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The resilience of object predictions: Early recognition across viewpoints and exemplars

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Abstract

Recognition of everyday objects can be facilitated by top-down predictions. We have proposed that these predictions are derived from rudimentary shape information, or *gist*, extracted rapidly from low spatial frequencies (LSFs) in the image (Bar, 2003). Because of the coarse nature of LSF representations, we hypothesize here that such predictions can accommodate changes in viewpoint as well as facilitate the recognition of visually similar objects. In a repetition-priming task, we indeed observed significant facilitation of target recognition that was primed by LSF objects across moderate viewpoint changes, as well as across visually similar exemplars. These results suggest that the LSF representations are specific enough to activate accurate predictions, yet flexible enough to overcome small changes in visual appearance. Such gist representations facilitate object recognition by accommodating changes in visual appearance due to viewing conditions and help to generalize from familiar to novel exemplars.

Humans can identify objects at a glance. It has been proposed that in order to achieve such fast and accurate recognition, the visual system uses coarse information in the image to rapidly activate a rough estimate about the content of a visual input (e.g., ‘a dog?’ ‘a kitchen?’, Bar, 2003; Neisser, 1967; Oliva, 2005; Potter, 1975). This approximation of visual input at a glance, or *gist* (Oliva, 2005), can be verified and refined when fine image details are processed. By first relying on gist, observers can extract meaningful information from complex visual inputs (Potter, 1975; Bar, 2004). For instance, observers can categorize scenes or faces based on the overall image structure (Schyns & Oliva, 1994; 1999) and can detect whether a particular type of object is present in a scene (Davenport & Potter, 2004; Fabre-Thorpe et al., 2001; Joubert et al., 2007; Mack & Palmeri, 2010), even when the images are presented briefly (e.g., for 20ms–80ms). The concept of gist is central to visual cognition, but it remains elusive how exactly gist may facilitate object recognition.

Objects are often quickly recognized at the basic level (e.g., dogs, cats), which is the level that is most informative for discrimination among categories (compared with the superordinate level, e.g., living vs. non-living things, or the subordinate level: e.g., beagle vs. collie; Jolicoeur et al., 1984; Rosch et al., 1976). Because objects within a basic-level

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category typically share similar features, whereas objects from different basic-level categories have more distinct features (Rosch et al., 1976), it is often possible to recognize objects at the basic level based on the knowledge about the global object shape (Bar, 2003; see also Oliva & Torralba, 2006). It is also possible that memory representation of an object category evolves from previous encounters with various instances from that category, and it subserves recognition of new instances of objects from that category. During early processing, a gist representation derived from low spatial frequencies (LSFs) of images may be particularly useful for generating initial guesses about object identity (Bar, 2003), as LSFs are often perceptually available faster than fine image details, or high spatial frequencies (HSFs) (Breitmeyer, 1975; Gish et al., 1986). We propose here that a gist representation will be flexible and resilient to slight changes in visual details. Specifically, LSF information may accommodate the differences between exemplars of a category and between adjacent views of a single object. While HSF information is useful for differentiating similar exemplars within a category (e.g., beagle, collie; Collin & McMullen, 2005), LSF information may be sufficient for a generic estimate of the category to facilitate recognition (Bar, 2003).

The nature of object representation can be examined by a priming paradigm, where briefly presented images may facilitate recognition of subsequent stimuli. Specifically, a prime image may activate relevant representations that are useful for rapid recognition of a target image. Facilitation in object priming has been observed across viewpoint and exemplar variations (Harris & Dux, 2005; Harris et al., 2008; Biederman & Cooper, 1991; Koustaal et al., 2001; Simon et al., 2003). For instance, object representations appears to be invariant to viewpoint changes at early stages of processing (Harris & Dux, 2005), although object recognition may be susceptible to viewpoint changes during later processing (Harris et al., 2008). While priming is strongest for identical images (i.e., repetition priming), priming can also be observed for different exemplars of a category (Biederman & Cooper, 1991; Koustaal et al., 2001; Simon et al., 2003; but see Harvey & Burgund, 2012; Vuilleumier et al., 2002).

