The Fidelity of Visual Long-term Memory
Role of Memory in Vision
Role of Memory in Vision

Determines What You See Things "As"
Role of Memory in Vision

Basis for Inference About the World
Role of Memory in Vision

Interacts With Perceptual Organization
Vision Provides Many Inputs to Potentially Remember
Vision Provides Many Inputs to Potentially Remember

2-3 Eye Movements Per Second
Vision Provides Many Inputs to Potentially Remember

2-3 Eye Movements Per Second
Vision Provides Many Inputs to Potentially Remember

2-3 Eye Movements Per Second
Vision Provides Many Inputs to Potentially Remember

**Fixating Many Different Objects**
Vision Provides Many Inputs to Potentially Remember

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Vision Provides Many Inputs to Potentially Remember

162,000 Images Per Day
60,000,000 Images Per Year
1.5 Billion Images in 25 Years

Torralba, Fergus, Freeman – CSAIL – MIT – 80 millions of images
What Should a Memory System do With This?

Remember them all sparsely?

Remember few with high detail?

Remember them ALL with high detail?

Remember them ALL with selective details? If so, which details?
The Broad Motivation

Understand Capacity and Fidelity of LTM

LTM informs “online” visual perception

Understanding these aspects of LTM is integral to understanding “online” visual processing

How visual perception interfaces with LTM

NOT going to answer these questions today
The Broad Motivation

Understand **Capacity and Fidelity of LTM**

LTM informs “online” visual perception

Understanding these aspects of LTM is integral to understanding “online” visual processing

How visual perception interfaces with LTM

NOT going to answer these questions today
Outline

1. Detailed Memory for Thousands of Objects
2. Comparing the Fidelity of Perception, Short-term Memory, & Long-term Memory
3. Preliminary Insights into the Temporal Dynamics of Encoding
1. Detailed Memory for Thousands of Objects

2. Comparing the Fidelity of Perception, Short-term Memory, & Long-term Memory

3. Preliminary Insights into the Temporal Dynamics of Encoding
1. Detailed Memory for Thousands of Objects

How Much Can You Remember About What You See?

Thousands of Objects
Standing (1973)

10,000 Images

92% Recognition

A massive storage capacity, but what’s remembered?
Standing’s Image Set

According to Standing

“Basically, my recollection is that we just separated the pictures into distinct thematic categories: e.g. cars, animals, single-person, 2-people, plants, etc.) Only a few slides were selected which fell into each category, and they were visually distinct.”
Standing’s Image Set

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Could Span A Huge Range of Conceptual Space
“Old” or “New”?
“Old” or “New”?
But What Did You Remember?

Highly Detailed

Sparse Details

Dogs Playing Cards

“Gist” Only
Vary Similarity to Probe Contents of Memory

Exactly which wedding did you see?
Experiment 1

1-back

Showed observers 2500 unique objects
1 at a time, 3 seconds each
800 ms blank between items
Study session lasted about 5.5 hours
N-back task to maintain focus
Followed by 300 2-alternative forced choice tests
Experiment 1 - Subject Instructions

- Completely different objects...
- Different instance of the same kind of object...
- Different state of the same object...
Experiment 1 - Conditions Varying In Similarity

- Completely different objects...
- Different instance of the same kind of object...
- Different state of the same object...

“Novel” Requires “Gist”
“Exemplar” More Details
“State” Even More Details
Experiment 1 - Demonstration
10 Minutes Later...
30 Minutes Later...
1 Hour Later...
2 Hours Later...
4 Hours Later...
5:30 Hours Later...
Experiment 1 - Results
High Detection Rate, Even at 1024-back!

false alarm rate 1 %
Experiment 1 - Results, Recognition Performance
Experiment 1 - Results, Recognition Performance

92%
Experiment 1 - Results, Recognition Performance

Visual Cognition Expert Predictions

Percent Correct

92%

Novel

Exemplar

State
Experiment 1 - Results, Recognition Performance

Experiment 1

<table>
<thead>
<tr>
<th>Condition</th>
<th>Percent Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Novel</td>
<td>92%</td>
</tr>
<tr>
<td>Exemplar</td>
<td>88%</td>
</tr>
<tr>
<td>State</td>
<td>87%</td>
</tr>
</tbody>
</table>

Note: The graph shows the percentage of correct recognitions for novel, exemplar, and state conditions. The data indicates that the recognition performance is highest for the novel condition, followed by the exemplar and state conditions.
Experiment 1 - Results, Recognition Performance

