Revisiting the theoretical foundation of visual working memory

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THE UNIVERSITY OF CHICAGO

I respectfully acknowledge the unceded land on which we reside and work – the land of the Patwin people for the UC Davis campus, and the land of the Odawa, Ojibwe and Potawatomi people for the UChicago campus.

Based on https://diversity.ucdavis.edu/land-acknowledgement-statement and https://crownschool.uchicago.edu/about/land-acknowledgement

Talk outline

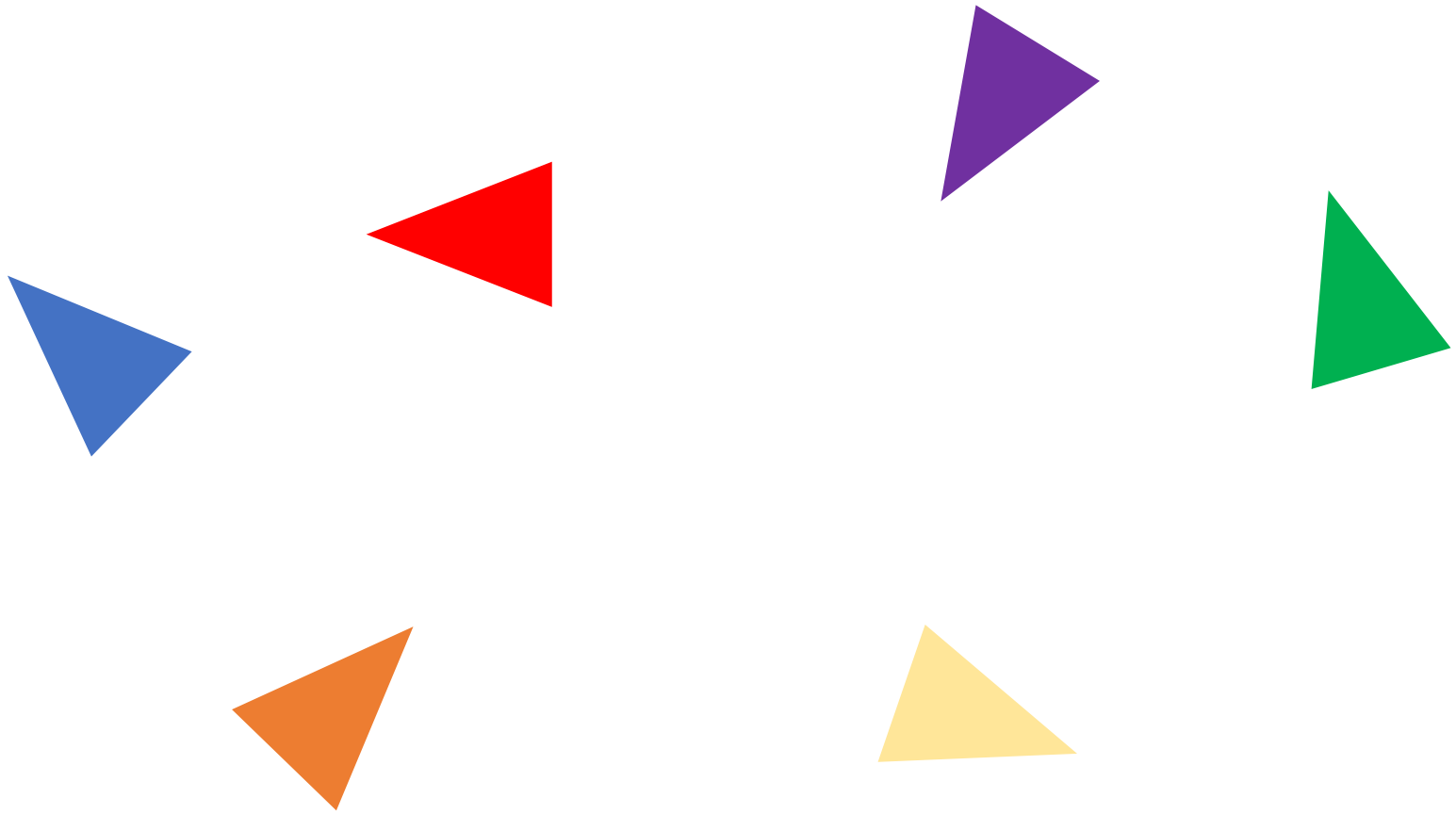
- I invite you to reflect and reconsider what visual working memory *is*

- I will present two research projects:
  - Conjunction whole-report
  - Guess bands

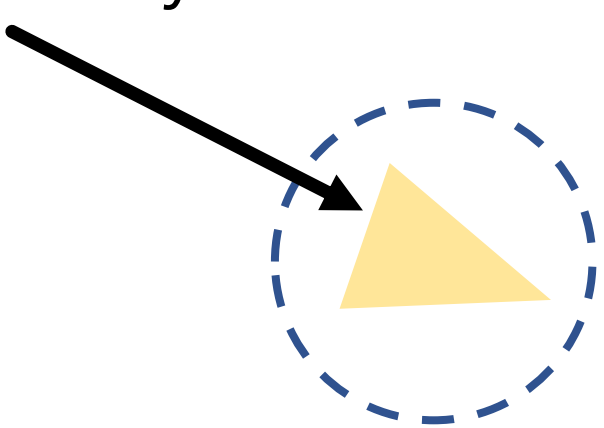
- I will suggest a theoretical framework for visual working memory

What *is* visual working memory?

What do you remember?



You stored this in
visual working memory!



What *is* visual working memory?

- "The system responsible for maintaining visual information in a state of heightened accessibility for ongoing perception and cognition."

A *theory crisis* in psychology

- An understated precursor to the *reproducibility crisis* may be the lack of coordinated theoretical development
  - An over-reliance on the hypothetico-deductive method (e.g. null hypothesis significance testing) for inferences
    - Questionable research practices (QRPs): *p*-hacking, HARKing, data manipulation, etc.
  - Under-specified theories with under-determined experimental designs
    - *Ad hoc* changes in models, straw-man of competing models, blunt instruments of measurement
  - Overgeneralization of a theory or model to all related phenomena or empirical conditions
    - A lack of intellectual humility…

Borsboom D. (2013, November 20). Theoretical amnesia. *Center for Open Science*

Borsboom, D., van der Maas, H. L., Dalege, J., Kievit, R. A., & Haig, B. D. (2021). Theory construction methodology: A practical framework for building theories in psychology. *Perspectives on Psychological Science*, *16*(4), 756-766.

Oberauer K., Lewandowsky S. (2019). Addressing the theory crisis in psychology. *Psychonomic Bulletin & Review*, 26, 1596–1618.

Maatman, F. O. (2021). Psychology's theory crisis, and why formal modelling cannot solve it. *PsyArXiv*

Meehl P. E. (1978). Theoretical risks and tabular asterisks: Sir Karl, Sir Ronald, and the slow progress of soft psychology. *Journal of Consulting and Clinical Psychology*, 46, 806–834.

What *is* visual working memory?

- "The system responsible for maintaining visual information in a state of heightened accessibility for ongoing perception and cognition."

- This same definition could also describe visual attention, perhaps visual imagery, psychological introspection

- What does it mean to *maintain* visual information?
- What details a state of *heightened accessibility*?

What *is* visual working memory?

- Many subtly different definitions:

The many faces of working memory and short-term storage

Nelson Cowan

Psychonomic Bulletin & Review **24**, 1158–1170 (2017) | Cite this article

It has become clearer to me that a major source of confusion is that researchers use different definitions of the malleable and useful concept of WM. We do not seem to be converging on a common definition of the term. Others also have

What *is* visual working memory?

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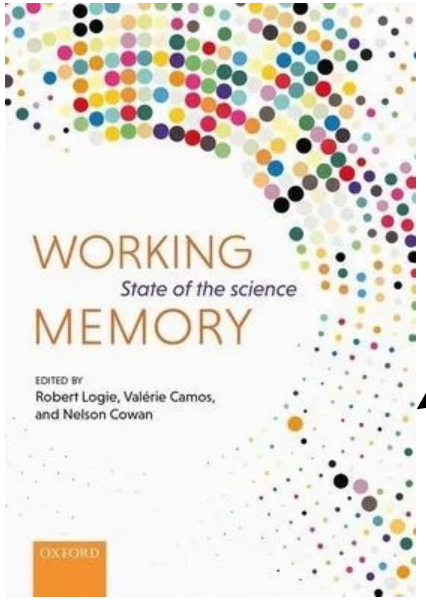
Integrating Theories of Working Memory

Robert H. Logie, Clément Belletier, and Jason M. Doherty



First published in late 2020

- "We argue that many of these differences reflect different research questions, different levels of explanation, differences in how participants perform their assigned tasks in different laboratories, rather than fundamental theoretical adversity"

Robert H. Logie, Clément Belletier, and Jason M. Doherty, Integrating Theories of Working Memory In: Working Memory. Edited by: Robert H. Logie, Valérie Camos, and Nelson Cowan, Oxford University Press (2021). © Oxford University Press. DOI: 10.1093/oso/9780198842286.003.0014

How do we make progress if:

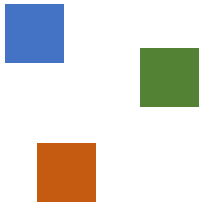
- There exist subtly different definitions
  - Due to different research questions, different methods, different measures, different contexts, etc.
- Theories (or models) attempt to explain all empirical phenomena related to ill-defined construct (overgeneralization)
- Models are underspecified such that empirical tests cannot be definitive
  - And these models may not reflect fundamental theoretical adversity

What *is* visual working memory?

- One enduring "theoretical framework" has been

Object-based theory

"slot models"
(Luck and Vogel, 1997;
Zhang and Luck, 2008)



versus

Feature-based theory

"resource models"
(Alvarez and Cavanagh, 2004;
Wilken and Ma, 2004)

Luck, S. J., & Vogel, E. K. (1997). https://doi.org/10.1038/36846
Zhang, W., & Luck, S. J. (2008). https://doi.org/10.1038/nature06860
Alvarez, G. A., & Cavanagh, P. (2004). https://doi.org/10.1111/j.0963-7214.2004.01502006.x
Wilken, P., & Ma, W. J. (2004). https://doi.org/10.1167/4.12.11

Conjunction whole-report

Krystian Loetscher

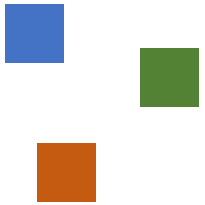
Ed Awh

What *is* visual working memory?

- The mind is sharply limited in what it can actively maintain

Object-based theory

"slot models"
(Luck and Vogel, 1997;
Zhang and Luck, 2008)



Feature-based theory

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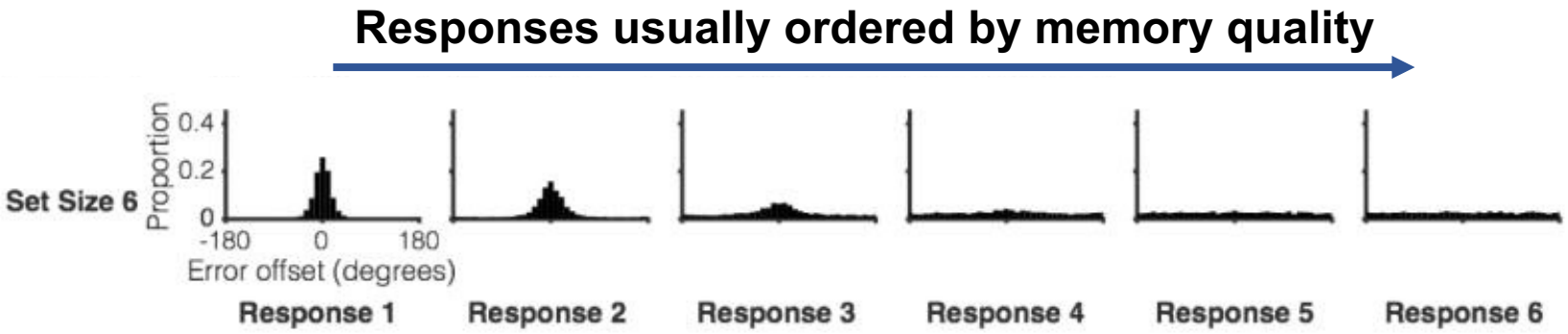
Wilken, P., & Ma, W. J. (2004). https://doi.org/10.1167/4.12.11

Introducing the conjunction whole-report paradigm

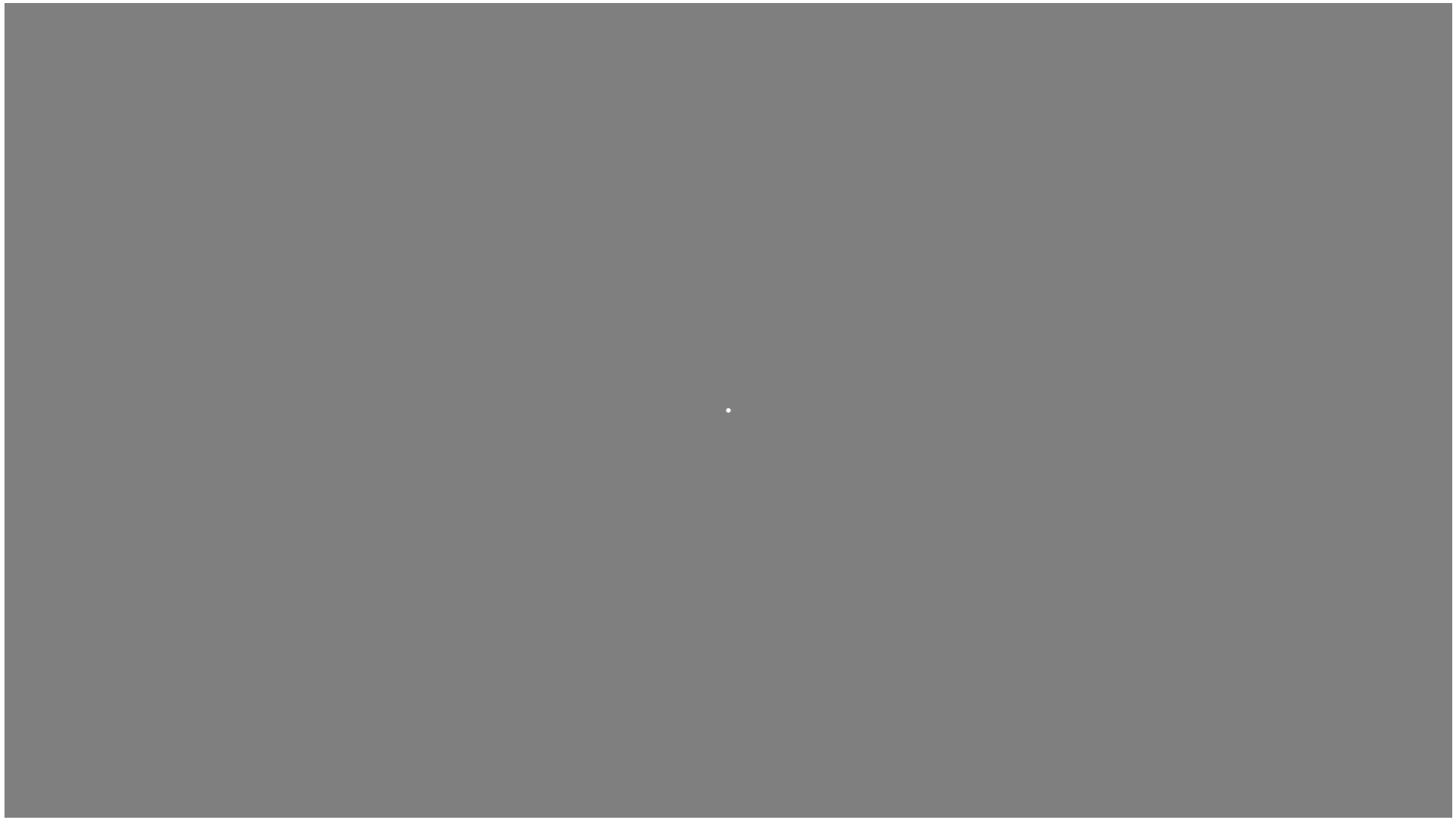
- Test recall for all items rather than just the one item (Adam et al., 2017)



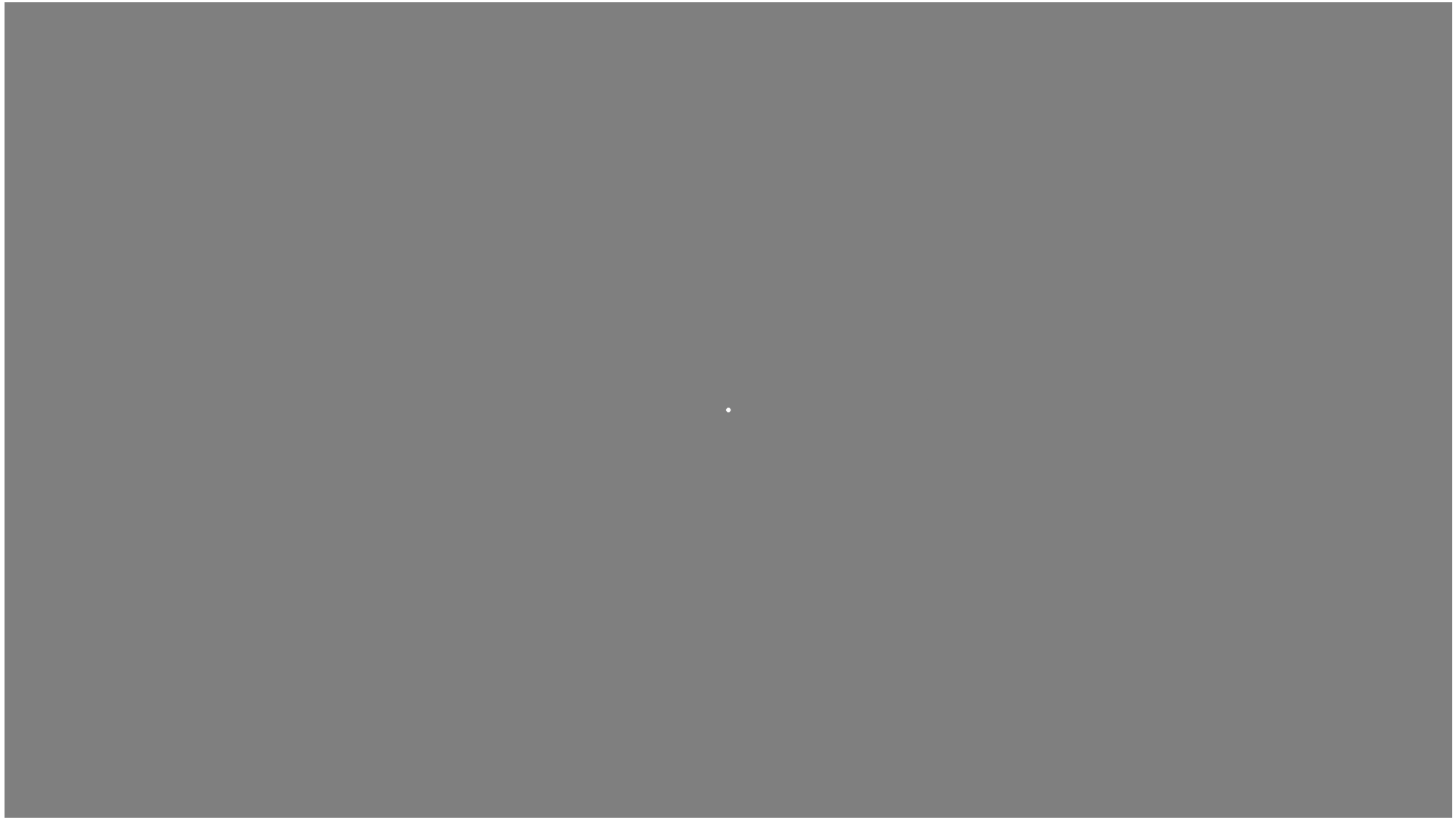
- The first whole-report experiments with conjunction stimuli
- Response interface that collects both features with one click (Sone et al., 2021)

Figure from Adam, K. C. S. et al. (2017) https://doi.org/10.1016/j.cogpsych.2017.07.001
Sone, H. et al. (2021) https://doi.org/10.1016/j.cognition.2020.104579

