Redundancy effects in the perception and memory of visual objects

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Is visual representation of an object affected by whether surrounding objects are identical to it, different from it, or absent? To address this question, we tested perceptual priming, visual short-term, and long-term memory for objects presented in isolation or with other objects. Experiment 1 used a priming procedure, where the prime display contained a single face, four identical faces, or four different faces. Subjects identified the gender of a subsequent probe face that either matched or mismatched with one of the prime faces. Priming was stronger when the prime was four identical faces than when it was a single face or four different faces. Experiments 2 and 3 asked subjects to encode four different objects presented on four displays. Holding memory load constant, visual memory was better when each of the four displays contained four duplicates of a single object, than when each display contained a single object. These results suggest that an object's perceptual and memory representations are enhanced when presented with identical objects, revealing redundancy effects in visual processing.

Keywords: Perceptual priming; Redundancy effects; Visual long-term memory; Visual short-term memory.

Guests are welcomed to a hotel in Las Vegas by five big screens that feature identical advertisements. In its nearby sports-bar dozens of televisions are showing the same game. At the same time, a hotel room TV is showing an advertisement from a fast-food store, with four food choices displayed simultaneously for a low price. The visual redundancy shown in the first two examples stands in sharp contrast to the richness of information in the last. But is such redundancy simply a reflection of the extravagance of the "sin city"? Could there be any perceptual benefit when viewing a display with redundant visual information, as opposed to viewing highly heterogeneous but rich visual information?

Vision scientists have long been interested in how perception of visual objects is affected by surrounding context. Studies have observed contextual influences at multiple levels of information processing. At early levels, surrounding objects affect the perception of basic visual properties such as an object's size, orientation, luminance, and colour through assimilation or contrast effects (Jaeger, 1999). At later levels, object recognition is often faster when placed among scenes that are semantically congruent (as opposed to incongruent) with it (Biederman, Mezzanotte, & Rabinowitz, 1982; Davenport & Potter, 2004; Hollingworth & Henderson, 1998). Such contextual influences can be induced in a short laboratory training session by presenting a target object repeatedly with the same context (Chun & Jiang, 1998). In almost all of the studies, the contextual information is visually different from the object of interest, and contextual influence is exerted through semantic association or assimilation and contrast effects.

One type of contextual influence that has received relatively few investigations is the role of visual redundancy. Redundant visual input is often encountered in nature (e.g., forests, mountains), artwork (e.g., texture patterns), and other man-made environments (e.g., parking lots, Las Vegas hotel's five-screen ads). This type of input is characterized by the presence of an object in the context of other identical or similar objects. There is some evidence that the human brain is equipped with processing redundant information, especially when it involves symmetry. Symmetry detection is highly efficient (Driver & Baylis, 1996; Sally & Gurnsey, 2001), and patterns that are left–right symmetric lead to widespread activation in the ventral visual areas compared with nonsymmetric patterns (Sasaki, Vanduffel, Knutsen, Tyler, & Tootell, 2005; Tyler et al., 2005). The processing advantage is reduced, however, for stimuli that are repetition patterns rather than symmetric patterns (Driver & Baylis, 1996; Sasaki et al., 2005). Repeating the same stimuli on the display does lead to an advantage in simple reaction time and visual search tasks (Corballis, Corballis, & Fabri, 2004; Miller, 2007), especially when multiple targets are presented in separate visual hemifields. Specifically, target detection is faster when there are two bilateral targets rather than a single target. However, this advantage

is observed even when the two targets are perceptually different (Eriksen, Goettl, St. James, & Fourgnier, 1989), suggesting that it does not originate entirely from perceptual repetition.

The main focus of the present study is to investigate the perceptual and memorial consequences of visual redundancy produced by repetition. We compare perceptual priming and visual memory of (1) objects presented in isolation, (2) objects presented with other, visually different objects, and (3) objects presented with duplicates of themselves. The experiments used diverse paradigms with different task demands. They characterize the effects of visual redundancy on visual processing at short (priming), moderate (short-term memory), and long (long-term memory) time scales.

From a simple information processing perspective, one may not expect any differences between the perception and memory of isolated objects and duplicated objects, as duplicates do not add any additional information over and above that provided by an isolated object. Indeed, duplicating an object may increase visual clutter, leading to suppressive interactions that impair the perception and memory of each instance. This is analogous to previous observations of semantic congruency effects in scene perception: Although objects are recognized faster when presented in a congruent than incongruent context, they are recognized slower in a congruent context than when presented without any context (Davenport & Potter, 2004; Liu & Jiang, 2005). A third possibility is that perception and memory of duplicated objects may be better than that of isolated objects, possibly because neurons with different receptive fields are used to represent the different instances of an object, enabling greater tolerance of any degradation in perception and memory of each instance.

EXPERIMENT 1: PERCEPTUAL PRIMING IN A GENDER DISCRIMINATION TASK

The purpose of this experiment was to use perceptual priming as an index of the strength of the visual representation of an object when it is displayed alone, with copies of itself, or with different objects. Participants were shown a target face at the centre of the screen and indicated whether it was a male or a female face. Prior to the presentation of the target face, we presented a masked prime display. The prime was a single face, four identical faces, or four different faces of the same gender. On half of the trials, the target face was the same as the prime face(s) ("congruent" trials). On the other half of the trials, the prime face(s) was a different gender from the target face ("incongruent" trials). We examine whether identity priming produced by the four-same condition differs from that produced by the other conditions.

