Visual search with heterogeneous distractors

Andra Mihali[1,2,] Joshua Calder-Travis[1,3] and *Wei Ji Ma*[1]

[1]Center for Neural Science and Department of Psychology
New York University

[2]Research Foundation for Mental Hygiene and Department of Psychiatry,
Columbia University
[3]University of Oxford and University Medical Center Hamburg-Eppendorf

The psychophysics of visual search with heterogeneous distractors

Andra Mihali, Wei Ji Ma
doi: https://doi.org/10.1101/2020.08.10.244707

Explaining the effects of distractor statistics in visual search

Joshua Calder-Travis, Wei Ji Ma
doi: https://doi.org/10.1101/2020.01.03.893057

Visual search

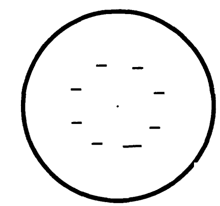
Photo by Johannes Eisele/AFP—Getty Images

Photo by Lucy Orloski, Flickr

Photo from QLP Locksmith

Psychophysics / Signal detection approaches to visual search

- Deliberately very simple stimuli: *Palmer, Verghese, and Pavel (2000)*
  - unidimensional stimuli, parametrically varied
  - brief stimulus presentation times to prevent eye movements
  - stimuli at equal retinal eccentricities
  - wide spacing between stimuli



Palmer, Ames and Lindsay, 1993

- SDT models
  - dissociate component processes (encoding and decision stages)
  - can predict accuracy as a function of set size and target-distractor similarity *Palmer, 1990, Shaw, 1982; Palmer et al., 1993; Eckstein et al., 2000; Verghese, 2001*

Distractor type	Psychophysics / SDT approach	Ecological validity
Homogenous	Extensive work, well understood	Lower
Heterogeneous	Less work, Less well understood	Higher

Visual search with heterogeneous distractors

- Distractor heterogeneity increases search time

Gordon, 1968; Gordon, Dulewicz, & Winwood, 1971; Farmer & Taylor, 1980, Lleras et al, 2019

- *Duncan & Humphreys (1989)* proposed that search performance
  - decreases as target-distractor similarity increases
  - decreases as distractor heterogeneity increases
  - interaction

- Tests: *Duncan and Humphreys 1989, Duncan 1989, Nagy & Thomas, 2003; Vincent et al., 2009*

- But:
  - heterogeneity has not been systematically varied (e.g. letters)
  - no process-level understanding of observer decision-making like in SDT

Psychophysics / Signal detection approaches to visual search with heterogeneous distractors

Some work with heterogeneous distractors within the SDT approach:

Rosenholtz, 2001, Vincent et al, 2009, Ma et al, 2011,
Mazyar, van den Berg and Ma, 2012, 2013
Bhardwaj, van den Berg, Ma, and Josic, 2016

But detailed characterizations of search performance with respect to distractor statistics and task types are still lacking

Outline

1. Assess in a comprehensive fashion which summary statistics related to distractor heterogeneity affect performance. Compare with *Duncan and Humphreys, 1989*
   – Two task types within subject: localization and detection *Liu, Healey and Enns, 2003, Cameron et al, 2004, Dukewich and Klein, 2009, Vincent 2011*

2. Fit an optimal-observer model and see if it accounts for these effects *Ma et al, 2011, Mazyar, van den Berg and Ma, 2012, Ma et al, 2015, Calder-Travis et al, 2020*

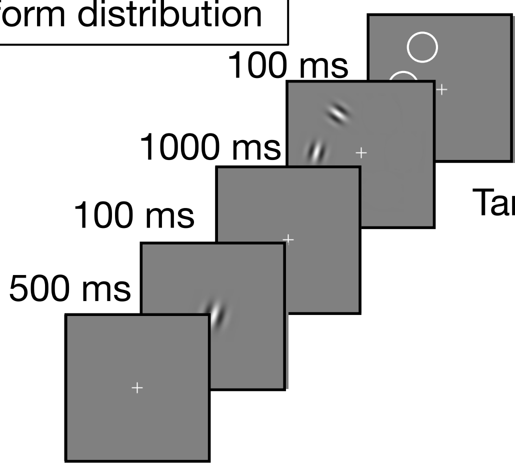
3. Visual search in memory: comparison with perception *Kuo, Rao, Lepsin and Nobre, 2009; Kong and Fougnie, 2019*

Visual search task: n-AFC localization and detection

Localization

Where was the target?
Mouse click

Set size: 2, 3, 4 or 6
Uniform distribution

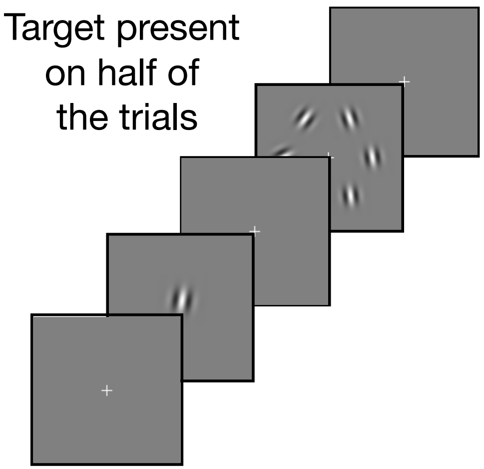


Target always present

Detection

Target present or absent?
Button press

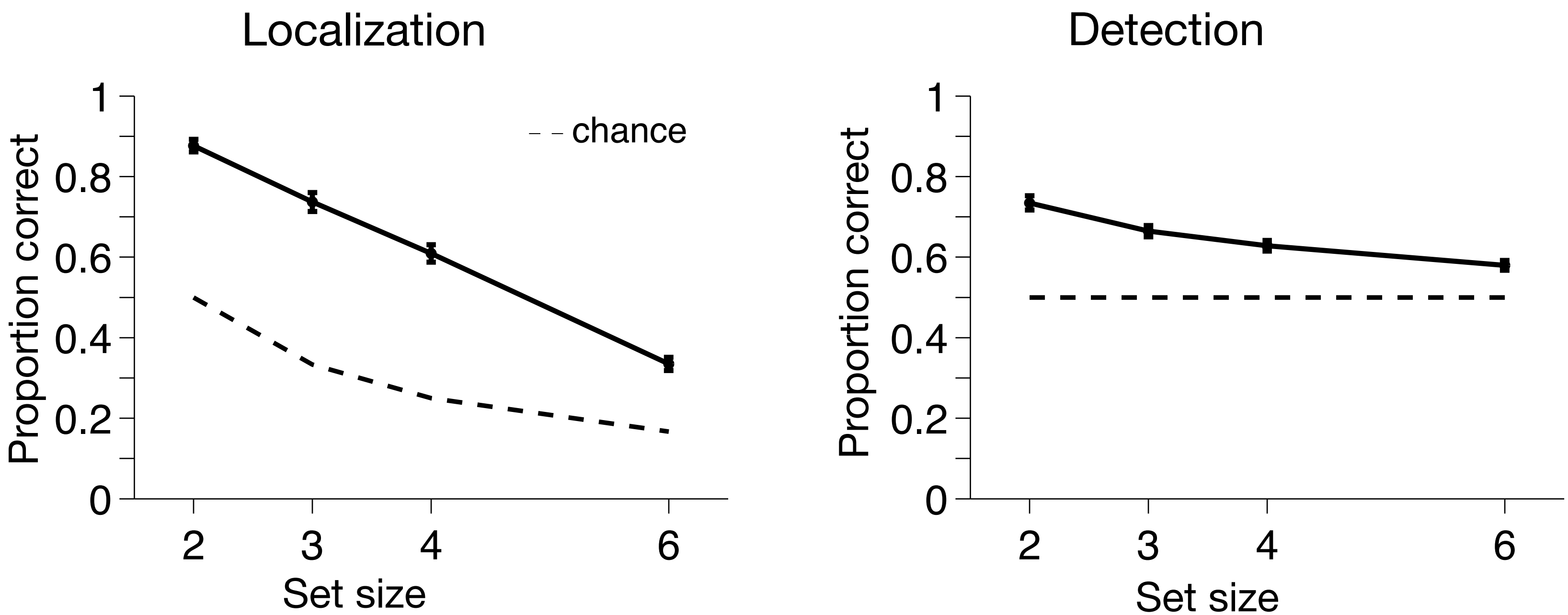
Target present on half of the trials



Observers also did a Memory condition, which we will discuss later

Accuracy as a function of set size

11 observers



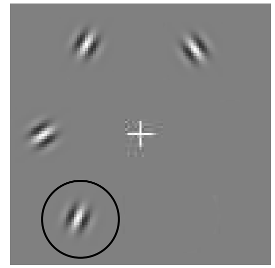
Effect of set size: $p < 0.001$

Effect of set size: $p < 0.001$

- However, many factors besides set size may affect performance
- More so than homogenous distractors, heterogeneous distractors afford rich summary statistics, which we will use to characterize behavior

Trial-by-trial summary statistics

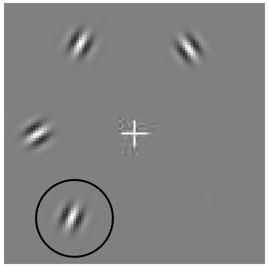
target T



Within a trial, what distractor statistics can we extract?