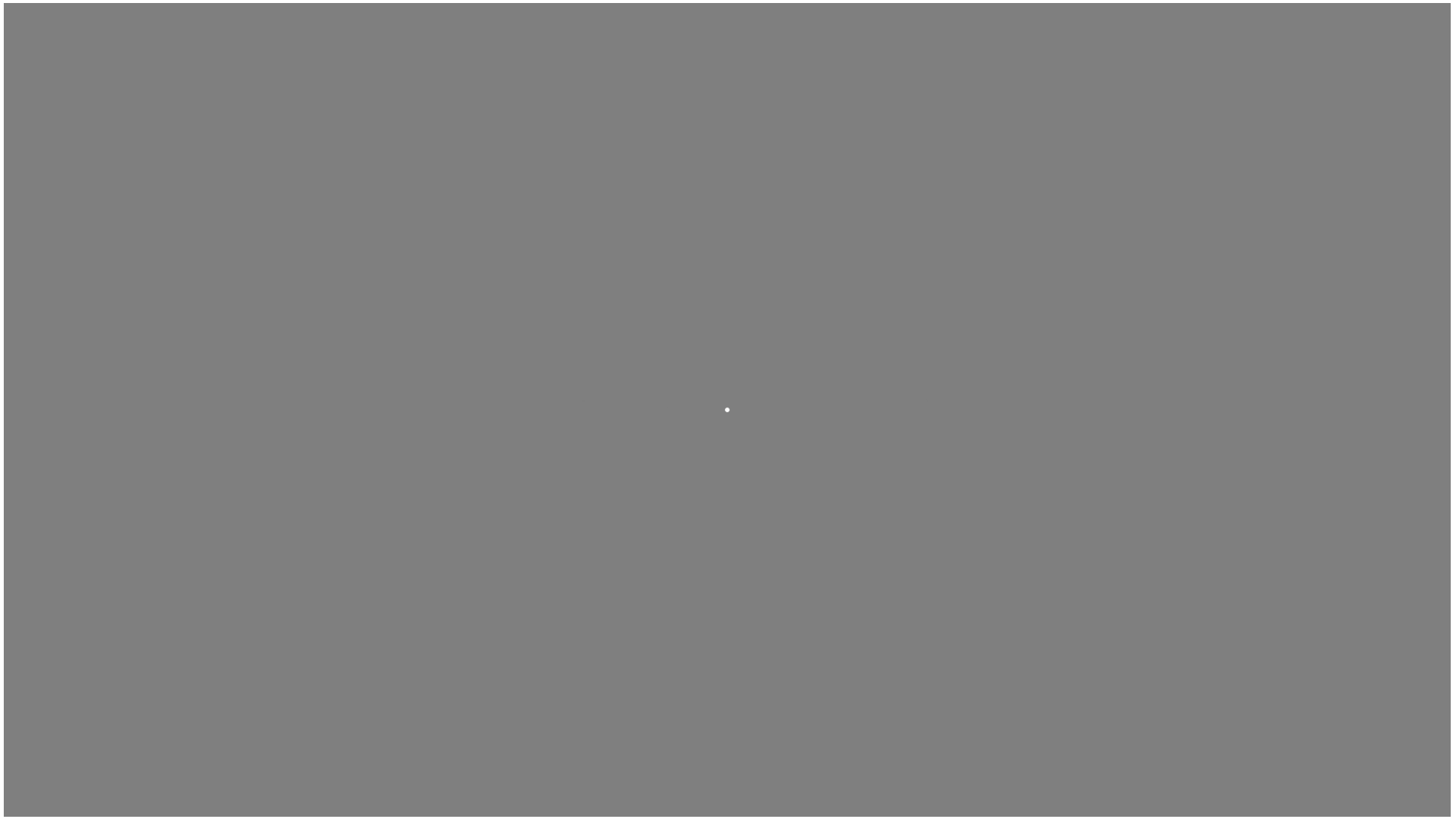
Orientation whole-report



Color whole-report

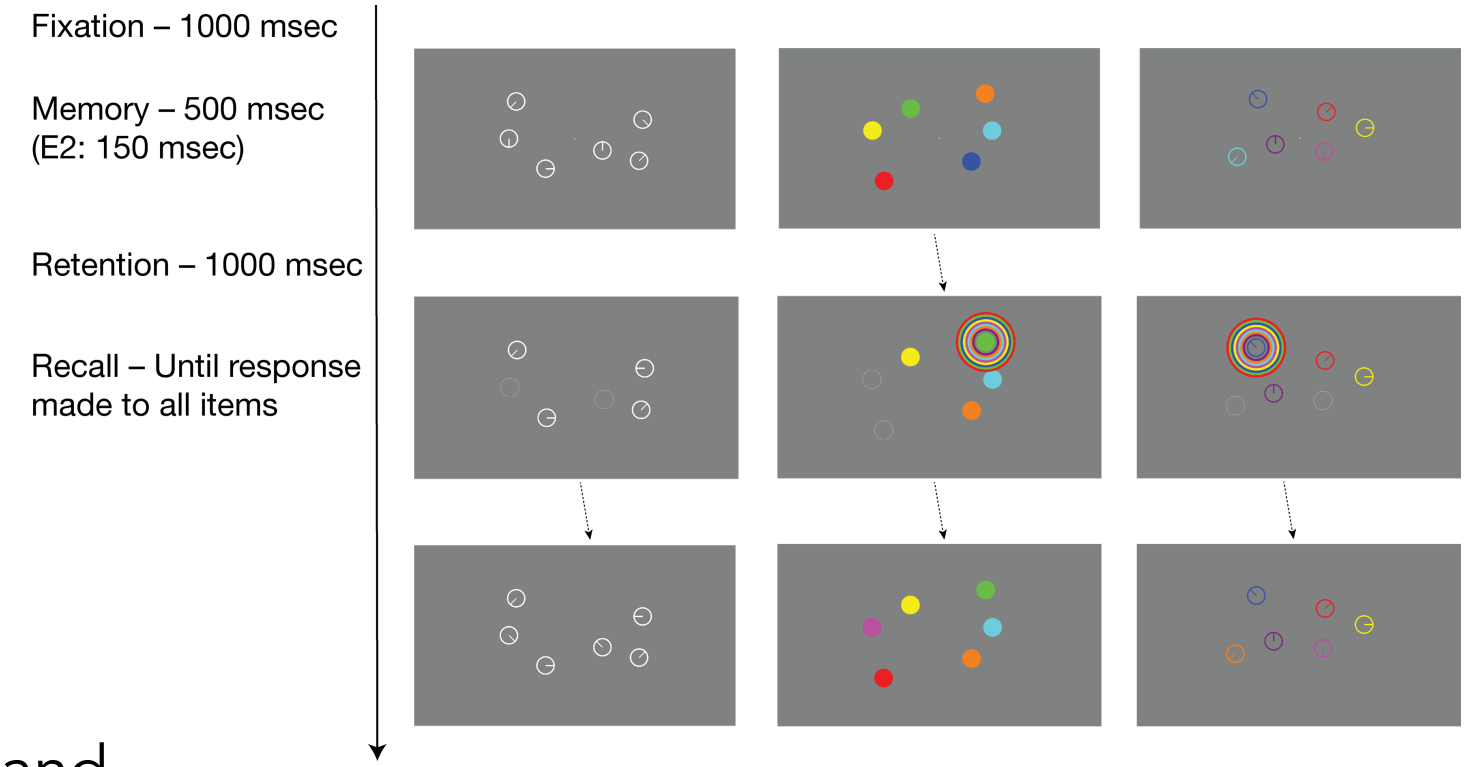


Conjunction whole-report

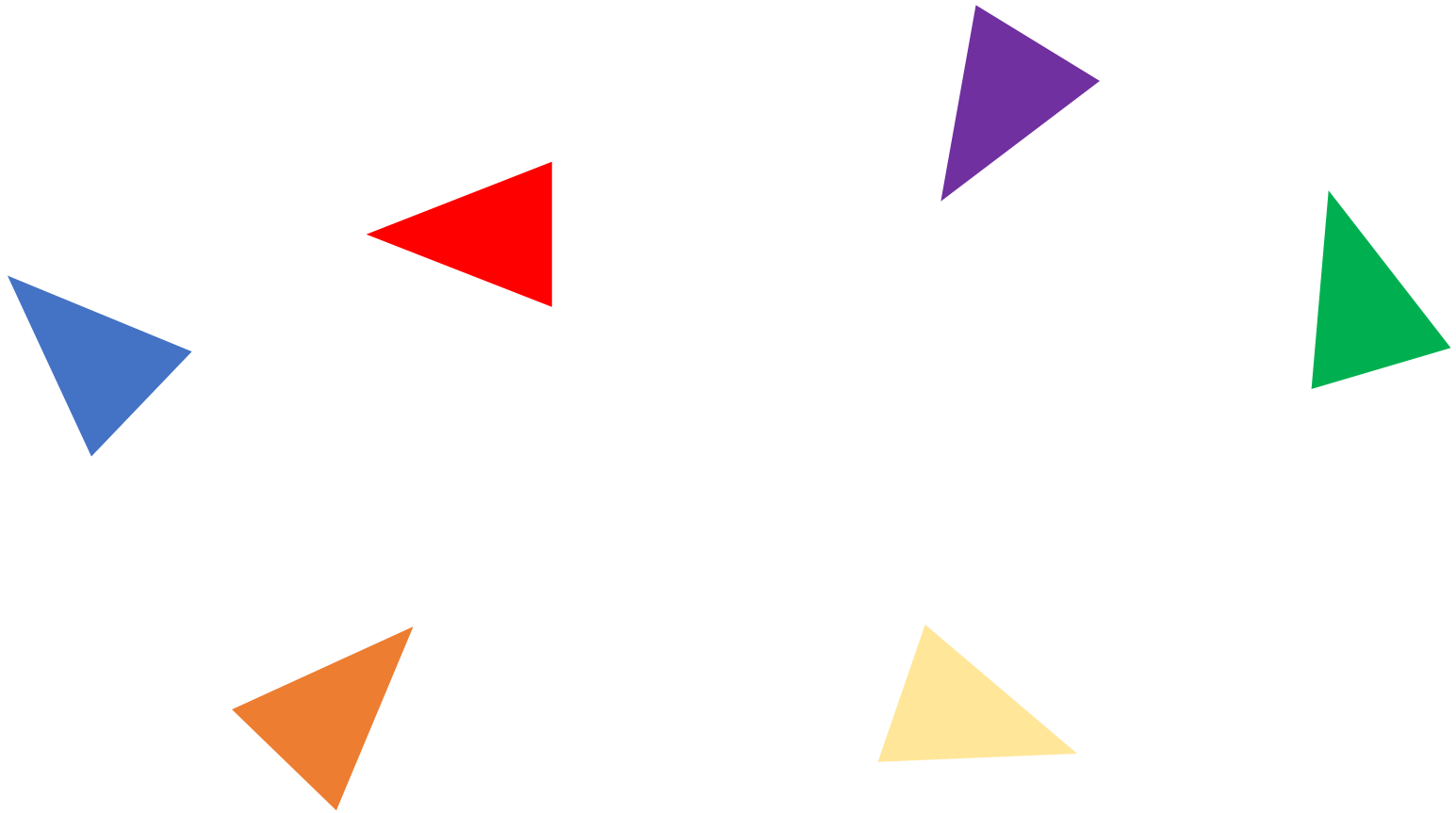


Our conjunction whole-report experiments

- Four experiments (30 subjects each)
  - E1: Colored clock faces
  - E2: Colored clock faces but rapid
  - E3: Colored triangles
  - E4: Colored shapes
- Three conditions (300 trials each)
  - Color only
  - Orientation only or Shape only
  - Conjunction
- Eight discrete colors, orientations, and shapes.

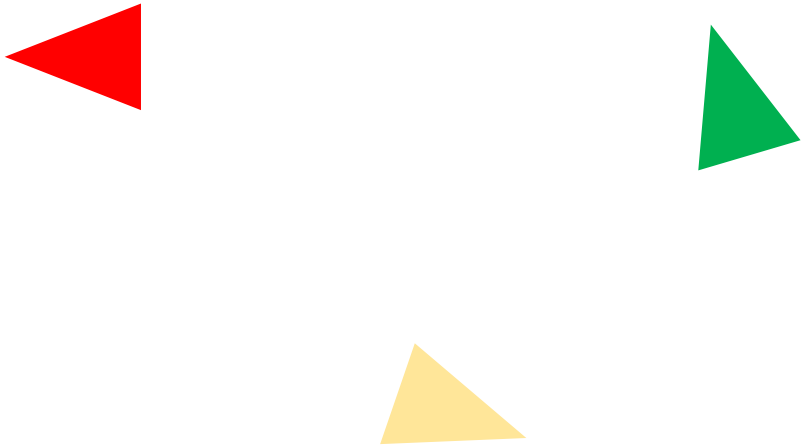


What is the unit of working memory?



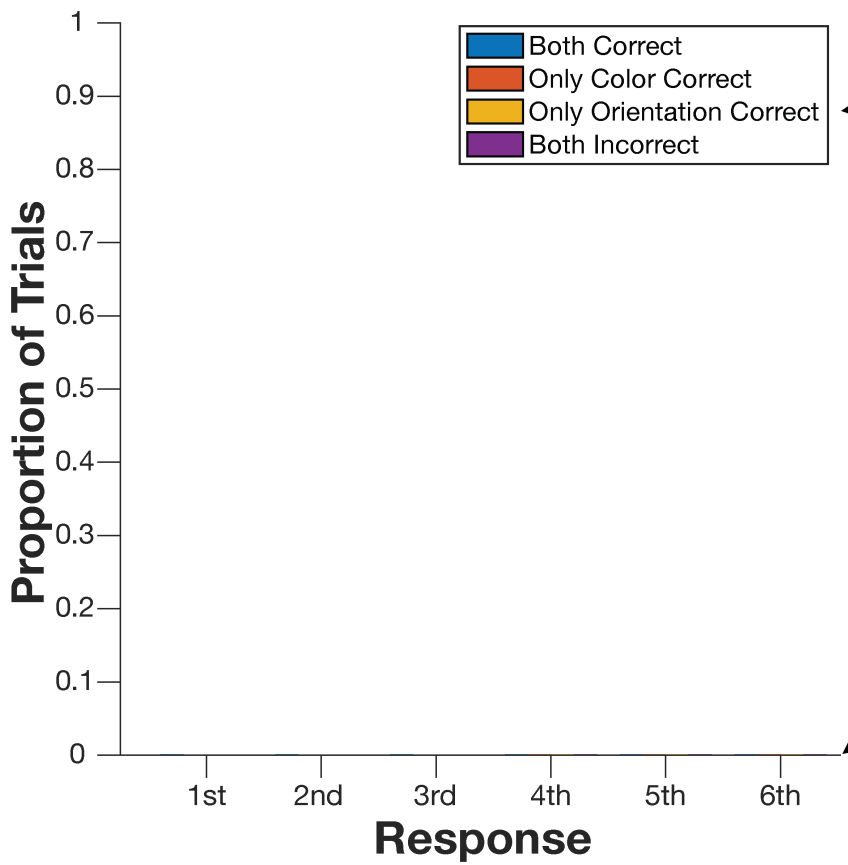
A *specific* object-based model – strong objects

- Fixed object capacity limit
- Lossless representations (“all-or-none”)
- No impact of complexity (additional features)



Has anyone ever truly believed this? Anyhow, an early rejection of this model: Olson, I. R. and Jiang, Y. (2002) https://doi.org/10.3758/BF03194756

A *specific* slot model – strong objects

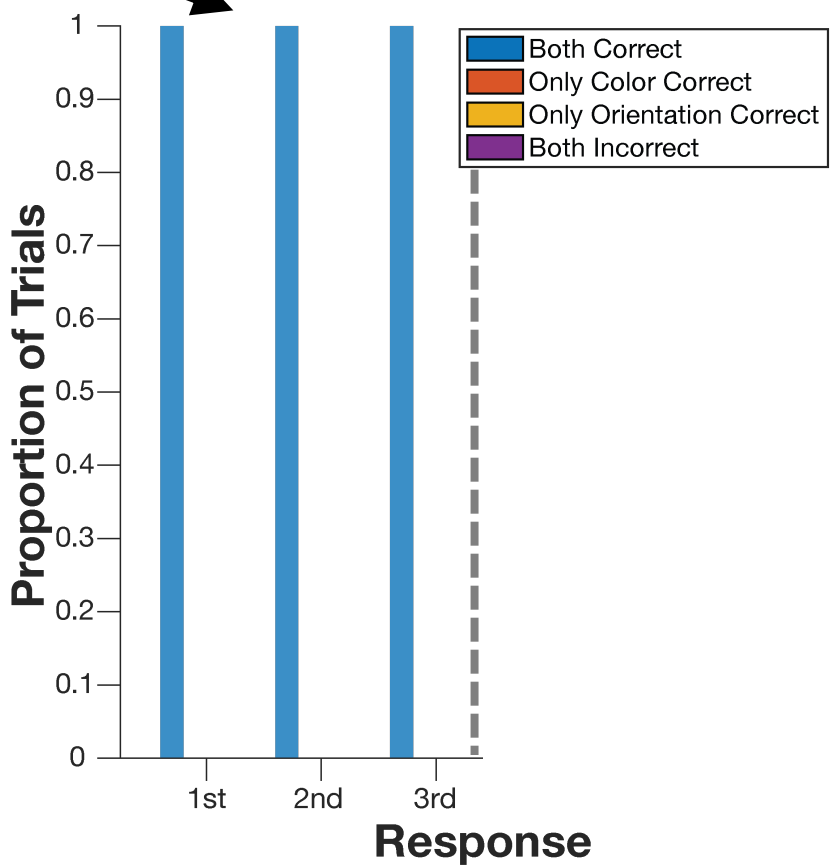


Possible types of recall

Ordered by responses

A *specific* slot model – strong objects

Perfect recall within item limit



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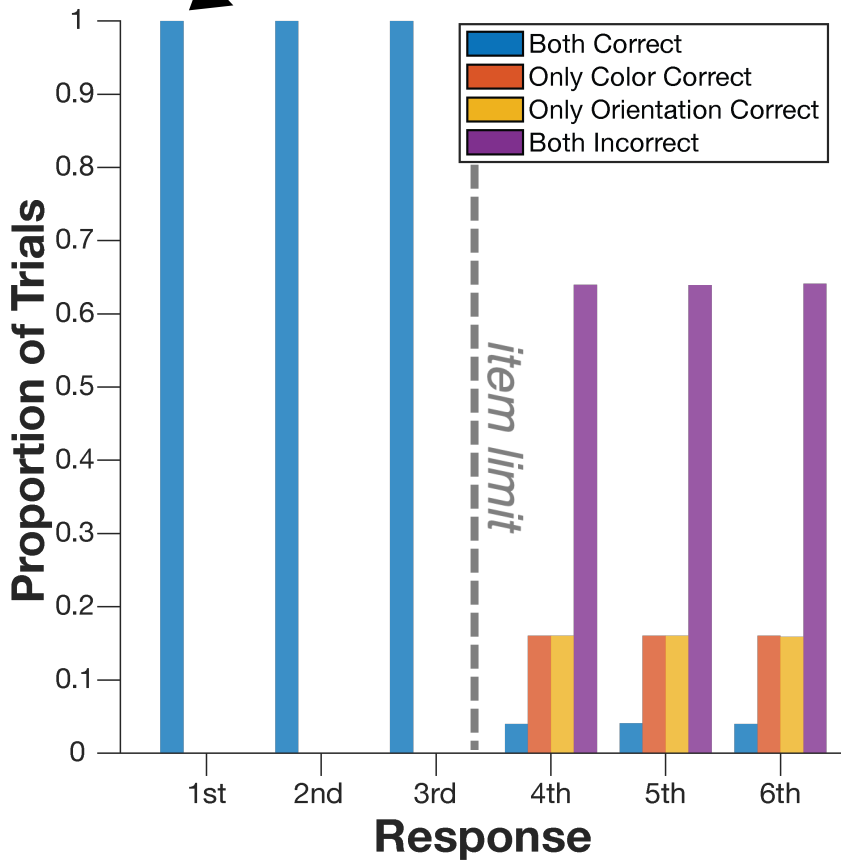
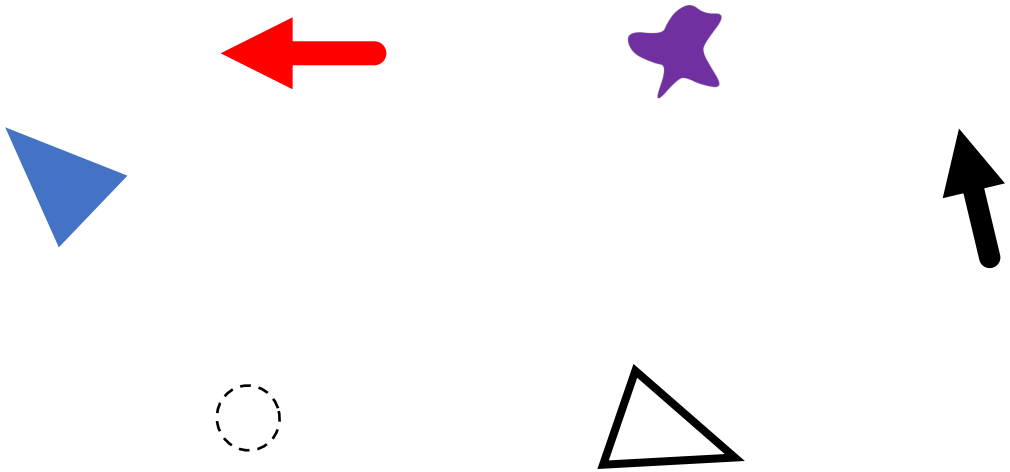


Guessing for remaining responses

A *specific* resource model – independent features

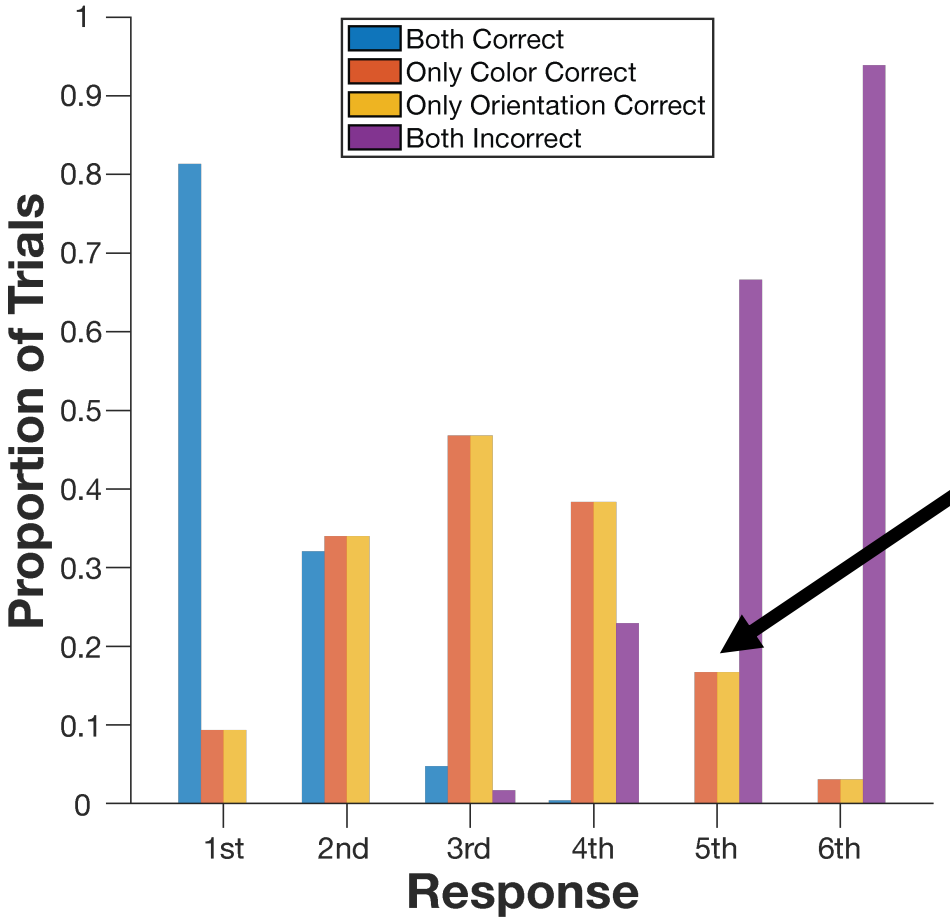
- Working memory resources are distributed to all items in the array
- Feature storage is not constrained by which objects contain the features
  - Probability of successful feature storage is independent of objecthood



Bundesen, C. (1990) https://doi.org/10.1037/0033-295X.97.4.523

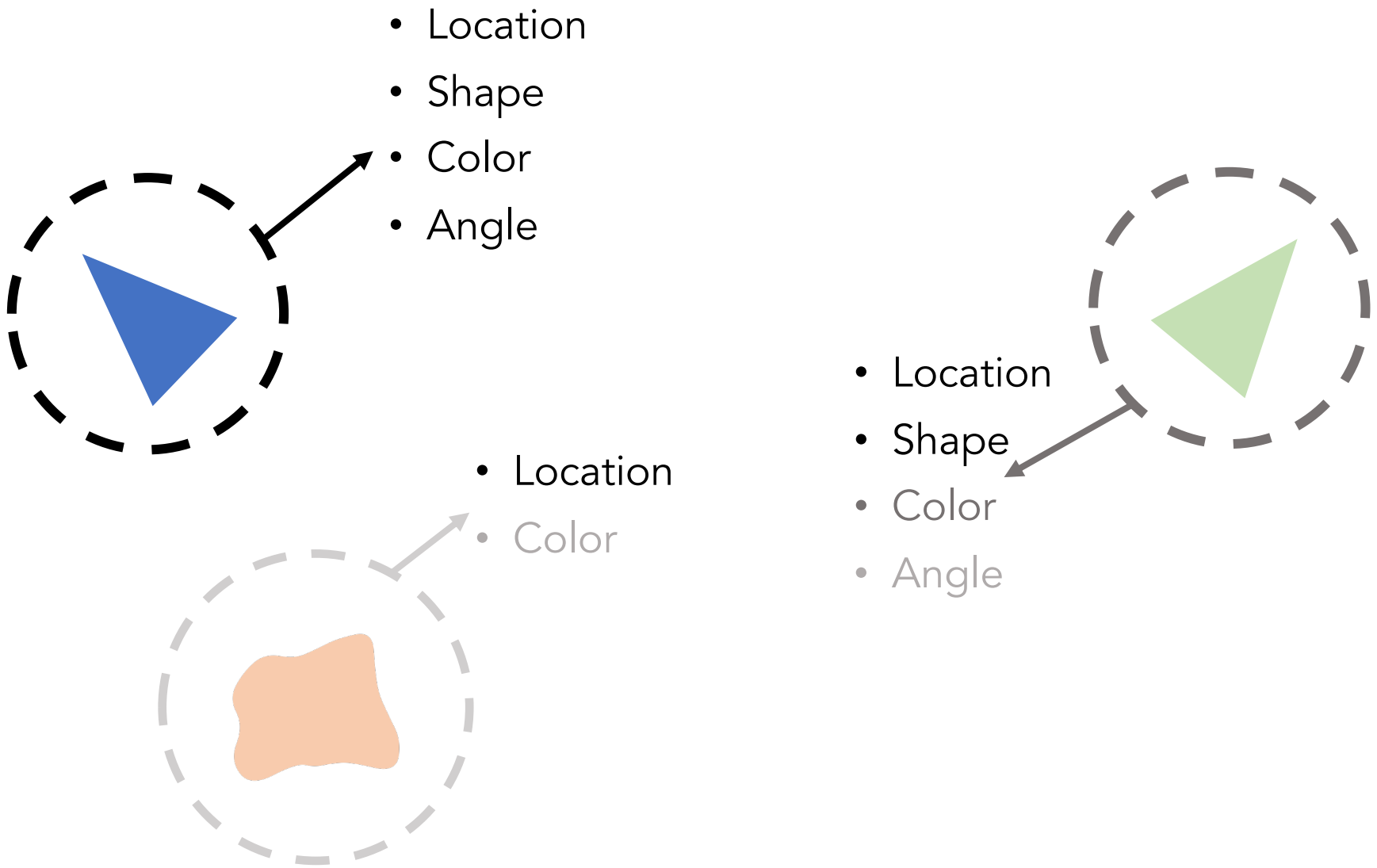
A *specific* resource model – independent features

