Representation, Retention, and Recognition of Information in Visual Working Memory

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Abstract

Previous experiments on visual working memory (WM) have inspired the hypothesis that information about briefly displayed objects is stored in separate object files whose contents may endure for several seconds (e.g., Vogel, Woodman, & Luck, 2001). Supposedly, visual WM can contain about four such files. Yet data from these experiments seem problematic to interpret and were perhaps contaminated by some artifacts. To help resolve such problems, we have conducted new studies that required same-different judgments and cued recall under conditions where successive object displays changed in various ways. Our results suggest that at least two distinct types of extra-iconic visual storage contributed to performance there. One type involves unintegrated location-independent visual features. The other involves integrated location-dependent features, consistent with the object-file hypothesis. However, it appears from our results that visual WM has a capacity of only about three rather than four object files.

Visual Working Memory

- Visual information about objects can be stored in two general forms:
  - **Individual object features**: no connection to other information (e.g., color, shape, location).
  - **Bound object features**: grouped together in "chunks" (e.g., color-location pairs, object files).
- Any task that can be performed with individual object features can also be performed with bound features, but not vice versa.
- In principle, visual working memory (WM) could be based on either level.

Object-File Theory of Visual WM

- According to this theory, visual WM stores object files (e.g., Irwin & Andrews, 1996; Schneider, 1999; and Vogel, Woodman, & Luck, 2001).
- The theory makes several assumptions:
  - Object files consist of bound features.
  - Each object file can contain an unlimited number of individual features.
  - A limited number of objects can be stored.
  - Object files are created and stored independently of one another.

Elaboration of Object-File Theory

Object-file theory has been elaborated by recent researchers:

- Jiang, Olson, and Chun (2000) proposed that visual objects are stored with respect to relative spatial location, implying dependence between object files.
- Wheeler and Treisman (2002) proposed that both individual and bound features (e.g., color and location) can be retained and are interdependent.
- These and other proposals assume that there is dependence between different levels of storage and between object files in visual WM.

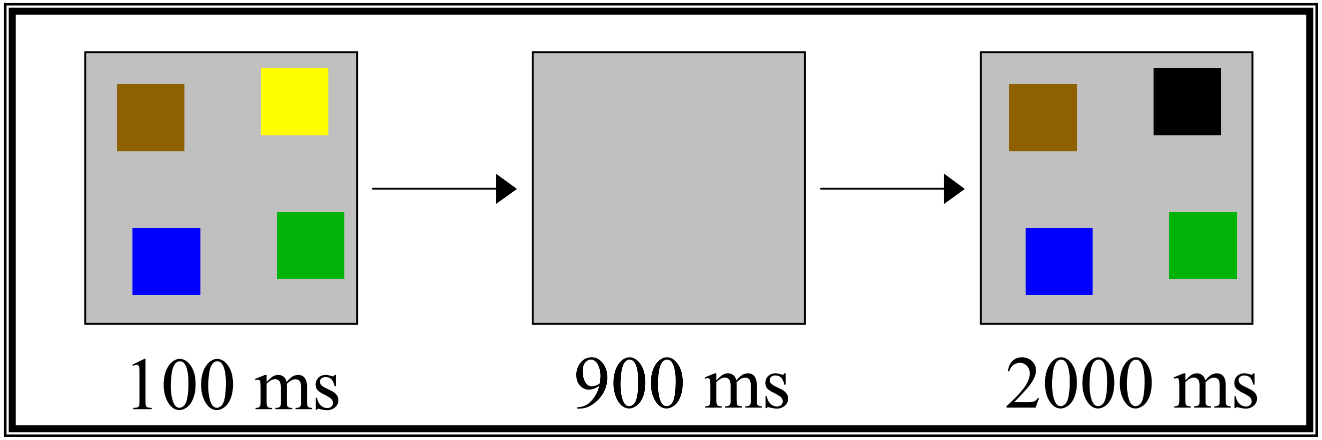
Previous Tests of Object-File Theory

- The theory is consistent with past research using partial-report procedures (e.g., Irwin & Andrews, 1996; Sperling, 1960).
- Vogel et al. (2001) used **change-detection tasks** to study visual WM, and found that:
  - Change detection accuracy depended on the number of objects, not individual features.
  - People could retain about four objects.
- Limitations of past research:
  - Most studies have used tasks that did not require storage of bound features (e.g., Vogel et al., 2001).
  - Few if any studies have precisely measured visual WM capacity for bound features.
  - The independent-storage assumption has not been tested rigorously.