To test our hypothesis that the facilitation of object processing based on LSF gist can accommodate appearance changes, we asked to what extent briefly presented images with LSF information might produce priming across viewpoint and exemplar variations. In the *Viewpoint* experiment, we tested whether faster performance would be obtained with LSF primes, when the prime and target were of an identical object across slight viewpoint changes, compared with when the prime and target were of different objects. In the *Exemplar* experiment, we measured performance when the prime and target were of different exemplars within a basic-level category (e.g., two types of dogs), compared with when the prime and target were of objects from different basic-level categories, to examine whether LSF facilitation is based on visual or semantic features. If the facilitation is based primarily on the global shape of an object, then facilitation should only be expected for visually similar exemplars (e.g., collie and golden retriever). In contrast, if semantic information about an object category is utilized during early processing, priming should also be found for exemplars that are visually dissimilar (e.g., collie and Chihuahua).

It is important to note that HSF information may also be sufficient to facilitate early object processing. Specifically, a recent study (de Gardelle & Kouider, 2009) reported stronger priming for HSF than LSF in a face judgment task. However, the HSF stimuli were more visible than the LSF stimuli in that study, and might thus have resulted in stronger priming. Moreover, it is unclear whether any HSF facilitation may be specific to the exact image details, or if it can also accommodate slight image changes. Because our question of interest is whether object priming across image changes may depend on LSF or HSF, we first equated the visibility of LSF and HSF in a pilot study to prevent any possible confound due to visibility. In the main priming study we then examined how LSF and HSF information may accommodate variations in image details to facilitate subsequent object processing.

Methods

Participants

Twenty-four young adults from the Harvard University community participated in both *Viewpoint* and *Exemplar* experiments for payment. The experiment order was counterbalanced across participants. Data from one participant was discarded because the individual's overall RT was two standard deviations slower than the group average.

Stimuli

The *Viewpoint* and *Exemplar* experiments each used 96 everyday objects and 192 abstract sculptures. The *Viewpoint* experiment involved 3 consecutive views (0°, 30°, or 60° rotation in depth) of 96 objects, obtained from <http://www.tarrlab.org>. The *Exemplar* experiment used 3 exemplars of 96 objects (identical, 1 visually similar and 1 visually dissimilar exemplars), obtained from <http://cvcl.mit.edu/MM/stimuli.html>. Perceptual similarity ratings of object shapes (on a scale of 1–5) collected from a separate participant group ($n=22$) showed higher similarity for the similar than dissimilar pairs (similar: $M=3.43$, $SD=.57$, dissimilar: 2.10 , $SD=.71$; $t_{21}=11.86$, $p<.0001$). To evaluate the influence of low-level visual properties, we found in additional analyses of the priming study that regressing out pixelwise similarity between image pairs did not affect the results. Images of abstract 3D sculptures were obtained from several art websites. All images showed minimal occlusion of object parts, and were adjusted to 256×256 pixels in size.

For each participant, different subsets of 32 objects were randomly selected for each spatial frequency condition, with 24 objects as the *primes* and *targets* for the *same* trials and the remaining 8 objects used as the *targets* for the *different* trials. Sample prime and target for the two experiments are illustrated in Figure 1. The prime objects were shown in full spectrum (FS; unfiltered, containing LSF and HSF), LSF (<8 cycle per image, cpi, or <1 cycle per degree, cpd), or HSF (40–48 cpi; 6–7 cpd). All target objects in both experiments were in FS. For LSF and HSF, the relevant spatial frequencies remained intact while the rest were phase-scrambled. Each participant sat 50cm away from the monitor and rested his/her head on a chin rest. The primes and targets extended 4° and 5° of visual angle, respectively. In each experiment, each prime was shown six times: once for each of the four “object” conditions and twice for the “sculpture” condition. Each target was shown once.

