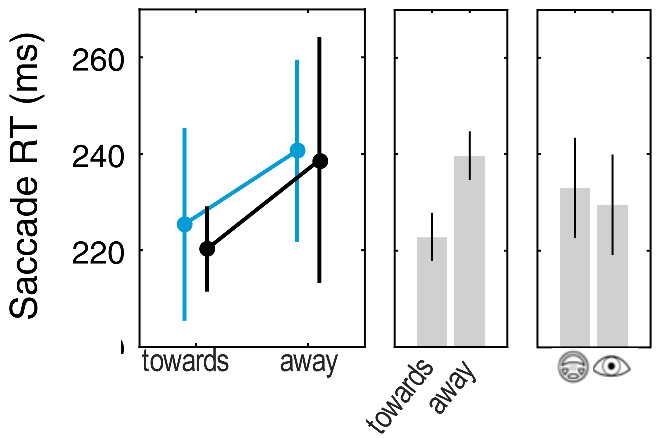
from steering to discrimination

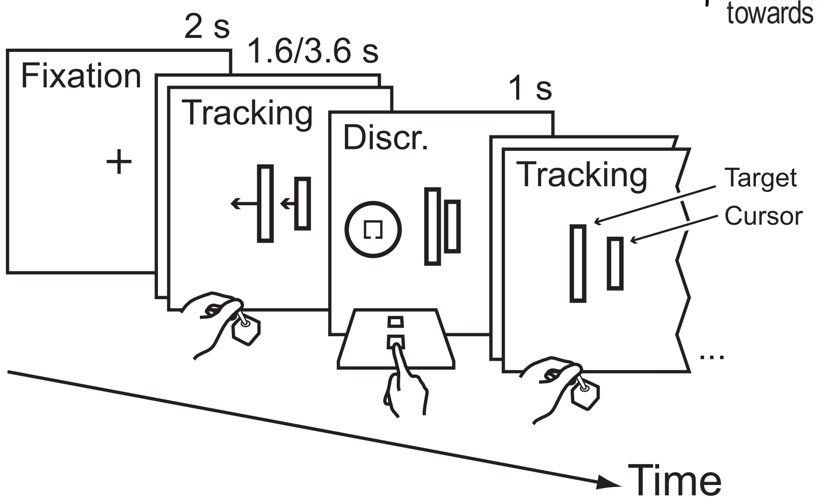
Primary tasks

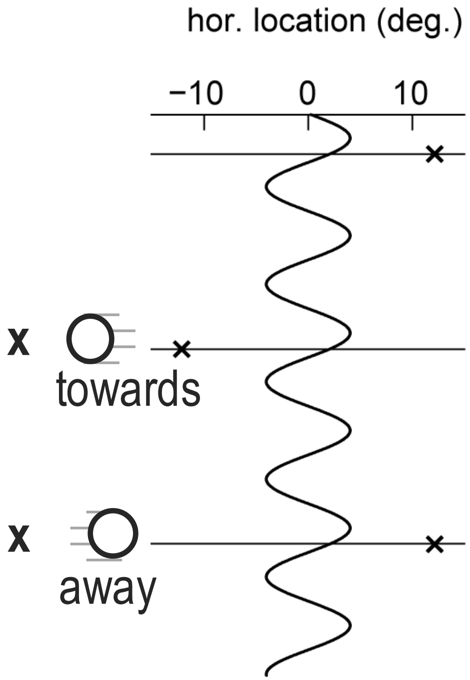
Steering

Looking

no effect of task (same task of discriminating?)
main effect of saccade direction







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Seeing is influenced by cognition

from discrimination back to steering

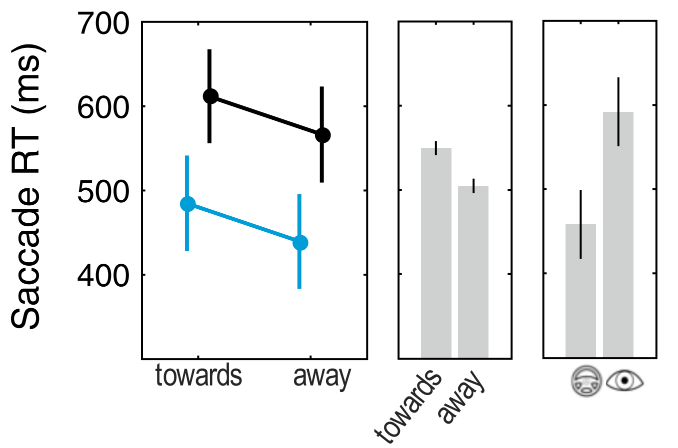
Primary tasks

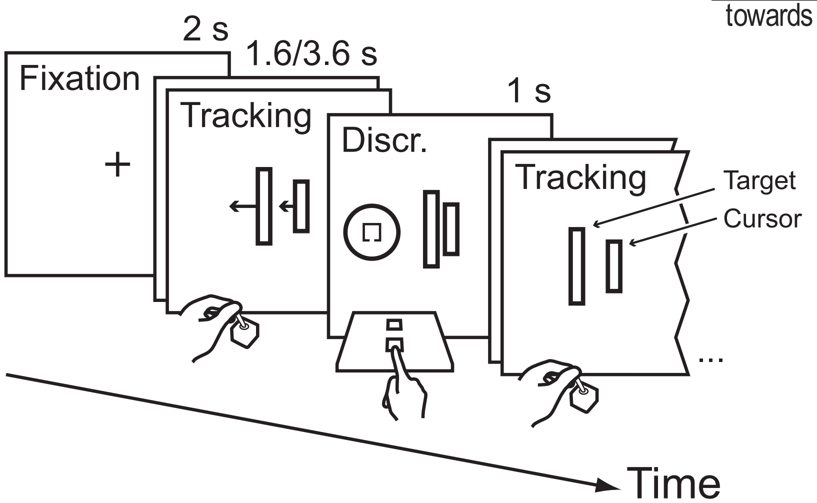
Steering

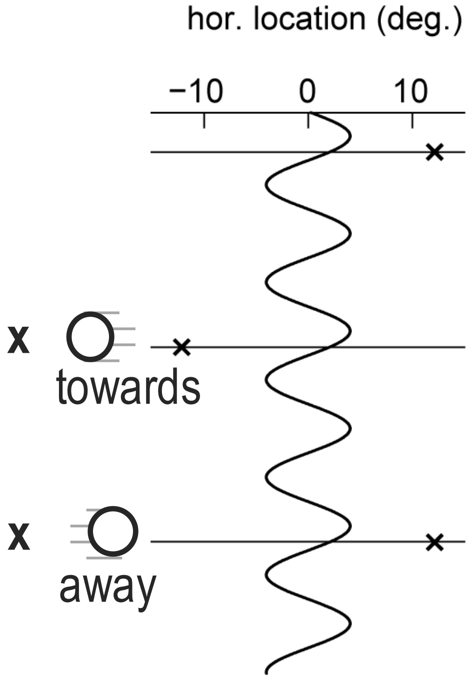
Looking

main effect of task

main effect of saccade direction







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Seeing is influenced by cognition