Feature storage independent of objecthood



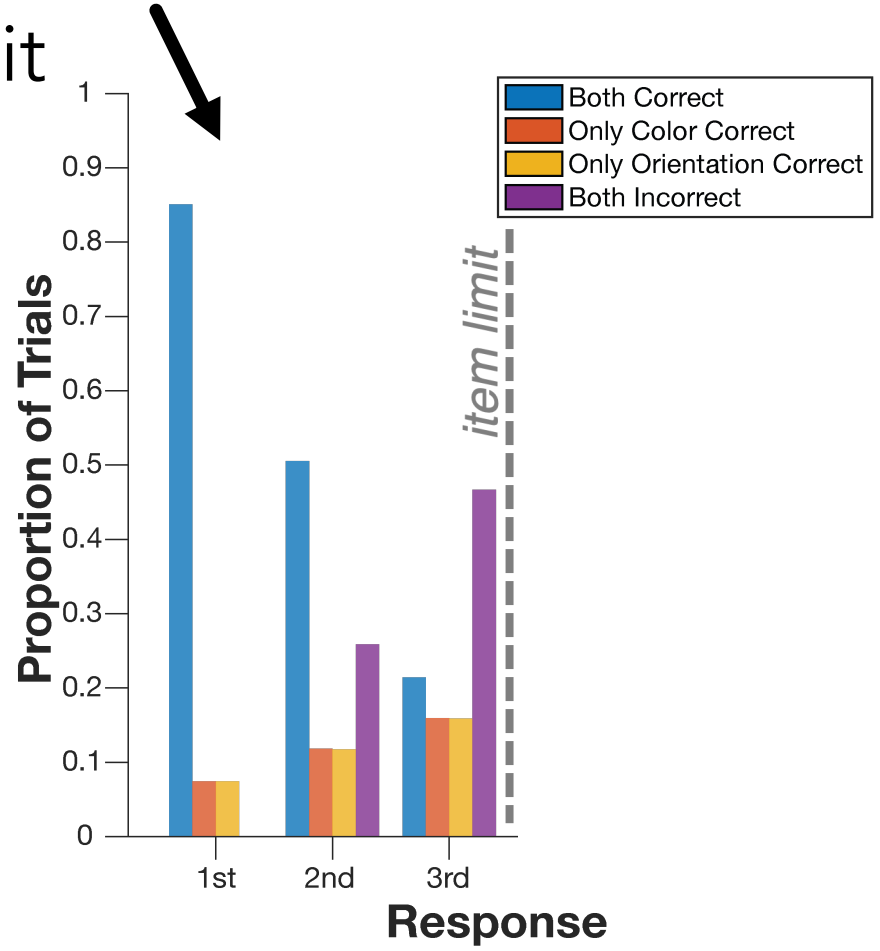
Accurate recall distributed across *all* responses

A new model characterization – pointers



A new model characterization – pointers

Accurate recall constrained within the item limit



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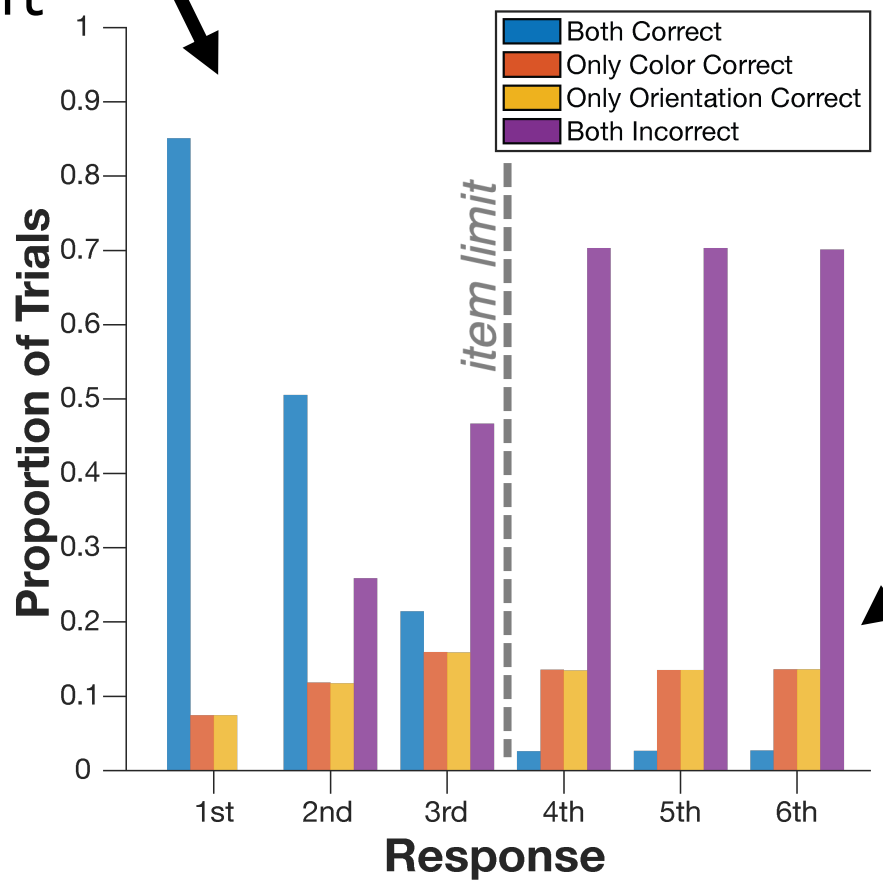

Guessing beyond the item limit

Recall accuracy

Mean Recall	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Colors	3.21 ± 0.74	2.94 ± 0.64		3.61 ± 0.75
Orientations/Shapes	2.79 ± 0.44	2.45 ± 0.45		3.39 ± 0.64
Conjunctions	1.62 ± 0.38	1.38 ± 0.42	1.47 ± 0.44	1.92 ± 0.43

- Memory for conjunction stimuli is not lossless
  - Less conjunctions are fully recalled overall

Recall accuracy

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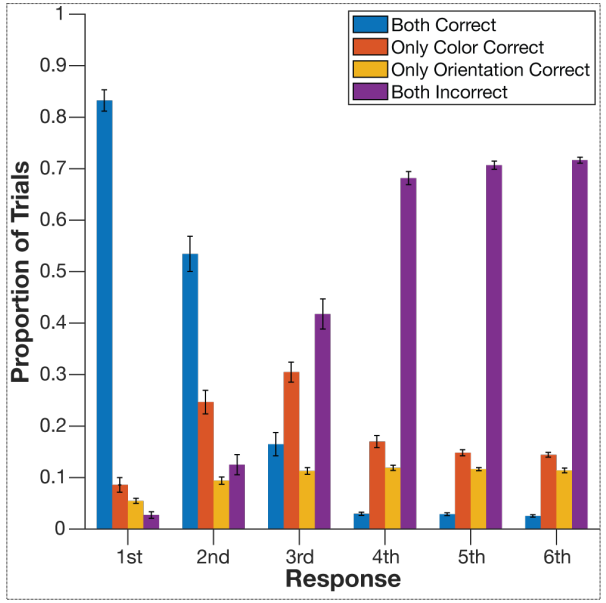
Features	4.94 ± 0.68	4.52 ± 0.83	5.11 ± 0.65	5.34 ± 0.85

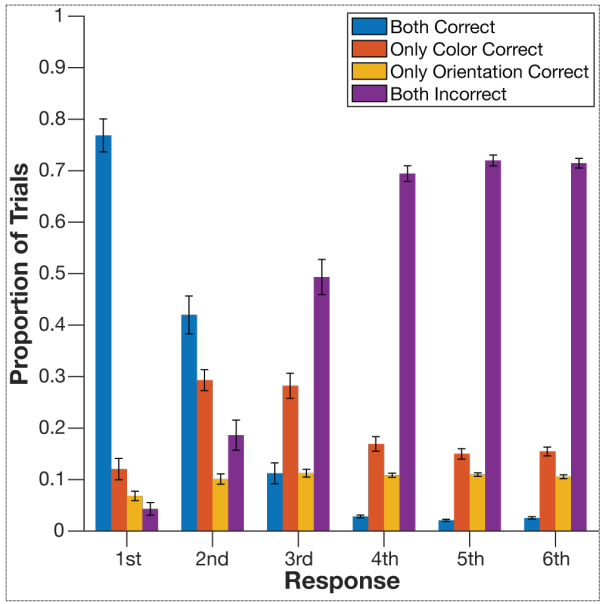
- Memory for conjunction stimuli is not lossless
  - Less conjunctions are fully recalled overall
- But we observe an object-based benefit
  - More features are recalled overall in the conjunction condition compared to the single-feature conditions (~5 features versus ~3 features)

Accuracy across responses

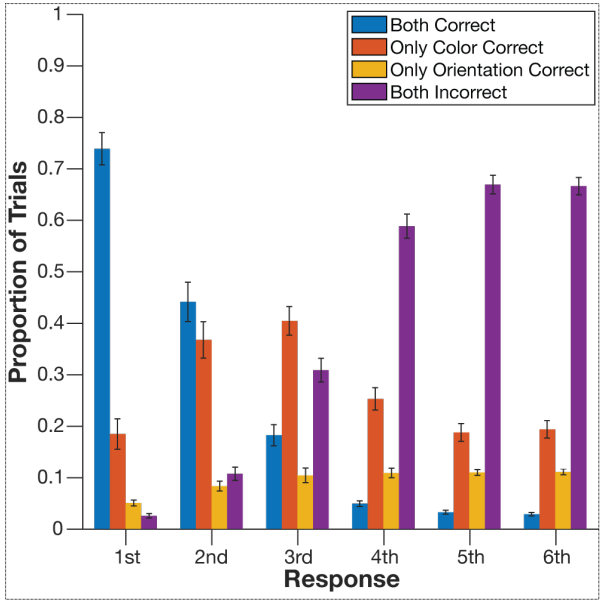
Experiment 1



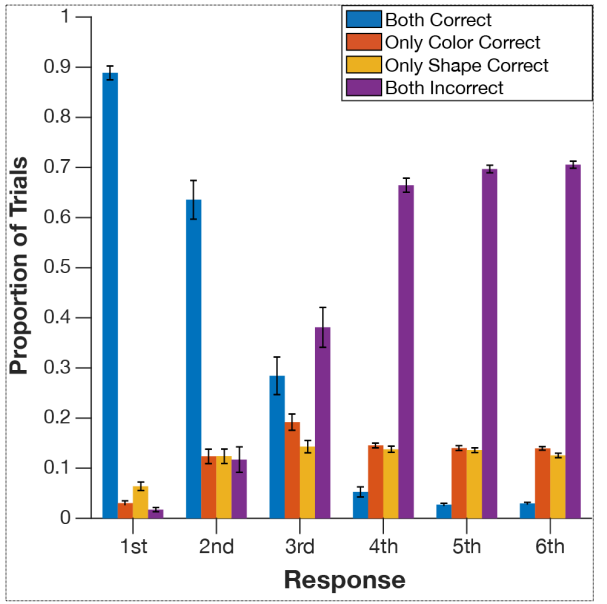
Experiment 2



Experiment 3



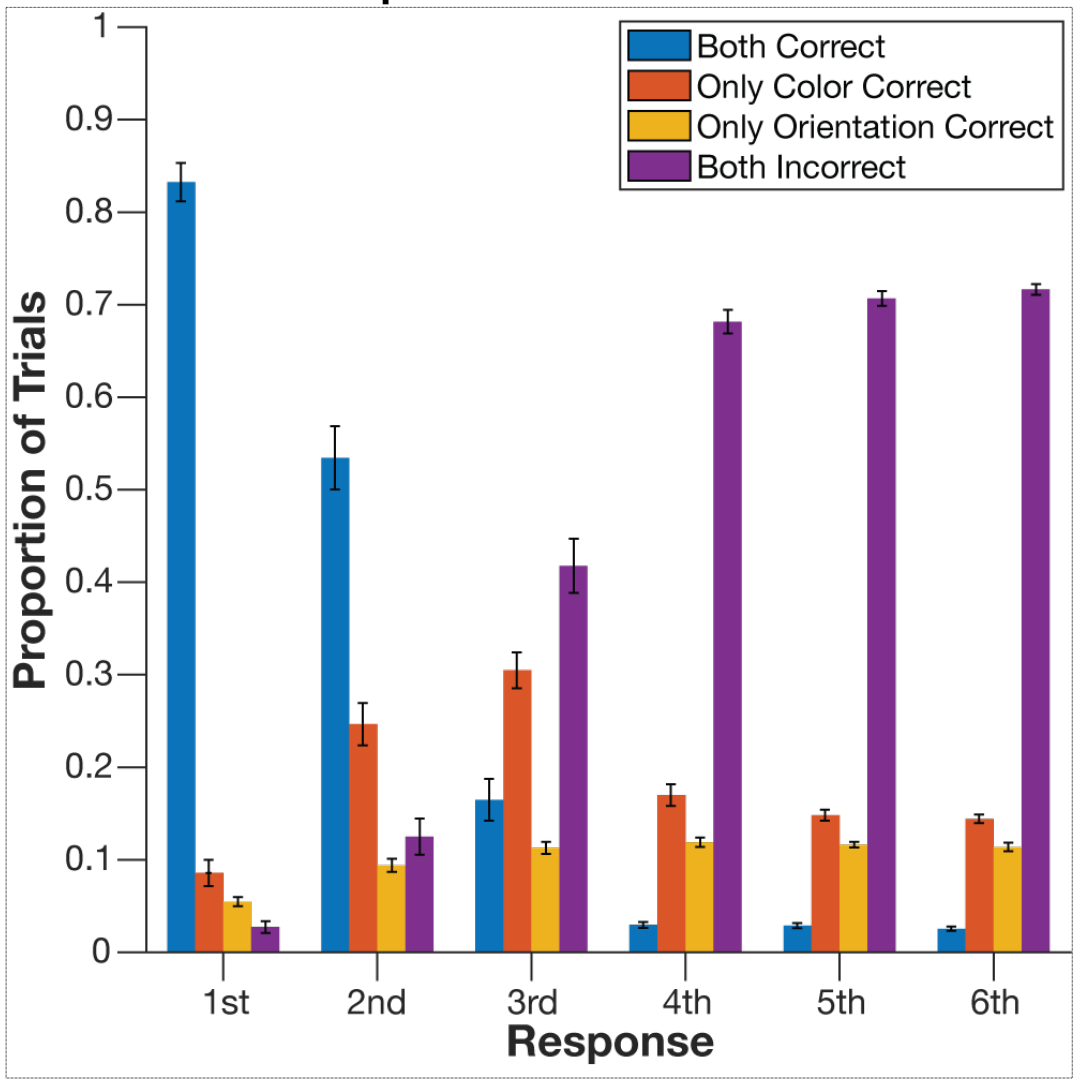
Experiment 4



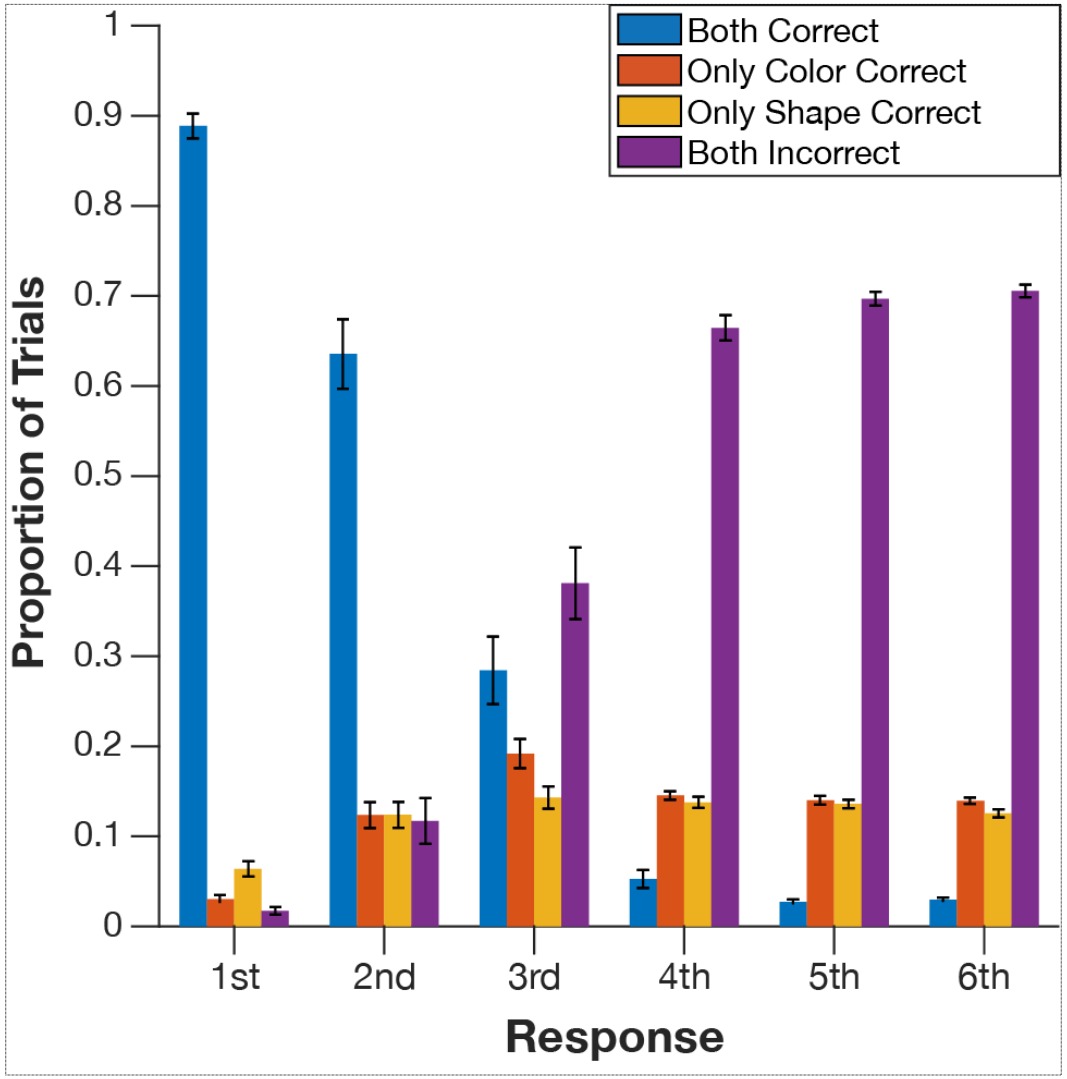
- The same empirical pattern was replicated across four experiments

Accuracy across responses

Experiment 1



Experiment 4



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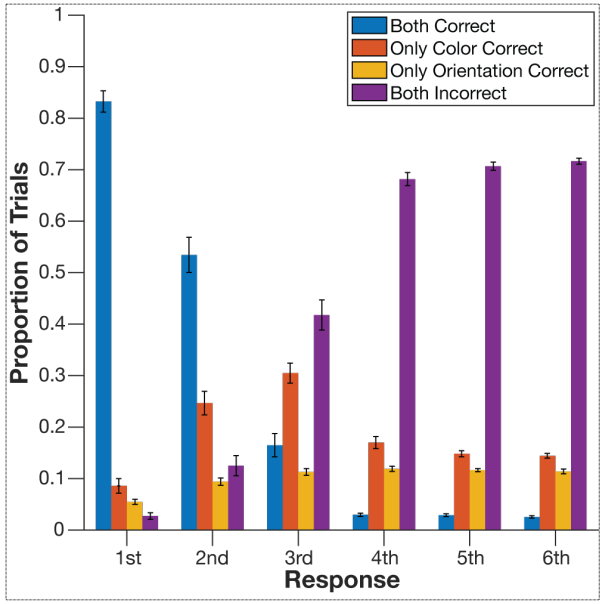
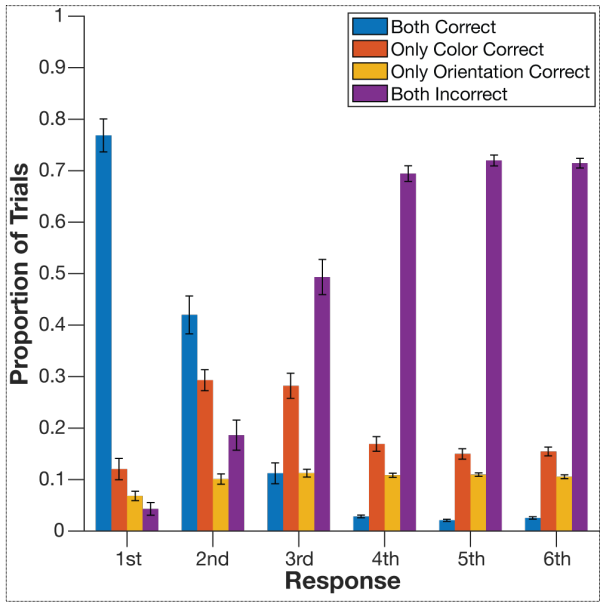
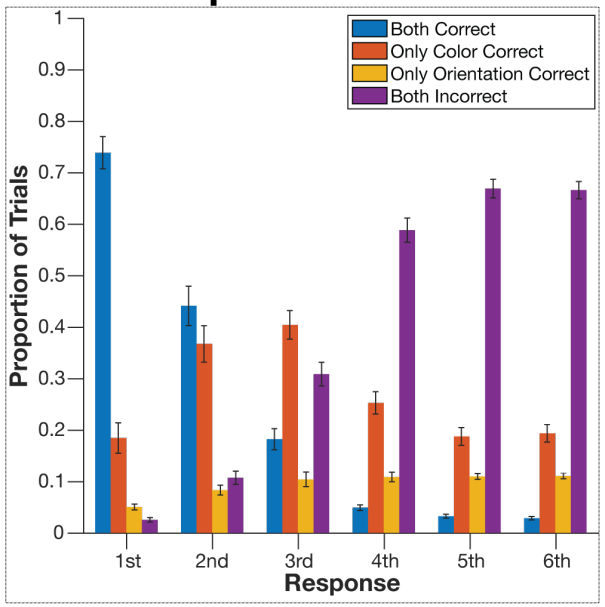