Methods

Participants.   Fifteen participants (seven females and eight males) volunteered in Experiment 1 for course credit. They were 18–35 years old (mean age = 20 years) and students at the University of Minnesota. All had normal or corrected-to-normal visual acuity.

Equipment.   Participants were tested individually in a room with normal interior lighting. They sat unrestrained at approximately 40 cm away from a 19-inch CRT computer monitor (resolution 1024×768 pixels; refresh rate: 75 Hz). The program was written in PsychToolbox (Brainard, 1997; Pelli, 1997) implemented in MATLAB (www.mathworks.com).

Materials.   Faces were randomly selected from a set of 480 unique faces (240 males and 240 females) with the constraint that a face shown on one trial did not appear again on another trial. All the faces were greyscale, front-view faces with neutral facial expression (256×256 pixels; $8° \times 8°$). About half of the faces were from the FERET database (Phillips, Moon, Rizvi, & Rauss, 2000; Phillips, Wechsler, Huang, & Rauss, 1998), and the other half were from online searches and personal collections. The target face of each trial was presented at the centre of fixation (see Procedure and Design). The prime faces were centred at $4.06°$ away from the fixation point. In the single-face condition, the prime face was equally likely to be displayed in any of the four quadrants. In the four-same condition, a given prime face was duplicated four times, one in each visual quadrant. In the four-different condition, four different individuals (from the same gender) were presented, one in each quadrant. The background was grey.

Procedure and design.   Participants were tested in a gender discrimination task. Each trial started with the presentation of a central fixation point for 500 ms. Then a prime display was presented for 200 ms, followed by a mask of randomly placed white dots ($0.4° \times 0.4°$) ($18.75° \times 18.75°$; the random placement of the white dots changed from trial to trial) for 200 ms. After a blank screen of 100 ms, a target face was presented at the centre of the screen until subjects pressed the "m" key (for male) or the "f" key (for female). Subjects were told to ignore the prime display and to report the target face's gender as quickly as possible. Upon the keypress, participants were shown the word "correct" (for 500 ms) or "incorrect" (for 2000 ms), depending on whether their response was correct. The negative feedback was presented for a longer duration to discourage incorrect responses. Figure 1 shows the schematic illustration of a trial sequence.

Subjects completed 192 trials, divided randomly and evenly into three prime conditions (single face, four-same faces, or four-different faces of the
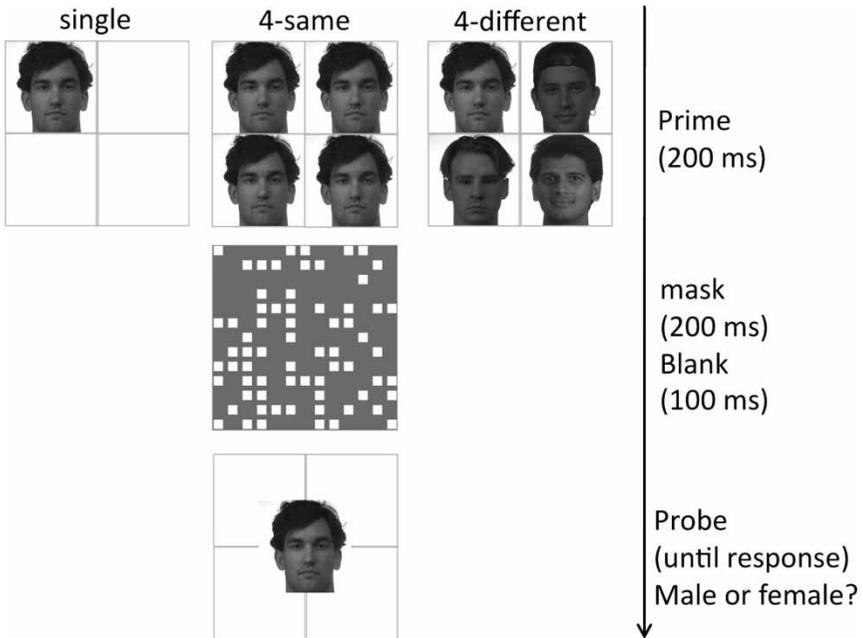
Figure 1.   A schematic illustration of trial sequence in Experiment 1. Only the congruent condition is shown here: the probe face was the same as (one of) the prime face(s).

same gender) and two congruency conditions. A stimulus shown on one trial did not appear again on another trial. In the congruent condition, the gender of the target face was consistent with the gender of the prime. In fact, the target face was identical to the face shown in the single and four-same conditions, and identical to one of the faces shown in the four-different condition. In the incongruent condition, the gender of the target face was different from that of the prime display. The target was equally likely to be a male or a female face. We examined priming (the difference between incongruent and congruent trials) in different prime conditions.

Results

Mean accuracy was slightly lower in the single-prime condition ($M = 96.4\%$ and 96.3% for the congruent and incongruent conditions, respectively) than the four-same (98.4% and 98.1% for the congruent and incongruent conditions) or four-different (98.8% and 98.1% for the congruent and incongruent) conditions, $F(2, 28) = 7.53$, $p < .01$. However, it was unaffected by prime-probe congruency, $F(1, 14) < 1$, or by the interaction between congruency and prime condition, $F(2, 28) = 1.64$,

$p > .20$. Because accuracy was high and because priming was absent in accuracy, we next focus primarily on mean response time (RT).