Trial-by-trial summary statistics

target T



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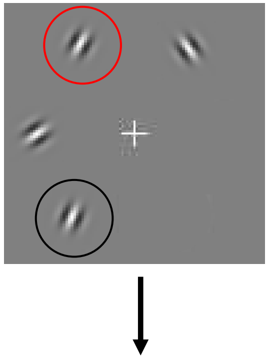
Most similar distractor

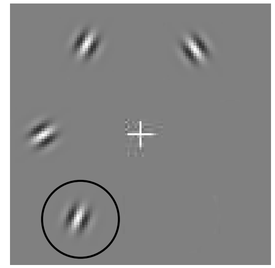


Min T-D difference (°)

For both localization and detection

Trial-by-trial summary statistics

target T



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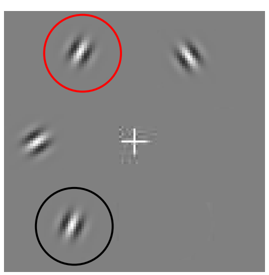
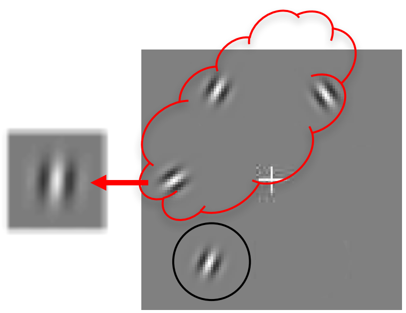


Min T-D difference (deg)

Circular mean of distractors

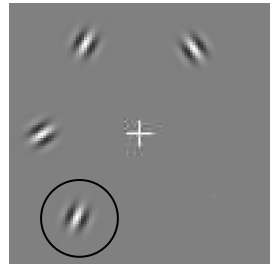


T-D mean (deg)

For both localization and detection

Trial-by-trial summary statistics

target T →



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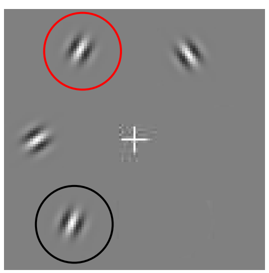
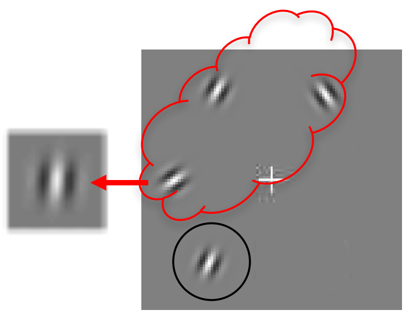


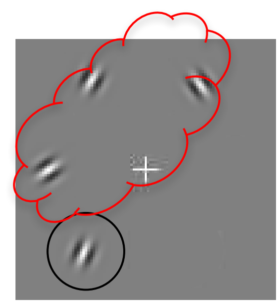
Min T-D difference (deg)

Circular mean of distractors



T-D mean (deg)

Circular variance (CV) of distractors

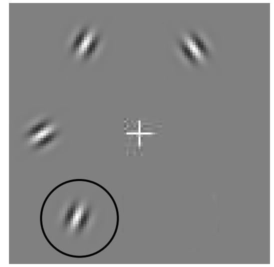


Distractor variance
>0, <1

For both localization and detection

Trial-by-trial summary statistics

target T →



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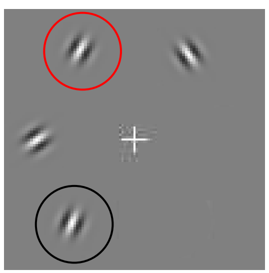
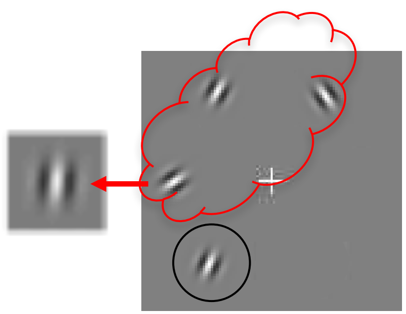


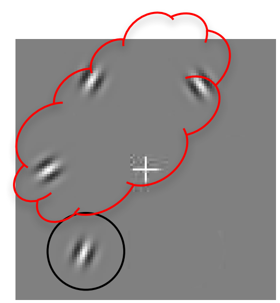
Min T-D difference (deg)

Circular mean of distractors



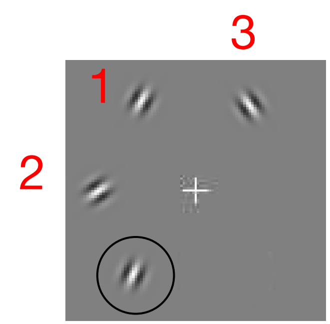
T-D mean (deg)

Circular variance (CV) of distractors



Distractor variance
>0, <1

response to T?



Rank of similarity of response to the target

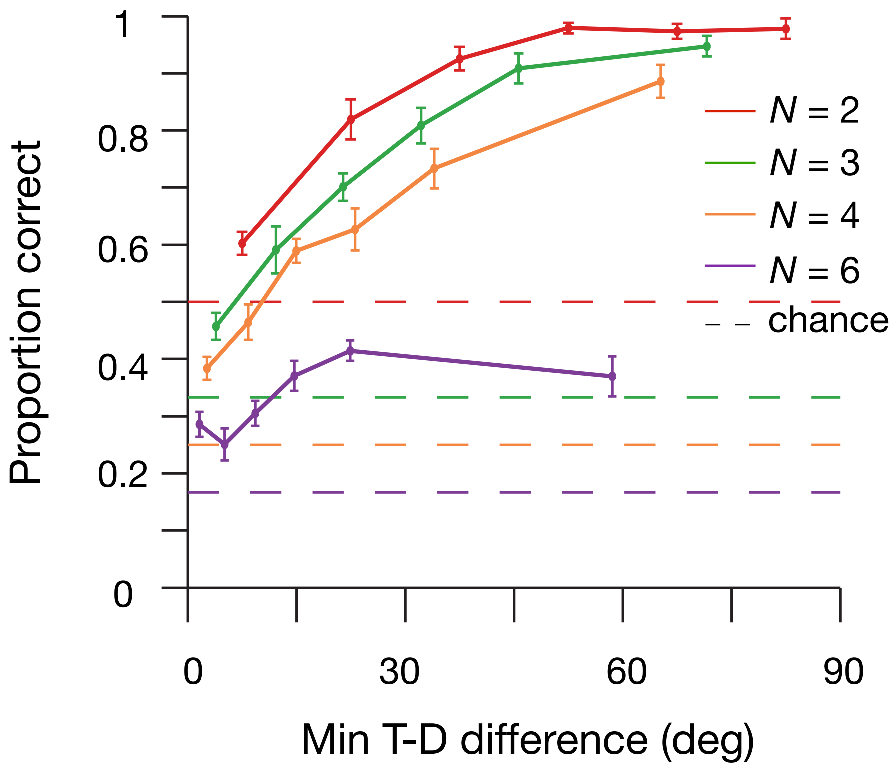
For both localization and detection

For localization errors only

How does performance depend on these 4 trial-by-trial summary statistics?

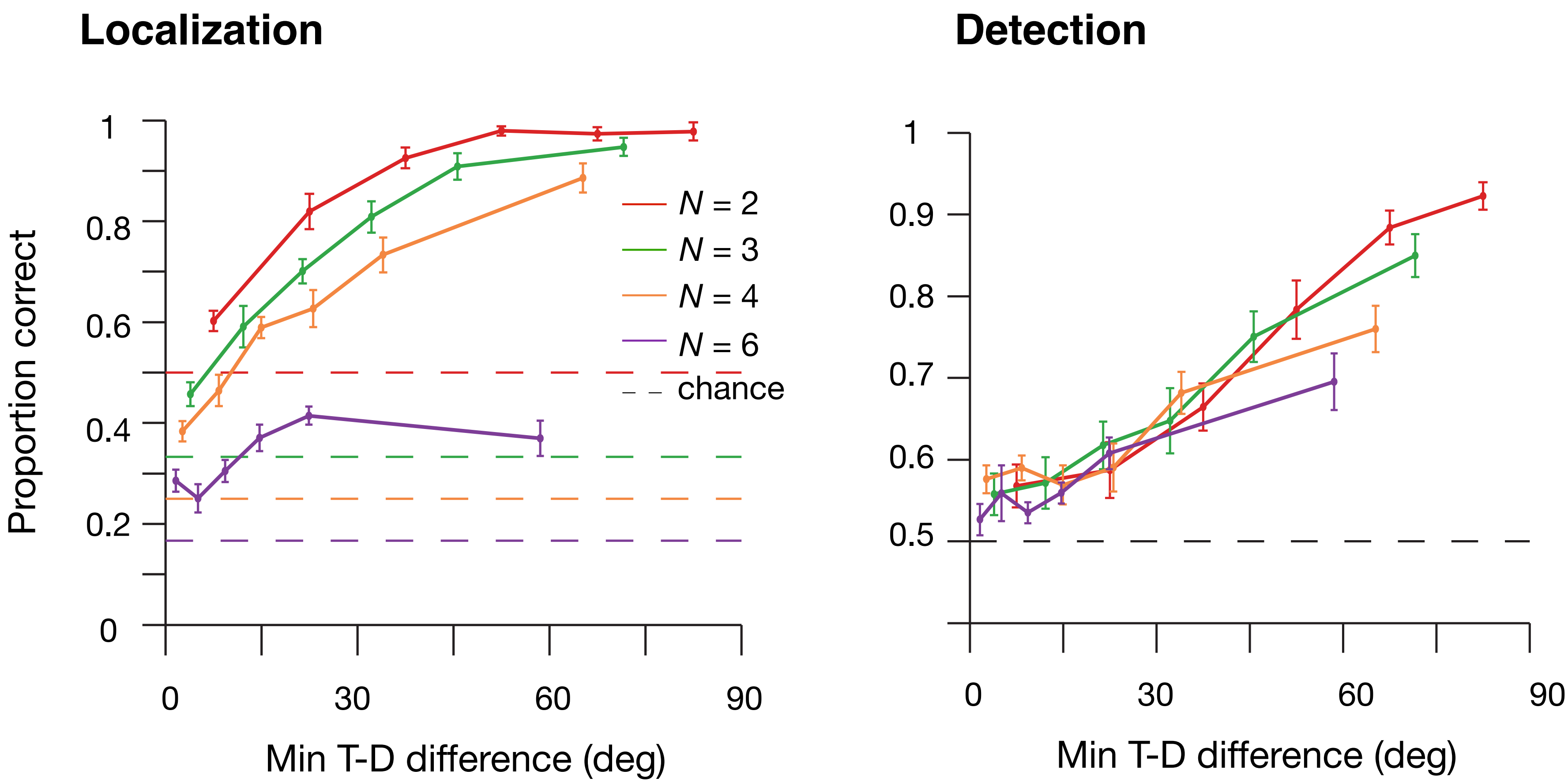
Summary statistic 1: most similar distractor