Experiment 2



Experiment 3



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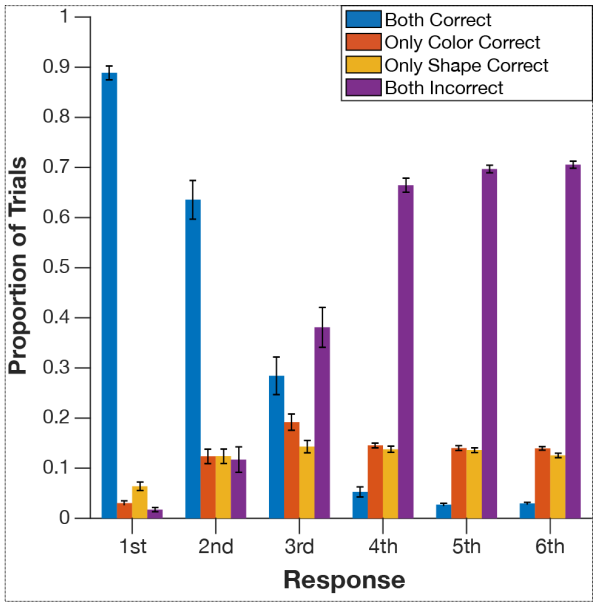
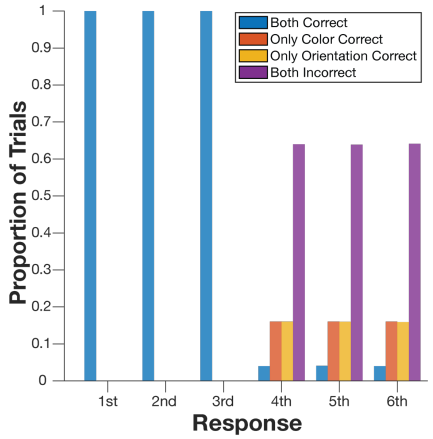


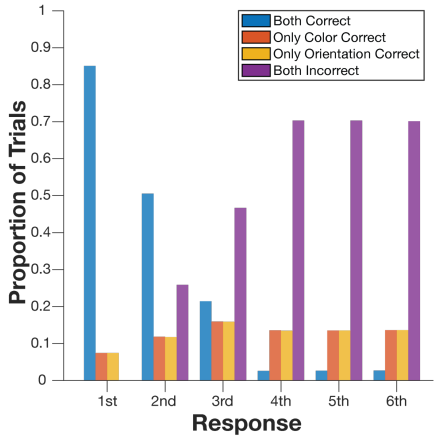
Strong Object Model

Accurate storage of three objects



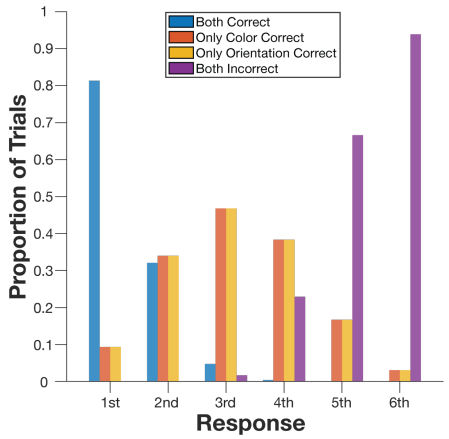
Pointer Model

Item-based storage with feature loss



Independent Feature Model

Feature storage independent of objecthood



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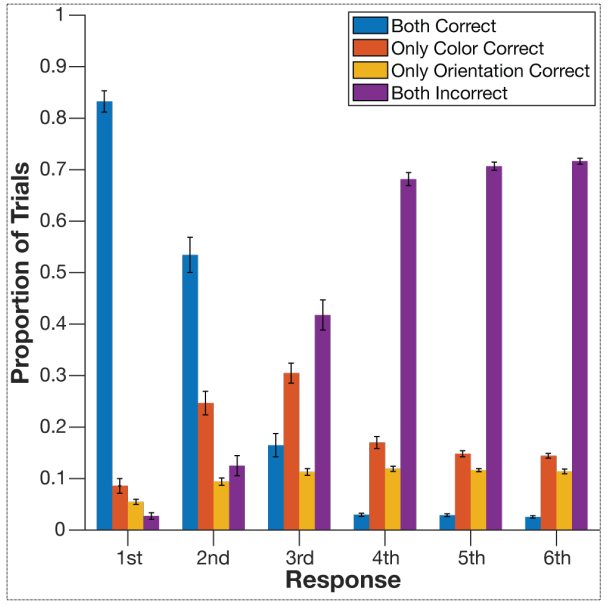
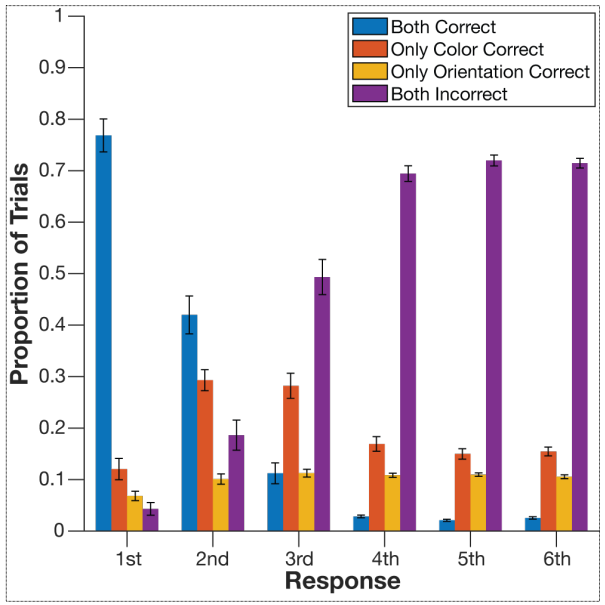


Experiment 2



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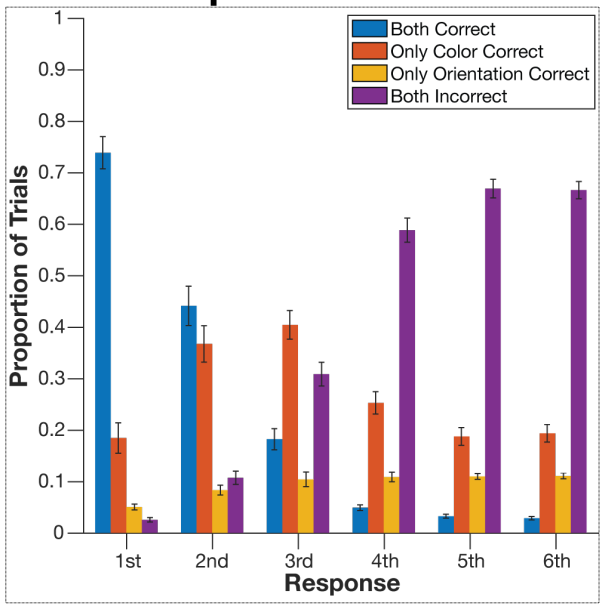
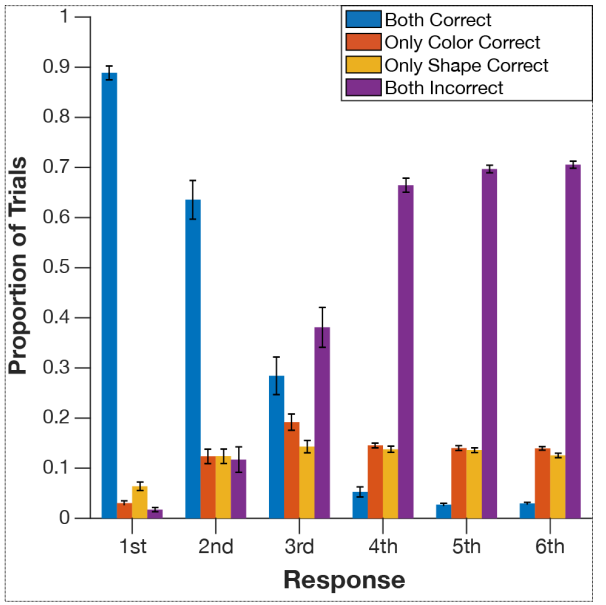


Experiment 4



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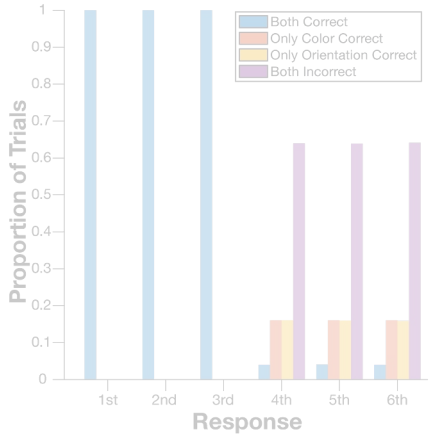
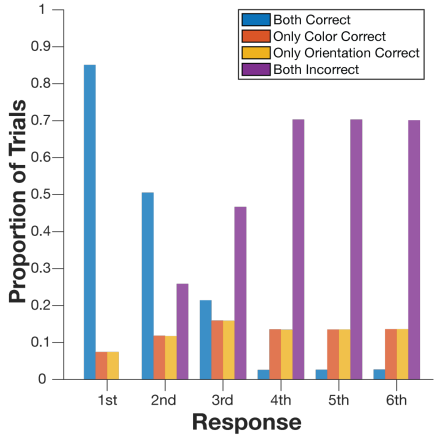


Pointer Model

Item-based storage with feature loss



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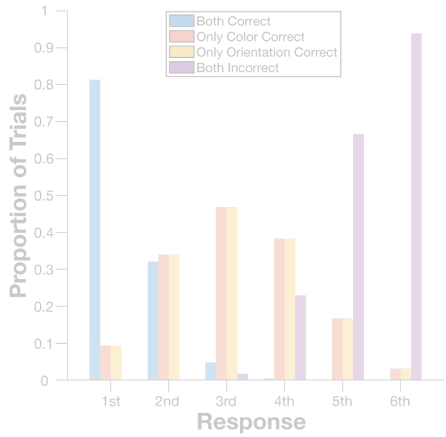


Formal model comparison

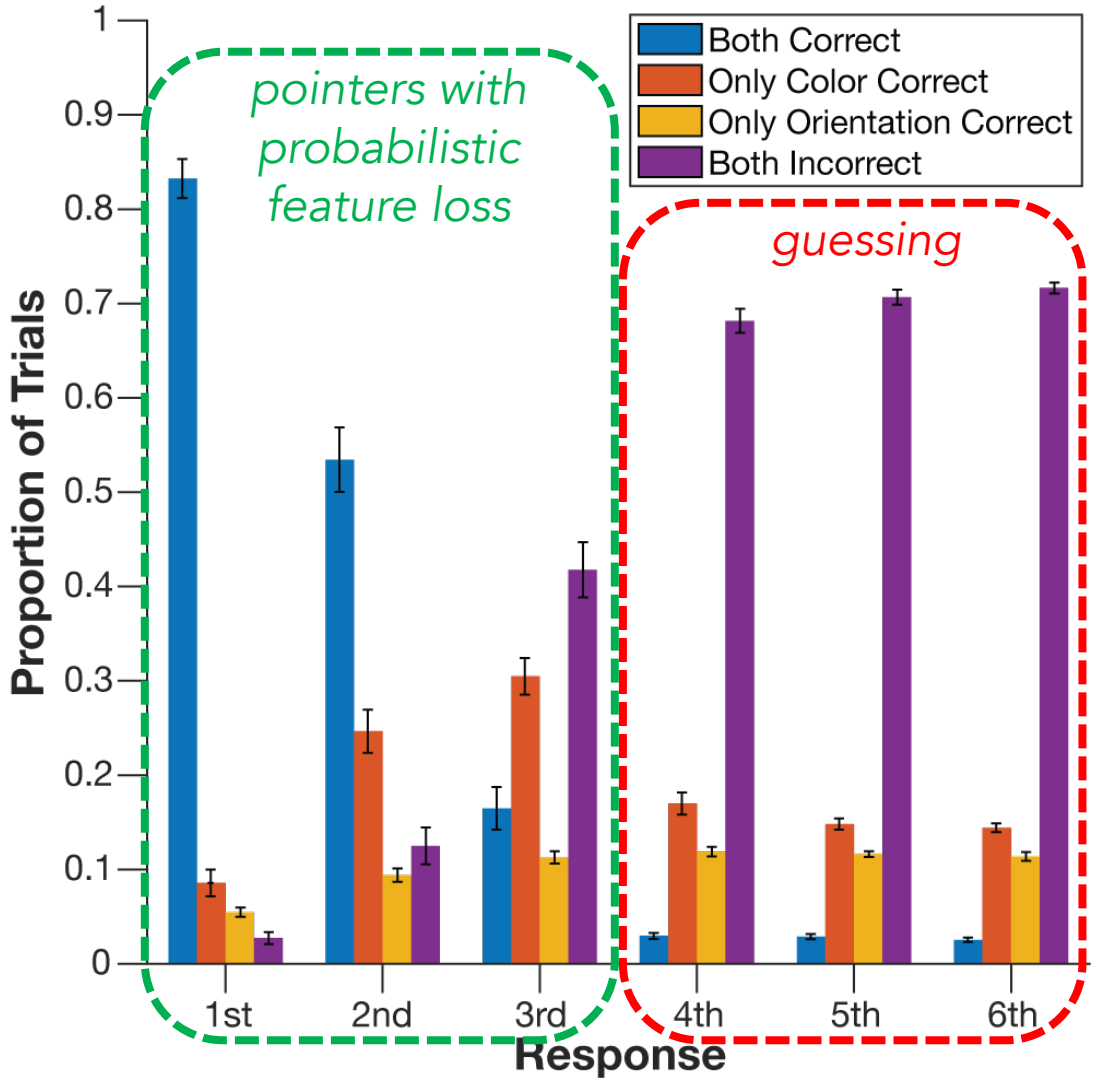
- The pointer model was best-fitting for all participants in all experiments

	✗	✓	✗
Model	Strong Object Model	Pointer Model	Independent Features Model
E1 AIC	4978.8	3326.2	4833.7
E1 BIC	4984.3	3337.2	4839.2
E2 AIC	4907.3	3310.2	4700.6
E2 BIC	4912.8	3321.2	4706.1
E3 AIC	5657.2	3497.4	4870.6
E3 BIC	5662.7	3508.4	4876.1
E4 AIC	4730.0	3211.5	4877.6
E4 BIC	4735.5	3222.5	4883.1

A pointer model

- Pointers are supposed to maintain representations of objects through changes in its features
  - Like *FINSTs* or *Object Files* (Pylyshyn, 1989; Kahneman et al., 1992)

- Not simply objects *or* features
  - We see object-based and feature-based phenomena in concert



Pylyshyn, Z. (1989). https://doi.org/10.1016/0010-0277(89)90014-0
Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). https://doi.org/10.1016/0010-0285(92)90007-O
Thyer, W. et al. (2022). https://doi.org/10.1177/09567976221090923

Guess bands

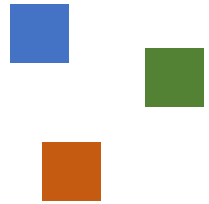
Joshua Foster

Kirsten Adam

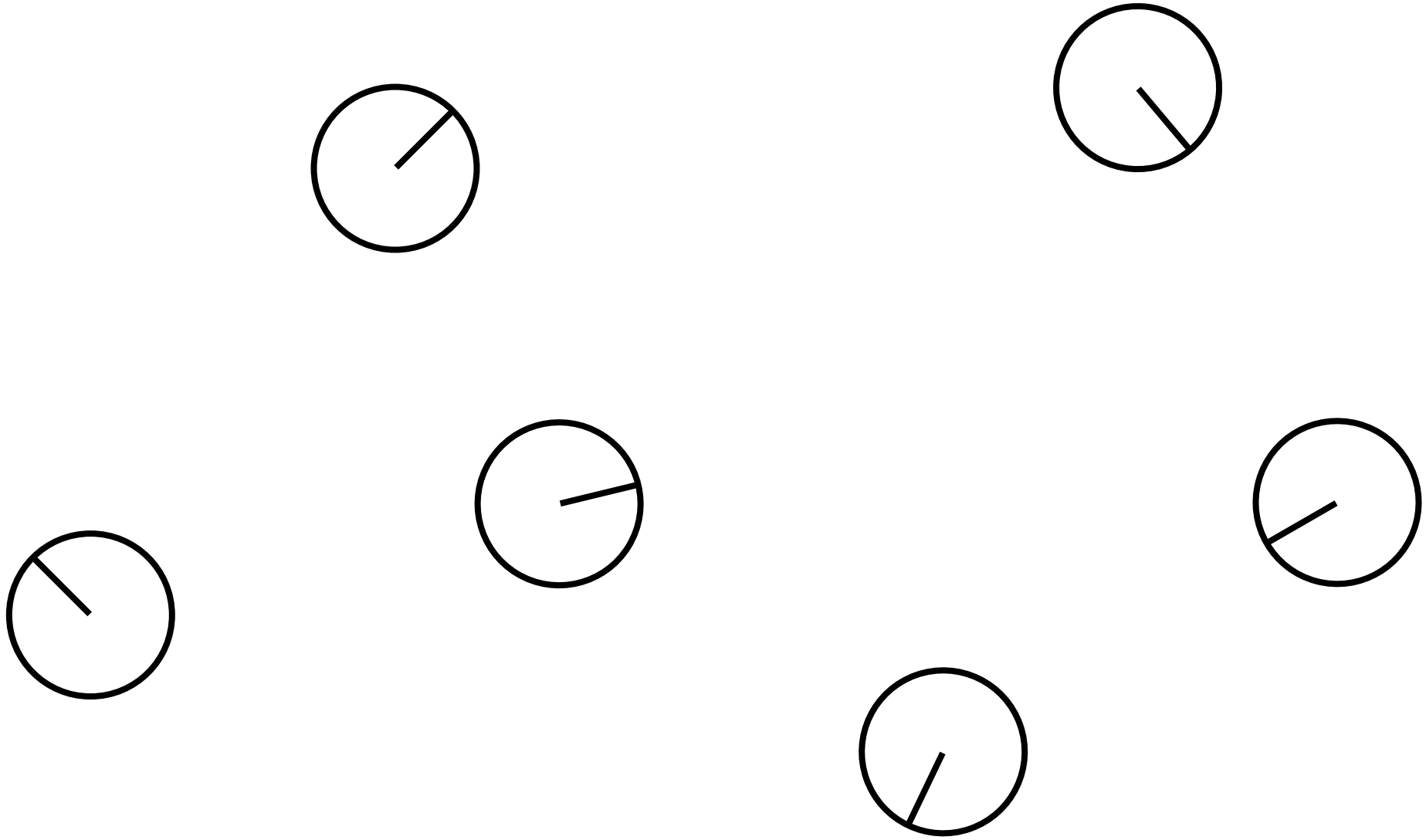
Ed Awh

What *is* visual working memory?

- Item-limit models (previously *slot models*)
  - Memory is contained to a few objects
  - There is no memory for objects beyond this capacity limit

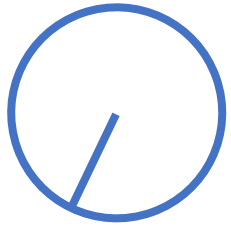


- Variable precision models (previously *flexible resource models*)
  - Memory is distributed across all items
  - There is flexible allocation of mnemonic resources to all items
    - More allocation of resources leads to a higher fidelity memory representation



Three items are stored

But nothing for
the other items

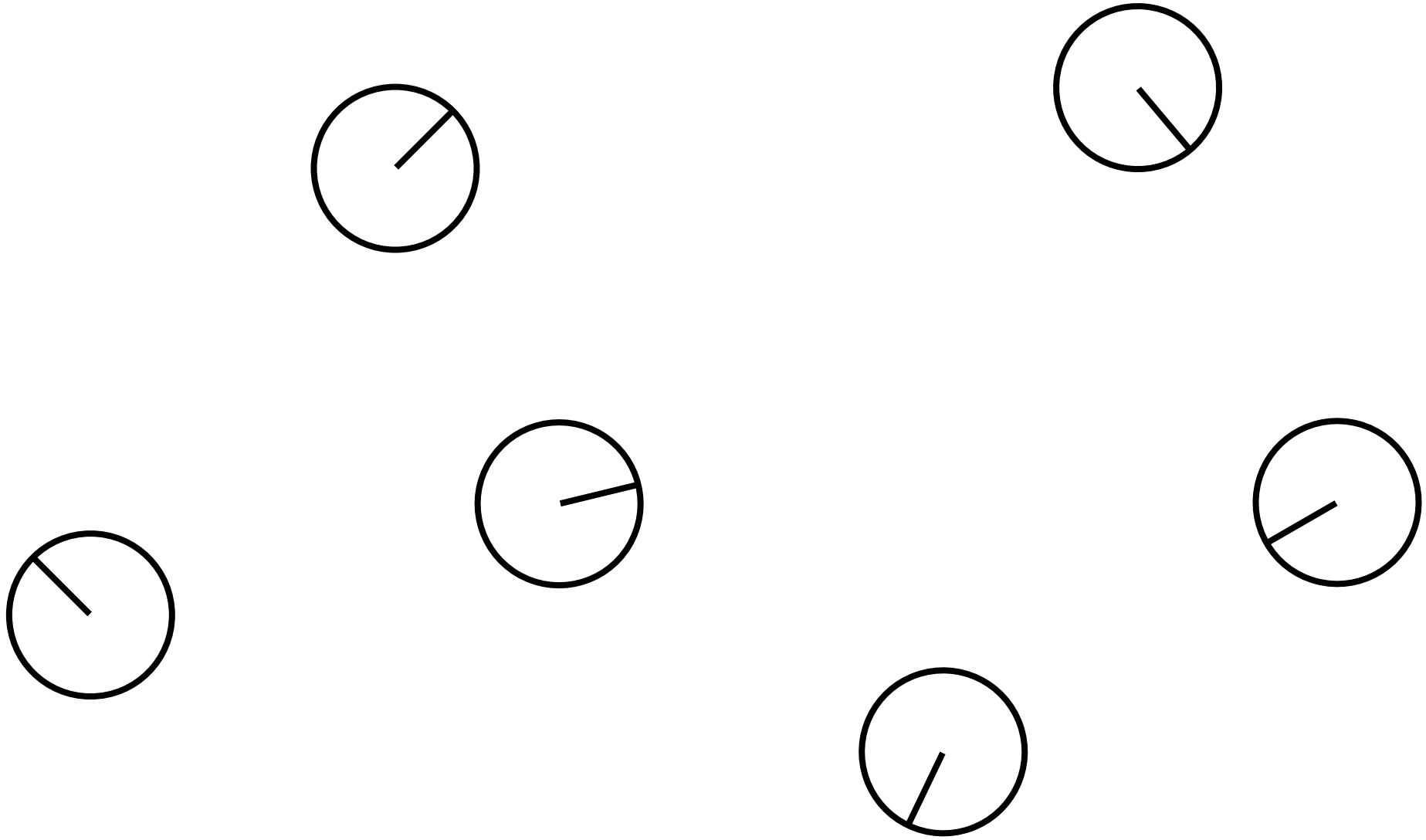


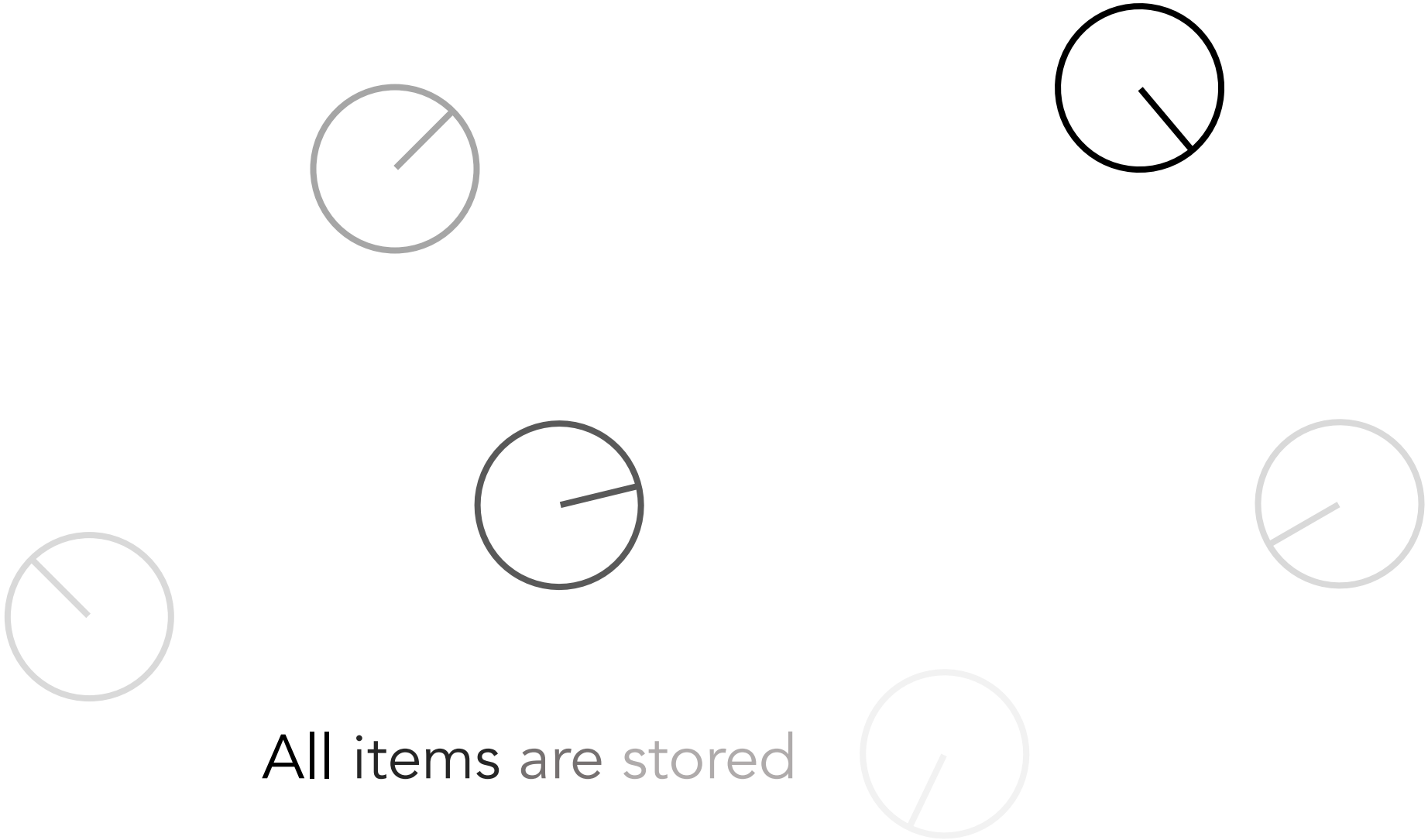
The competing models

- Item-limit models (previously *slot models*)
  - Memory is contained to a few objects
  - There is no memory for objects beyond this capacity limit

- Variable precision models (previously *flexible resource models*)
  - Memory is distributed across all items
  - There is flexible allocation of mnemonic resources to all items
    - More allocation of resources leads to a higher fidelity memory representation

NB. An item limit is not mutually exclusive with a variable precision process (more on this later).