Overview of Present Experiments

- The two experiments reported here provide rigorous tests of the object-file theory: We fit quantitative models to data from both experiments to demonstrate the plausibility of the theory.
- Experiment 1 uses a change-detection task under conditions that require storage of bound features (color-location).
- Experiment 2 generalizes the findings of Experiment 1 by using a cued-recall task to study storage of different bound features (color-shape).

The Change-Detection Task



- Participants judge whether the two displays are the same or different; typically the two displays are the same on 50% of the trials.
- The number of objects (numerosity) in each display is manipulated.
- Objects can be composed of one or more features (e.g., color, orientation).
- Objects can change with respect to spatial location, individual features, and bindings between features.

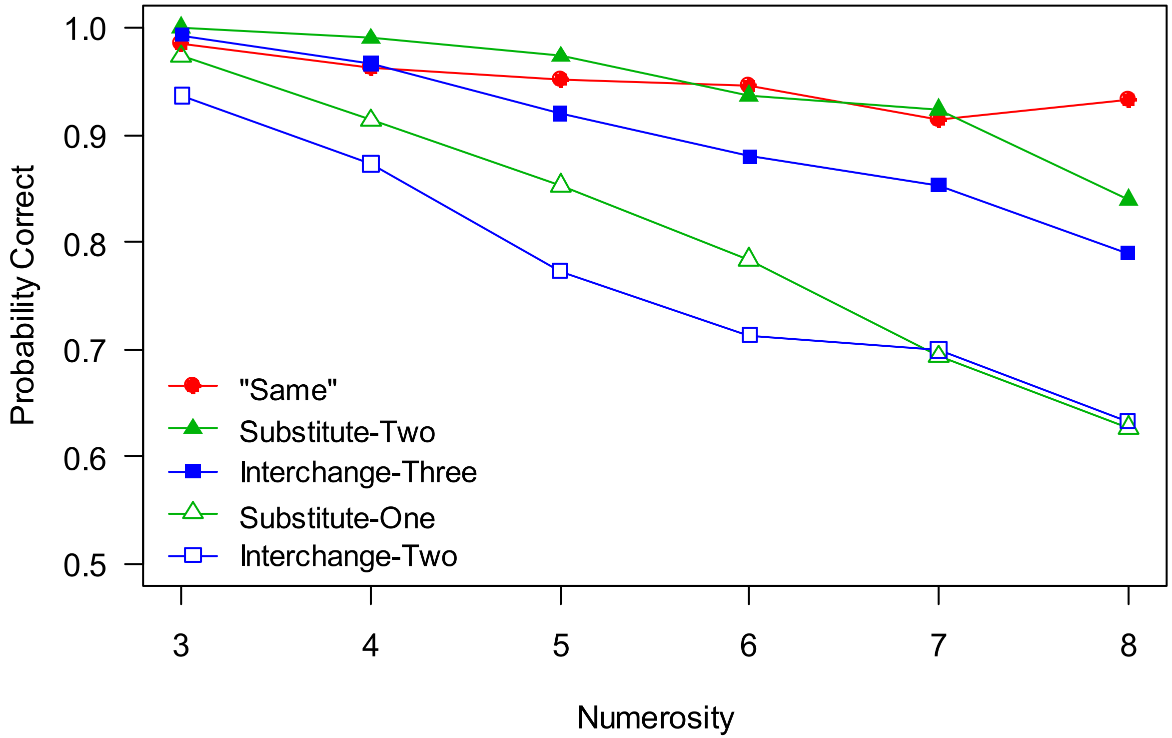
Experiment 1 – Method

- We used a change-detection task to investigate storage of individual and bound features.
- On "different" trials, changes were generated in one of four ways:
  - **substitute-one**: one square changed to a new color;
  - **substitute-two**: two squares changed to new colors;
  - **interchange-two**: the colors of two squares were swapped;
  - **interchange-three**: the colors of three squares were swapped.
- Thus, two factors were manipulated: **number of changes** and **change type**.