Localization



Effect of set size: $p < 0.001$
Effect of min T-D difference : $p < 0.001$
Interaction: $p < 0.001$

Summary statistic 1: most similar distractor

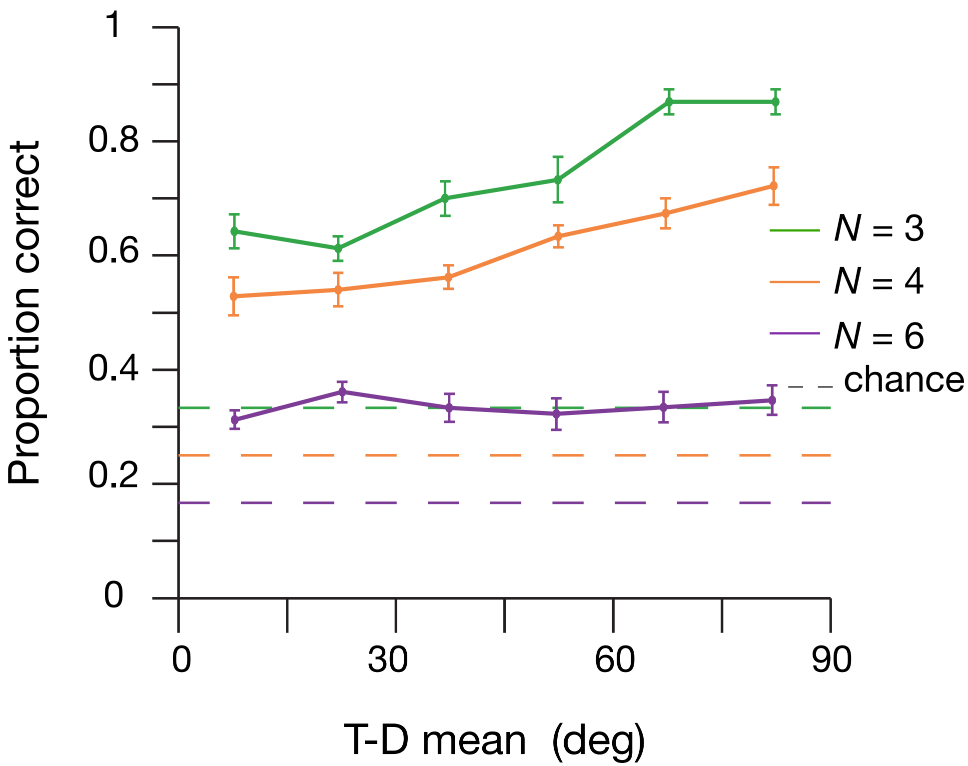


Effect of set size: $p < 0.001$
Effect of min T-D difference : $p < 0.001$
Interaction: $p < 0.001$

Effect of min T-D difference : $p < 0.001$

Summary statistic 2: based on the mean of distractors

Localization



Effect of set size: $p < 0.001$
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Interaction: $p < 0.001$

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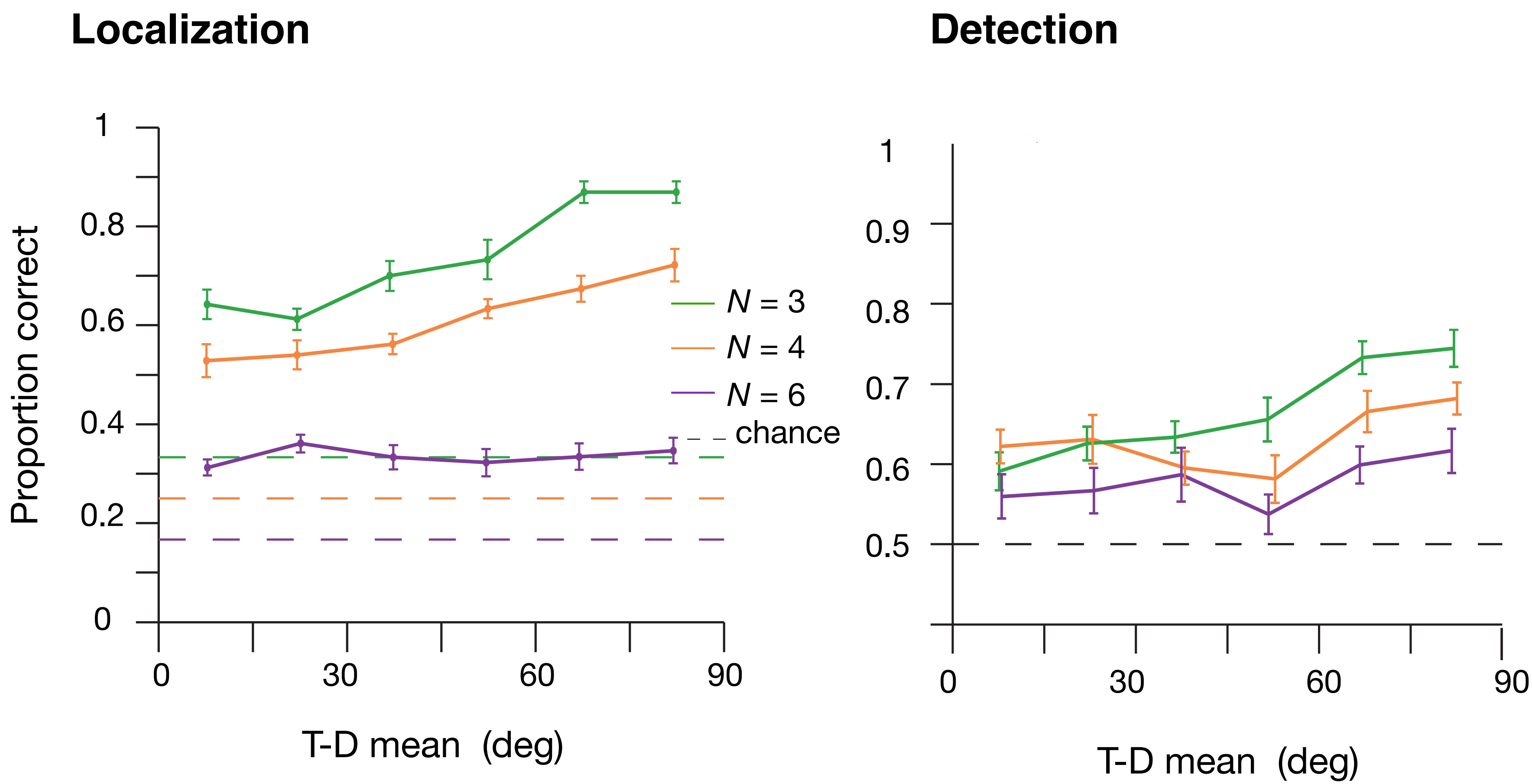
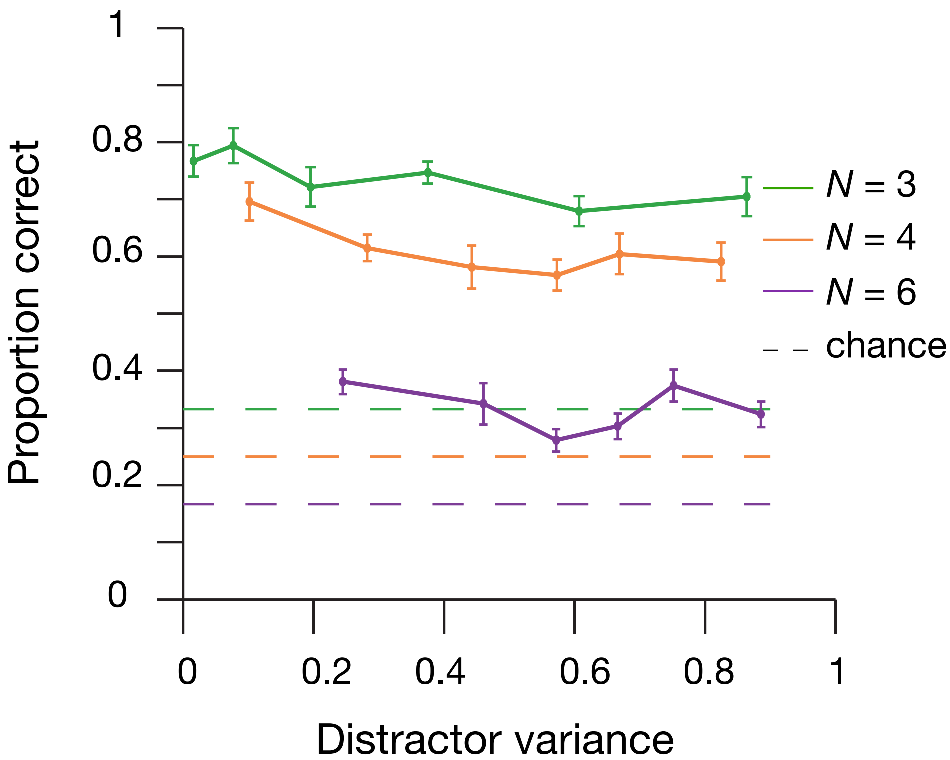


Effect of set size: $p < 0.001$
Effect of T-D mean: $p < 0.001$
Interaction: $p < 0.001$

Effect of set size: $p < 0.001$
Effect of T-D mean: $p < 0.001$
Interaction: $p < 0.05$