from discrimination back to steering

Summarized findings

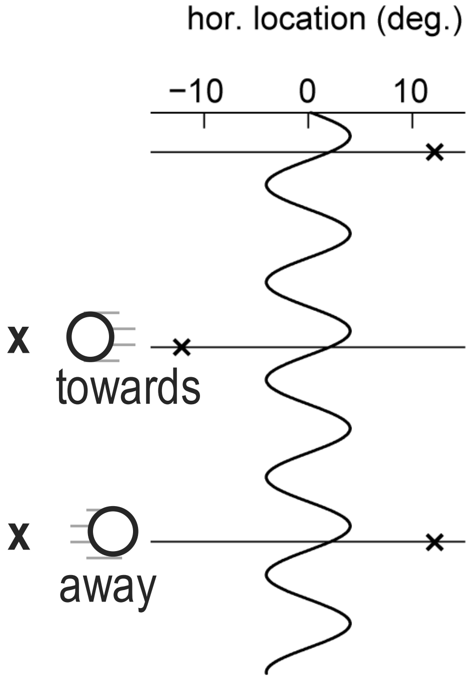
discriminate peripheral object

 =  *saccades to nearing targets are faster*

return to steering or looking

 =  *saccades to nearing targets are slower*

 >  *saccades for steering are faster than saccades for looking*



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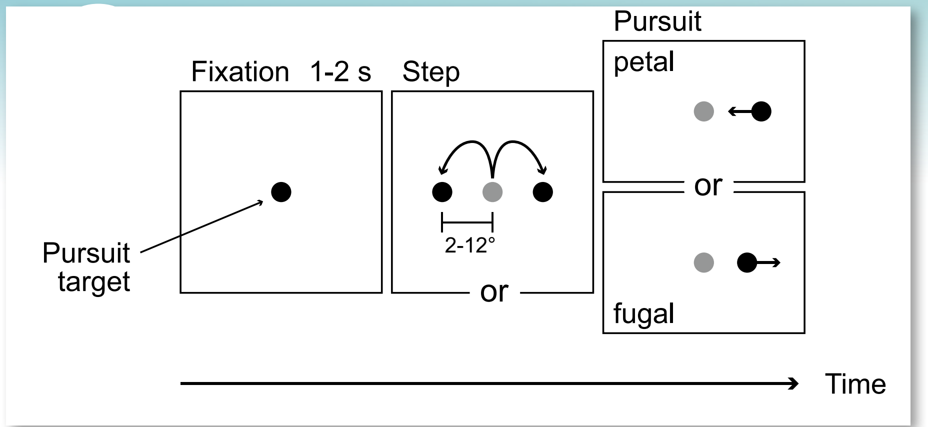
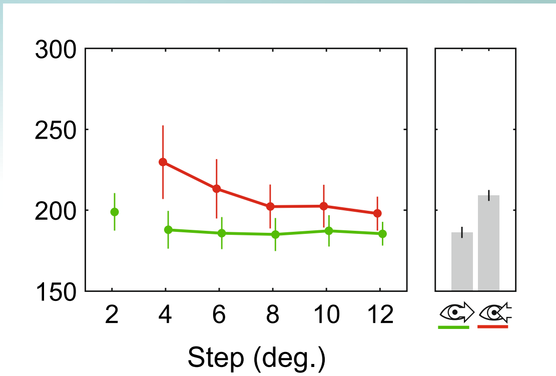
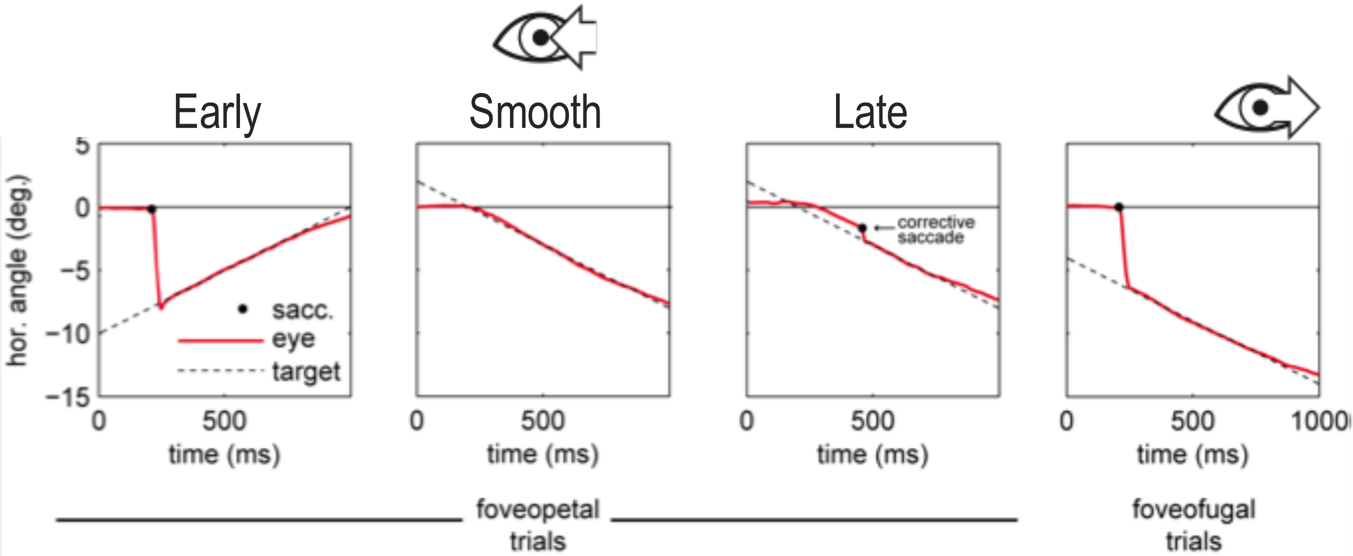
Saccade to Smooth-Pursuit

Different types of eye-movement transitions



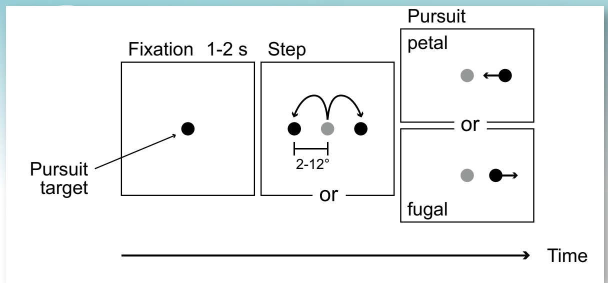




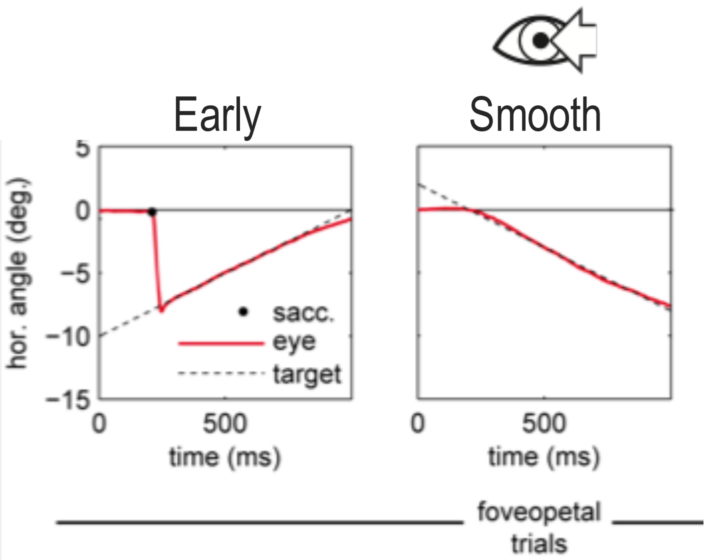
Bieg H-J , Chuang LL , Bülthoff HH and Bresciani J-P (2015) **Asymmetric saccade reaction times to smooth pursuit** *Experimental Brain Research* **233(9)** 2527-2538.

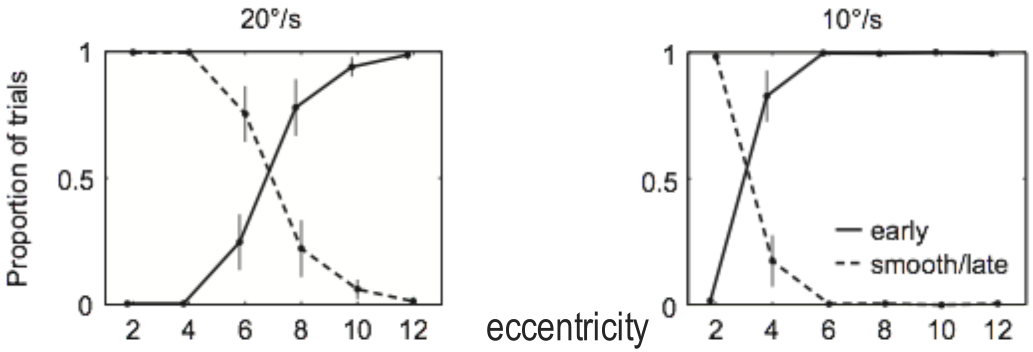
Saccade to Smooth-Pursuit

When do we perform an Early or Smooth transition?



position of peripheral object does **not** determine early saccade versus smooth pursuit