Experiment 1 – Predictions

- Substitute trials can be performed with just individual features, but interchange trials require binding of color and location information (Wheeler & Treisman, 2002).
- The object-file theory predicts that bound features are stored in visual WM, hence:
  - Accuracy should increase with the number of changes.
  - Change type should not matter.
- Alternately, substitute trials might be performed using unbound features, so there could be a difference due to change type.

Experiment 1 – Results



The figure shows accuracy by numerosity on “same” (red line, filled circles), substitute-two (green line, filled triangles), interchange-three (blue line, filled squares), substitute-one (green line, open triangles), and interchange-two (blue line, open squares) trials. There were significant effects of the number of changes and change type. Note that accuracy was lower on interchange-two trials than on substitute-two trials, even though both conditions involved changes in two objects.

Experiment 1 – Conclusions

- Substitutions are more easily detected than interchanges, suggesting that the object-file theory cannot explain performance for both change types.
- Detection of an interchange requires retention of bound color-location information; detection of a substitution does not.
- Substitute trials might be performed with just unbound features, or with a combination of unbound features and object files.
- Interchange trials are better for studying object file storage in visual WM.

Experiment 1 – Modeling

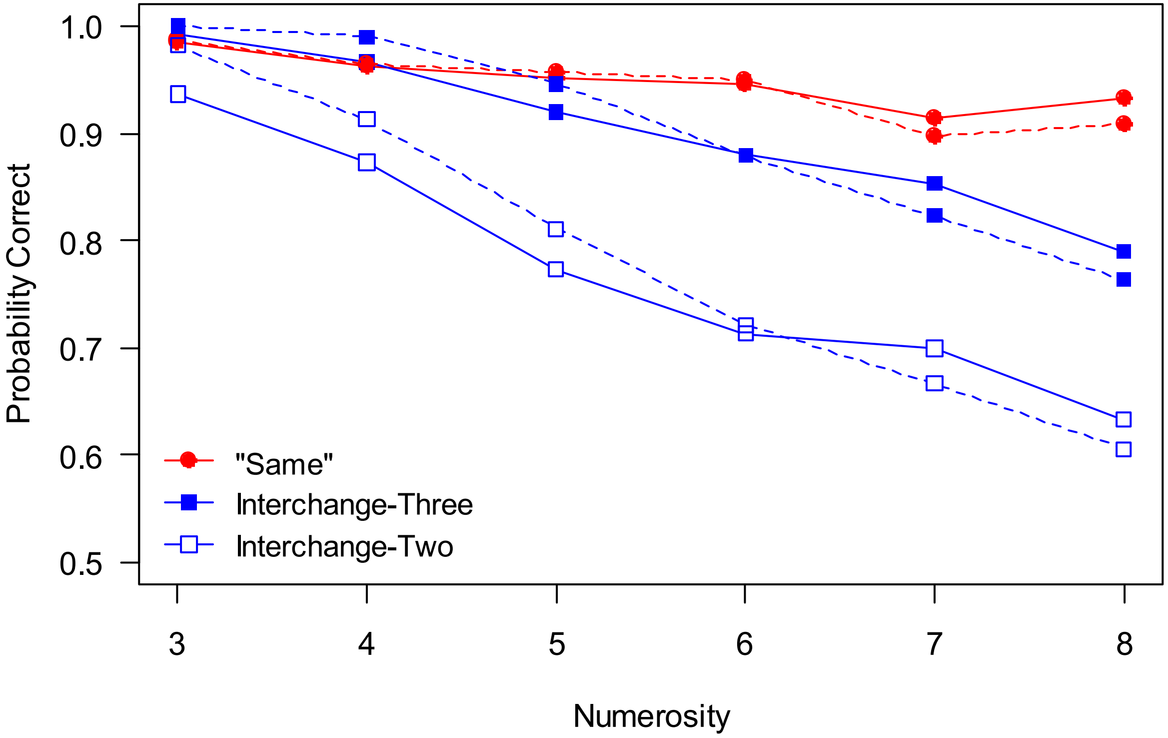
- To test the object-file theory, we fit the results of Experiment 1 with a mathematical model based on its assumptions.
- The assumptions of the model are:
  - The probability of correctly detecting a change (p_{cor}) depends on the probability of storing the to-be-changed object (p_{store}), plus a guessing rate parameter (g) for each numerosity:

$$p_{\text{cor}} = p_{\text{store}} + \left(1 - p_{\text{store}}\right) \cdot g$$