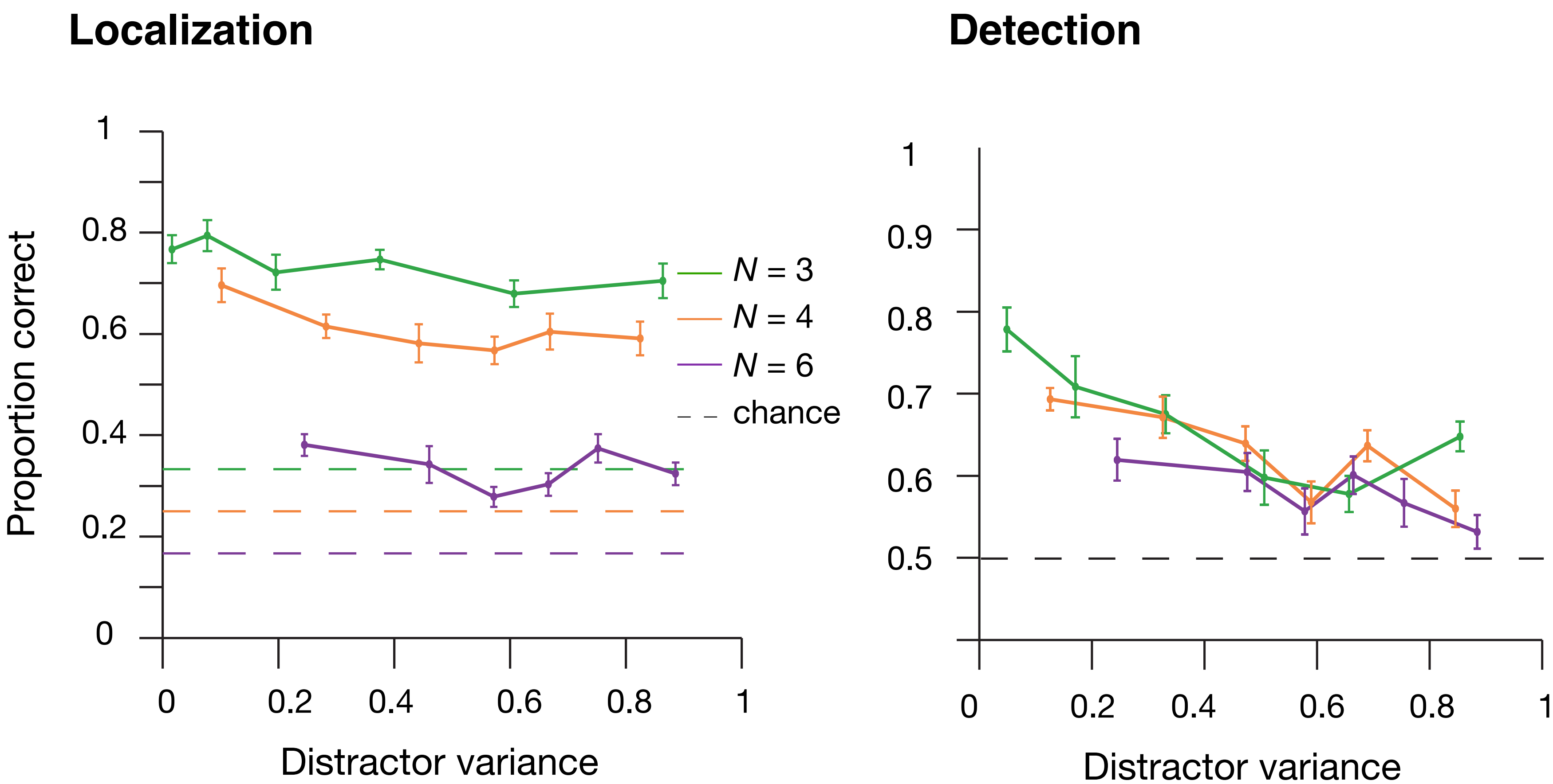
Summary statistic 3: the circular variance of distractors

Localization



Effect of set size: $p < 0.001$
Effect of distractor variance: $p < 0.001$

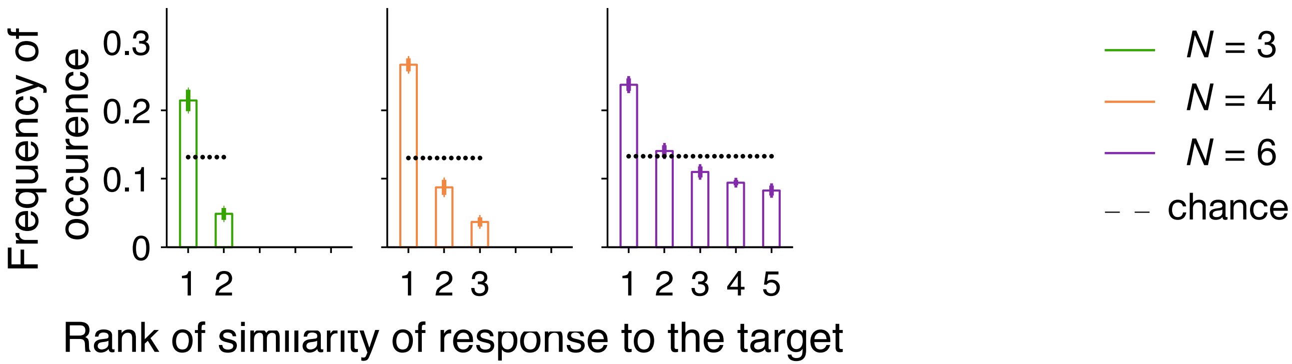
Summary statistic 3: the circular variance of distractors

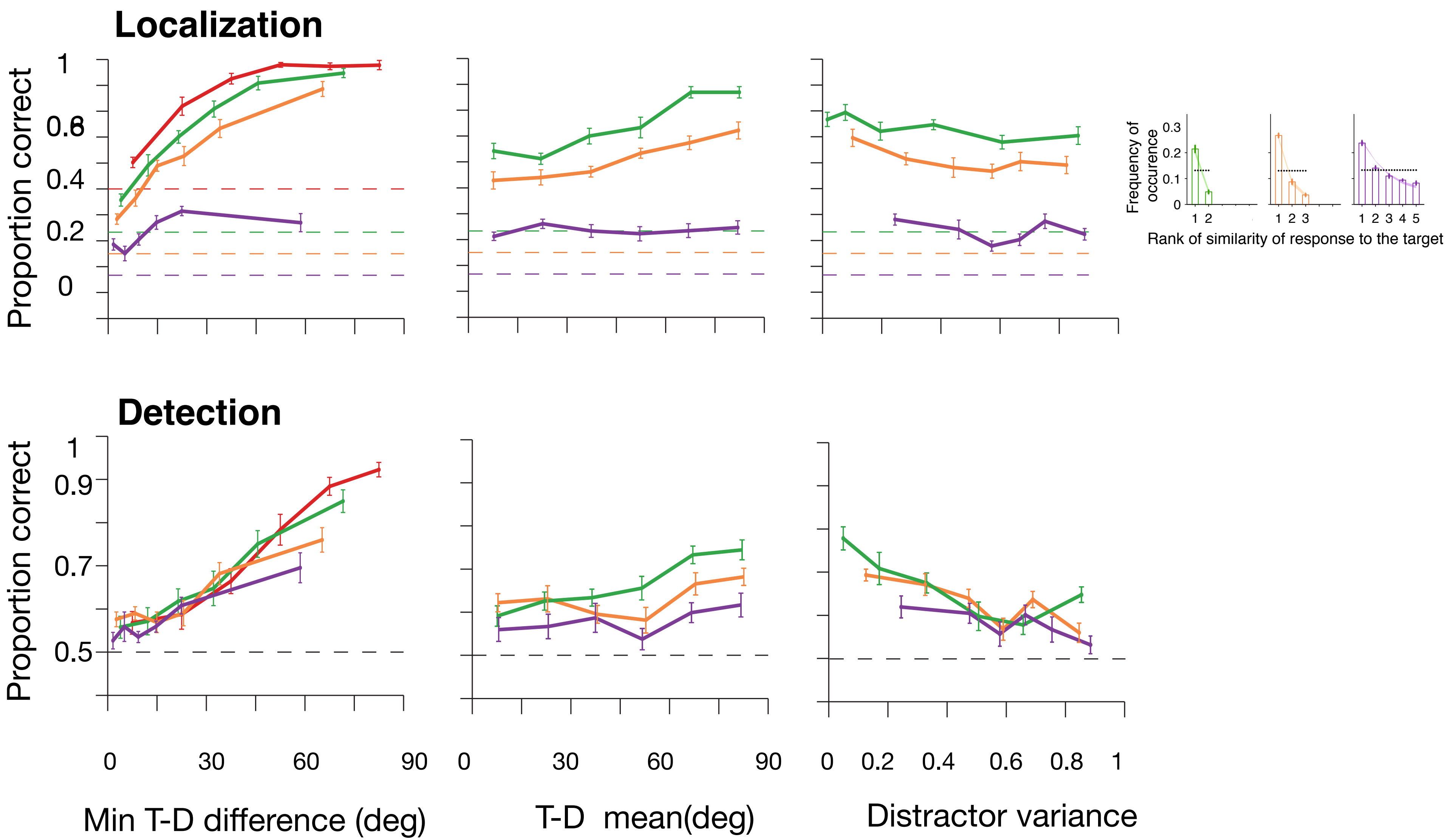


Effect of set size: $p < 0.001$
Effect of distractor variance: $p < 0.001$

Effect of set size: $p < 0.05$
Effect of distractor variance: $p < 0.001$

Summary statistic 4 (Localization errors only): Rank of similarity of response to the target





Localization
Detection
Proportion correct
1
0.8
0.6
0.4
0.2
0
0.9
0.7
0.5
Frequency of occurence
0.3
0.2
0.1
1 2
1 2 3
1 2 3 4 5
Rank of similarity of response to the target
0
30
60
90
0.2
0.4
0.6
0.8
Min T-D difference (deg)
T-D mean(deg)
Distractor variance

Which summary statistics are *useful and necessary* for explaining performance?