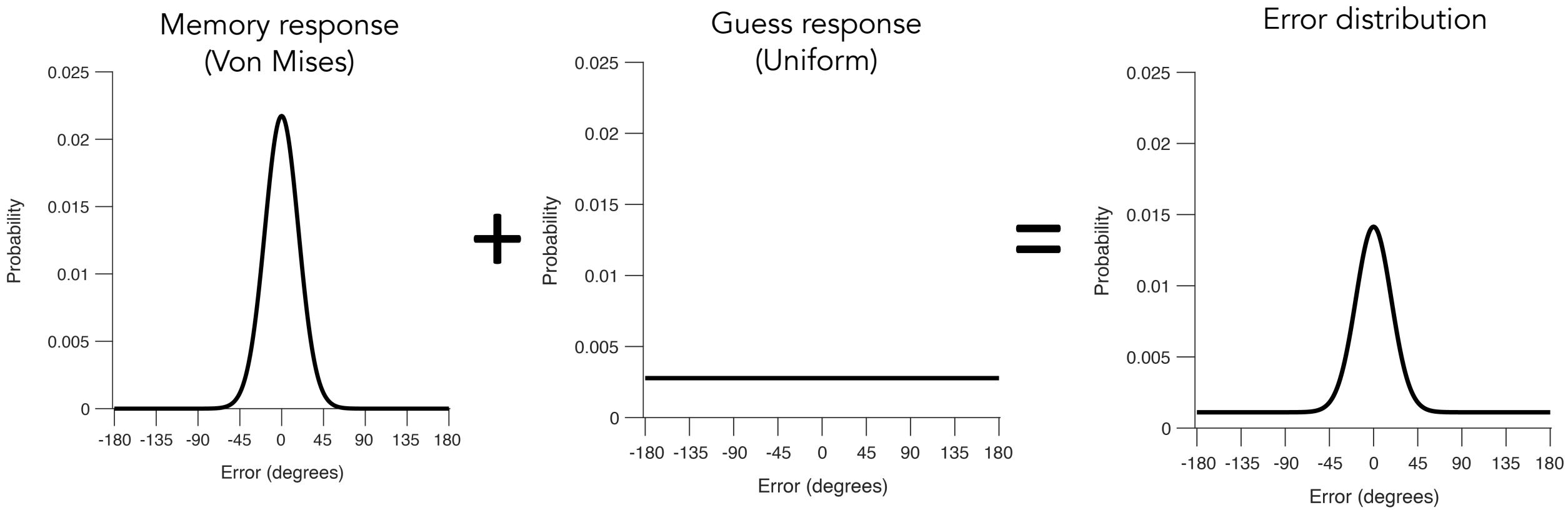




All items are stored

Formal models

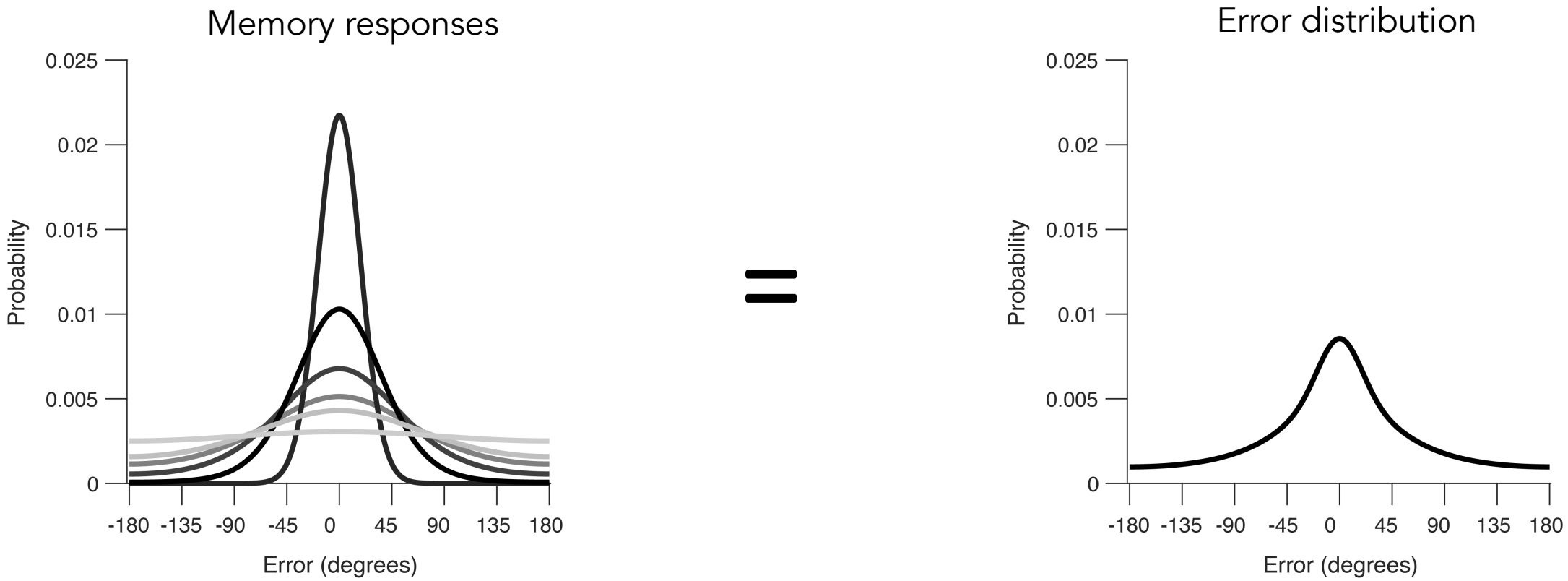
- Item-limit models (Zhang and Luck, 2008)



Zhang, W., & Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature*, *453*(7192), 233-235.

Formal models

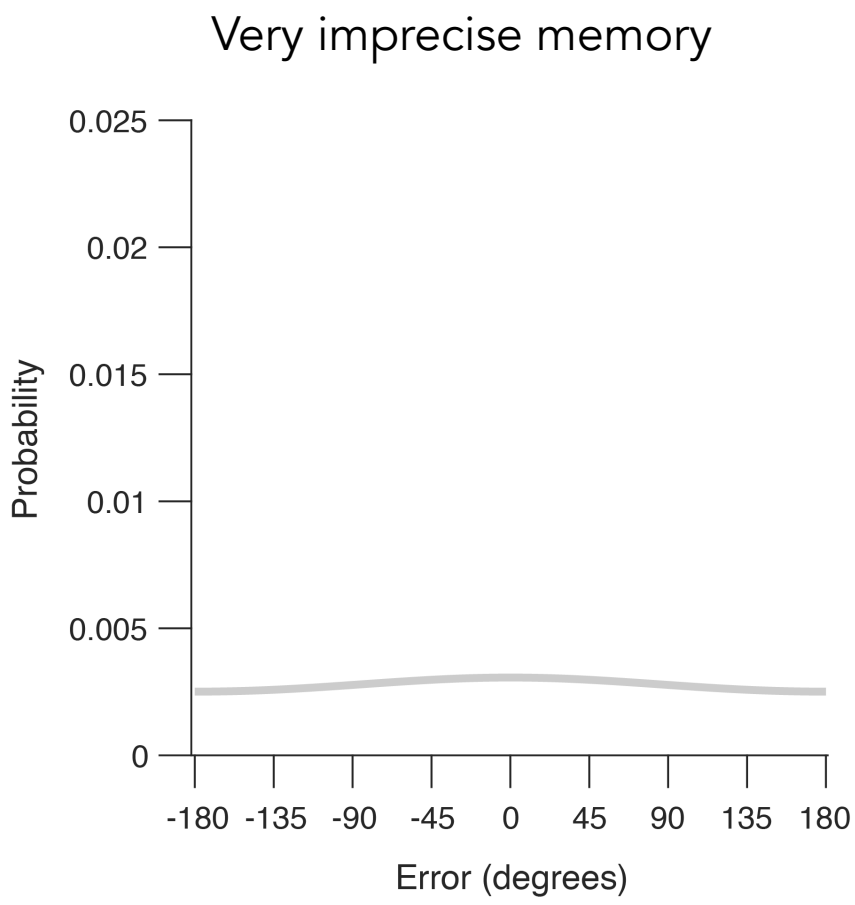
- Variable precision models (van den Berg et al., 2012)

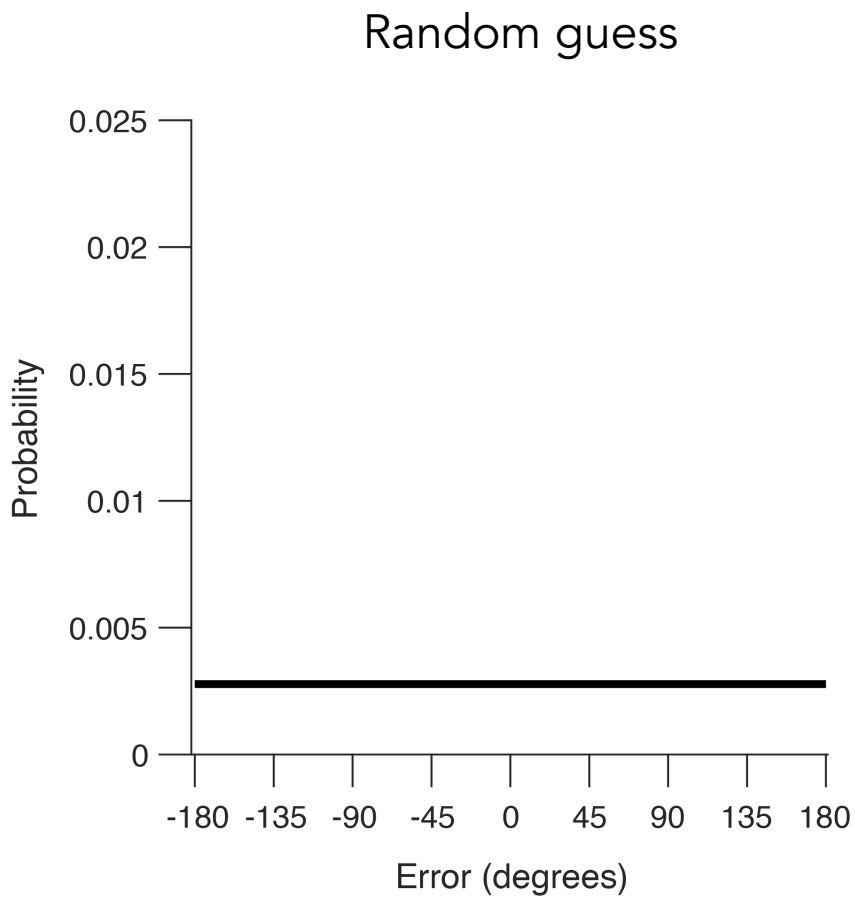


Van den Berg, R., Shin, H., Chou, W. C., George, R., & Ma, W. J. (2012). Variability in encoding precision accounts for visual short-term memory limitations. *Proceedings of the National Academy of Sciences*, *109*(22), 8780-8785.

The issue

- A very imprecise memory response can mimic a random guess





Whole-report recall task

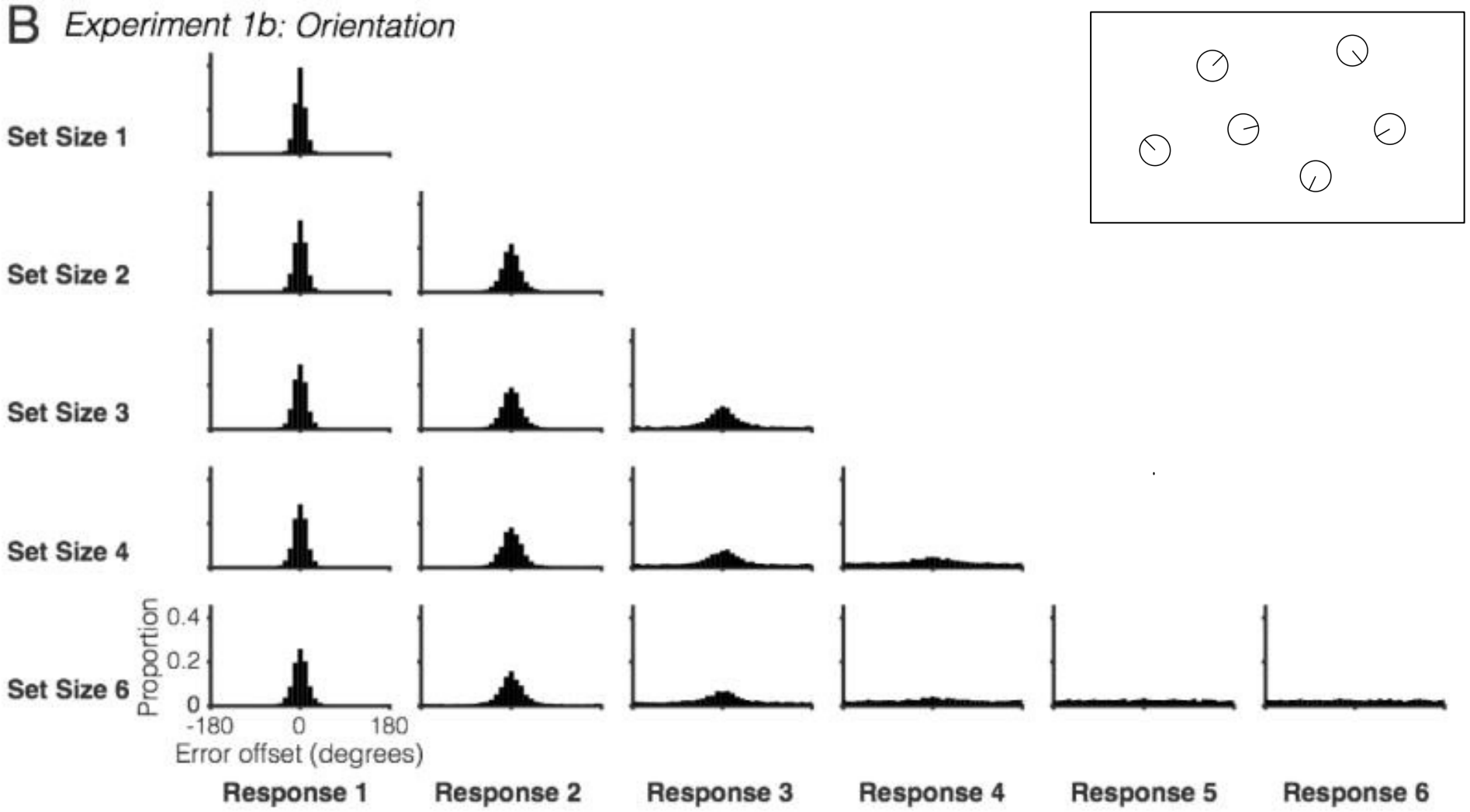
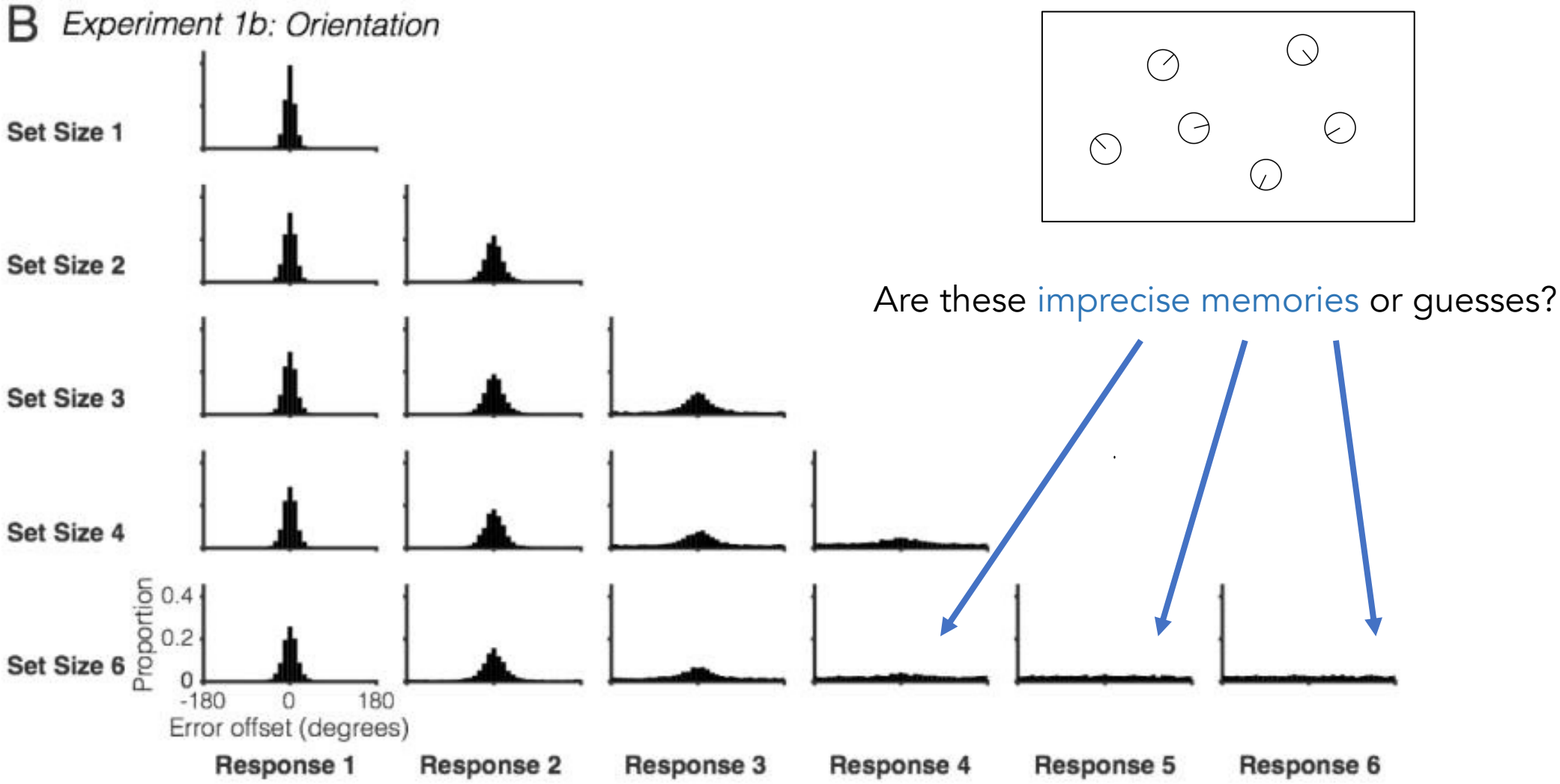


Figure from Adam, K. C., Vogel, E. K., & Awh, E. (2017). Clear evidence for item limits in visual working memory. *Cognitive psychology*, *97*, 79-97.

The issue



Are these imprecise memories or guesses?

Figure from Adam, K. C., Vogel, E. K., & Awh, E. (2017). Clear evidence for item limits in visual working memory. *Cognitive psychology*, *97*, 79-97.