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Saccade to Smooth-Pursuit

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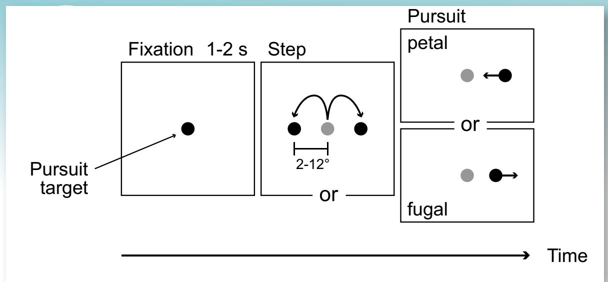
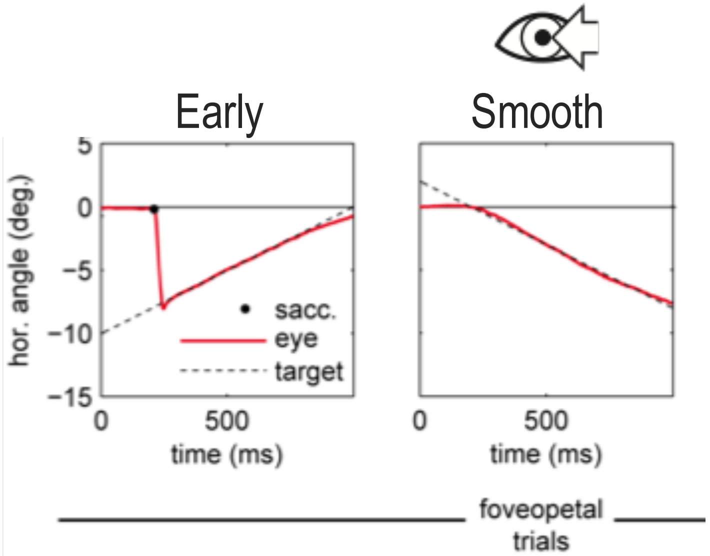
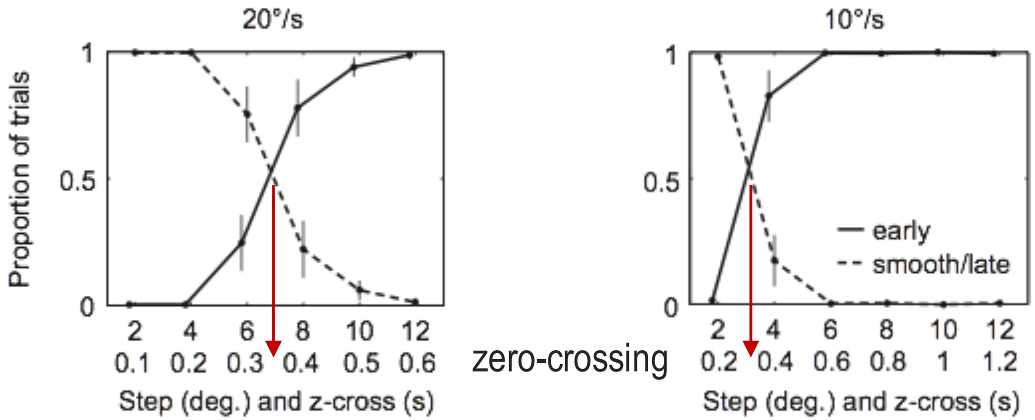


estimated time-of-arrival

determines early saccade versus smooth pursuit





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Saccade to Smooth-Pursuit

When do we perform an Early or Smooth transition?

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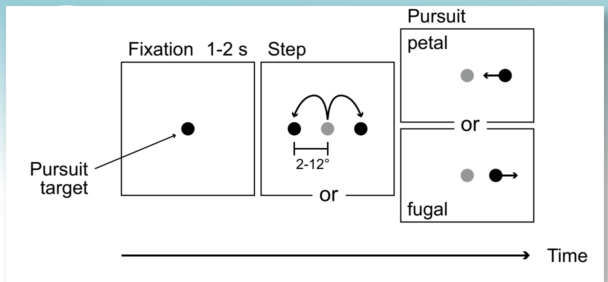
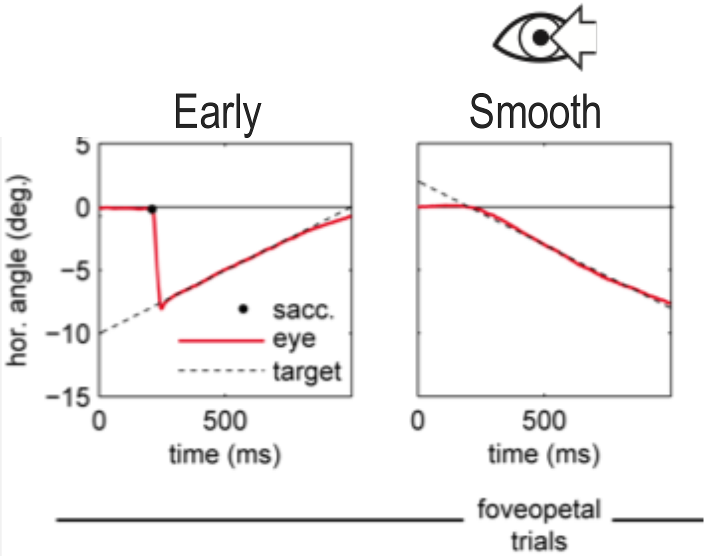
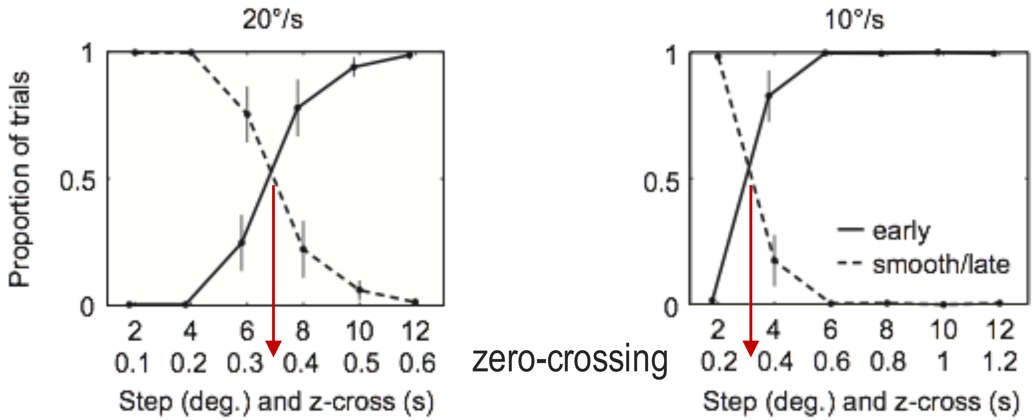


Eye-movements are based on predicted variables, **not** sensed variables

estimated time-of-arrival
determines early saccade versus smooth pursuit





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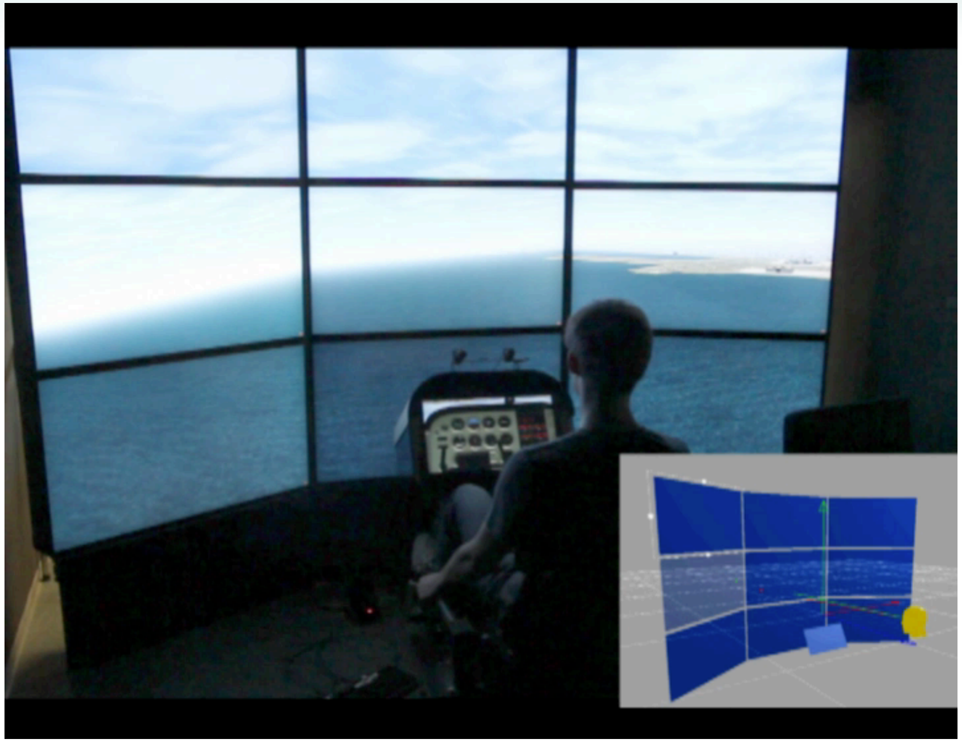
Experimental Brain Research **233(9)** 2527-2538.