Model comparison: method inspired by stepwise regression, from *Shen and Ma, 2019*

- Min T-D difference is the most *useful* regressor
- No regressor is *necessary*

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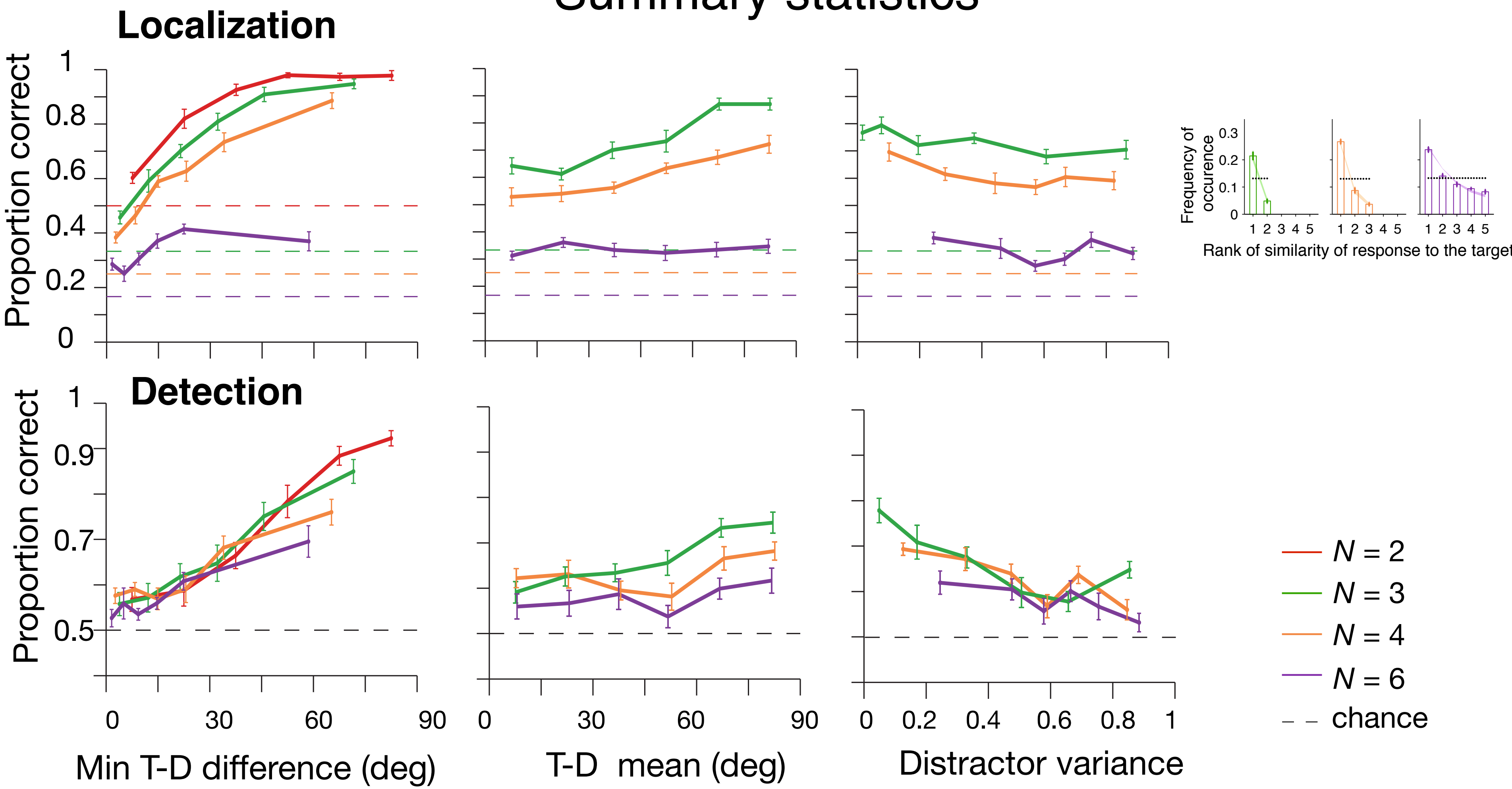
Summary statistics



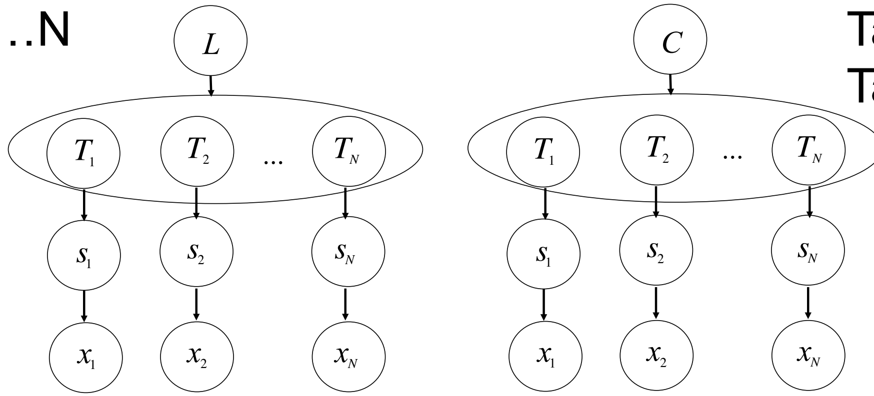
- Not just qualitative trends
- We will use the exact shapes of these curves to constrain the optimal-observer model.

Bayesian optimal-observer model

1. Encoding stage

- Stimuli ⟶ noisy measurements
- Same structure in Localization and Detection

Location L = 1,2,3…N



Target present C = 1
Target absent C = 0

2. Decision stage

Based on the noisy measurements and knowledge of the encoding process:

- Localization: The observer calculates the probability of each possible target location, chooses the most probable location.
- Detection (*Ma et al. 2011, Mazyar, van den Berg and Ma 2012*): the observer calculates the probability that the target is present and reports “target present” when it exceeds a criterion.

The optimal observer maximizes performance given the noise.

Optimal-observer model: encoding stage

$L = 3$

Each location is equally likely to contain the target

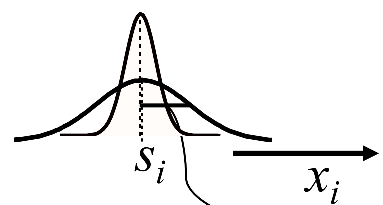
Target orientation
$s_T = 30°$

Stimulus vector
$\mathbf{s}$ = (-10°, 38°, 30°, 27°)

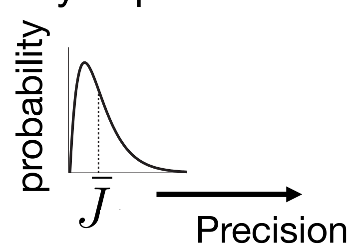
All orientations independently drawn from uniform

Noisy measurements of these orientations, independently drawn from Von Mises centered on the true orientation s_i

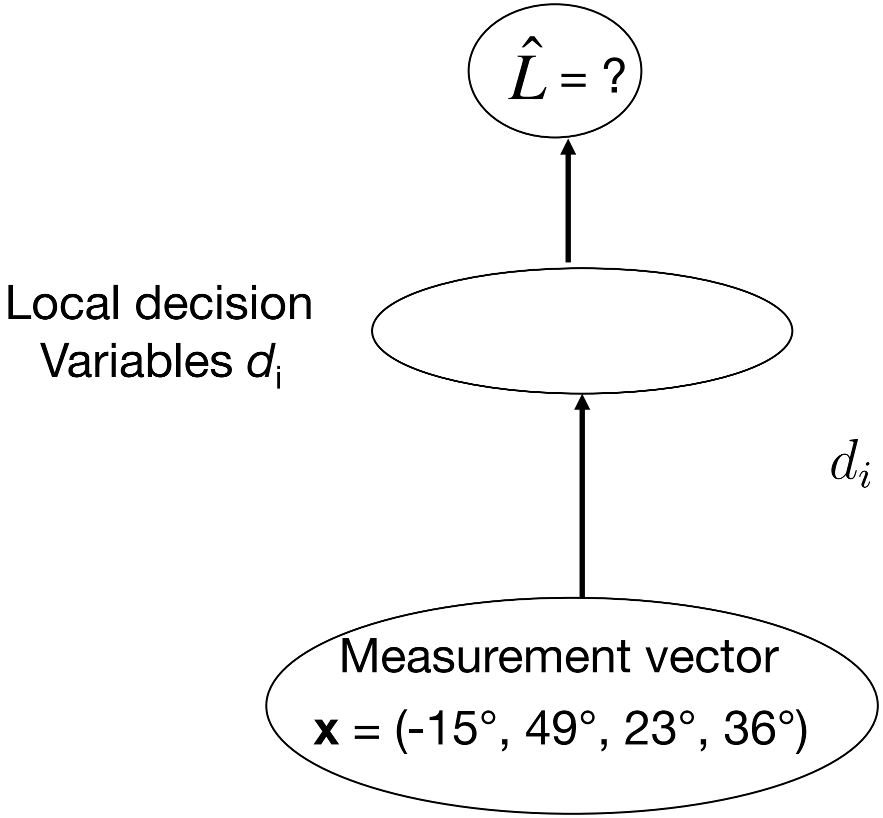
Measurement vector
$\mathbf{x}$ = (-15°, 49°, 23°, 36°)



Variability in precision



Optimal-observer model: decision stage



$$
\begin{aligned}
d_i &= \log \frac{p(x_i|\text{target at location } i)}{p(x_i|\text{distractor at location } i)} \\
&= -\log I_0(\kappa_i) + \kappa_i \cos(x_i - s_T)
\end{aligned}
$$

Parameters and model fitting

- Parameters:
  - Mean precisions at set sizes 2, 3, 4, 6
  - Parameter for variability in precision
  - For detection: extra p_{present} parameter
  - decision noise parameters

Both separate and joint for Localization and Detection

- We fit the localization and detection data both separately and jointly

- Maximum-likelihood estimation of parameters
  - Fit individual-subject data
  - Trial-by-trial predictions obtained through simulations
  - Algorithm: Bayesian Adaptive Direct Search, *Acerbi and Ma, 2017*

https://github.com/NYUMaLab
https://www.cns.nyu.edu/malab/resources.html
https://github.com/lianaan/Vis_Search