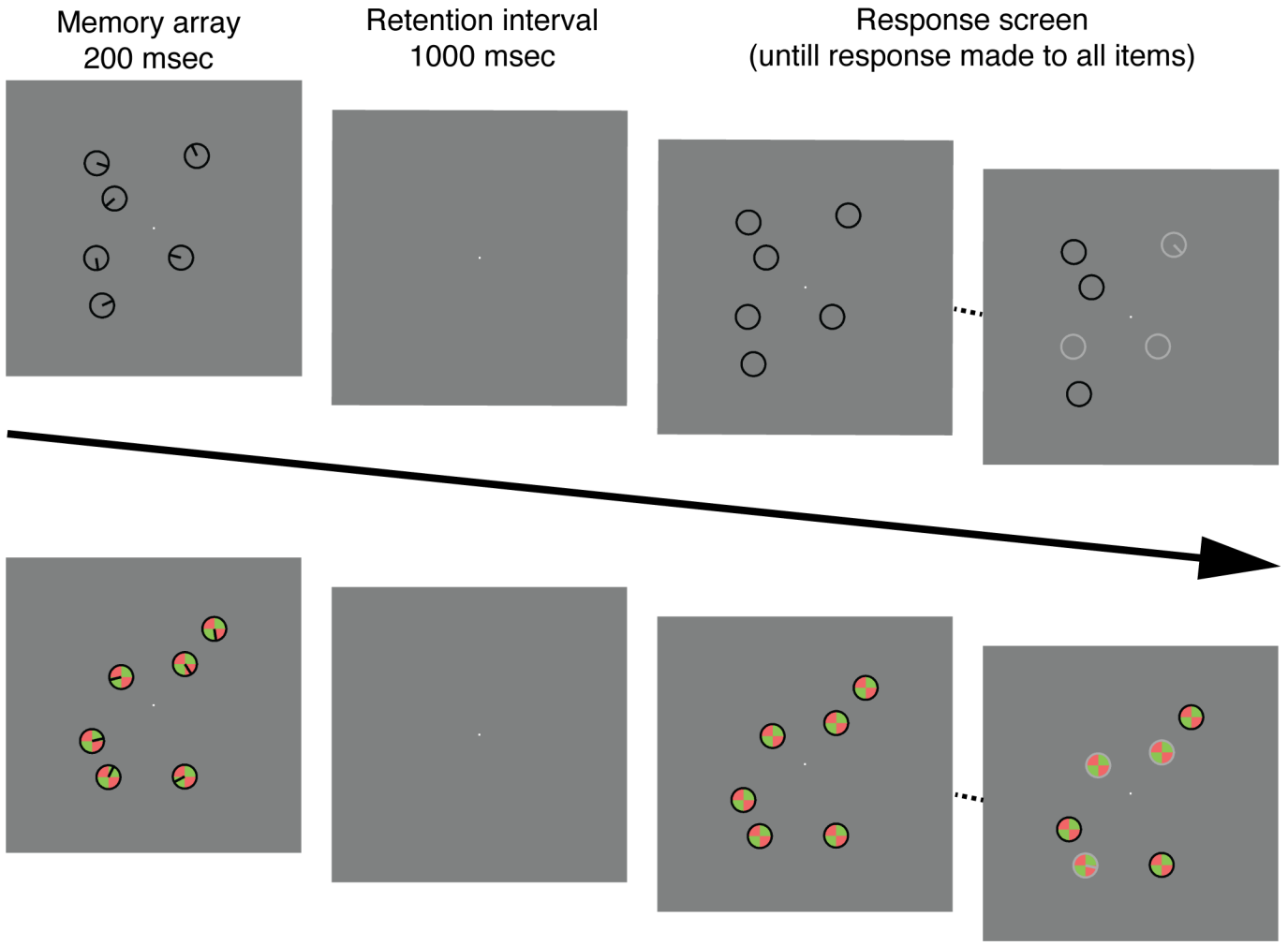
Our solution

- A supposed fundamental difference between these models is the existence of guessing

- Create an experimental paradigm where guesses are clearly distinct from imprecise memories
  - Have guesses produce a different distribution to a uniform distribution

Experiment design

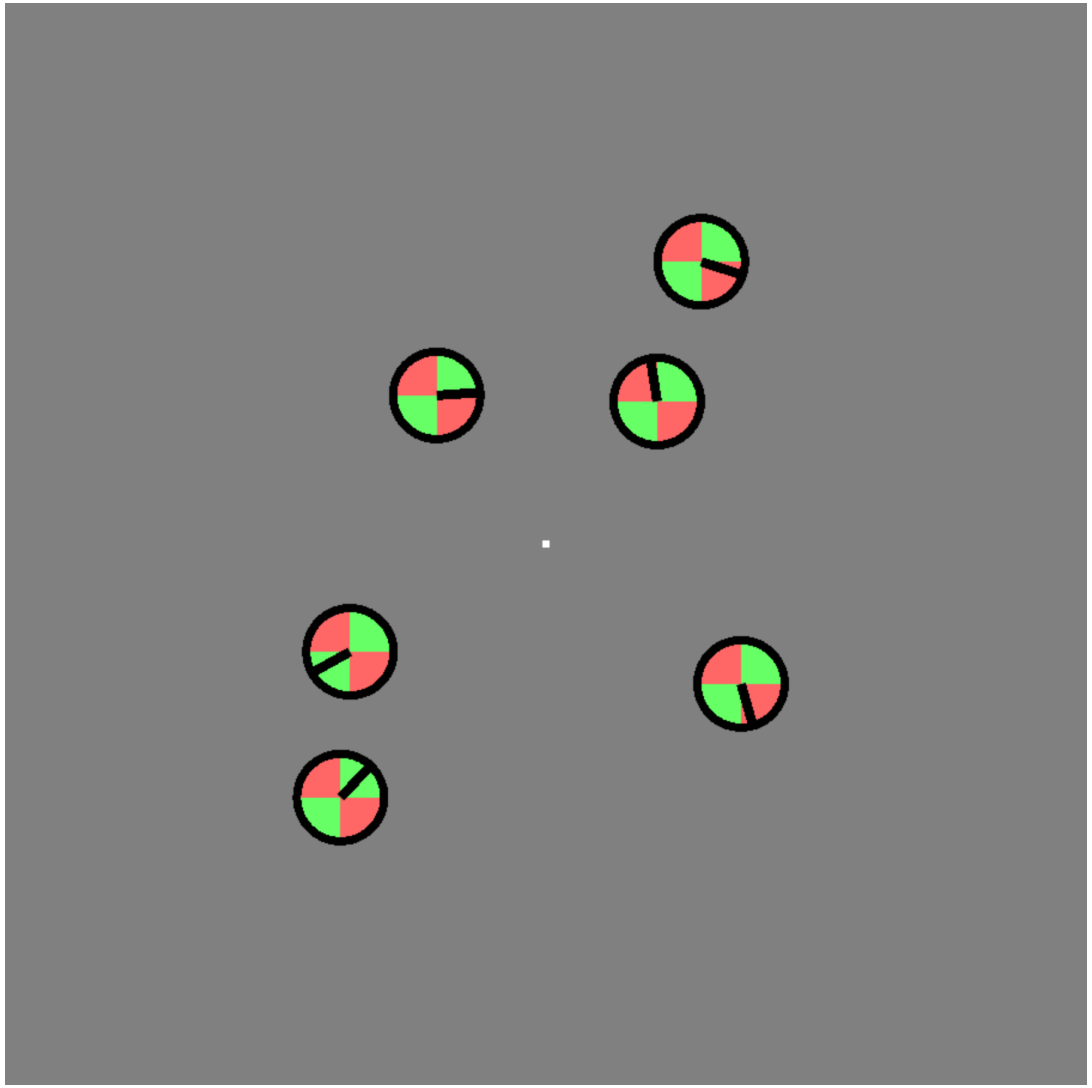
- Whole-report of six orientations
- Experiment 1 (n = 40)
  - 120 trials with colored quadrant backgrounds
  - 80 trials with no background
- Experiment 2 (n = 30)
  - 160 trials with the colored quadrant background rotated 45 degrees



What will guesses look like?

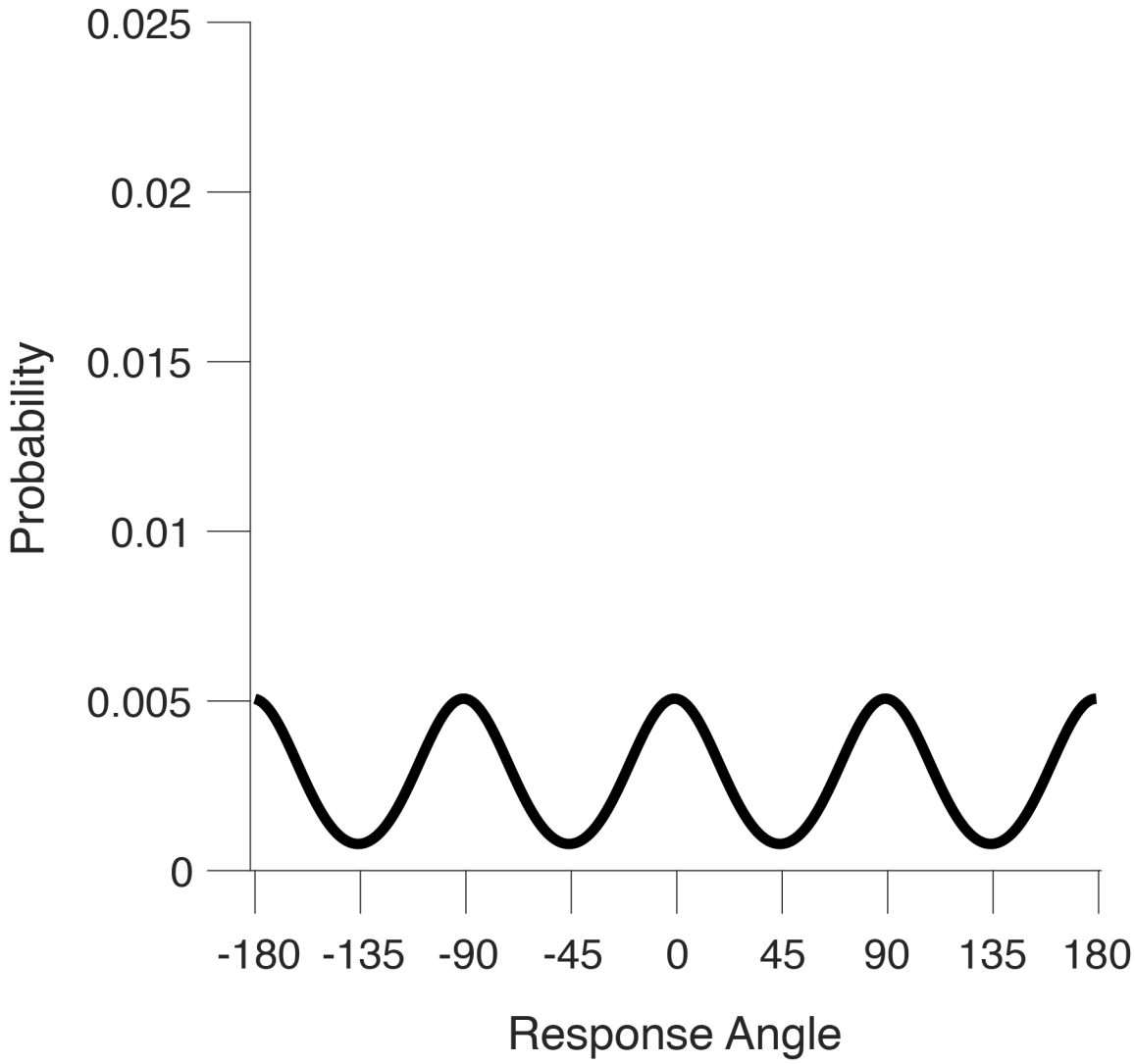
- We expect participants to respond towards the middle of the colored quadrants

- A response that is independent to the presented angle

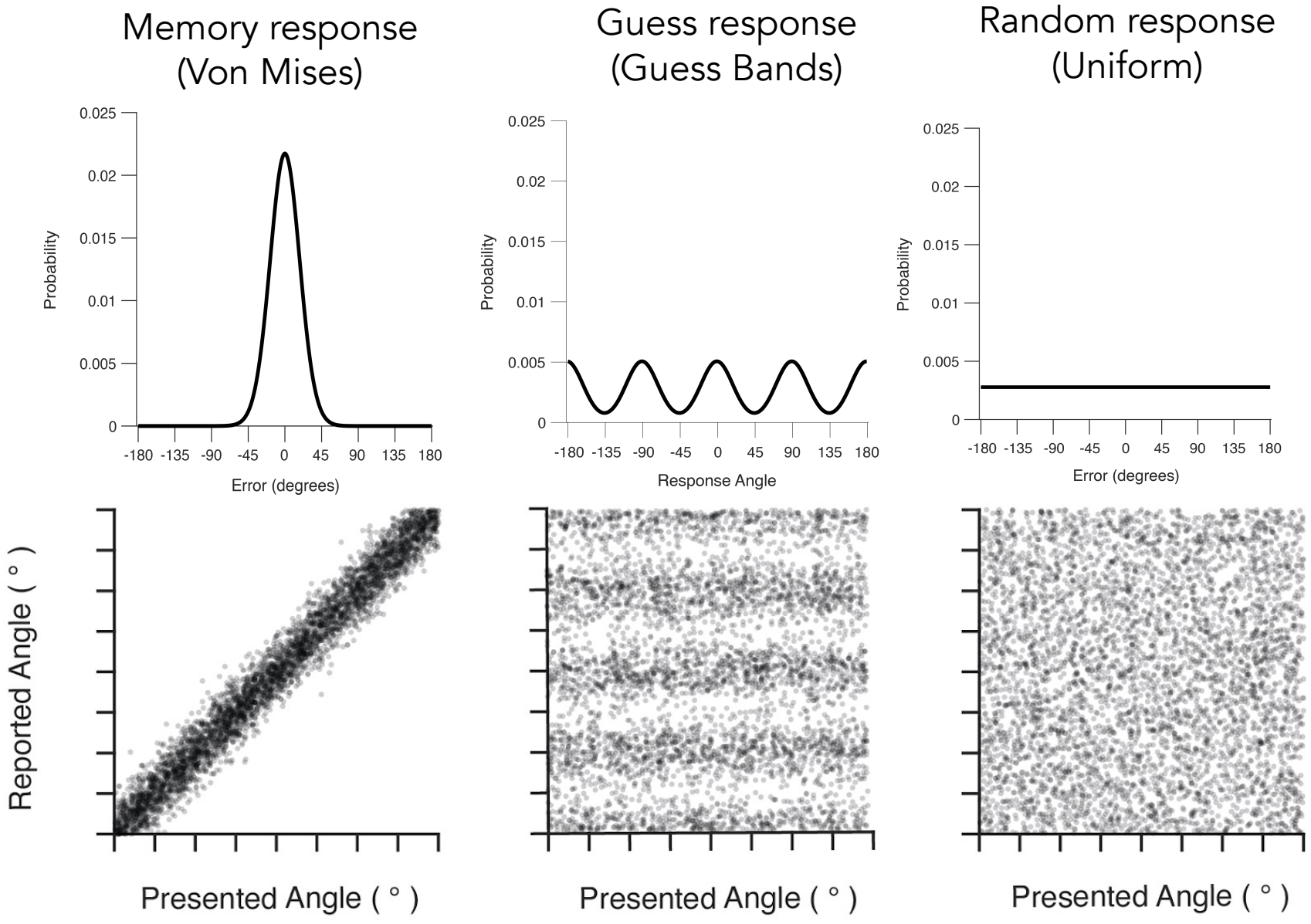


What should guesses look like?

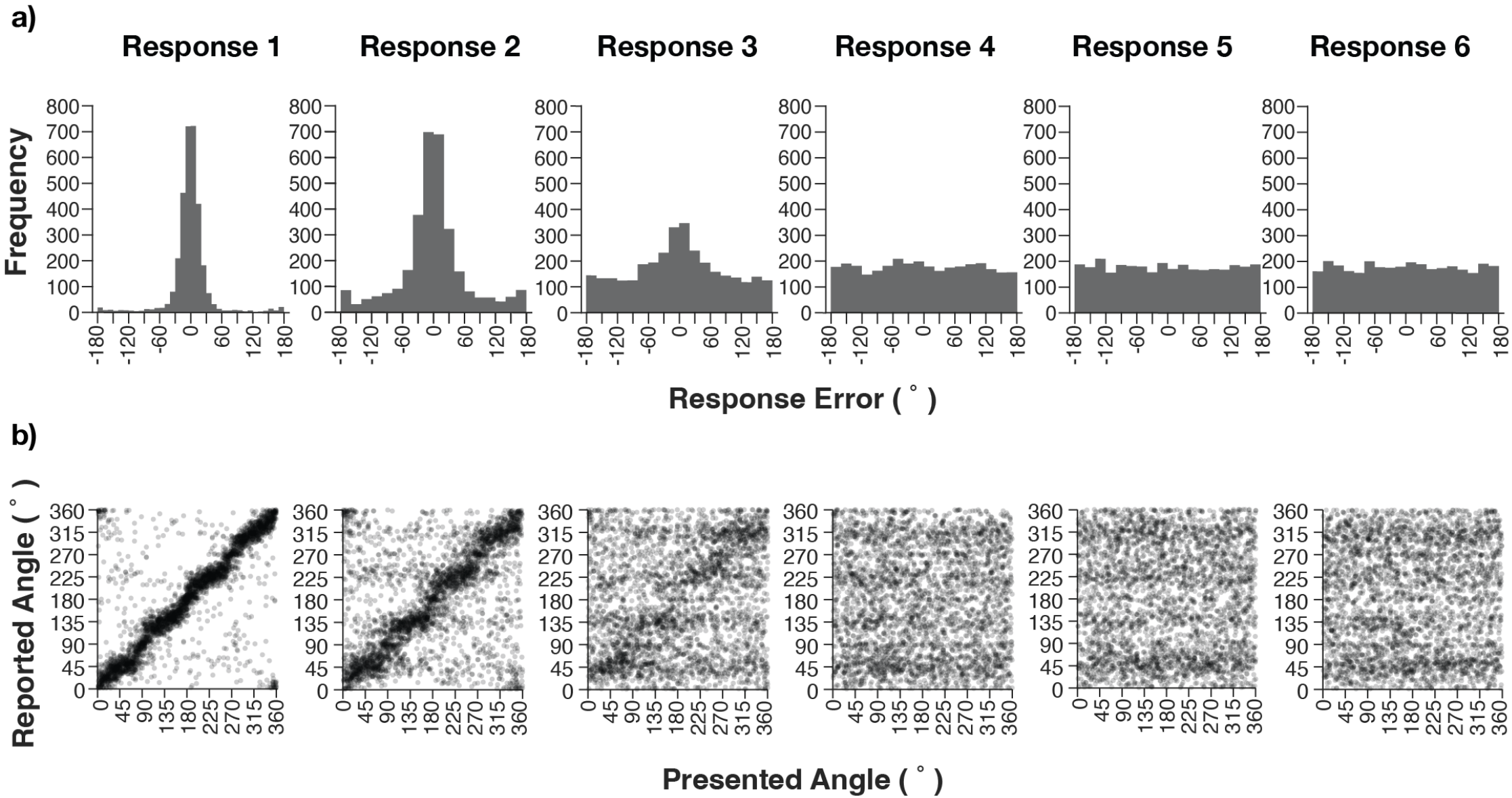
- We expect participants to respond towards the middle of the colored quadrants
- Probability distribution is clearly distinguishable from a wide Von Mises distribution
- A response that cannot be explained by an imprecise memory



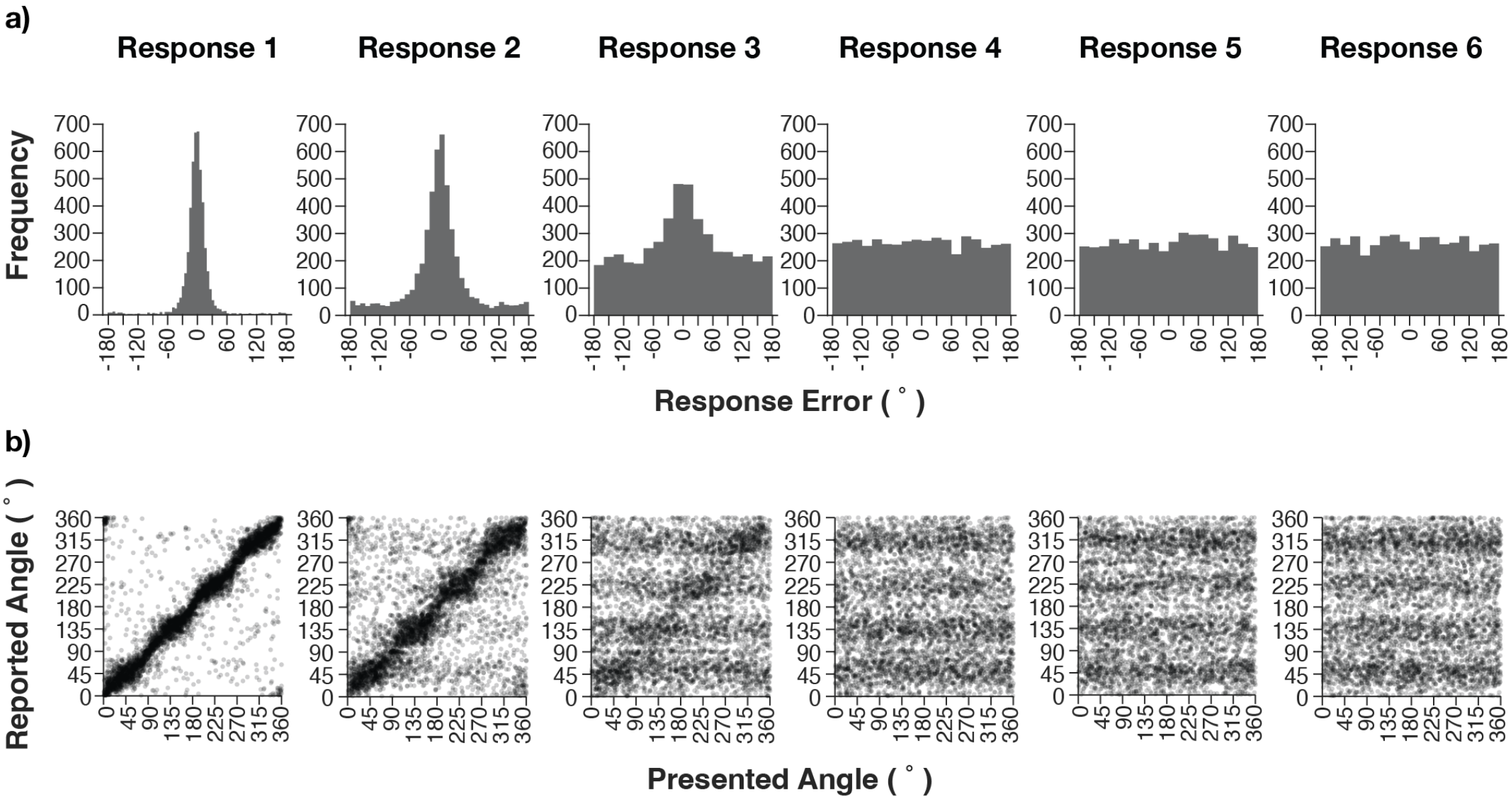
What we predict we will observe



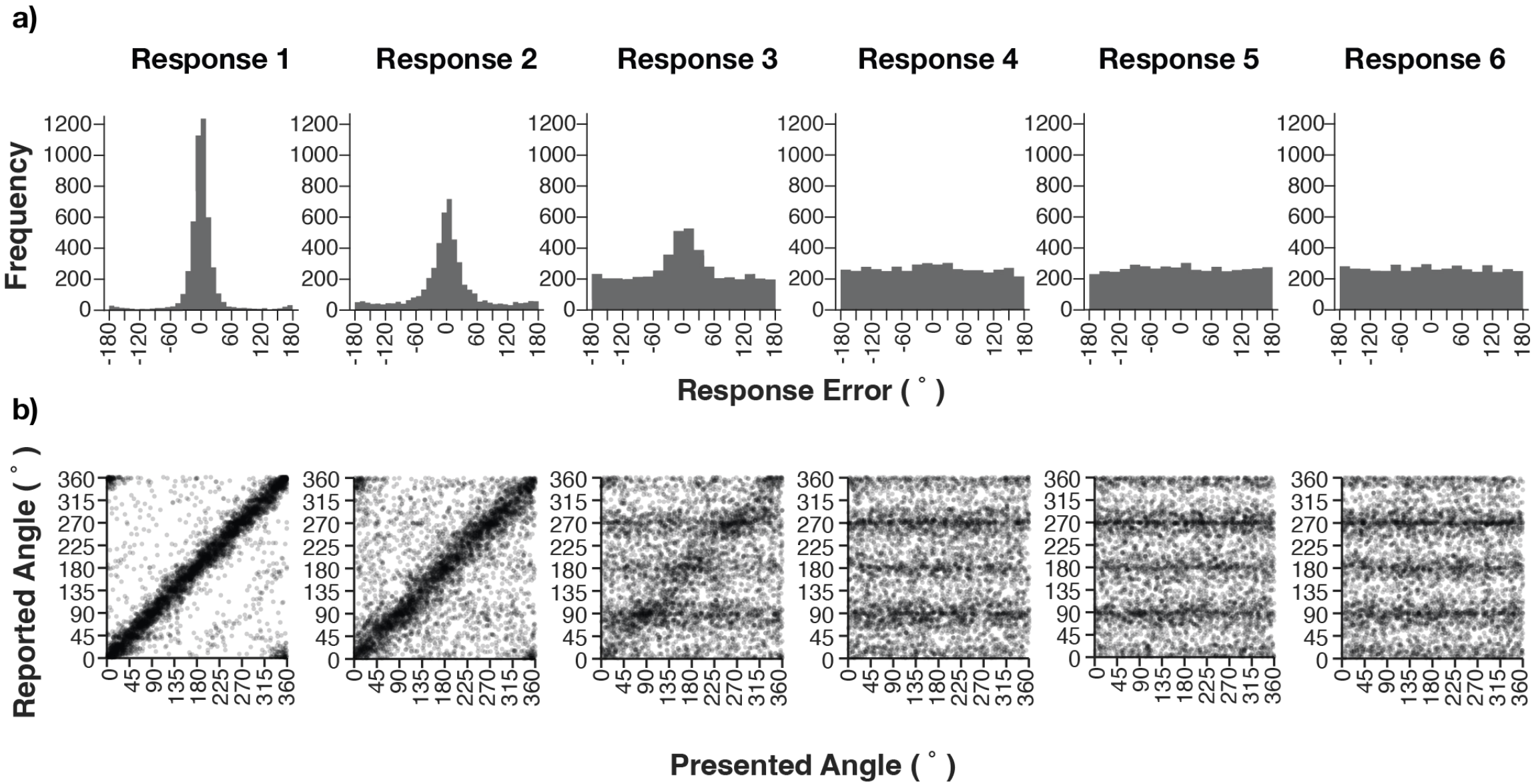
Experiment 1 Results – Standard condition