User-state influences eye-movement planning

Eye-movement Planning

for instrument scanning

Light-weight rotorcraft, BO105



Light-weight fixed-wing aircraft, Cessna

Instrument scanning & Control Performance

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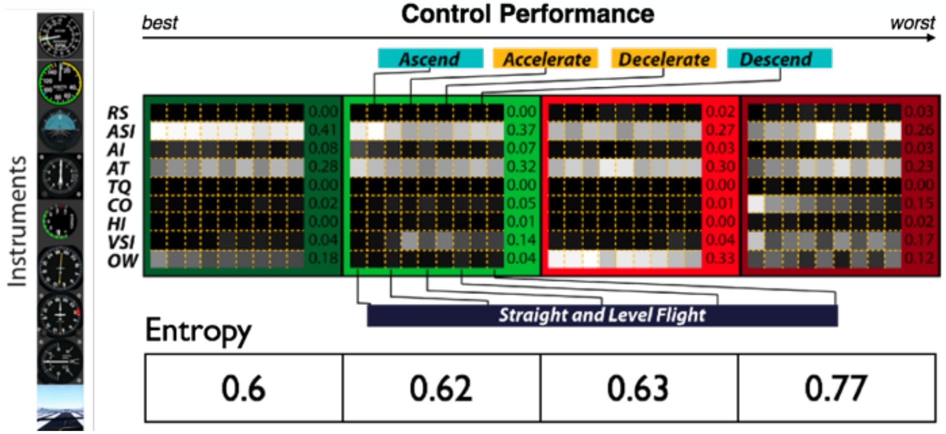
Dwell Frequencies



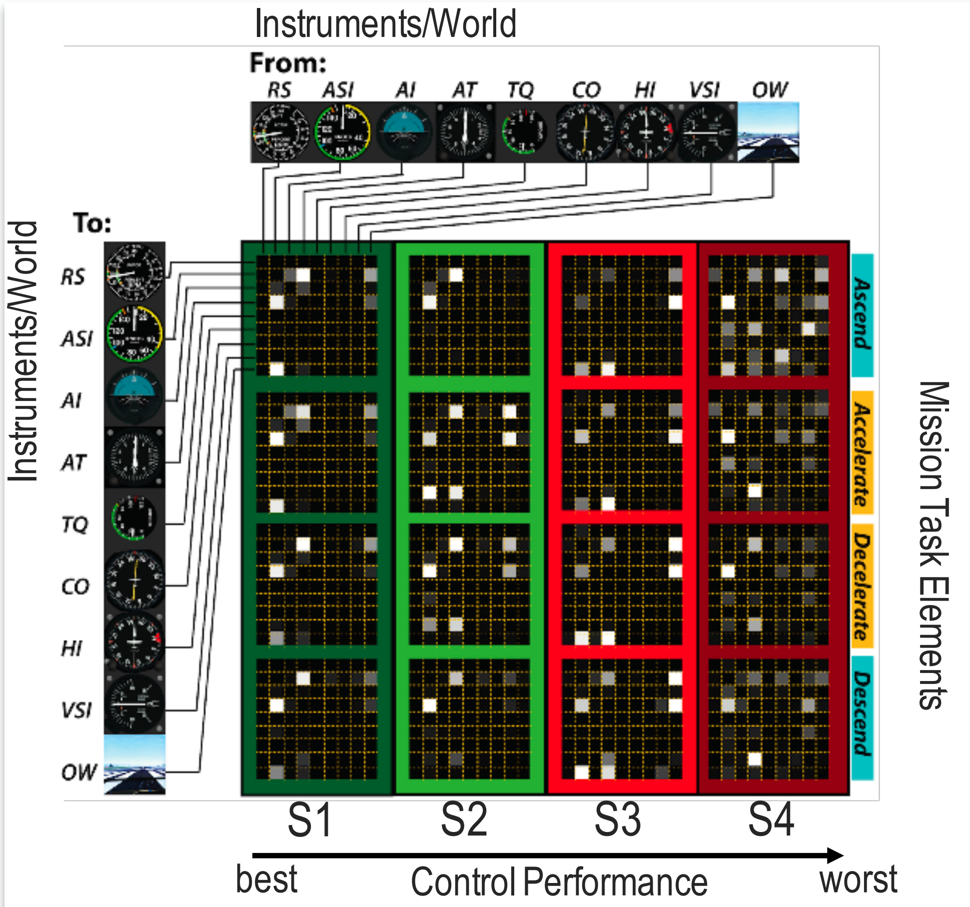
Fixation data can be interpreted in two ways

- good pilots have attentional tunneling, or
- good pilots know where to look

Transition-matrix is unambiguous

- good pilots have consistent scan-pattern

Dwell Transitional Probabilities



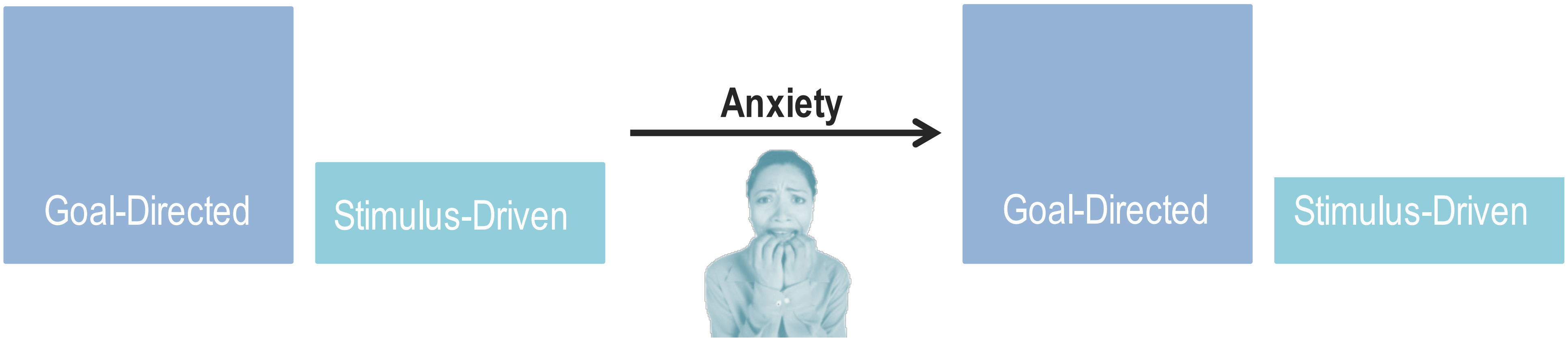
Chuang, L. L., Nieuwenhuizen, F. M., & Bülthoff, H. H. (2013). A fixed-based flight simulator study: the interdependence of flight control performance and gaze efficiency. In Engineering Psychology and Cognitive Ergonomics. Applications and Services (pp. 95-104). Springer Berlin Heidelberg.

Attentional Control Theory (ACT)

(Eysenck et al., 2007)

Anxiety imbalances two attentional subsystems

- Goal-directed system (Endogenous)
- Stimulus-driven system (Exogenous)



Goal-directed resources

Executive functions: Updating, Shifting, Inhibition

Hypothesis: Eye-movement planning involves executive functions

- anxiety reduces "goal-directed resources"
- executive functions require "goal-directed resources"

n-Back delayed-matching task

0-back

- updating

2-back

- updating, shifting, inhibition

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, a H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. *Cognitive Psychology*, *41*(1), 49–100. http://doi.org/10.1006/cogp.1999.0734

Tanji, J., & Eiji, H. (2008). Role of the Lateral Prefrontal Cortex in Executive Behavioral Control. *Physiological Reviews*, *88*(140), 37–57. http://doi.org/10.1152/physrev.00014.2007.

Fixed-wing Landing Task

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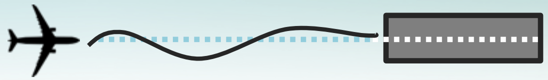
Dual axis tracking task