We included trials with correct responses in the RT analysis (inclusion of incorrect trials did not change the pattern of results). We also removed trials with RT faster than 200 ms or slower than four standard deviations of the mean RT of all data. The outlier elimination procedure eliminated 0.75% of all data. The pattern of results was the same when the outliers were included. Figure 2 shows the group average of subject's mean RT.

A repeated-measures ANOVA using prime condition and prime–target congruency as within-subject factors revealed no main effect of prime condition, $F(2, 28) = 2.05$, $p > .14$, no main effect of congruency, $F(1, 14) < 1$, but a significant interaction between the two factors, $F(2, 28) = 5.85$, $p < .008$. Specifically, priming (faster RT on congruent than incongruent trials) was revealed when the prime display contained four identical faces, $t(14) = 5.06$, $p < .01$, but not when it contained a single face, $t(14) = 0.12$, $p > .90$, or four different faces, $t(14) = -1.62$, $p > .12$. Further pairwise comparison among the three prime conditions revealed that the priming effect shown in the four-same condition was significantly greater than the four-different condition (Condition × Congruency interaction), $F(1, 14) = 11.17$, $p < .005$, or the single face condition (Condition × Congruency interaction), $F(1, 14) = 7.26$, $p < .017$. Priming was statistically equivalent between the four-different condition and the single-face condition, $F(1, 14) = 1.71$, $p > .20$.
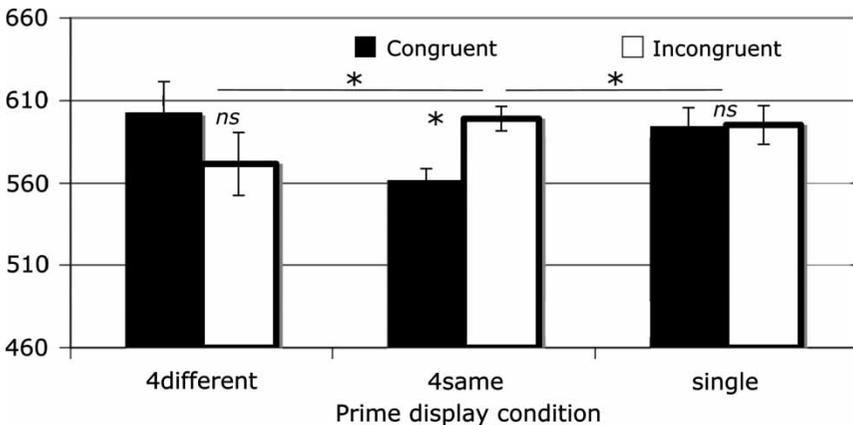

Figure 2. RT results from Experiment 1. Error bars $= \pm 1$ SE of the difference between congruent and incongruent conditions. *$p < .05$; ns = non-significant.

Discussion

Experiment 1 measured priming effects in a gender discrimination task. Priming was revealed when the prime display contained four identical faces, reflecting a decrease in the amount of time needed to identify the gender of the primed face. The priming effect was absent when the prime display contained a single face or four different faces (one of which was presented as the target face on congruent trials). These results suggest that perceptual representation of a face is enhanced when the face is duplicated on the visual display.

Was the priming effect shown in Experiment 1 a perceptual effect? The faster response in the congruent condition may originate from identity priming (due to the repetition of the same face identity across prime and target displays) or from response priming (e.g., male faces on the prime display may speed up the response of "male" on the target display). To demonstrate that the priming effect shown in Experiment 1 was perceptual in nature, we tested 14 new participants (11 females and three males; mean age = 19.6 years) in a control experiment using a design similar to that of Experiment 1. The only modification was in the congruent condition: The target face was the same gender as the prime faces, but not the same identity as any of the prime faces. Any priming effects observed here would originate primarily from response priming. Results showed that neither the main effect of congruency, $F(1, 13) < 1$, nor the interaction between condition and congruency was significant, $F(2, 26) < 1$. In the four-same condition RT was nearly identical for the congruent (566 ms) and the incongruent conditions (570 ms). Thus, the priming effect observed in Experiment 1 was primarily driven by the repetition of the same face identity rather than the same response.

Previous studies have shown that there may be separate pools of neurons encoding faces presented at different visual quadrants (Afraz & Cavanagh, 2008). These spatially nonoverlapping neurons may sum up to increase perceptual priming in the four-same condition. Such pooling of population responses may underlie the results shown in Experiment 1. In other words, the advantage seen in the four-same condition may originate from increased activation of the perceptual representation associated with that particular face (activation account). However, it is also possible that the redundancy effect in priming occurs at the retrieval stage. That is, because the probe induces retrieval of four instances of that face in the four-same condition, this may convey an advantage as measured by priming. Presently we cannot rule out the retrieval account of the redundancy effects. Future research is needed to differentiate the activation account from the retrieval account in producing redundancy effects in visual priming.