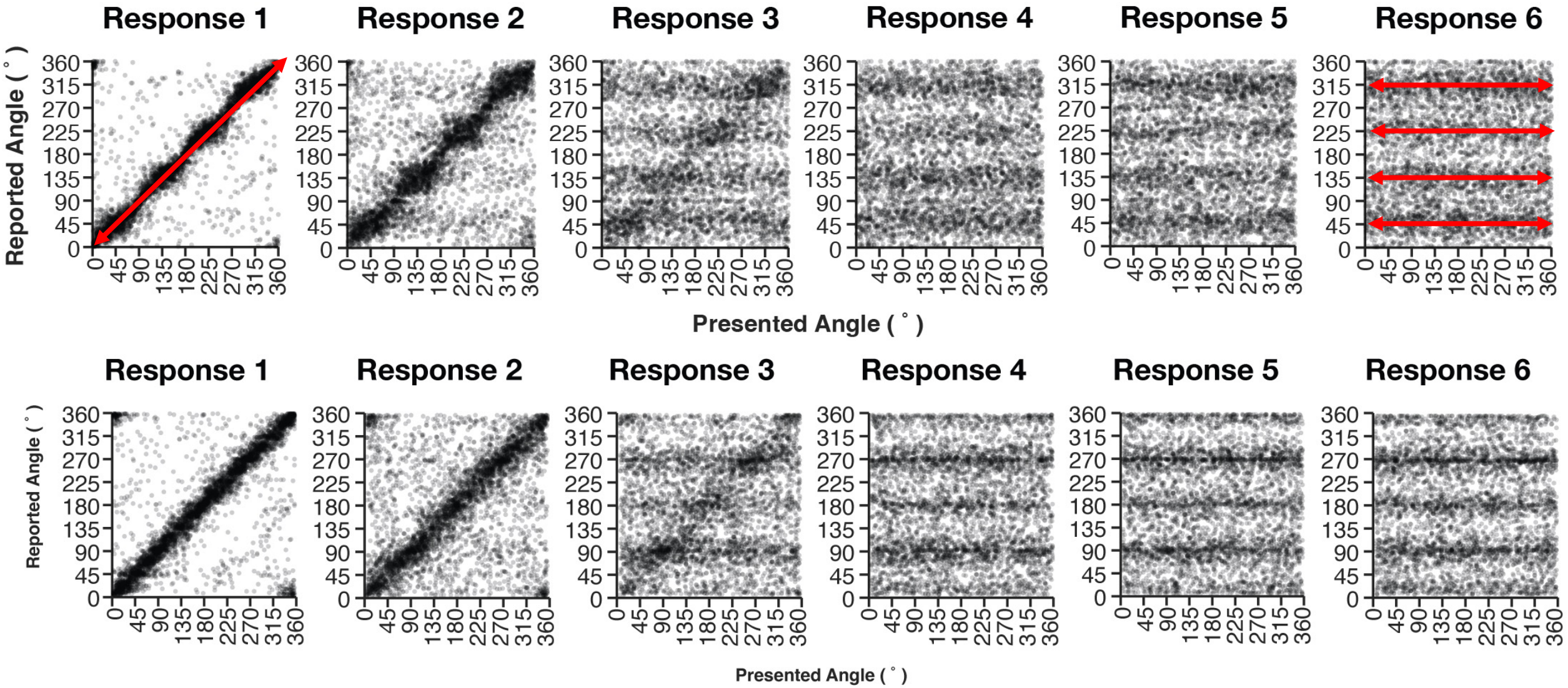
Experiment 1 Results – Background condition



Experiment 2 Results

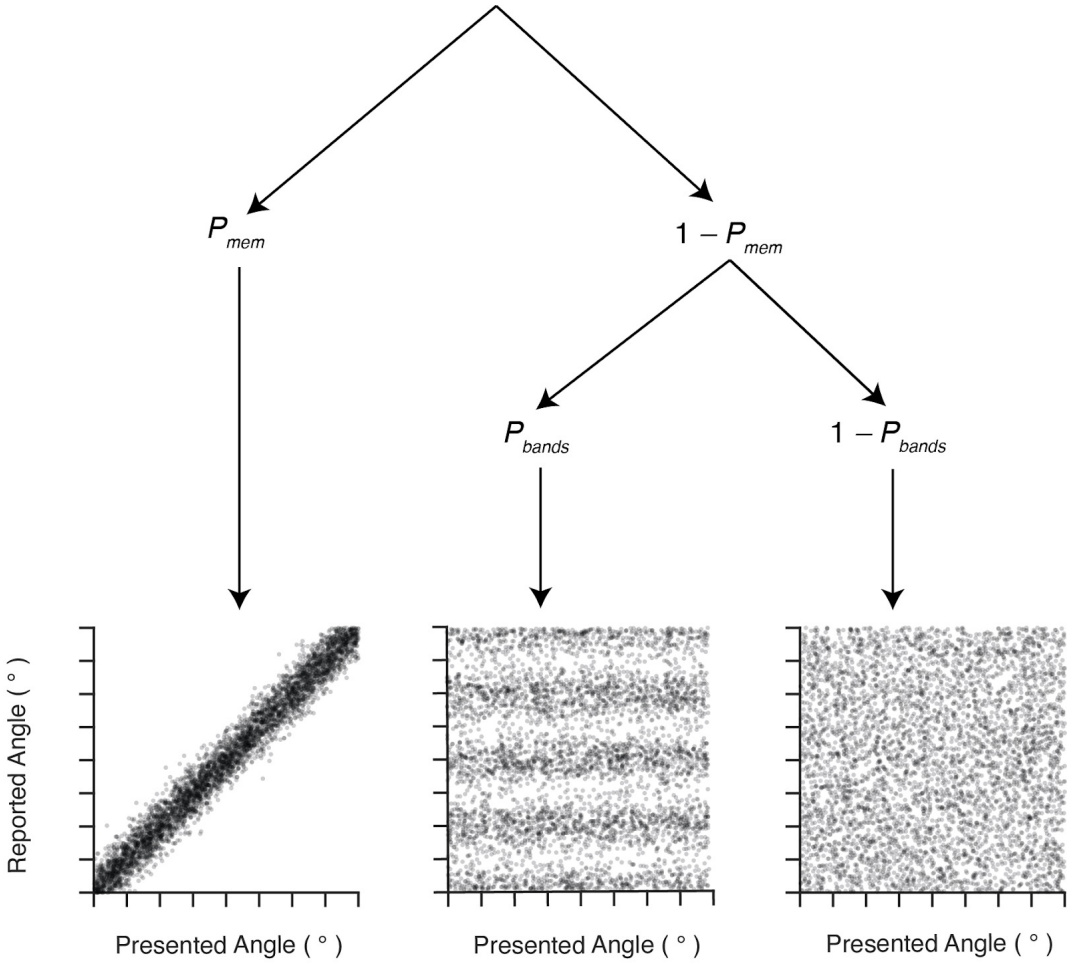


Clear visual evidence for ‘guess bands’



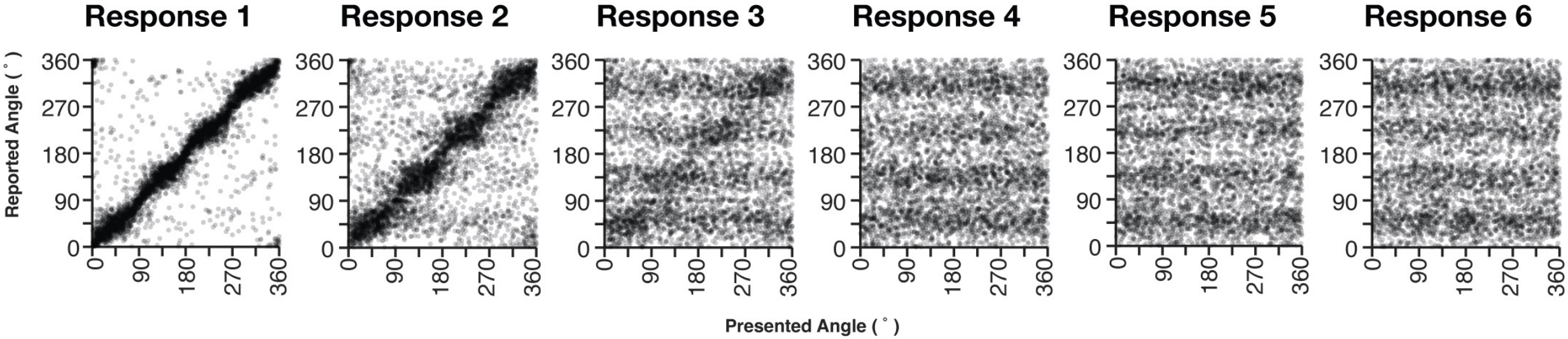
Formal model comparison

- Maximum likelihood estimation of the parameters for models with each possible permutation of the components:
  - Von Mises (a memory response)
    - Width of the Von Mises was a free parameter
  - Bands (a guess response)
    - Width of the bands was a free parameter
  - Uniform (a random response)
- 100 replicates with a maximum of 10000 iterations
  - Compared on the Bayesian Information Criterion (BIC)



Experiment 1 model comparison

- At the **aggregate level:**
  - For the first three responses, Von Mises + Guess Bands was the best-fitting model (ΔBIC < 9).
  - For the last three responses, Von Mises + Guess Bands + Uniform was the best-fitting model (ΔBIC > 57)



Estimated prevalence of responses

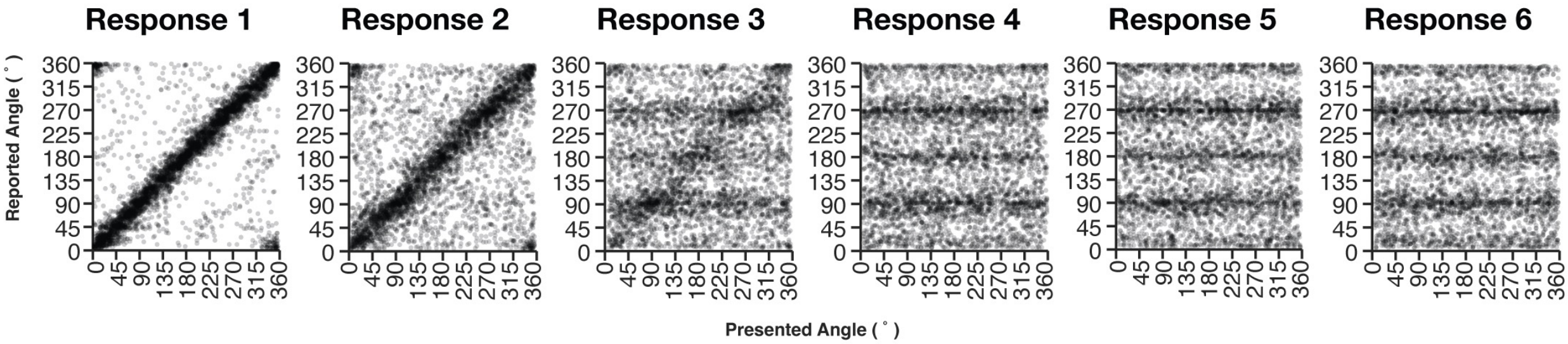
- Parameter estimates from Von Mises + Guess Bands + Uniform model

Response	Memory	Guess Bands	Uniform
1st	90.59% ± 0.57%	9.41% ± 1.15%	0% ± 0.58%
2nd	66.03% ± 1.68%	33.97% ± 2.20%	0% ± 0.52%
3rd	20.37% ± 0.63%	46.64% ± 12.16%	32.99% ± 11.53%
4th	0.19% ± 0.09%	41.96% ± 8.29%	57.85% ± 8.20%
5th	0.30% ± 0.12%	35.78% ± 4.53%	63.92% ± 4.41%
6th	0.39% ± 0.12%	39.12% ± 6.25%	60.49% ± 6.13%

- Memory responses are constrained to the first three responses
- Substantial prevalence of 'guess band' responses in later responses

Experiment 2 model comparison

- At the **aggregate level**:
  - For the first response, Von Mises + Uniform was the best-fitting model (ΔBIC = 8).
  - For the last four responses, Von Mises + Guess Bands + Uniform was the best-fitting model (ΔBIC > 24 from 3rd response onward)



Estimated prevalence of responses

- Parameter estimates from Von Mises + Guess Bands + Uniform model

Response	Memory	Guess Bands	Uniform
1st	87.84% ± 0.00%	0.64% ± 0.00%	11.52% ± 0.00%
2nd	64.13% ± 1.18%	2.08% ± 0.90%	33.79% ± 2.08%
3rd	21.07% ± 0.61%	37.26% ± 6.25%	41.67% ± 5.65%
4th	0.31% ± 0.11%	48.10% ± 6.02%	51.59% ± 5.91%
5th	0.21% ± 0.11%	48.70% ± 4.70%	51.09% ± 4.58%
6th	0.25% ± 0.11%	47.22% ± 4.35%	52.53% ± 4.24%

- Memory responses are constrained to the first three responses
- Substantial prevalence of 'guess band' responses in later responses

Formal model comparison on individual data

- Experiment 1
  - In early responses, the Von Mises + Uniform (M1) model best fits most participants' data
  - In later responses, the Guess Bands only (M4) model best fits most participants' data

	M1	M2	M3	M4	M5	M6
1st	**28**	-	-	-	10	2
2nd	**19**	-	1	2	18	-
3rd	**14**	-	1	2	13	-
4th	6	-	-	**30**	4	-
5th	5	2	2	**25**	6	-
6th	6	1	2	**23**	8	-

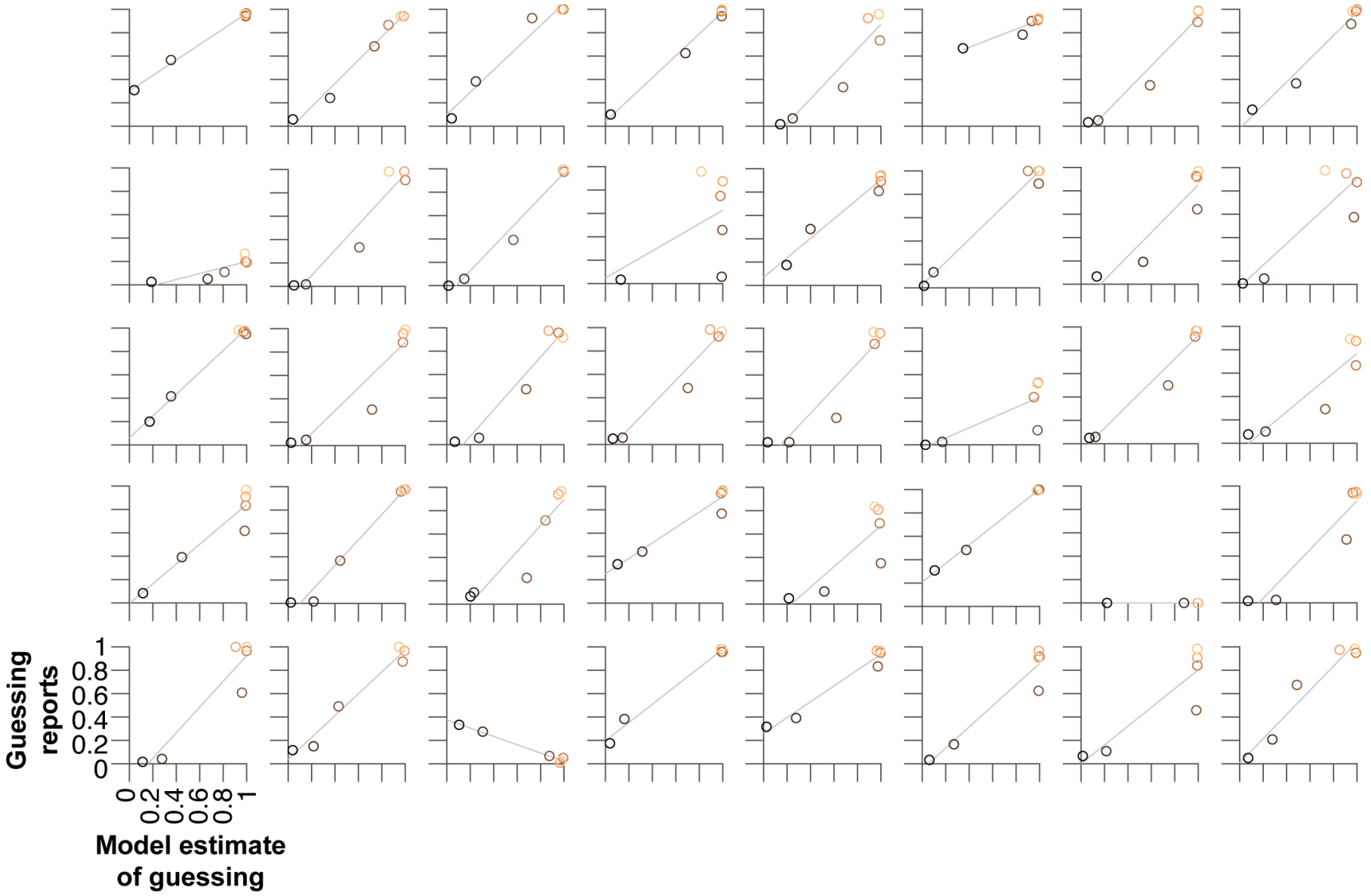
Formal model comparison on individual data

- Experiment 2
  - In early responses, the Von Mises + Uniform (M1) model best fits most participants' data
  - In later responses, the Guess Bands only (M4) model best fits most participants' data

	M1	M2	M3	M4	M5	M6
1st	**23**	-	1	-	4	2
2nd	**17**	-	3	-	10	-
3rd	4	4	5	7	**10**	-
4th	4	7	5	**9**	5	-
5th	5	**11**	1	**11**	2	-
6th	1	5	3	**16**	5	-

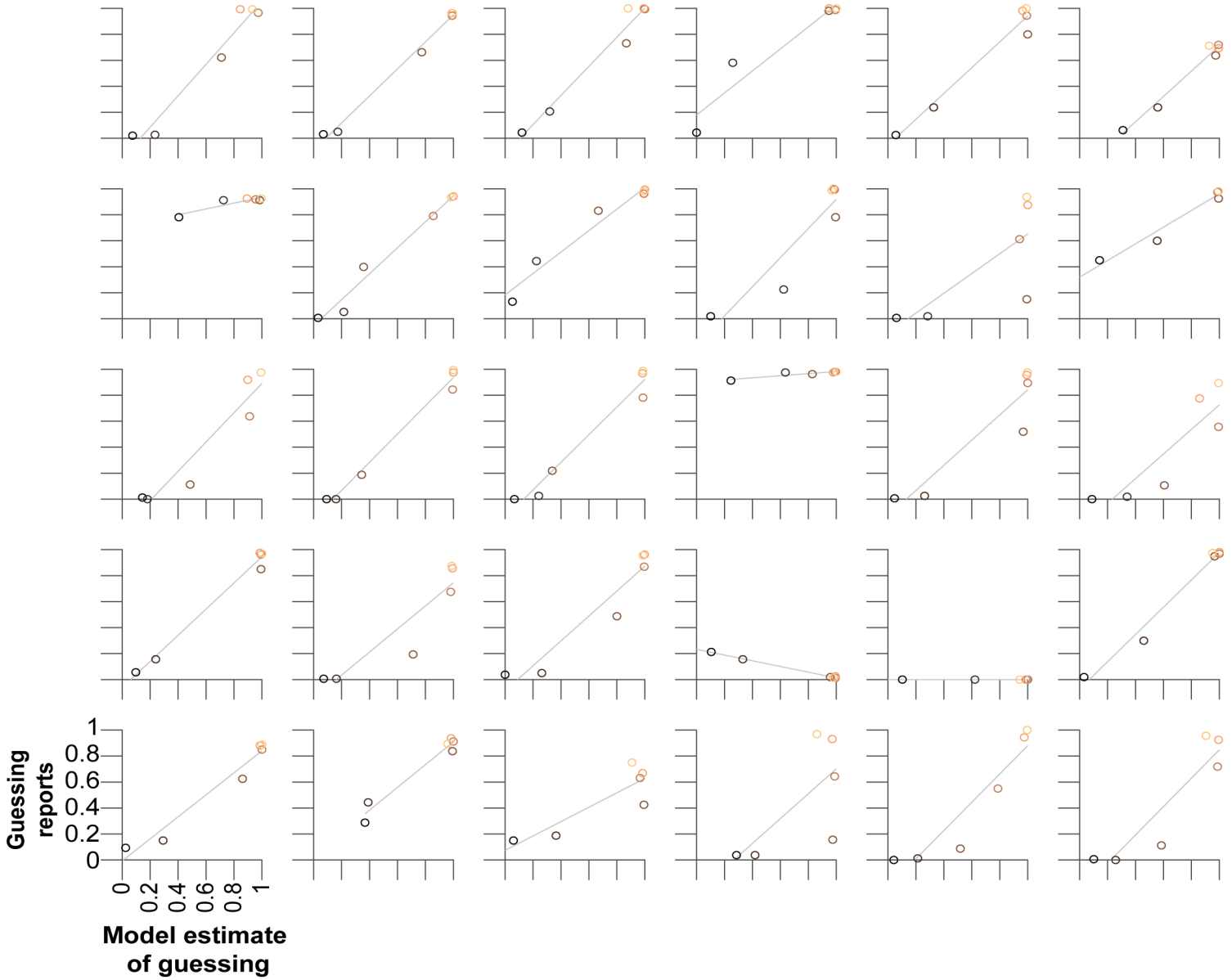
Self-reports of guesses match model estimates