**Novel**
- 14 / 14
- 13 / 14
- 12 / 14
- 14 / 14
- 14 / 14

**Exemplar**
- 13 / 14
- 14 / 14
- 12 / 14
- 14 / 14
- 14 / 14

**State**
- 13 / 14
- 12 / 14
- 13 / 14
- 12 / 14
- 14 / 14
Experiment 1 - Results, Recognition Performance

<table>
<thead>
<tr>
<th>Novel</th>
<th>Exemplar</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Image" /></td>
<td>12 / 14</td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td><img src="image3" alt="Image" /></td>
<td>12 / 14</td>
<td><img src="image4" alt="Image" /></td>
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<td><img src="image5" alt="Image" /></td>
<td>13 / 14</td>
<td><img src="image6" alt="Image" /></td>
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<td><img src="image7" alt="Image" /></td>
<td>14 / 14</td>
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<td>14 / 14</td>
<td><img src="image10" alt="Image" /></td>
</tr>
<tr>
<td><img src="image11" alt="Image" /></td>
<td>14 / 14</td>
<td><img src="image12" alt="Image" /></td>
</tr>
</tbody>
</table>
Summary & Interim Conclusions

LTM can hold a massive number of items

The fidelity of storage is high

Much higher than previously believed

But exactly how accurate are these representations?

How would it compare to the fidelity of perception (upper bound) or short-term memory (upper bound for memory)
1. Detailed Memory for Thousands of Objects

2. Comparing the Fidelity of Perception, Short-term Memory, & Long-term Memory

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2. Comparing the Fidelity of Perception, Short-term Memory, & Long-term Memory
Qualitative Manipulation of “Required Fidelity”

**Completely different objects...**

**Different instance of the same kind of object...**

**Different state of the same object...**

“Novel” Requires “Gist” < “Exemplar” More Details < “State” Even More Details
A Continuous Measure of Fidelity

How Well Can Observers Perceive and Remember the Color of Objects?
A Continuous Measure of Fidelity

Typically Assessed With Color Patches...

But you cannot do the long-term memory experiment with color patches
A Continuous Measure of Fidelity

So we’re going to use real objects...
A Continuous Measure of Fidelity
A Continuous Measure of Fidelity
Perceptual Task
Perceptual Task
A Continuous Measure of Fidelity

Error = Angular Difference Between Target Hue and Color Setting
Short-term Memory Task, Remember 3 Items
Long-term Memory Task, Remember 180 Items
Long-term Memory Task, Remember 180 Items
Long-term Memory Task, Remember 180 Items
Long-term Memory Task, Remember 180 Items
Long-term Memory Task, Remember 180 Items
Long-term Memory Task, Remember 180 Items
Long-term Memory Task, Remember 180 Items
Long-term Memory Task, Remember 180 Items
Long-term Memory Task, Remember 180 Items
Long-term Memory Task, Remember 180 Items
Long-term Memory Task, Remember 180 Items

...About 20 Minutes Later
Long-term Memory Task, Remember 180 Items
Long-term Memory Task, Remember 180 Items
Long-term Memory Task, Remember 180 Items
Long-term Memory Task, Remember 180 Items
Long-term Memory Task, Remember 180 Items
Long-term Memory Task, Remember 180 Items

tested on all 180 objects
Introduced by Zhang & Luck (2008)
Mixture Modeling Analysis

Observed Data

Gaussian (von mises)

Uniform

standard deviation
measure of precision

probability of guessing

probability of guessing
Experiment 2: A Continuous Measure of Fidelity
Experiment 2: A Continuous Measure of Fidelity

Perceptual Task: Group Model Fit

![Graph showing proportion of responses vs. error (degrees).]
Experiment 2: A Continuous Measure of Fidelity

Short-term Memory Task: Group Model Fit

![Graph showing error distribution and proportion of responses.](image-url)
Experiment 2: A Continuous Measure of Fidelity

Long-term Memory Task: Group Model Fit

![Graph showing the proportion of responses against error (degrees).]
Experiment 2: A Continuous Measure of Fidelity

Summary Group Model Fits

![Graph showing proportion of responses across different error (degrees) for Perception, Short-term Memory, and Long-term Memory.](image)
Mixture Modeling Analysis

**Observed Data**

- **Gaussian (von mises)**
  - Standard deviation
  - Measure of precision

- **Uniform**
  - Probability of guessing

**Probability of guessing**

- 0.25
- 0.20
- 0.15
- 0.10
- 0.05
Experiment 2: A Continuous Measure of Fidelity

Summary Group Model Fits

![Graph showing proportion of responses vs. error (degrees) for Perception, Short-term Memory, and Long-term Memory. The graph illustrates the distribution of responses across different error values for each memory type.](image-url)
Likelihood Of Random Guessing

Much higher likelihood of random guessing in long-term memory condition
Short-term and Long-term Memory Have Comparable Fidelity!
Experiment 3: Continuous Report + Yes/No Response

Long-term memory condition only. Same as E2, except half the test items are foils (items that were never seen).