The advantage in the four-same condition compared with the other conditions is reminiscent of the "redundancy gain" shown previously in simple reaction time and in visual search tasks (Corballis et al., 2004; Miller, 2007). In these studies, target detection is faster when there are two targets (usually bilaterally arrayed) rather than a single target. However, this gain is observed even when the two targets are perceptually different (Eriksen et al., 1989). This suggests that the redundancy gain, as previously reported, is at least in part due to enhanced processing at a postperceptual stage. In our study, the advantage in the four-same condition most likely reflects a perceptual component of the redundancy gain effect, as it was only present when identity, rather than gender, was primed.

EXPERIMENT 2: VISUAL SHORT-TERM MEMORY

Experiment 1 suggests that perceptual priming is enhanced by an increased number of instances of the same identity. However, the redundancy effects are revealed in a single experimental paradigm—perceptual priming. This paradigm has unique characteristics that may limit its generality: The prime display was briefly presented and was irrelevant to the main task. Consequently, participants may not have processed the prime display as thoroughly as they would in daily activities. It is possible that the pattern of object interactions shown in Experiment 1 is restricted to conditions where encoding is suboptimal. In addition, the prime items were probed almost immediately after their initial presentation. It is unclear whether the redundancy effects are short-lived or whether they also manifest when visual representation is probed after a longer delay.

To examine the generality of results obtained from Experiment 1, we tested participants in a visual short-term memory task where visual objects were task relevant, and participants were given sufficient time to encode each object. During each trial, participants encoded four different items into short-term memory. The stimuli were shown on four consecutive displays at a rate of 1 s per display. We manipulated whether each display contained a single stimulus, four identical stimuli, or four different stimuli. When there were four different stimuli on each display, they would be repeated on the four consecutive displays. The memory load in all conditions was four (see Figure 3 for a schematic illustration of encoding sequences).

Prior to this experiment, redundancy effects have not been examined in high-level processes such as visual memory. Some researchers believe that "redundancy gain" seen previously in detection or search RT is a relatively low-level, perceptual effect (Fischer & Miller, 2008). If so,

redundancy effects may not be revealed in a visual short-term memory task when there is ample time for encoding. In addition, "redundancy" was introduced in Experiment 2 in both the four-same and the four-different conditions. In the four-same condition, the stimulus was redundant within a single display. In the four-different condition, the stimulus was redundant in consecutive displays, because the same display was presented several times. The former is a type of simultaneous redundancy (redundant in space), whereas the latter is a type of sequential redundancy (redundant in time). The comparison between these conditions will shed some light on the critical element of redundancy that is necessary to produce a memory advantage.
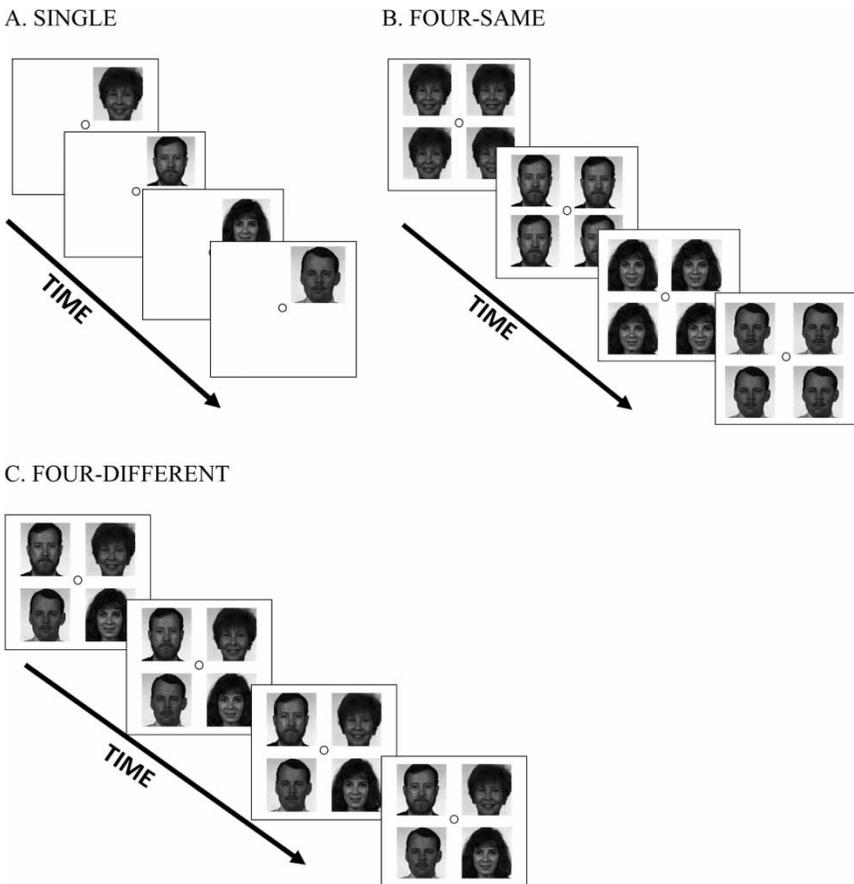

Figure 3. A schematic illustration of three conditions used during the encoding phase of Experiment 2. After a retention interval of 1 s, participants were shown two choices and indicated which one matched their memory. Note that memory load was held at 4 in all conditions.

Method

Participants.   Eighteen participants from the University of Minnesota (11 females and seven males) aged 18–32 years old (mean age = 22.7 years) completed this experiment for course credit or payment.