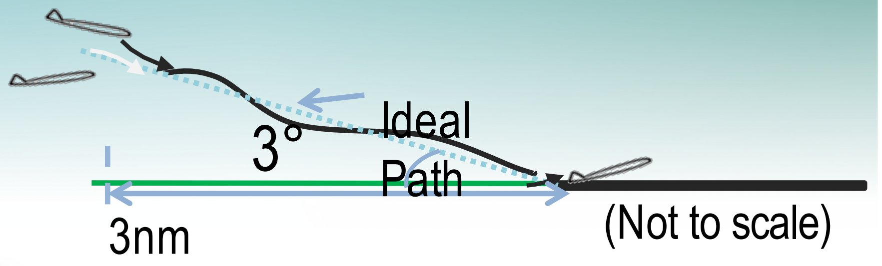


Not to scale

Lateral Control - Track
Runway Centreline

Fixed-wing Landing Task

Dual axis tracking task



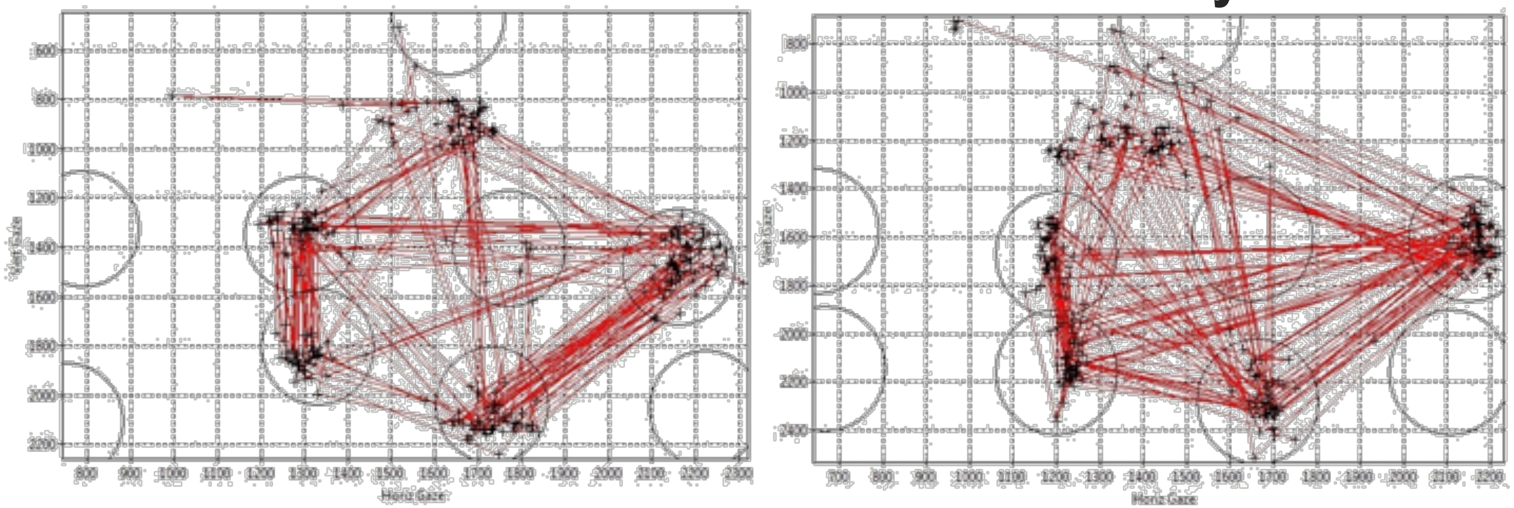
Vertical Control - Track Glideslope

ACT predicts that…

… anxiety should reduce goal-directed resources,
which should reduce the efficiency of goal-directed behavior

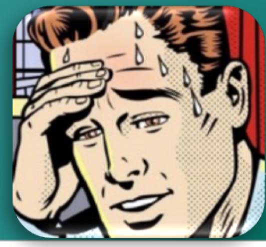
Representative participant

Pre-test **Anxiety**



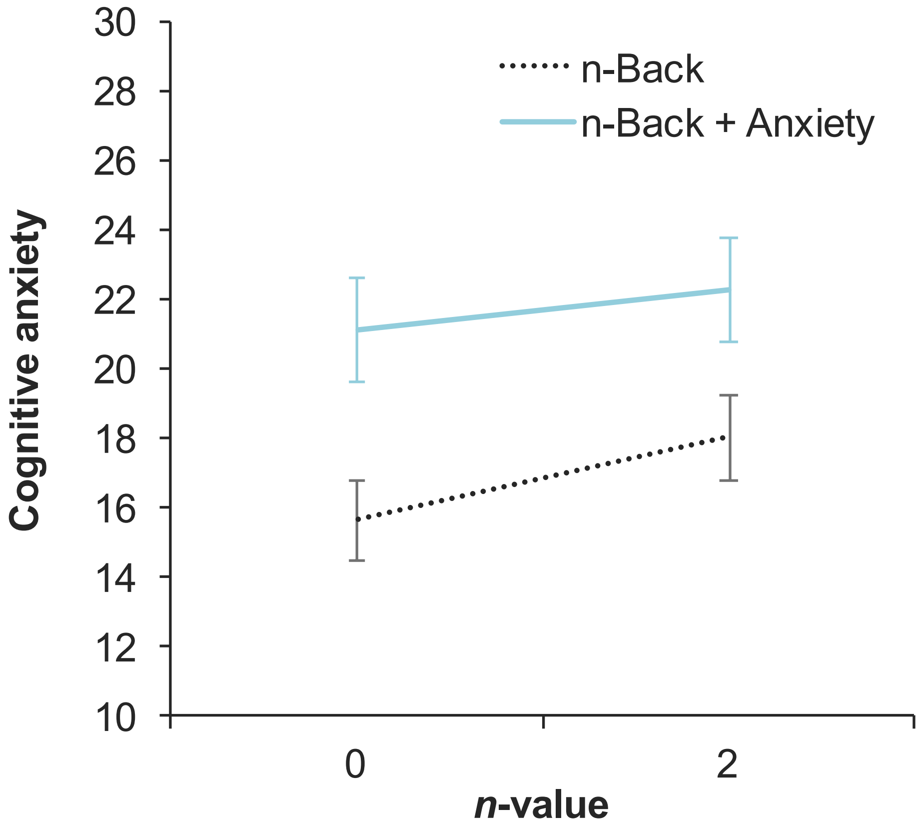
- *Instructions*
- *Monetary incentives – 50€*
- *Video camera*
- *VATSIM*

Anxiety manipulation validated

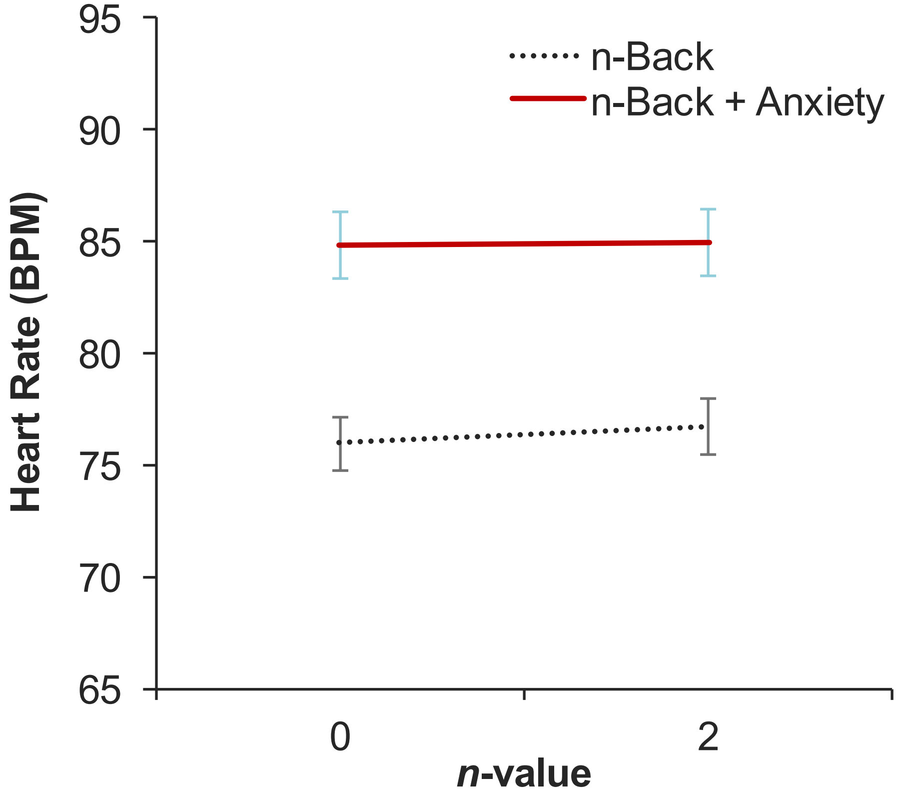


Cognitive Anxiety Questionnaire

CSAI (Cox, Martens, Russell, 2003)



Heart Rate



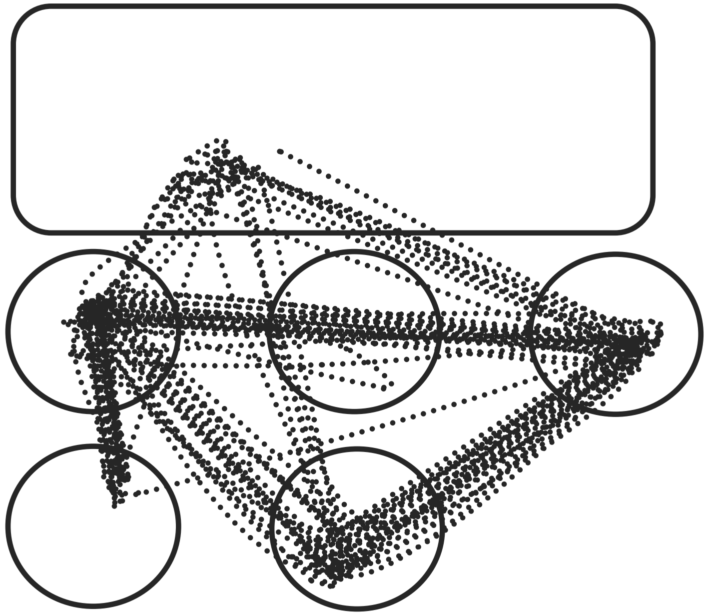
ACT predicts that…

… anxiety should reduce goal-directed resources,
which should reduce the ***efficiency of goal-directed behavior***