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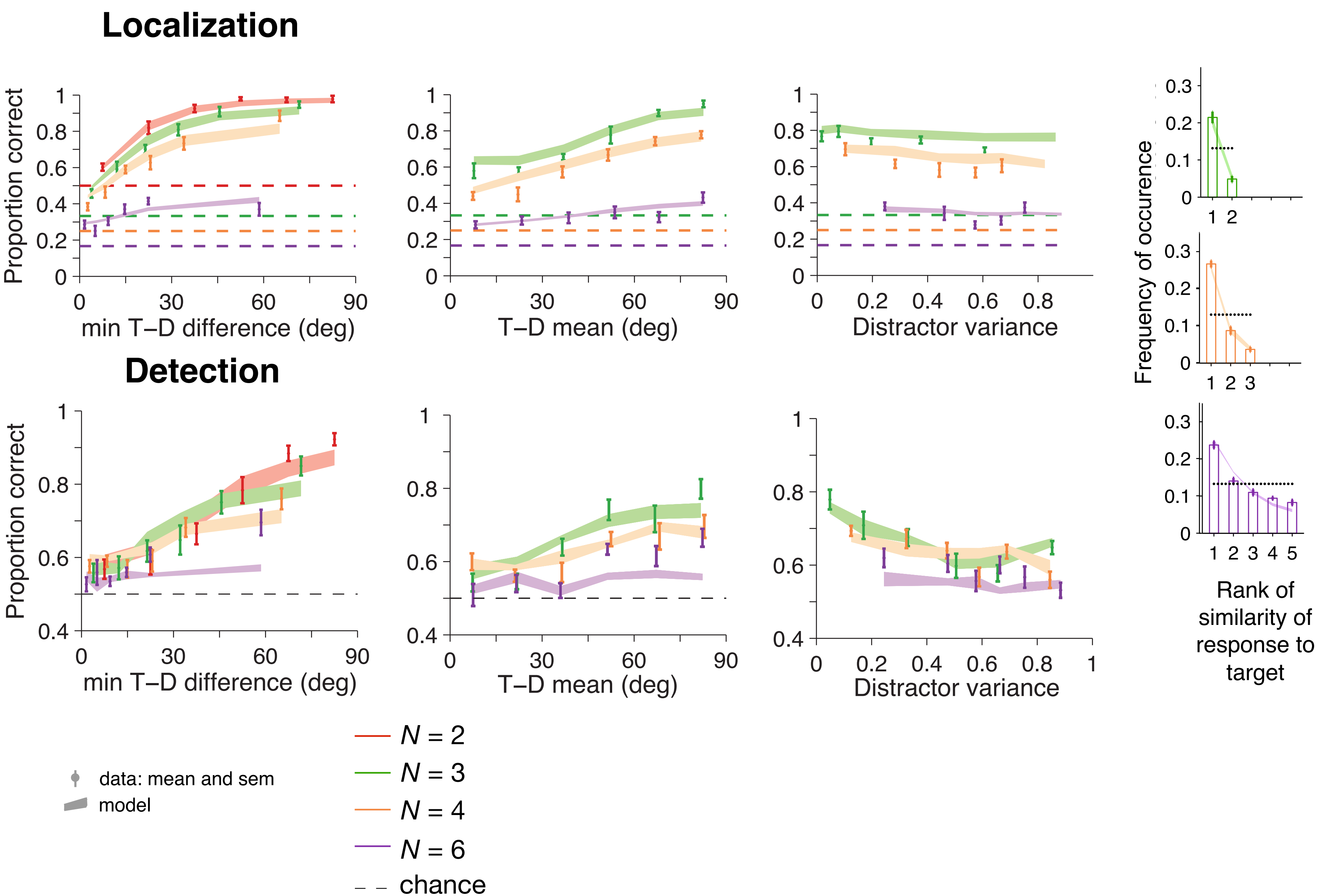
How well does the fitted optimal-observer model account for the summary statistics?

Optimal-observer model fits – jointly to Localization and Detection



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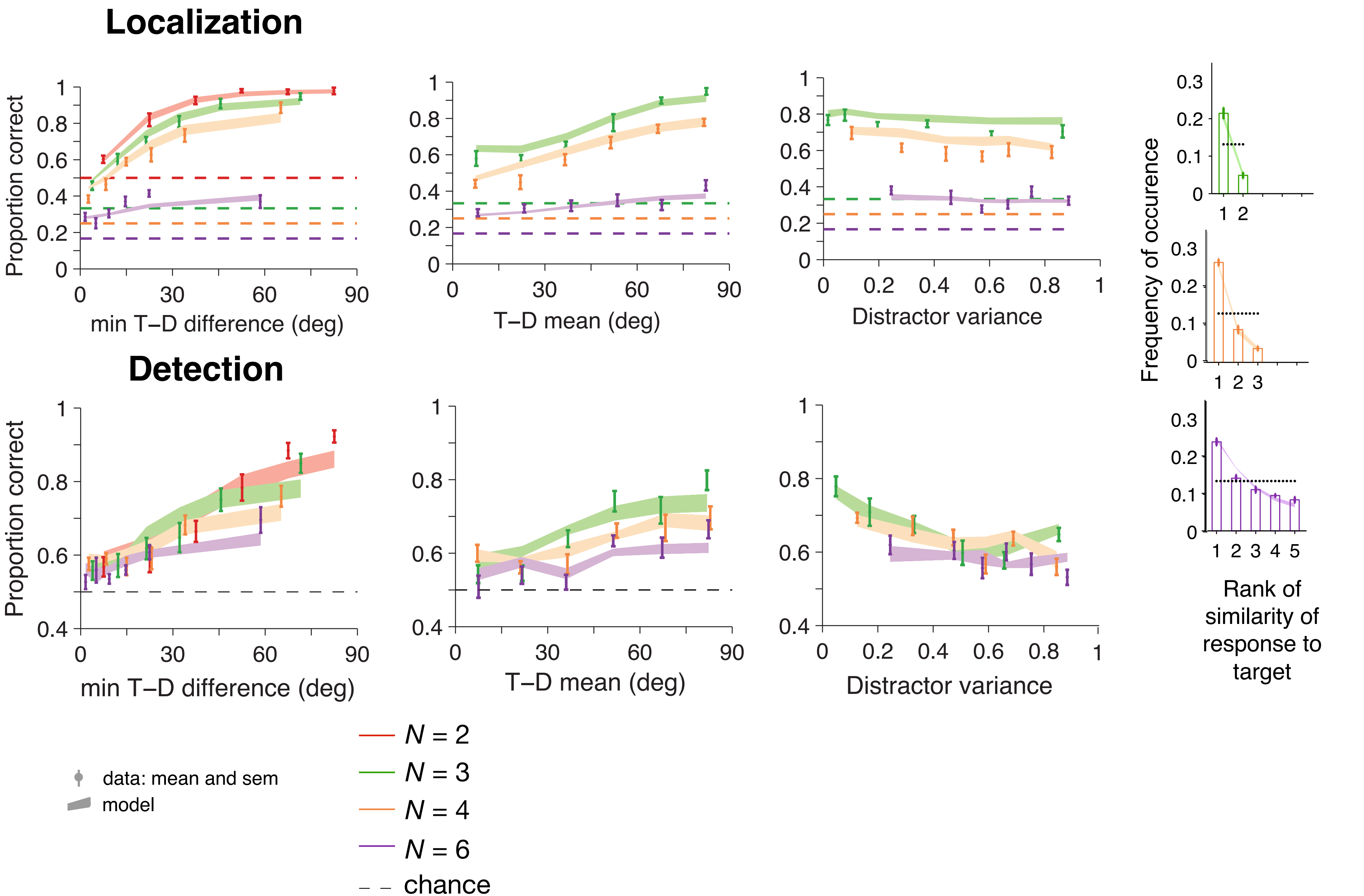

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   - Optimal-observer model captures the localization and detection data, separately and also jointly
   - Accounts for rich summary statistics in both task types

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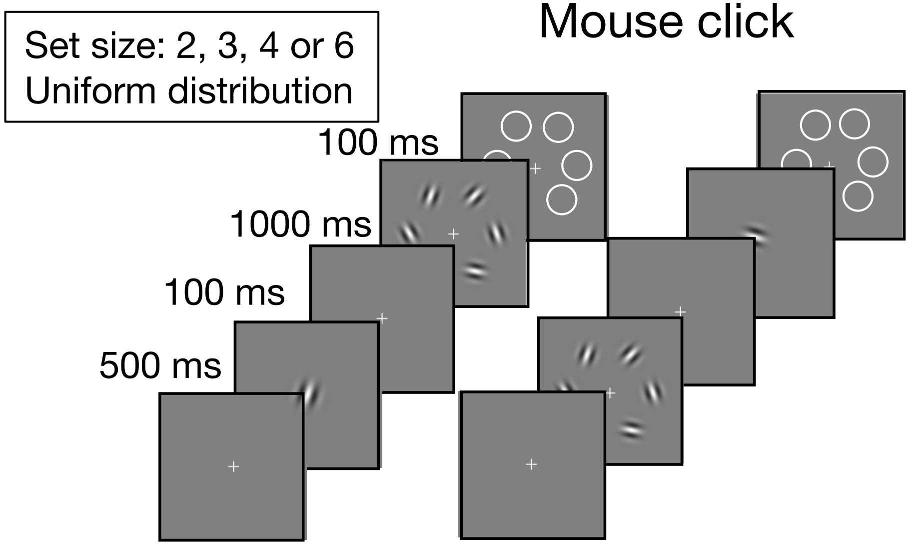
Memory-based search