Materials.   Participants were tested in a visual short-term memory task using three types of stimuli on separate trials: Faces, houses, and simple man-made objects. We used all three types of stimuli, rather than just faces, to examine the generality of the redundancy effects across different categories of stimuli. There were 30 different stimuli in each category; they were all greyscale images. The faces were pictured with a frontal view and were a subset of those used in Experiment 1. Houses and objects were selected from online sources and personal collections. Each stimulus subtended $8° \times 8°$ at a viewing distance of 40 cm and was presented at one of the four visual quadrants during encoding. The centre of each stimulus was $4.06°$ away from a central fixation point.

Procedure and design.   Each participant completed 300 trials, randomly and evenly divided into three categories of stimuli (faces, houses, and objects). Articulatory suppression was used to reduce the likelihood that subjects would rely on naming to perform the task. On each trial subjects saw a three-letter word and were instructed to repeat it aloud throughout the trial. They then pressed the spacebar to initiate the trial. They saw four unique items presented on four consecutive encoding displays at a rate of 1 s/ display. After a 1 s retention interval, they were presented with two choices (i.e., temporal Two Alternative-Forced-Choice, or 2AFC), one after the other (each choice was presented for 200 ms with a 500 ms interstimulus interval), at the centre of the screen. Subjects were asked to press 1 if the first choice matched one of the four items in memory, or press 2 if the second choice matched one of the four items in memory. Although we used a temporal 2AFC (rather than a spatial 2AFC) procedure here (e.g., Giorgi, Soong, Woods, & Peli, 2004), we think the results would be the same if a spatial 2AFC had been used to probe memory.

We manipulated the presentation sequence of the four stimuli during the encoding phase. In the four-same condition, each encoding display contained four duplicates of the same stimulus (Figure 3, middle); there were 20 trials in each of the three categories of stimuli in this condition. In the single-stimulus condition, each display contained one item (at a randomly selected quadrant), and the four items were presented on the four different displays. There were 40 trials for each category of stimuli in this condition. Half of these involved fixed locations across the four consecutive displays (Figure 3, left; e.g., all were in the upper-left quadrant; the specific quadrant was randomly selected on each trial). The other

half involved four different quadrants for the four displays (not shown in Figure 3; e.g., item 1 was shown in the upper-left position, item 2 in the lower-right position, and so on). We will refer to these conditions as *single-fixed locations* and *single-shuffled locations*. We deemed it necessary to test the shuffled-locations trials so that all four quadrants would be occupied (just like the four-same condition), but we also tested the fixed-locations trials to control for effects of location uncertainty. Finally, in the four-different condition, each display contained all four items, and these four items were shown four times across the four consecutive displays. The locations of the four items were randomly selected. There were 40 trials (for each category of stimuli) in this condition, but half of these involved fixed locations across the four consecutive displays (Figure 3, right) and the other half involved shuffled locations across the four displays (not shown in Figure 3; e.g., an item shown in the upper-left at Time 1 may be shown in upper-right at Time 2; a particular item occupied all four quadrants over the course of a trial). We will refer to these conditions as *four-different fixed locations* and *four-different shuffled locations*. All trials were randomly intermixed. Subjects were given a short break every 25 trials.

Results

As described in the Method section, the "single" and "four-different" conditions included trials where the items either kept their locations or shuffled their locations across the four consecutive encoding displays. However, this factor did not affect performance. Table 1 lists performance for different stimuli in different encoding conditions. An ANOVA showed no effect of fixed versus shuffled locations across the four encoding displays, $F(1, 17) < 1$, *ns*. We averaged data across this factor to produce the three conditions of interest: Single-stimulus, four-same, and four-different. Figure 4 shows results across these three conditions for different categories of stimuli.

TABLE 1
Percentage correct in Experiment 2 for different stimuli and encoding conditions
(± 1 SE of the mean is shown in parentheses)

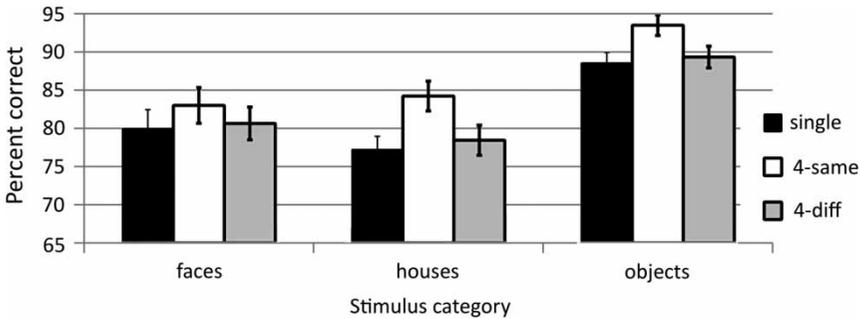|		Single		Four different	
Stimulus	*Four-same*	*Fixed locations*	*Shuffled locations*	*Fixed locations*	*Shuffled locations*
Faces	83.0 (2.4)	78.9 (3.3)	80.9 (2.2)	81.6 (2.4)	79.5 (2.6)
Houses	84.2 (2.0)	78.7 (2.7)	75.7 (2.1)	81.3 (2.4)	75.6 (2.5)
Objects	93.5 (1.4)	87.9 (2.0)	89.2 (2.2)	87.9 (2.3)	90.8 (1.9)
Average	87.0 (1.3)	81.9 (2.0)	81.9 (0.9)	83.6 (1.8)	82.0 (1.5)

Figure 4. Experiment 2 memory accuracy as a function of stimulus category and encoding conditions. Error bars show ± 1 SE of the mean.