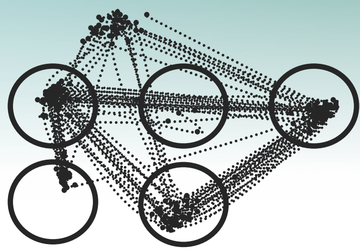
Visual scanning entropy (Stark & Ellis, 1986)

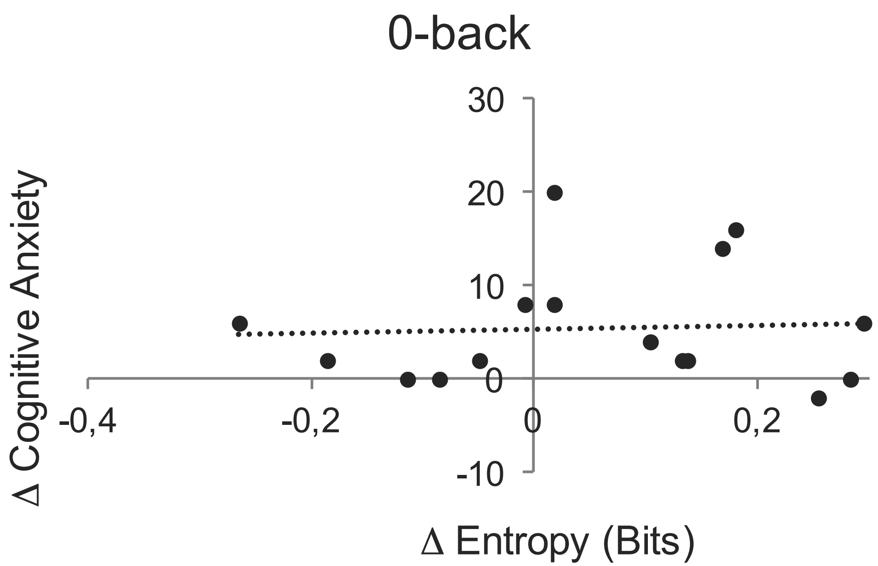
- Predictability of next dwell location

$$\text{Entropy} = \sum_{i=1}^{n} p(i)\left[\sum_{j=1}^{n} p(j\,|\,i)\log_2 p(j\,|\,i)\right], i \neq j$$

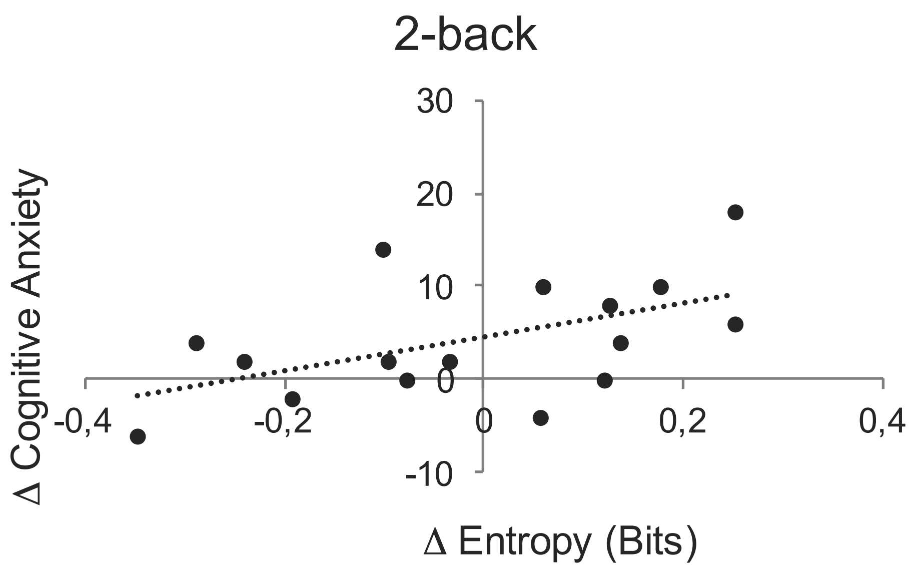


Instrument Scanning Entropy





r = .06, *p* = .82



r = .53, *p* = .036

Summary: Eye-movement planning

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The transition probability of dwells reflects eye-movement planning and executive functions.

- Eye-movement planning relies on executive functions (shifting, updating, inhibition).
- Anxiety reduces the role of executive functions on eye-movements.
- Increasing executive functions' load can further reduce its influence on eye-movements.

Conclusions

What you see is what you get(?)

How to develop a steering model

wear a silly contraption and perform a dangerous task

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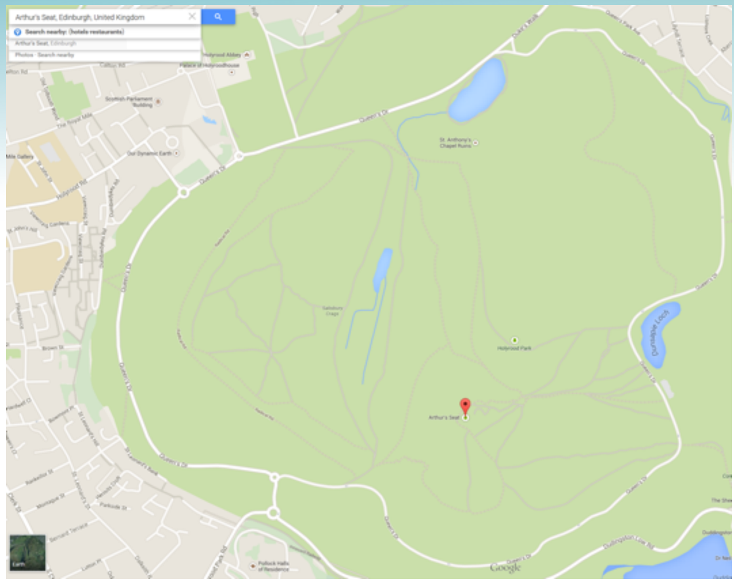
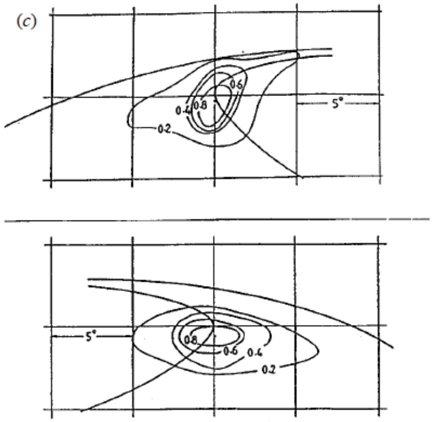
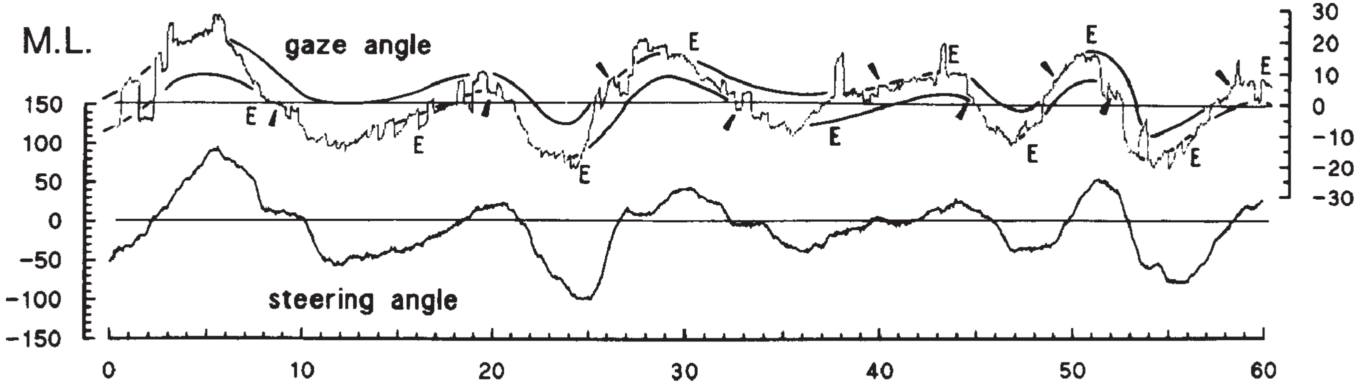


Queen's Road, Edinburgh, Google Maps

Image: Land M, Mennie N, Rusted J (1999)





Land, M. F., & Lee, D. N. (1994). Where we look when we steer. *Nature*, *369*(6483), 742–744.