- Experiment 1 (background condition)



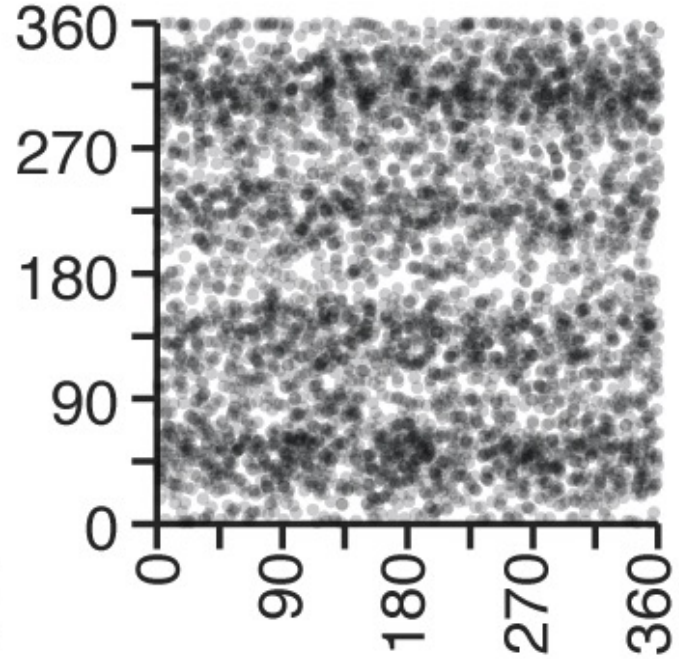
Self-reports of guesses match model estimates

- Experiment 2



Conclusions

- We found evidence for guesses that cannot straightforwardly described as an imprecise memory
  - In line with an item-based capacity limit
- But the pattern of results can be explained by a resource model
  - One that includes an *ad hoc* change to incorporate priors
  - There may still be a "working memory" masked by the guess responses



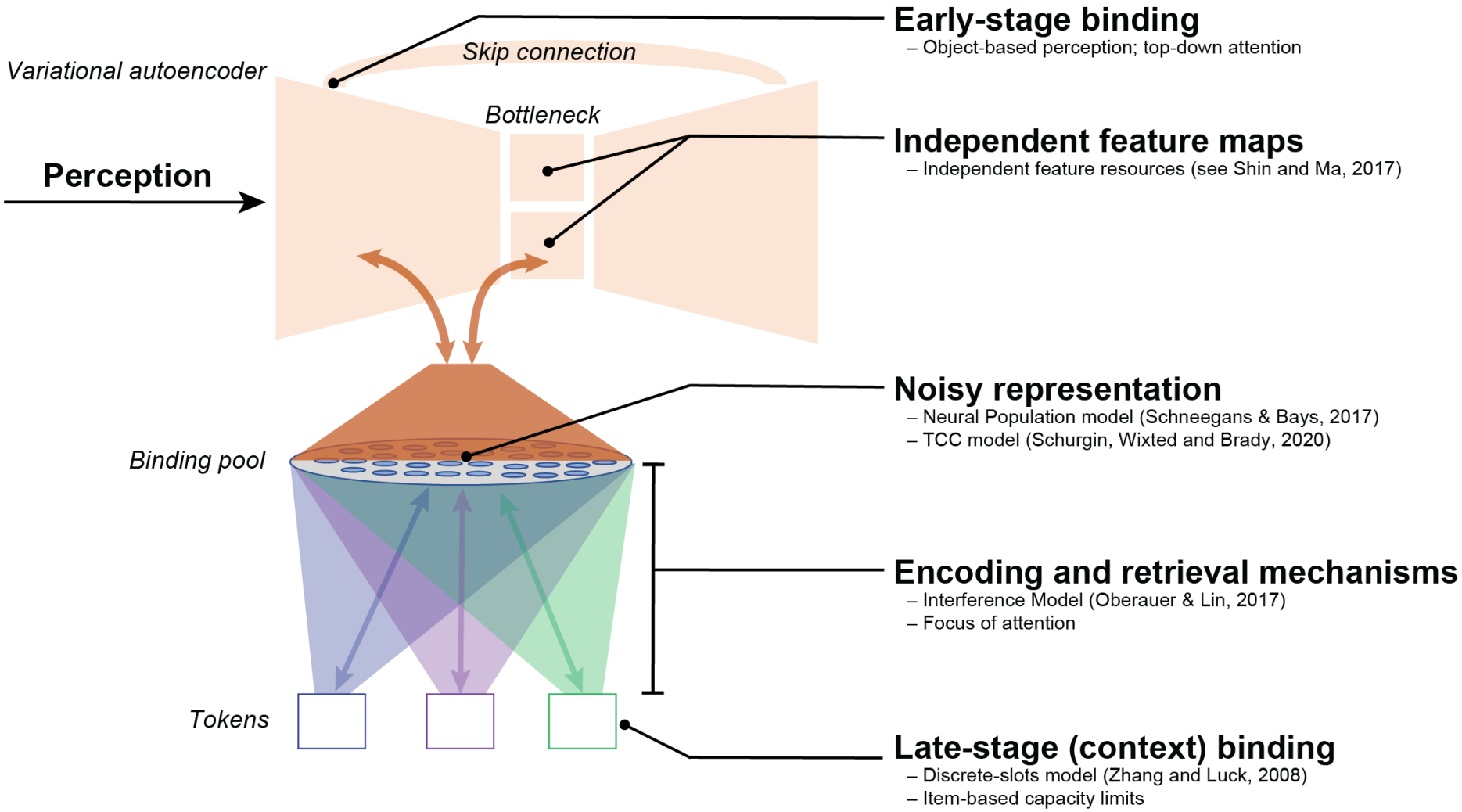
What have we learnt from these projects?

- **Conjunction whole-report:**
  - We see both object-based and feature-based phenomena occurring in concert
  - Working memory is not simply explained as objects or features, likely to be both

- **Guess bands:**
  - We find clear evidence for guessing, in line with a discrete item limit model
  - But a continuous resources (*variable-precision*) model can still account for the pattern of data
    - With an *ad hoc* inclusion of priors

Can we bring these models into accordance?

Presenting a theory map for visual working memory

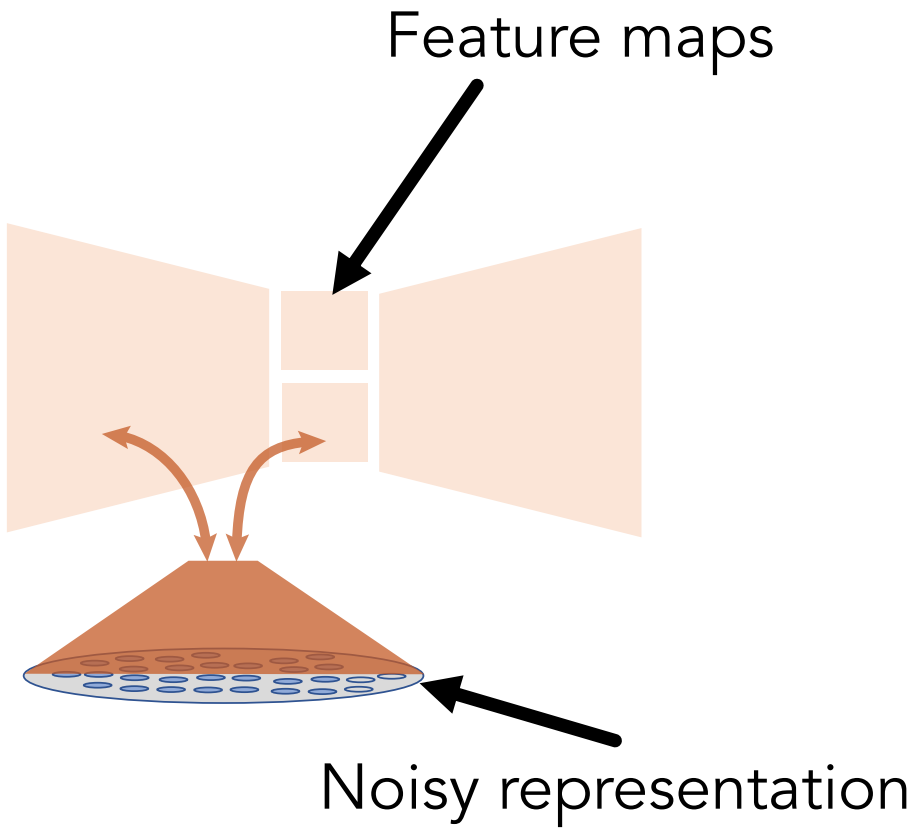


Hedayati, S., O'Donnell, R. E., & Wyble, B. (2022). A model of working memory for latent representations. *Nature Human Behaviour*, *6*(5), 709-719.

Binding pool as a locus for feature-based ideas

- Independent feature layers project into the binding pool (Shin and Ma, 2017)
  - But early-stage object-based attention may also be in play

- Noisy representations in VWM are well-captured by neural population and signal detection accounts (Bays, 2014; Schurgin et al., 2020)

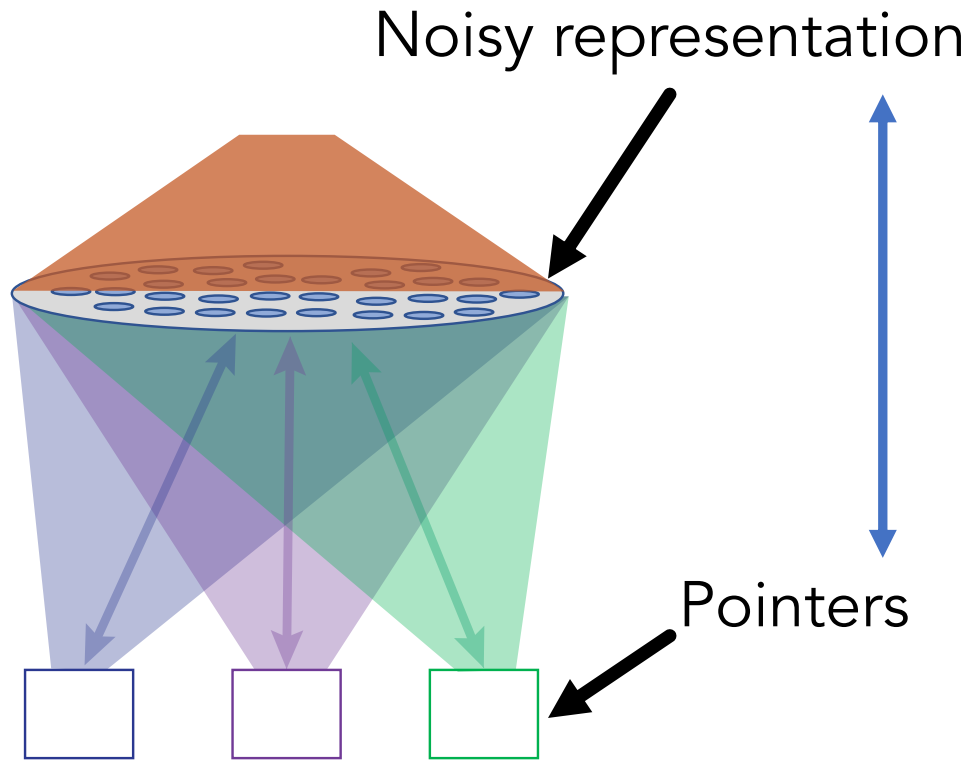


Bays, P. M. (2014). Noise in neural populations accounts for errors in working memory. *Journal of Neuroscience*, *34*(10), 3632-3645.
Schurgin, M. W., Wixted, J. T., & Brady, T. F. (2020). Psychophysical scaling reveals a unified theory of visual memory strength. *Nature human behaviour*, *4*(11), 1156-1172.
Shin, H., & Ma, W. J. (2017). Visual short-term memory for oriented, colored objects. Journal of Vision, 17(9), 12-12.

Tokens as a locus for object-based ideas

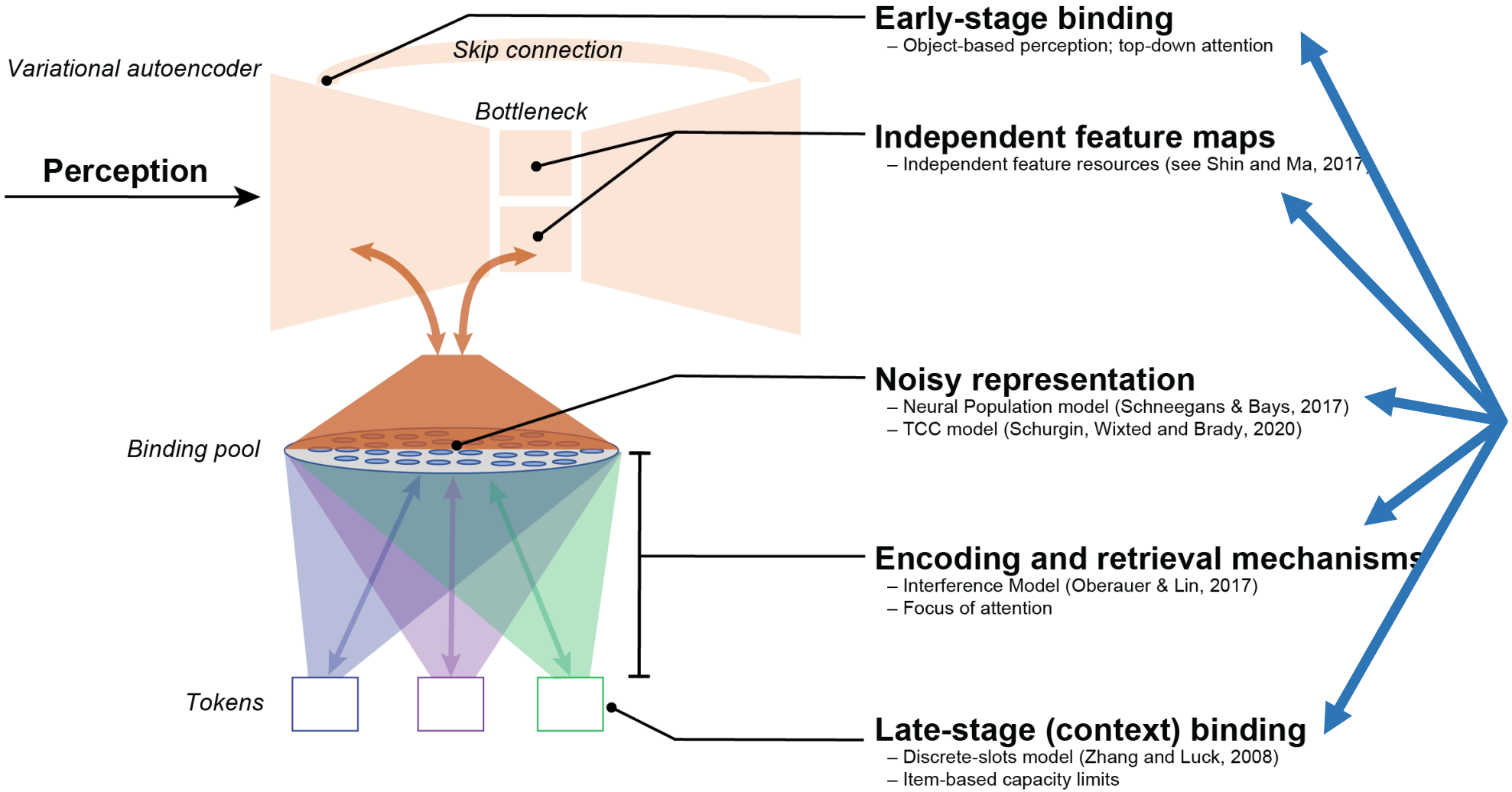
- Content-independent pointers
  - Like *FINSTs* or *Object Files* (Pylyshyn, 1989; Kahneman et al., 1992)

- Evidence for a neural signature that indexes VWM load and generalizes across feature content (Thyer et al., 2022; Balaban et al., 2019)



Pylyshyn, Z. (1989). The role of location indexes in spatial perception: A sketch of the FINST spatial-index model. *Cognition*, *32*(1), 65-97.
Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive psychology*, *24*(2), 175-219.
Thyer, W., Adam, K. C., Diaz, G. K., Velazquez Sanchez, I. N., Vogel, E. K., & Awh, E. (2022). Storage in visual working memory recruits a content-independent pointer system. *Psychological Science*, *33*(10), 1680-1694.
Balaban, H., Drew, T., & Luria, R. (2019). Neural evidence for an object-based pointer system underlying working memory. *cortex*, *119*, 362-372.

Presenting a theory map for visual working memory



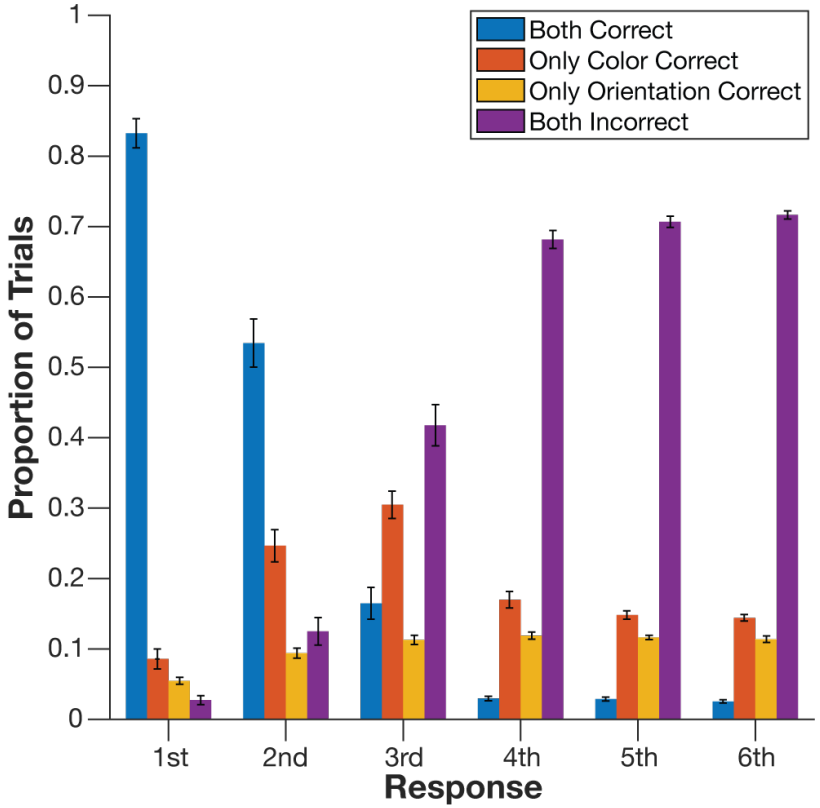
Capacity limits or changes in representation or any empirical effects can occur and interact at any of these levels

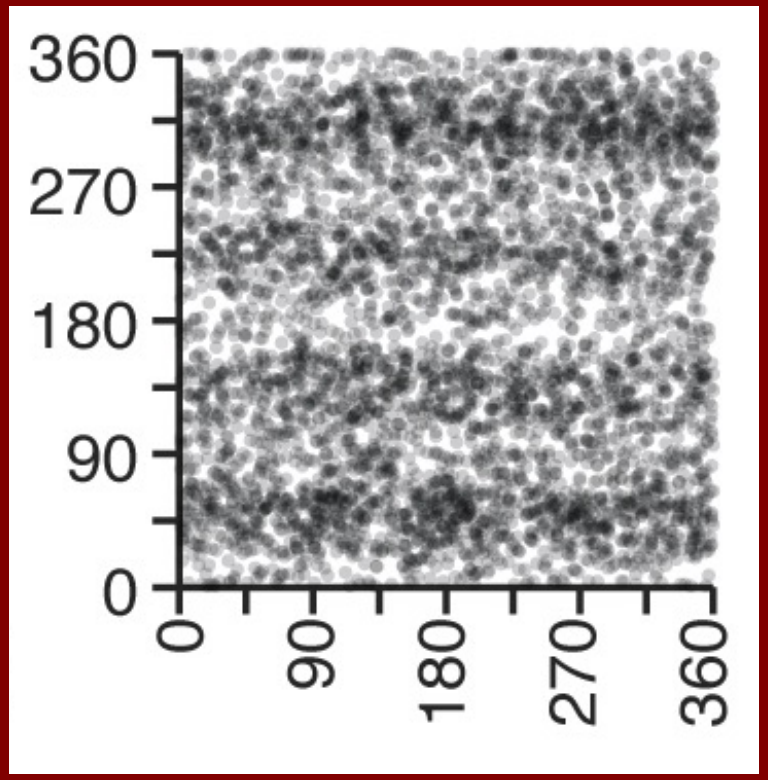
Hedayati, S., O'Donnell, R. E., & Wyble, B. (2022). A model of working memory for latent representations. *Nature Human Behaviour*, *6*(5), 709-719.

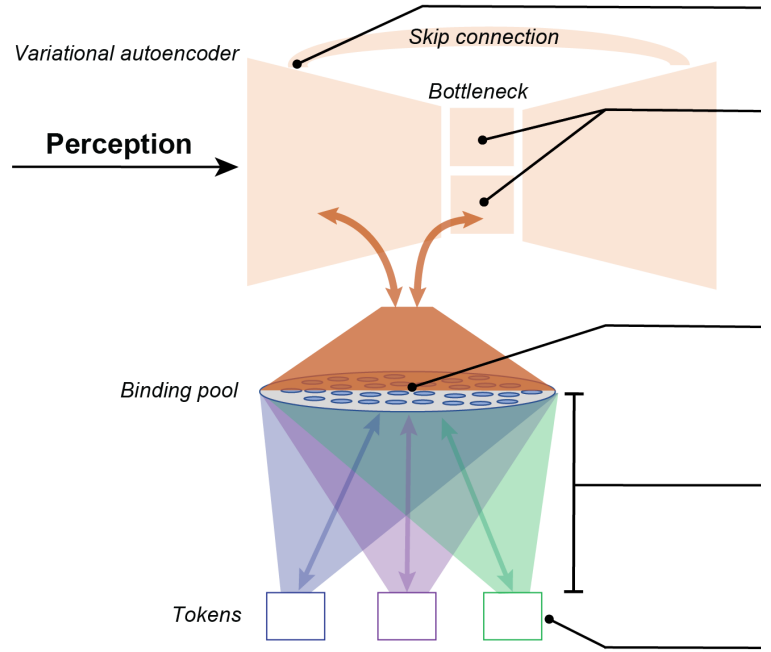
How does a theory map help?

- Provides a common core language and framework to discuss theories, models, and phenomena
  - Reveals hidden intuitions
  - Prevents misunderstandings from varying definitions
  - Better specifies connection between models and phenomena
  - Reduces straw-man of various positions
  - Discourages a dualistic framework for experimental design
  - Initiates better determined model comparisons and definitive empirical tests

- Inspires theory development
  - Promotes counterinduction (the use and development of others' models)
  - Encourages slow science from better thought-out studies







- There seems to be an object-based item limit
- VWM is not simply objects *or* features

- We show evidence of guessing
- VWM is not simply discrete *or* continuous

- We need better theory development
- VWM *is* multi-faceted and complex

Please support my work

- **Guess bands** is published in AP&P!
  Ngiam, W.X.Q., Foster, J.J., Adam, K.C.S. et al. Distinguishing guesses from fuzzy memories: Further evidence for item limits in visual working memory. *Atten Percept Psychophys* (2022). https://doi.org/10.3758/s13414-022-02631-y

- **Conjunction whole-report** is in late preparation (preprint coming)

- **Theory review and map** is in early writing (feedback welcome)

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