Short-term memory accuracy was significantly affected by stimulus category, $F(2, 34) = 22.77$, $p < .001$, as subjects were more accurate during object trials (90% correct) in comparison to face trials (81%) or house trials (79%). This was largely due to the objects stimuli being more distinctive than faces or houses. However, stimulus category did not interact with encoding conditions, $F(4, 68) < 1$, *ns*. Notably, encoding conditions significantly affected memory accuracy, $F(2, 34) = 6.85$ $p < .003$. Recognition accuracy was greater in the four-same condition than in the single-stimulus condition, $F(1, 17) = 10.90$, $p < .004$, or in the four-different condition, $F(1, 17) = 6.38$, $p < .02$. The four-different condition did not differ significantly from the single-stimulus condition, $F(1, 17) < 1$.

In the single and four-same conditions, items were encoded serially on the four displays. We observed a significant serial position effect, $F(3, 51) = 9.12$, $p < .003$, as items encoded at the last serial position corresponded to higher accuracy (89% in the single condition, and 95% in the four-same condition) than items encoded at other serial positions (80% in the single condition, and 84% in the four-same condition). Accuracy for items encoded at the first three serial positions did not differ significantly from one another, $F(2, 34) = 1.21$, $p > .30$. The redundancy effect was significant both for the last serial position, $t(17) = 2.43$, $p < .026$, and for the other serial positions, $F(1, 17) = 8.02$, $p < .012$, and the interaction was not significant, $F < 1$.

Discussion

Experiment 2 explored the influence of encoding conditions on visual short-term memory. In all conditions subjects encoded four items into short-term memory. Performance was highest when each encoding display contained duplicates of the same stimulus. These results support the idea that increasing the number of instances of a single stimulus enhances the quality of its representation in

working memory. This is the first demonstration of a redundancy effect in a memory task, where ample time was provided to encode the stimuli.

Compared with the *s*ingle-stimulus condition, we did not observe any redundancy effect in the four-different condition, even though encoding was "redundant" across four consecutive displays. Both the four-same and four-different conditions involved encoding four different items, and both conditions involved stimulus repetition. However, the four items were presented sequentially in the four-same condition and simultaneously (and repeatedly) in the four-different condition. Superior performance in the four-same condition suggests that the redundancy effects are produced by simultaneous duplication of a stimulus, rather than by sequential repetition of a stimulus. In the brain, repeating a stimulus sequentially (e.g., on successive trials) leads to a reduction in brain activation compared with nonrepetition trials (a kind of "adaptation"; Grill-Spector & Malach, 2001). In contrast, repeating a stimulus simultaneously (e.g., our four-same condition) leads to greater brain activation compared with nonrepetition trials (Shim, Jiang, & Kanwisher, 2009). The differences in neural responses are consistent with the behavioural differences shown in our study. These differences (i.e., successive repetition adaptation vs. simultaneous redundancy gain) may reflect the way information is coded in the visual system: Competition for neuronal activation is greatest when multiple different objects are shown simultaneous, leading to a relative cost for multiple different objects than multiple identical objects. On the other hand, successive repetition indicates that an object is "old", resulting in reduced activation for the successively repeated object.

EXPERIMENT 3: VISUAL LONG-TERM MEMORY

In this experiment we further extend the temporal interval between object encoding and the recognition test. Specifically, we examined long-term visual memory for objects encoded in isolation or simultaneously with other objects. Subjects viewed 288 unique items (objects, faces, and scenes) in a learning phase that lasted for approximately 20 minutes. After a short break of 5 minutes, their memory for the items was tested. This experiment differed from Experiment 2 in that the memory test was administered after a delay of several minutes (rather than the 1s delay of Experiment 2) and in that we did not resample the same limited set of stimuli during encoding.[1] To ensure that

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[1] In Experiment 2, the same set of 30 stimuli was repeatedly sampled on different trials. Consequently, a memory object on one trial may be a nonmemory object on another. This procedure of resampling the same limited set of stimuli is common in studies of visual short-term memory, but can create significant proactive interference (Makovski & Jiang, 2008).

participants had ample time to perceive and encode the stimuli, each stimulus was encoded for 2 s (compared with the 1 s used in Experiment 2).

Method

Participants. Eighteen participants (13 females and five males, 18–29 years old, mean 21.5 years) from the University of Minnesota completed this experiment.

Materials. A set of 260 objects, 330 natural scenes, and 316 frontal view faces was selected from an online database and personal collections. All images were greyscale images. Of these, a randomly selected set of 96 items from each category was shown in the learning phase, and 96 additional items from each category were shown in the testing phase as foils. Each item subtended $8° \times 8°$ and was presented in one of the visual quadrants (centre distance from fixation was $4.06°$) in the learning phase.