How to develop a steering model

Infer what information/error is

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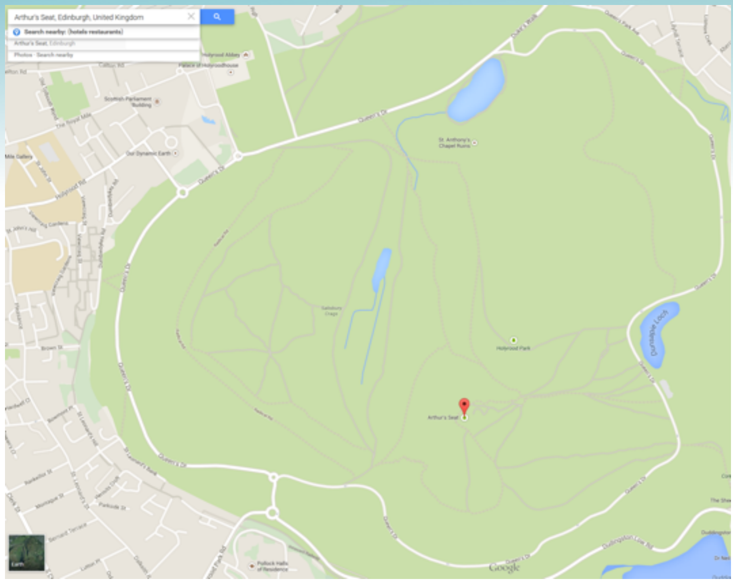

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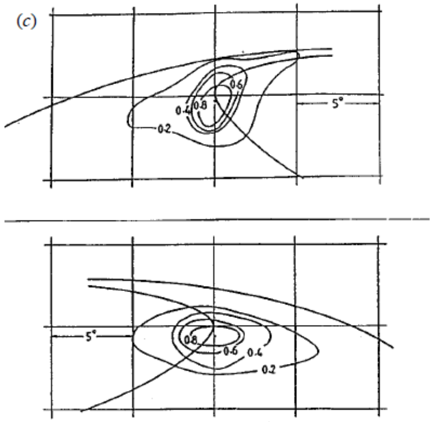

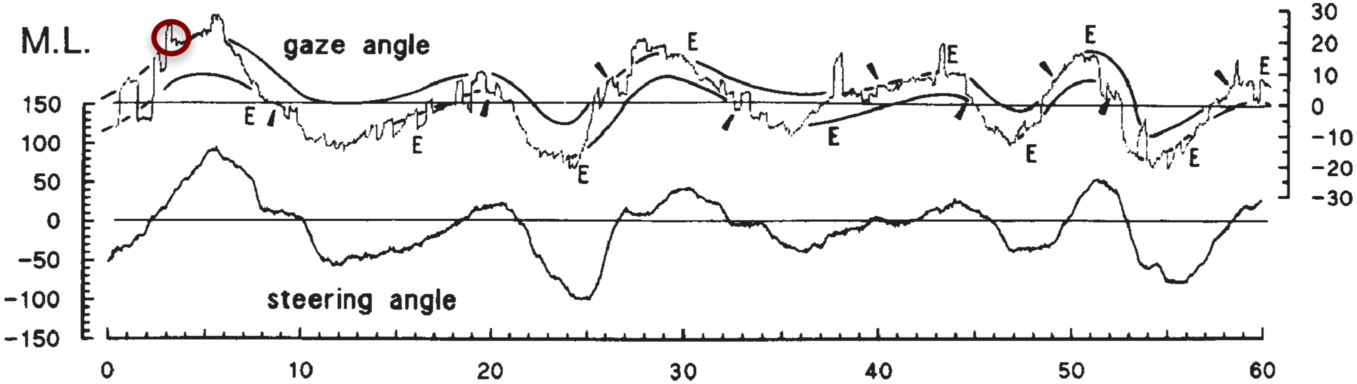

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How to develop a steering model

Infer what information/error is

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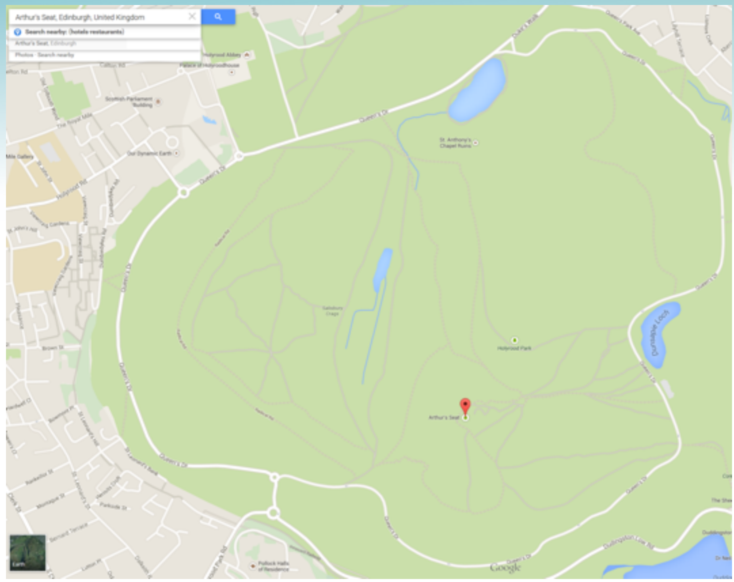

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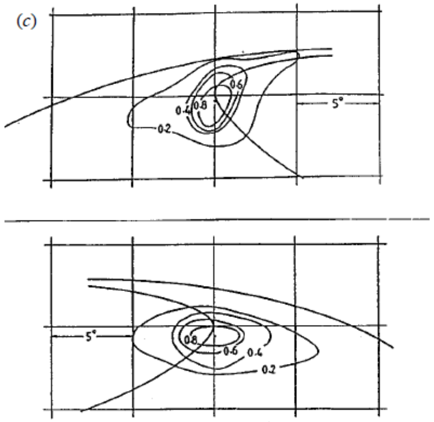
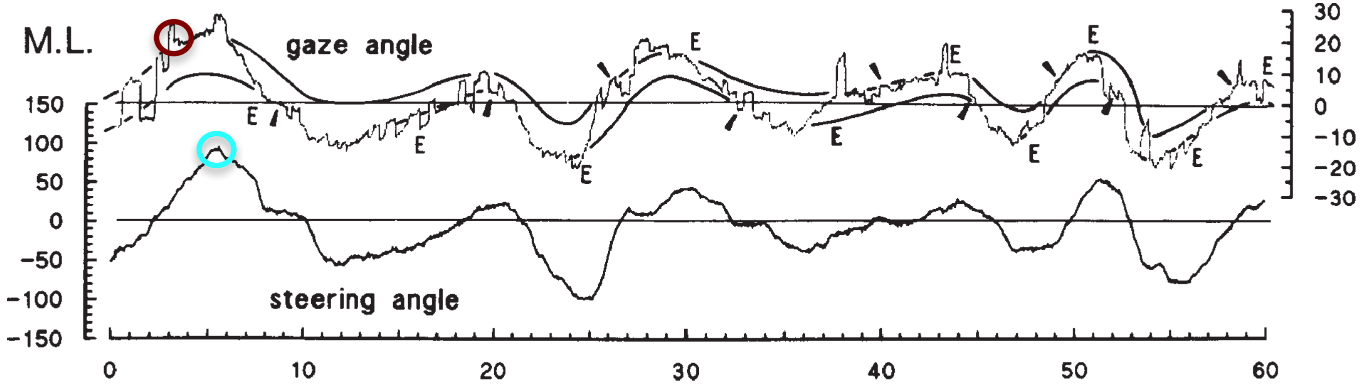




Land, M. F., & Lee, D. N. (1994). Where we look when we steer. *Nature*, *369*(6483), 742–744.