  - p_{store} depends on the numerosity (N), the number of objects that can change (c), and WM capacity (k), which is a free parameter:

$$p_{\text{store}} = 1 - \prod_{i=0}^{c-1} \frac{N - k - i}{N - i}$$

Experiment 1 – Model Fit



The figure shows observed and predicted accuracy on "same" (red line, filled circles), interchange-two (blue line, filled squares), and interchange-three (blue line, open squares) trials. Solid lines indicate observed accuracy and dashed lines indicate the corresponding predicted accuracy calculated from the model described above. The fit is based on one capacity parameter (k) and six guessing parameters (g_i), one for each numerosity. (R^2 = .961; mean k = 2.6)

Experiment 2

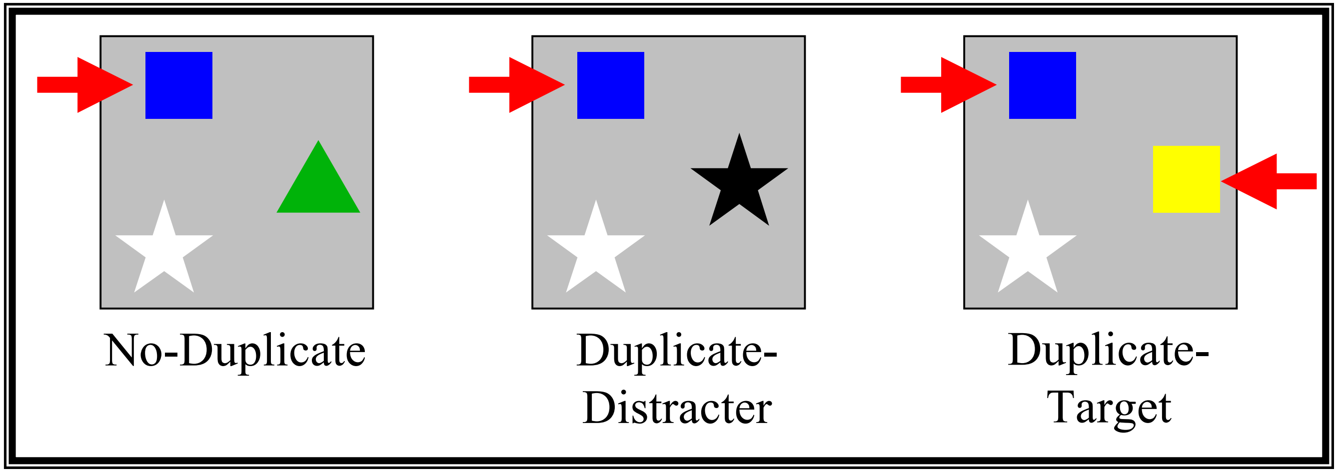
- Experiment 2 was conducted to extend Experiment 1 and overcome some limitations in its results.
- The results from Experiment 1 may be specific to the change-detection task.
- Storage of bound color-location information (i.e., for interchange trials) may be different from other bound features.
- Consequently, we designed Experiment 2 to investigate storage of bound color-shape information in a task that does not involve change detection.

Experiment 2 – Method

- On each trial, participants saw a brief visual display consisting of seven colored shapes.
- After a delay, an auditory cue indicated a shape and the corresponding color had to be recalled (similar to Nissen, 1985).
- There were three trial types (see the next figure):
  - On some trials, none of the shapes or colors were repeated (**no-duplicate** trials).
  - On the remaining trials, one shape was repeated: either a non-repeated shape was cued (**duplicate-distracter** trials) or a repeated shape was cued (**duplicate-target** trials).

Experiment 2 – Displays

The figure below illustrates displays from the three trial types when the shape "square" is cued.