Localization

Where was the target?
Mouse click

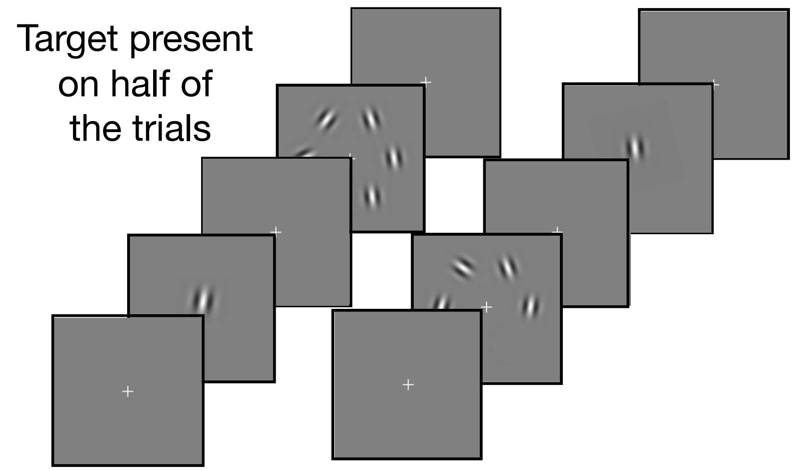


Perception Memory

Mihali and Ma, 2020

Detection

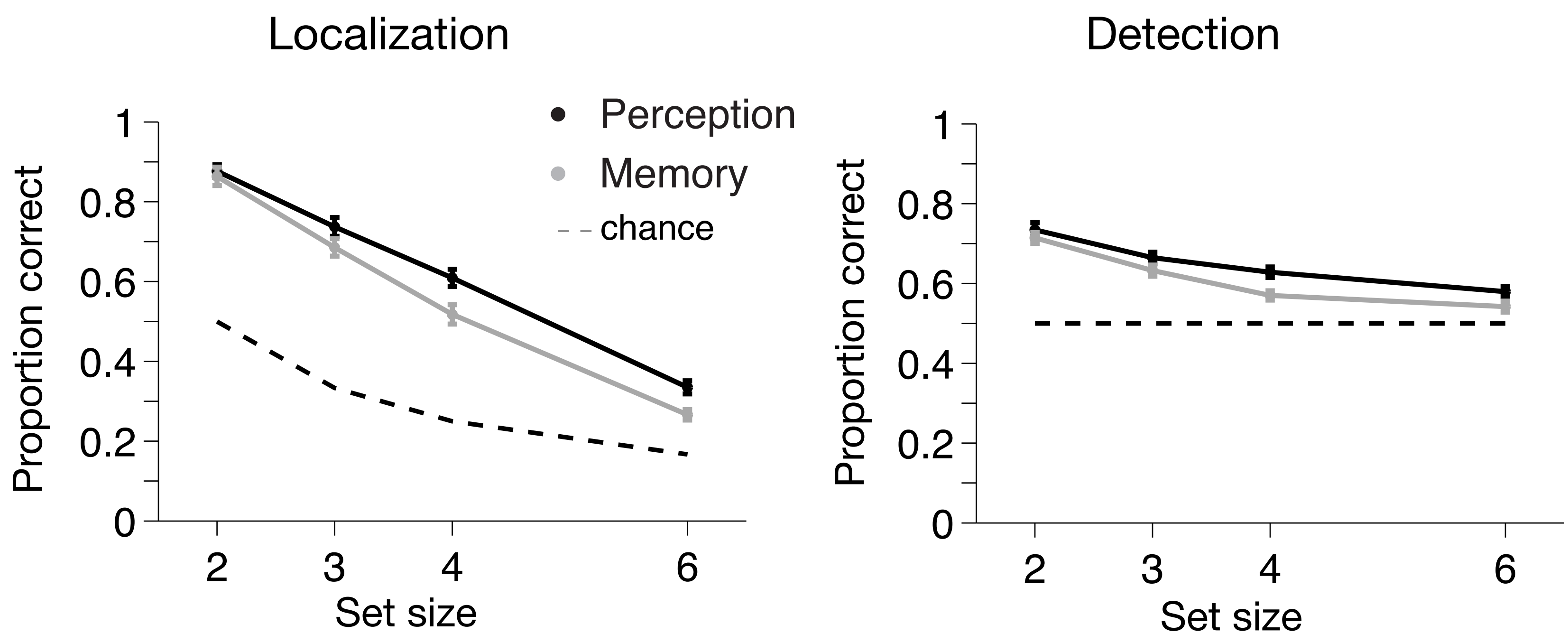
Target present or absent?
Button press



Perception Memory

Mazyar, van den Berg and Ma, 2012

Accuracy as a function of set size



Effect of set size: $p < 0.001$
Effect of Perception/Memory: $p < 0.001$

Effect of set size: $p < 0.001$
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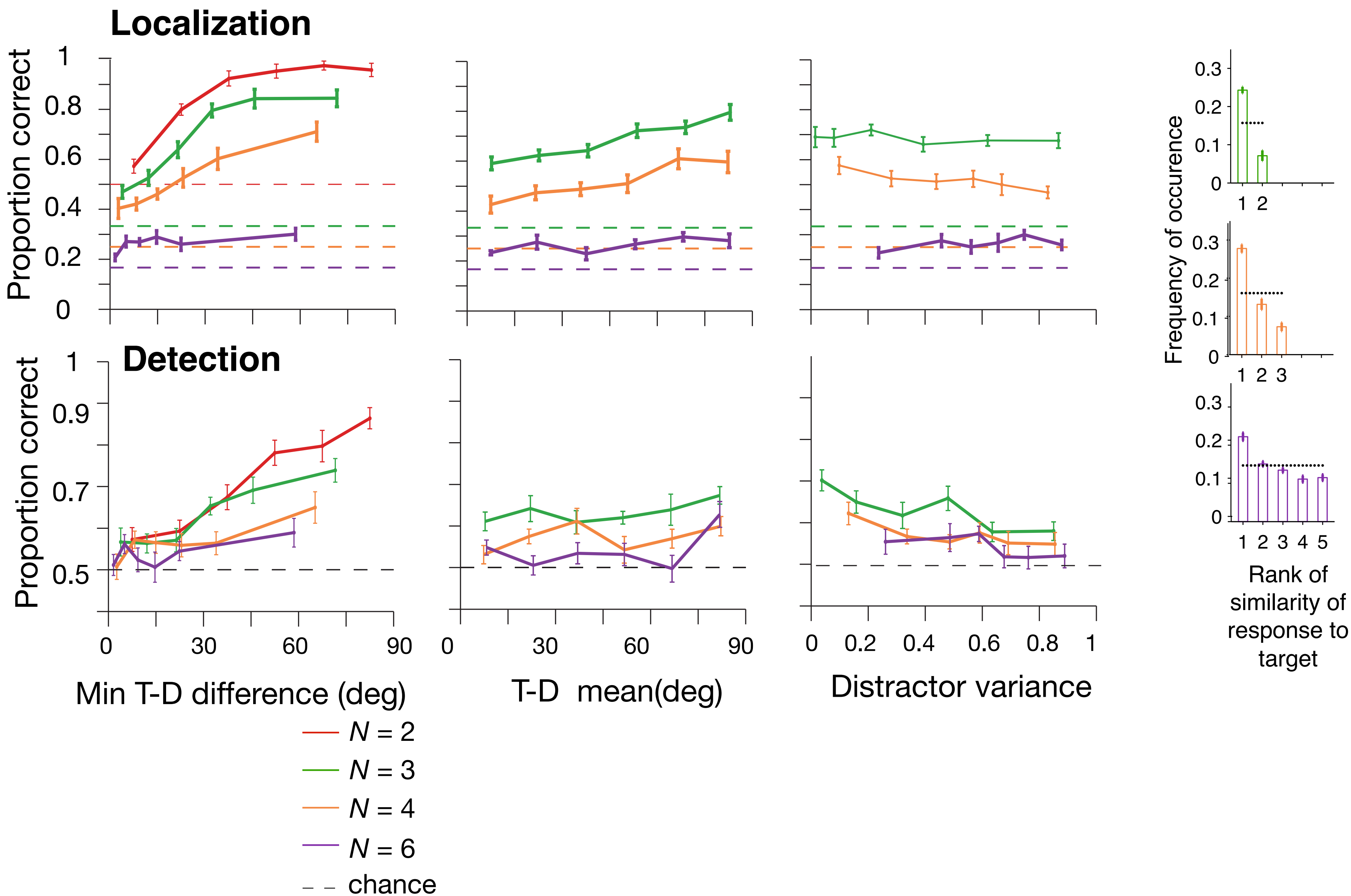
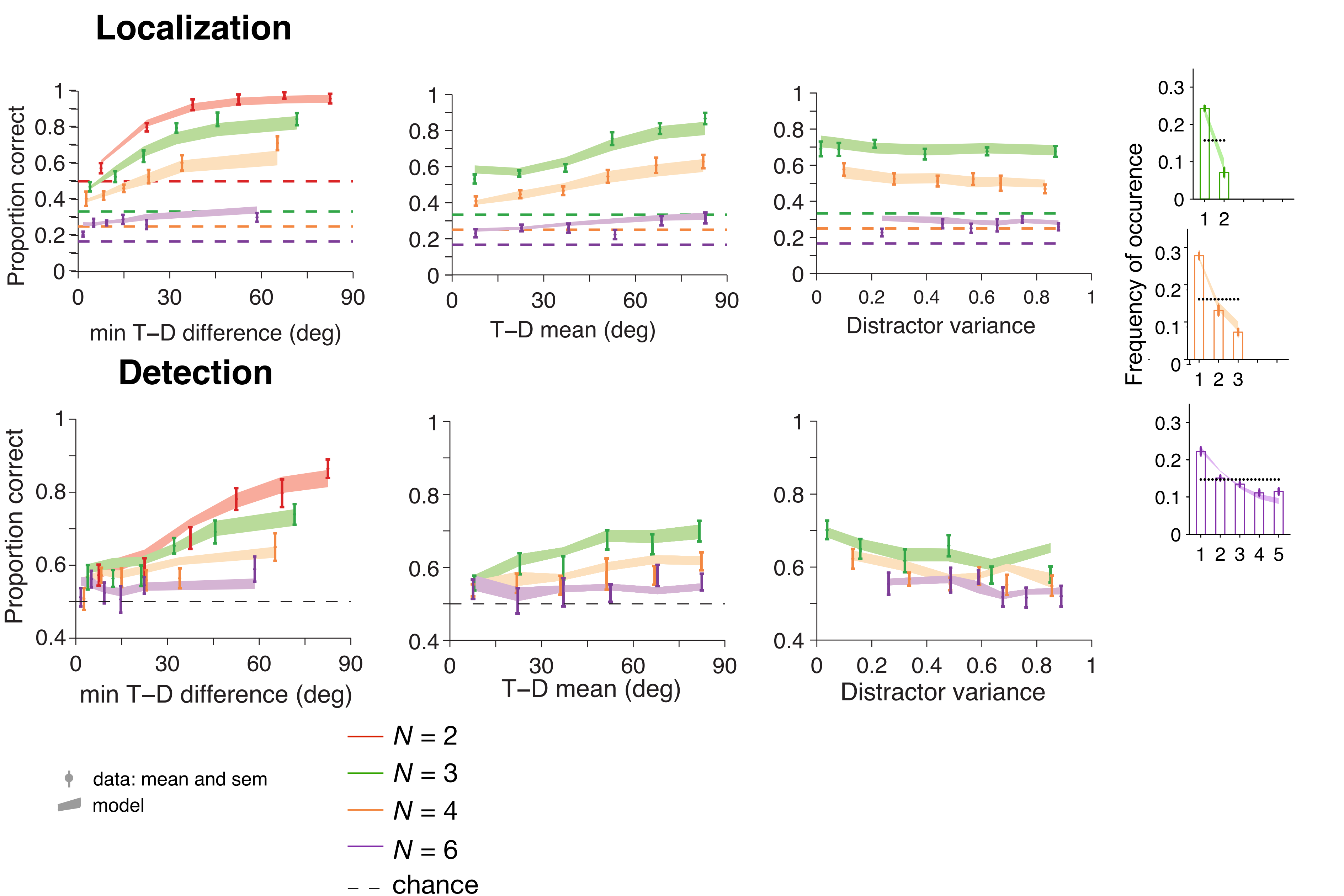
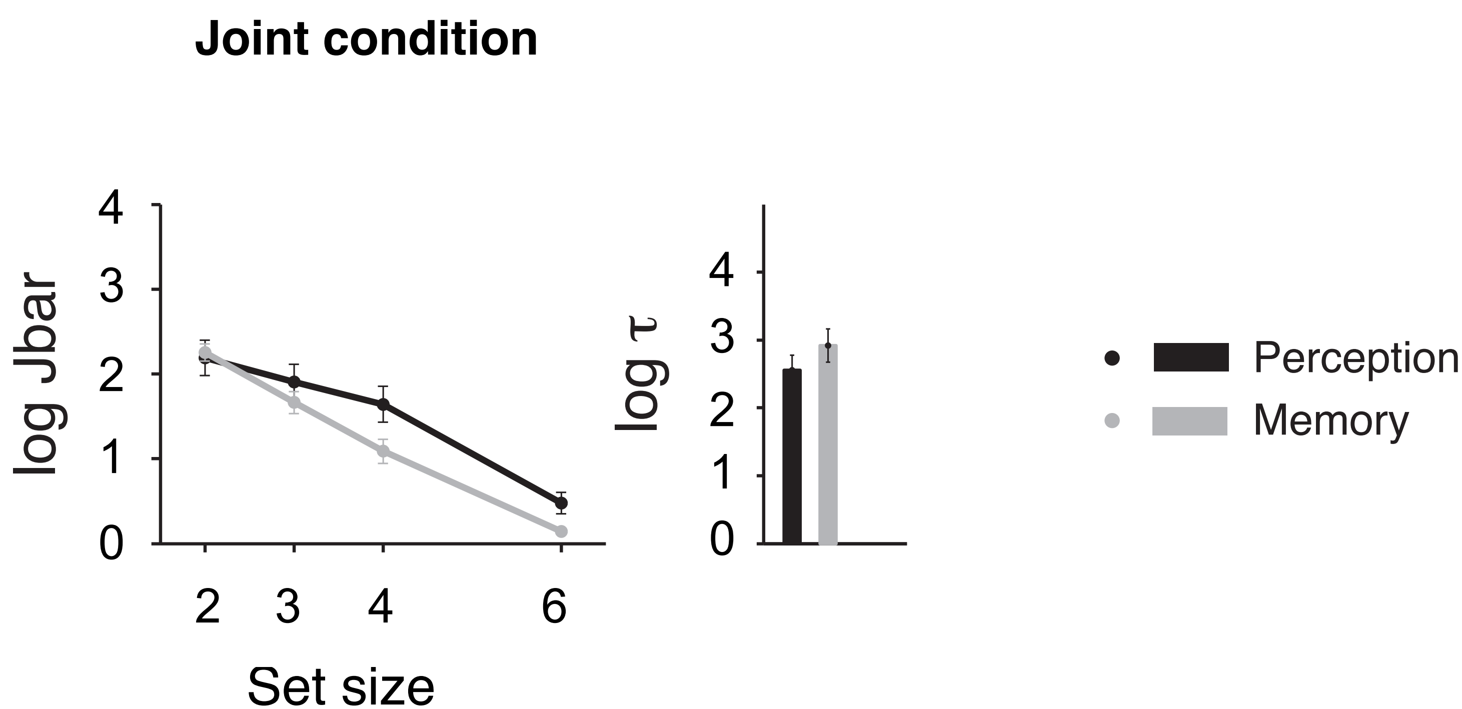
Summary statistics: Memory



Optimal-observer in Memory – joint fits to Localization and Detection



Mean precision parameter decreases with set size in perception and memory



Effect of set size: $p < 0.001$
Effect of Perception/Memory: $p < 0.05$

Outline

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   - Two task types within subject: localization and detection *Liu, Healey and Enns, 2003, Cameron et al, 2004, Dukewich and Klein, 2009*
   - Strong effect of min T-D difference, weaker effects of circular mean and circular variance of the distractors. Min T-D difference was the most useful factor.
   - Consistent to some extent with Duncan and Humphreys (1989)

2. Fit an optimal-observer model and see if it accounts for these effects *Ma et al, 2011, Mazyar, van den Berg and Ma, 2012*
   - Optimal-observer model captures the localization and detection data, separately and also jointly
   - Accounts for rich summary statistics in both task types

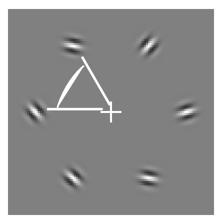
3. Visual search in memory: comparison with perception *Kuo, Rao, Lepsin and Nobre, 2009; Kong and Fougnie, 2019*