As mentioned above, one possible confound that could potentially affect the priming results is differential visibility of the objects across the LSF and the HSF conditions. In a pilot study (N=9), participants judged if each LSF or HSF image showed an everyday object or an abstract sculpture, with all objects that would be used as primes included. This task allowed for an estimation of general recognition performance of the filtered images, which was appropriate for our goal to test the extent that gist of visual input would facilitate recognition. Each image was presented for 100ms and then followed by a 150ms mask. We found that the HSF objects were more recognizable than the LSF objects (*Viewpoint*: LSF: $d' = 1.45$, RT=810ms, HSF: $d' = 2.23$, RT=707ms; *t*-tests: d' : $t_8 = 3.51$, $p < .01$; RT: $t_8 = -2.14$, $p = .07$; *Exemplar*: LSF: $d' = .81$, RT=738ms, HSF: $d' = 1.44$, RT=738.5ms, *t*-tests: d' : $t_8 = 5.25$, $p < .001$; RT: $t_8 = .03$, $p = .98$). Therefore, we attempted to equate the visibility of the objects across LSF and HSF conditions by adjusting the contrast of the phase-scrambled noise using Matlab (increasing the noise contrast for the HSF *Viewpoint* and *Exemplar* stimuli by sharpening the extreme 30% and 10% values, respectively, and reducing that for 30% for the LSF *Exemplar* stimuli). Another group of participants (N=16) performed the object vs. sculpture judgment task on the adjusted images, and showed comparable recognition performance on the LSF and HSF stimuli (*Viewpoint*: LSF: $d' = 1.46$, RT=691ms, HSF: $d' = 1.43$, RT=713ms; d' : $t_{15} = .39$, $p = .75$; RT: $t_{15} = -.95$, $p = .36$; *Exemplar*: LSF: $d' = 1.34$, RT=777ms, HSF: $d' = 1.51$, RT=774ms, d' : $t_{15} = -1.83$, $p = .09$; RT: $t_{15} = .09$, $p = .93$). We then used this visibility-adjusted stimulus set in the main priming task.

In the priming task, participants were instructed to look at the first image and judge whether the second image showed a common object or an abstract sculpture (Figure 1). The spatial frequency conditions (FS, LSF, HSF) were blocked. The other conditions (*Viewpoint*: 0°, 30°, 60°, different, or sculpture; *Exemplar*: same, similar, dissimilar, different, or sculpture) were randomized. In each experiment, each of the four “object” conditions (*Viewpoint*: 0°/30°/60°/different; *Exemplar*: same/similar/dissimilar/different) had 24 trials and the “sculpture” condition had 48 trials.

Results

First, discrimination performance in the object/sculpture judgment task was high across all spatial frequency conditions in both *Viewpoint* and *Exemplar* experiments (Table 1). One-way ANOVAs conducted on sensitivity (d') showed no significant effects of Spatial Frequency in either the *Viewpoint* experiment, $F_{2,44} = .48$, $MSE = .17$, $\eta_p^2 = .02$, $p = .62$, or the *Exemplar* experiment, $F_{2,44} = 1.61$, $MSE = .17$, $\eta_p^2 = .07$, $p = .21$.

Our primary interest was the priming effect within the “object” trials, i.e., faster RT for 0°, 30°, and 60° or for the same, similar, and dissimilar trials compared to that for the different object trials (see Figure 2). For RT, trials that required a response of “object” were analyzed in 3 (FS/LSF/HSF) $\times$ 4 (*Viewpoint*: 0°/30°/60°/different; or *Exemplar*: same/similar/dissimilar/different) ANOVAs. RT outliers ($> 2.5SD$ within each individual) were excluded (3% of total trials). Priming effects were revealed by Bonferroni-corrected *t*-tests comparing each of the 0°, 30°, 60° or the same, similar, dissimilar conditions to the *different* conditions.