How to develop a steering model

draw the rest of the fantastic owl

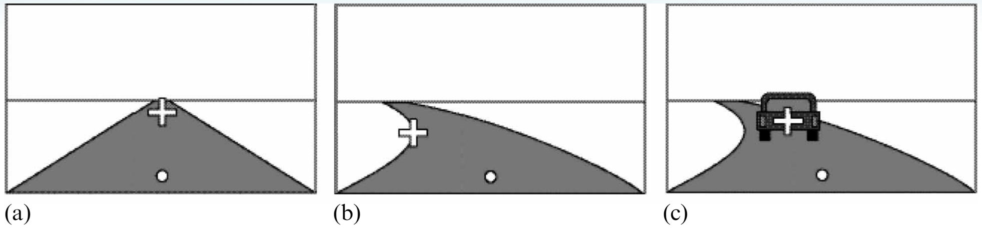
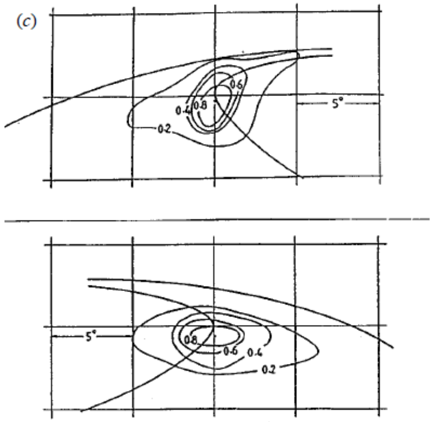


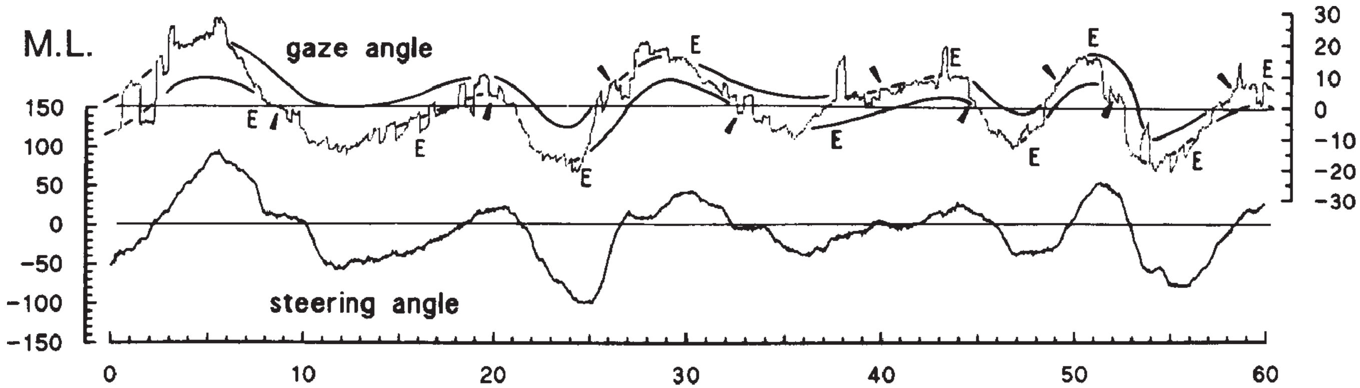
Figure 1. Near and far points for three scenarios: (a) straight roadway with vanishing point, (b) curved roadway with tangent point, and (c) presence of lead car.

Two point steering model

$$\dot{\varphi} = k_\mathrm{f}\dot{\theta}_\mathrm{f} + k_\mathrm{n}\dot{\theta}_\mathrm{n} + k_\mathrm{I}\,\theta_\mathrm{n}$$

Salvucci, D. D., & Gray, R. (2004). A two-point visual control model of steering. *Perception*, *33*(10), 1233–1248.



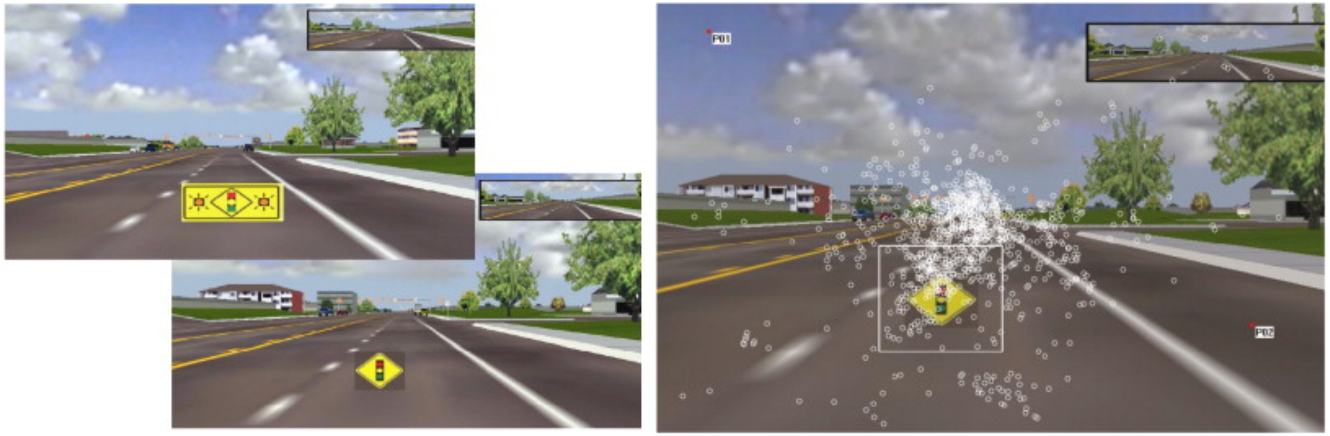


Land, M. F., & Lee, D. N. (1994). Where we look when we steer. *Nature*, *369*(6483), 742–744.

Simple models of human-machine interactions

could help us interpret eye-movement data

1. Fixation count (HUD): Young > Old
2. Fixation summed duration (HUD): Young > Old
3. Vertical spread: Young > Old
4. Horizontal spread: Old > Young

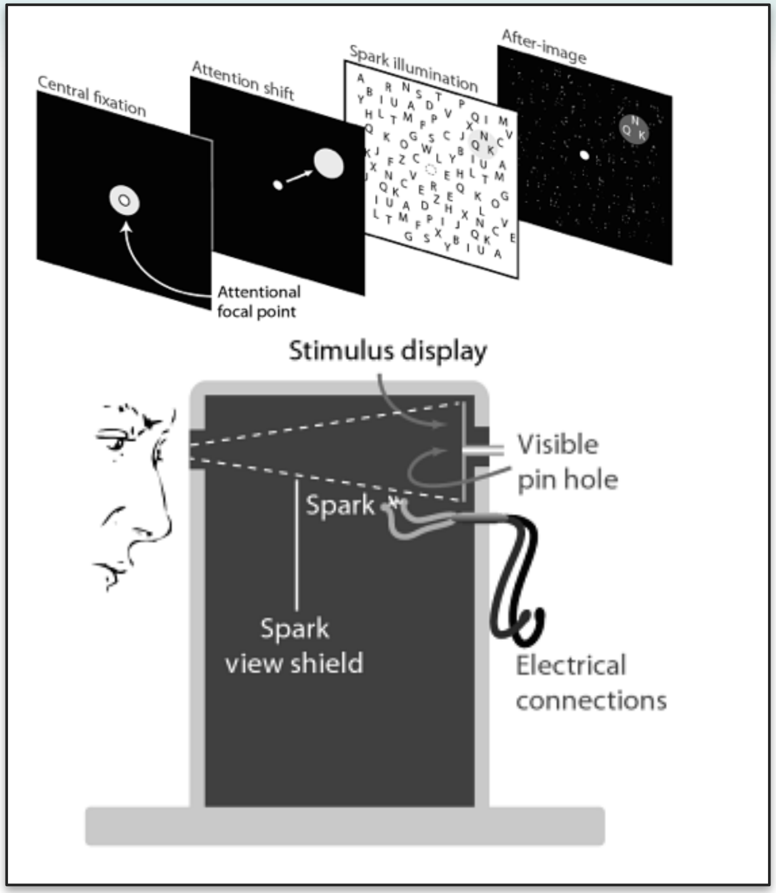


Caird, J. K., S. L. Chisholm, and J. Lockhart. "Do in-vehicle advanced signs enhance older and younger drivers' intersection performance? Driving simulation and eye movement results." *International Journal of Human-Computer Studies* 66.3 (2008): 132-144.

We have known since Helmholtz...

Fixation is not (covert) attention

Hermann von Helmholtz



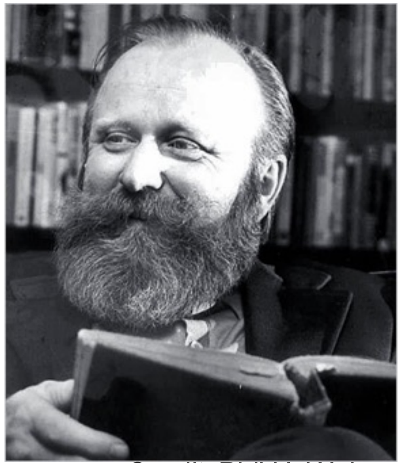
Credit: Orienting of Attention (Wright, 2008)

To conclude

- worthwhile challenge to track eye-movements, not just fixations
- top-down influences eye-movements, not fixations
- fixations indicate information that may or may not be task-relevant
- some measures of eye-movement:
  - ✓ *saccade response time*
  - ✓ *probability distributions of saccade length*
  - ✓ *probability distributions of AOI transitions*
- models of human behavior allow for meaningful measures of eye-movement

A process cannot be understood by stopping it. Understanding must move with the flow of the process, must join and flow with it.

Frank Herbert



Credit: Phil H. Weber

Thank you for your attention

Acknowledgements:
Dr. Boyan Bonev
Dr. Jon Allsop
Dr. Hans-Joachim Bieg
Prof. Heinrich Bülthoff

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