For each test item, subjects report the remembered color, guessing if they haven’t seen the item.

Then subjects report whether they remember seeing the test item (“Yes” or “No”).
Experiment 3: Continuous Report + Yes/No Response

Sanity Check!: Model Fit Correct Rejections (82%)
Sanity Check!: Model Fit False Alarms (18%)
Experiment 3: Continuous Report + Yes/No Response

Model Fit Misses (34%)
Experiment 3: Continuous Report + Yes/No Response

Model Fit Hits (66%)

![Graph showing proportion of responses vs error (degrees)]
If subjects only guess the color if they forget the item, you would expect guessing rate to disappear for HITS.
or at least drop to the level of the false alarm rate...

![Graph showing the likelihood of random guessing and probability of guessing across different memory stages (Perception, STM, LTM, LTM (HITS)). The X-axis represents the different memory stages, and the Y-axis represents the probability of guessing. The graph indicates that the probability of guessing is lowest in Perception and highest in LTM (HITS).]
Likelihood of Random Guessing

Same Guessing Rate!
Observers remember the items, but forget the colors

![Graph showing probability of guessing across different memory stages]

- Perception
- STM
- LTM
- LTM (HITS)

E2
E3
Estimate of Memory Precision

Not much change in the precision, if anything better
Summary & Interim Conclusions

Combined continuous report & mixture modeling method enables estimation of

1. Standard deviation as a measure of memory precision
2. Probability of random guessing

Perception vs. STM, precipitous increase in standard deviation

STM vs. LTM: Relatively high probability of random guessing of color in LTM (even when the item is remembered)

However, when the color is remembered, it is comparable to the fidelity of short-term memory
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 Experiment 4: Effect of Encoding Time on Detection of Changes at Category, Exemplar, and State Level

Short-term memory, change detection task
1.2, 6, or 18 second presentation of 6 objects
3 Conditions: novel, exemplar, state
Experiment 4: Effect of Encoding Time on Detection of Changes at Category, Exemplar, and State Level

It takes time to get the details
Experiment 4: Effect of Encoding Time on Detection of Changes at Category, Exemplar, and State Level

Maybe some changes require more precise representations, and precision increases with time.
Or maybe this is about a hierarchical order of encoding, from category-level features, to exemplar-level features, to state-level features...

Experiment 4: Effect of Encoding Time on Detection of Changes at Category, Exemplar, and State Level
Experiment 5: Effect of Encoding Time on Encoding Color (Using Continuous Report)

Short-term memory, continuous report
20, 40, 60, 80, 100, 120, 500 ms presentation
3 color patches, masked

Brief Presentation  Mask  Color Setting
Experiment 5: Effect of Encoding Time on Encoding Color (Using Continuous Report)

![Graph showing the variability of memory representations against presentation time in milliseconds. The x-axis represents presentation time (ms) ranging from 0 to 600, and the y-axis represents standard deviation of best-fit Von Mises, ranging from 0 to 60.]
Experiment 5: Effect of Encoding Time on Encoding Color (Using Continuous Report)
Effect of Encoding Time on Encoding Color In Long-term Memory

Experiment 2
3 Seconds/Item LTM

Experiment 6
1 Second/Item LTM

Estimate of Memory Precision

Standard Deviation (of best fit Von Mises)

Perception | STM | LTM
---|---|---

Perception | STM | LTM
Effect of Encoding Time on Encoding Color In Long-term Memory

Experiment 2
3 Seconds/Item LTM

Experiment 6
1 Second/Item LTM

Likelihood of Random Guessing

Probability of Guessing

Perception STM LTM

Likelihood of Random Guessing

Perception STM LTM
It takes time to encode the details

After the first 120ms, little benefit of additional time on encoding color

Suggests benefits of additional time after one second is not due to improved fidelity on any given feature dimension

Instead, additional time may reflect hierarchical, knowledge-guided encoding of object details

“Encoding of informative dimensions”
Visual Long-term Memory has a much higher fidelity than previously demonstrated or believed, comparable to the fidelity of short-term memory.

There is a high rate of randomly guessing in LTM, suggesting either catastrophic retrieval failure, interference, or decay.

This is the case, even when observers appear to remember the items themselves. This “binding failure” in LTM may reflect the non-integral nature of color for these stimuli.

Precision increases rapidly over time, suggesting benefits of time beyond 500 ms are related to searching for/encoding additional features (possibly in a hierarchical progression).
Thank You.

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