Procedure and design. The experiment was divided into a learning phase and a testing phase, separated by approximately 5 minutes. In the learning phase, subjects were exposed to 288 unique objects (96 from each of three categories) for an average duration of 2 s per object. Subjects were told to remember these objects for a later test. Each trial lasted 2 s. The 96 trials of each category were further divided into four encoding conditions. In the single-stimulus condition (24 trials in each stimulus category), a single item was presented in a randomly selected visual quadrant for 2 s. This item would not be shown again. In the four-same condition (24 trials in each stimulus category), an item was presented as duplicates of four, one in each visual quadrant. The trial lasted for 2 s and the item would not be shown again. In the four-different condition (48 trials in each stimulus category), four different items were presented on a display for 2 s, and the display would be shown on four trials (randomly spaced out in the experiment). On half of the trials, the placement of the four objects (in different quadrants) was held constant across the four exposures. On the other half of the trials, the placement of the four objects was randomized across the four exposures. Data were pooled across all trials in the four-different condition because we did not find any statistical differences between these two conditions ($ps > .25$). Trials from all conditions and stimulus categories were randomly intermixed. Figure 5 illustrates the three conditions tested in the experiment.

In the testing phase, subjects were presented with two choices side-by-side (they were centred at $4.06°$ on either side of fixation) and subjects pressed either the left key or the right key to indicate which choice was seen earlier in

Trial 7: 2000 ms (single)   **Trial 13: 2000 ms (4-same)**   **Trial 5: 2000 ms (4-diff)**
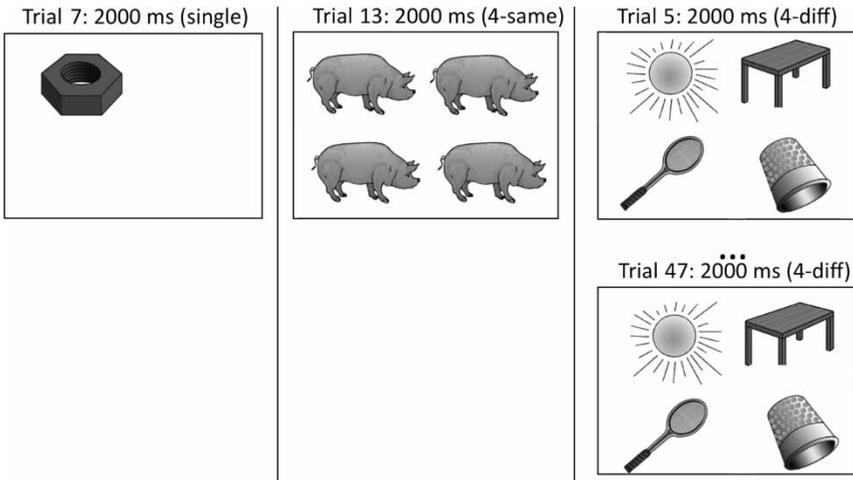
Trial 47: 2000 ms (4-diff)

Figure 5.   A schematic illustration of trials during the encoding phase of Experiment 3. Note that the four different objects in the 4-different condition were shown for a total of 8 seconds, spread across four trials.

the learning phase. There were 288 testing trials, each involving a learned object and a randomly selected foil. The relative left–right position of the old object and the foil was randomly determined for each trial.

Results

Figure 6 plots the mean accuracy for different stimulus categories and encoding conditions.

An ANOVA using encoding condition (single, four-same, and four-different) and stimulus category (faces, houses, and objects) as within-subject factors revealed significant main effects of encoding condition, $F(2, 34) = 17.82$,
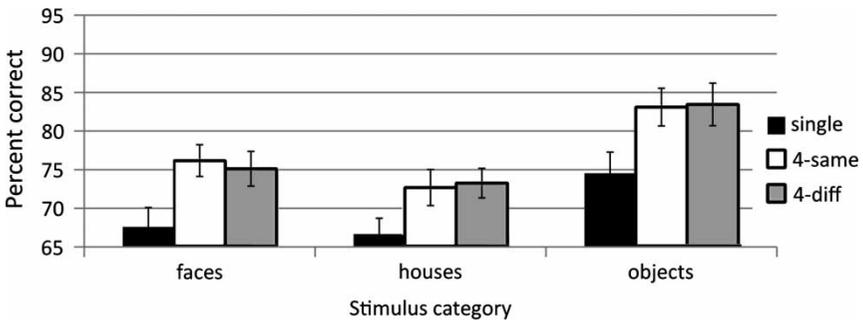
Figure 6.   Results from Experiment 3. Error bars show ± 1SE of the mean.

$p < .001$ and stimulus category, $F(2, 34) = 11.99$, $p < .001$, but no interaction, $F < 1$. Memory performance was superior for objects than faces or houses, again due to the greater distinctiveness of the objects used in the present study. Across all three stimulus categories, memory was significantly better for items presented in the four-same condition than the single condition, $F(1, 17) = 22.25$, $p < .001$. The four-different condition was also not different from the four-same condition, $F < 1$, but was significantly better than the single condition, $F(1, 17) = 34.79$, $p < .001$.

Discussion

Experiment 3 revealed superior visual long-term memory for stimuli encoded in duplicated format (four-same) than the single stimulus condition. This finding confirms the redundancy effects observed in earlier experiments. Unlike the other two experiments, however, we also observed an advantage for the four-different condition over the single stimulus condition. How can this difference be accounted for? We believe that this advantage originates from the well-known benefit of spaced presentation over massed presentation of stimuli (Crowder, 1976; Greene, 1989): Objects presented in the single stimulus condition were encoded on a single trial, whereas those presented in the four-different condition were encoded on four separate trials spaced out in time. In a follow-up experiment, we repeated Experiment 3 except that objects in the single-stimulus condition and in the four-same conditions were also spaced out on four separate trials (each for 0.5 s, randomly presented in trial order) rather than for a single trial of 2 s. We replicated the superior memory performance in the four-same (84%) than single-stimulus (80%) conditions ($p < .024$). However, the advantage of the four-different condition over the single-stimulus condition was eliminated (accuracy was 76% in the four-different condition, significantly lower than single-stimulus or four-same conditions, $ps < .025$), confirming an effect of massed versus spaced presentation in Experiment 3.