   - Effect of summary statistics on performance very similar between Perception and Memory
   - Optimal-observer model also fits well to Memory
   - Accuracy and precision tend to be lower in Memory than in Perception

Experiment 2:

Consistent pattern of results with smaller stimulus spacing
(still outside the Bouma limit)

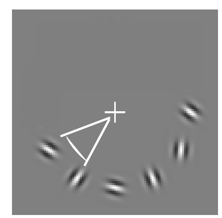
Experiment 1

60 deg



Experiment 2

30 deg



Conclusions

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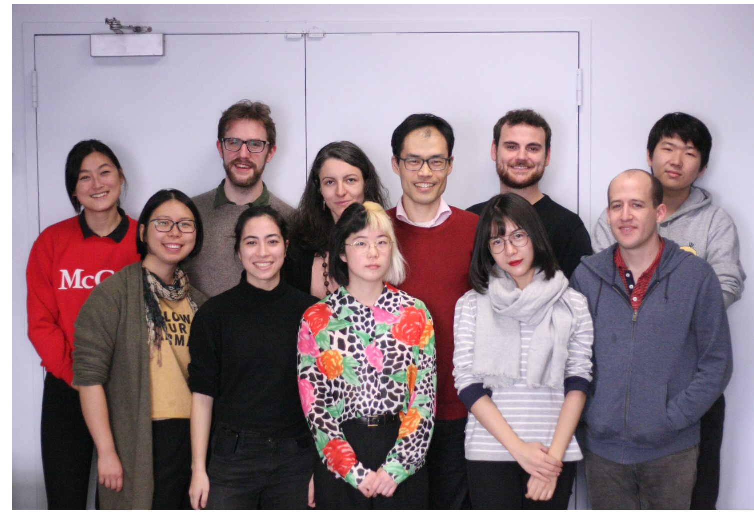
Limitations and open questions

- Interactions between summary statistics? Not enough trials to assess
- Why decision noise in detection, but not localization?
- Comparison with alternative models? either based on heuristics *Ma et al, 2011, Shen and Ma, 2016, Calder-Travis and Ma, 2020* or summary statistics *Rosenholtz, 1999, Avraham, Yeshurun, & Lindenbaum, 2008*
- Towards naturalistic visual search, but how close? *Wolfe, 1994, Najemnik and Geisler, 2005, Wolfe, 2010, Biggs and Mitroff, 2014, Yang et al, 2017, Boettcher et al, 2018, Geng and Witkowki, 2019, Radulescu, van Opheusden et al, 2020*
- Nevertheless, revisiting psychological theories with optimal-observer models can contribute to our understanding of visual search, and more broadly to psychology and neuroscience.

Thanks:

Ma Lab

- **Wei Ji Ma**
- Joshua Calder-Travis
- Bas van Opheusden
- Aditi Singh
- Aspen Yoo
- Heiko Schuett
- Maija Honig
- Yanli Zhou
- Ionatan Kuperwajs
- Will Adler
- Luigi Acerbi
- Emin Orhan
- Peiyuan Zhang
- Jenn Laura Lee
- Xiang Li
- Yichen Li
- Gianni Galbiati
- Zahy Bnaya
- Hongsup Shin



NYU CNS and Psych, faculty and students

National Eye Institute: R01EY020958

Thank you for your attention!