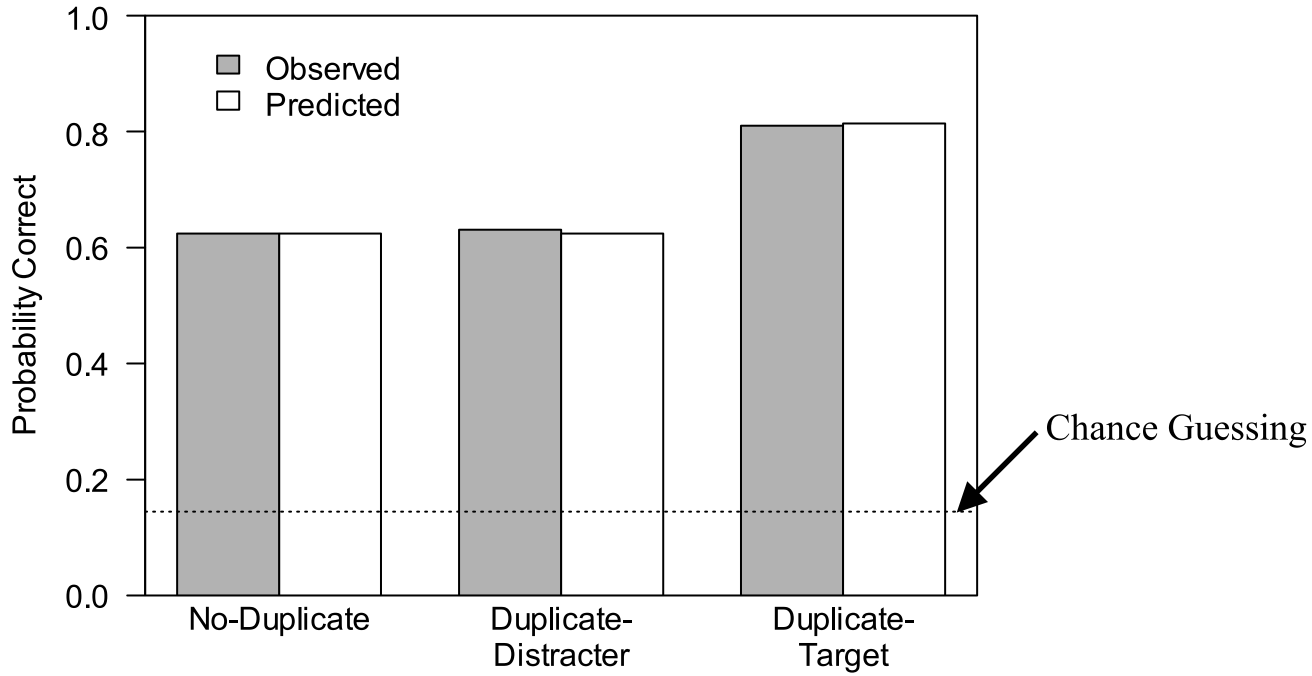


The red arrows indicate the to-be-cued shape(s) in each display. In these examples, on the no-duplicate and duplicate-distracter trials the correct response was "blue", and on the duplicate-target trial either "blue" or "yellow" was correct.

Experiment 2 – Modeling

- The mathematical model for Experiment 2 is identical to the change-detection model except for the following modifications:
  - Guessing rate is not a free parameter.
  - p_{store} is the probability of storing the to-be-cued object.
  - WM capacity (k) is the only free parameter.
- Participants should be more likely to select at least one of the repeated shapes for storage into WM, so accuracy should be higher on duplicate-target trials than on the other trial types.

Experiment 2 – Results



The figure shows observed and predicted accuracy for the three conditions as indicated on the horizontal axis. Dark bars indicate observed accuracy and white bars indicate predicted accuracy; the dotted line indicates chance guessing. Participants performed better in the duplicate-target condition than in the other two conditions, and the difference between conditions was nearly identical to that predicted by the model. (R^2 = .999; mean *k* = 3.4)

Experiment 2 – Conclusions

- The results were entirely consistent with the theory that participants randomly select objects from the display and store them independently.
- The object-file theory holds for a non-change-detection task requiring storage of different kinds of information than in Experiment 1.

General Discussion

- The object-file theory seems at least approximately correct: people apparently store about four object files in visual WM, consistent with other findings (e.g., Irwin & Andrews, 1996; Vogel et al., 2001).
- The object files are stored independently of one another.
- People can use additional visual information (i.e., unbound features), as suggested by the superiority of performance on substitute trials in Experiment 1 (cf. Wheeler & Treisman, 2002).

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