Thus, across all experiments reported in this study, we observed redundancy effects associated with presenting multiple, duplicates of the same item. Although we used different paradigms, the redundancy effects obtained in different experiments may originate from the same mechanism. That is, a perceptual advantage in the four-same condition may be reflected in perceptual priming and visual short-term and long-term memory.

GENERAL DISCUSSION

Previous work on object recognition has primarily focused on the perception of isolated objects (for review, see Kanwisher & Yovel, 2006, on face

processing; Peissig & Tarr, 2007, on object recognition). Some memory studies have presented multiple objects simultaneously for memory encoding, but the majority of work has not considered the interaction among the items. This study attempts to characterize the interaction of multiple objects in visual perception and memory, focusing on the visual redundancy effects. Our data demonstrated that the nature of the interaction among multiple objects depends on the heterogeneity of the objects. Compared with a single item, presenting multiple identical items leads to enhanced perceptual priming and visual short-term and long-term memory, a redundancy effect. In contrast, presenting multiple different objects did not produce an advantage over single-stimulus presentation, as long as additional factors such as spaced versus massed presentation are controlled.

Our findings may be reminiscent of the "redundancy gain" observed in target detection and search RT. For example, subjects are faster when detecting the onset of two stimuli rather than the onset of just one stimulus (Fischer & Miller, 2008). In addition, subjects are faster when reporting the presence of a target when the display contains two bilateral targets rather than one (Corballis et al., 2004; Eriksen et al., 1989; Fournier & Eriksen, 1990). Part of the gain in the redundant-target effect is at a postperceptual level, as the gain is observed when the two targets are different stimuli (Eriksen et al., 1989; Marks & Hellige, 2003). There is also a perceptual component of the effect, as RT is faster when the two targets are identical than when they are different (Fournier & Eriksen, 1990). Our study demonstrates a more general redundancy effect. First, redundancy advantages are observed not only in perceptual tasks but also in short-term and long-term memory tasks. In the latter tasks, encoding duration is long enough for all items to be adequately encoded. In addition, the retention interval is relatively long, revealing the long-term stability of the redundancy effects. Second, we have shown that the kind of redundancy that provides an advantage is limited to simultaneous stimulus duplication. Repetition of the stimulus over consecutive displays (rather than duplicating it simultaneously) does not lead to a benefit. Thus, we have shown that the redundancy effects are both general (applicable to memory as well as to perception) and specific (restricted to simultaneous stimulus duplication). Finally, the memory experiments (Experiments 2 and 3) used unspeeded responses, and the redundancy gain in accuracy cannot be attributed to speeded motor responses (unlike Miller, Beutinger, & Ulrich, 2009).

Several previous accounts attempt to explain the redundancy gain (Corballis et al., 2004; Miller, 2007; Miller & van Nes, 2007). Most of these accounts relate to the increased processing resources provided by two separate hemispheres of the brain. Our interpretation also draws on redundant neural encoding. Specifically, to account for the redundancy effects observed here, we must assume that the different instances of an

object are encoded by partially separate pools of neurons, an assumption supported by recent behavioural and neuroimaging data (Afraz & Cavanagh, 2008; Hung, Kreiman, Poggio, & DiCarlo, 2005; Schwarzlose, Swisher, Dang, & Kanwisher, 2008). Such redundant coding of the same identity information by separate pools of neurons may seem to challenge the efficient coding hypothesis (Barlow, 1961), according to which neuronal coding of sensory information attempts to be most efficient (e.g., the number of spikes needed to transmit a signal is minimized). However, the use of separate pools of neurons to encode the same identity (from different locations of the visual field) can supply information about an item's unique location. In addition, if the representation from each pool of neurons is susceptible to degradation, then the presence of partially separate pools of neurons can compensate for the loss of signal in any pool. Redundant coding can contribute to graceful degradation in neural representations. At the behavioural level, the benefit of redundant coding is reflected in enhanced perceptual priming and more robust visual short-term and long-term memory in the multiple, same-identity condition.

Our study has taken a first step in establishing the redundant effects in the visual representation of multiple objects. However, our research also leaves open many important questions. Perhaps the most pressing issue relates to what constitutes as "same" or "different" stimuli. Previous research has shown that redundancy gain in visual search RT is not restricted to two visually identical targets (Eriksen et al., 1989; Krummenacher, Müller, & Heller, 2002; Marks & Hellige, 2003). We do not know whether this generalization also applies to the kind of redundancy effects observed in the present study. Specifically, would items that differ in size or colour but not in shape be considered the same stimuli (and therefore leading to a redundancy effect)? What about items that have the same identity, but are pictured from different viewpoints? We also do not know how these effects relate parametrically with the size of each object and the number of duplicates. Addressing these questions in the future may provide more insight into how the brain resolves the computational challenge posed by the presentation of multiple objects.

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