Viewpoint experiment

The effect of Spatial Frequency was significant, $F_{2,44}=4.36$, $MSE=3668.8$, $\eta_p^2=.15$, $p=.02$, revealing faster RT for FS than HSF ($p=.015$) whereas there was no difference between FS and LSF ($p>.38$) or between LSF and HSF ($p>.37$). A significant effect of Viewpoint was also observed, $F_{3,66}=26.56$, $MSE=1037.8$, $\eta_p^2=.55$, $p<.0001$. The Viewpoint effect was modulated by a Spatial Frequency $\times$ Viewpoint interaction, $F_{6,132}=3.25$, $MSE=1270.7$, $\eta_p^2=.13$, $p=.005$. Bonferroni-corrected comparisons revealed significant priming for FS and LSF across 0° (FS: $p<.0001$; LSF: $p=.001$), 30° (FS: $p<.0001$; LSF: $p=.046$) and 60° (FS: $p<.0001$; LSF: $p=.015$) but not for HSF ($ps>.9$) primes.

Exemplar experiment

A significant effect of Exemplar was observed, $F_{3,66}=23.30$, $MSE=1743.3$, $\eta_p^2=.51$, $p<.0001$, but not for Spatial Frequency, $F_{2,44}=3.35$, $MSE=8193.6$, $\eta_p^2=.016$, $p=.70$. Although the Spatial Frequency $\times$ Exemplar interaction was not significant, $F_{6,132}=1.35$, $MSE=1560.6$, $\eta_p^2=.06$, $p=.24$, the significant 3 (FS, LSF, HSF) $\times$ 2 (same, different) interaction ($F_{2,44}=3.31$, $MSE=1337.5$, $\eta_p^2=.13$, $p<.05$) replicated a similar interaction in the *Viewpoint* experiment. More importantly, Bonferroni-corrected comparisons revealed that for FS and LSF primes, priming was significant with identical (FS: $p<.0001$; LSF: $p=.003$) and similar (FS: $p=.0002$; LSF: $p=.026$) exemplars but not with dissimilar exemplars (FS: $p>.87$; LSF: $p>.89$), whereas there was no significant priming effect in any HSF conditions ($ps>.79$).

Discussion

We observed significant object priming in accordance with our hypothesis that facilitation can arise from LSF information and that this facilitation accommodates some changes in visual appearance. Specifically, facilitation was found for repeated objects with up to 60° rotation and for visually similar exemplars, compared with different objects. The lack of facilitation for visually dissimilar exemplars indicates that the priming was based on visual similarity and not on semantic category. All priming effects were not only observed with FS primes (which contained LSF and HSF), but also with LSF primes. However, no significant facilitation was observed with HSF primes. These findings are consistent with the idea that the visual similarity of global shapes plays a key role in facilitating recognition processes and demonstrate that LSFs are critical elements towards building these representations.

To recognize objects quickly and accurately, it is advantageous to generate a set of limited but flexible predictions regarding the identity of an object during early visual processing (Bar, 2003). Using briefly presented object primes, our results reveal that LSF information is involved in activating such processes. LSFs are extracted early (Schyns & Oliva, 1994; 1997) and are projected rapidly to the dorsal stream predominately, and also to the ventral stream (Ferrera et al., 1992; Merigan & Maunsell, 1993; Shapley, 1990). It is possible that LSF information facilitates subsequent recognition either by bottom-up or local feedback process within the ventral stream (Ewbank et al., 2011; 2013), or by projecting the input to the orbitofrontal cortex through the dorsal magnocellular pathway to guide subsequent

processing in the ventral visual cortex (Bar et al., 2006; Chaumon et al., 2013; see also Li et al., 2010; Miller et al., 2011). Our results suggest that the mechanisms that support LSF facilitation in object processing should overcome slight changes in visual appearance. In other words, object recognition is facilitated when new or previously encountered objects fall under existing gist representations.

While we observed priming for LSF primes, we did not find significant facilitation with HSF primes. However, we cannot conclude that there is no facilitation from HSF information, as this would require accepting the null hypothesis. As one piece of evidence in support of a special role for LSFs, we found that the repetition priming effects were consistently stronger for LSF than HSF across our experiments: a 2 (Experiment: Viewpoint/Exemplar) $\times$ 2 (SF: LSF/HSF) $\times$ 2 (condition: same/different) ANOVA revealed a significant Spatial Frequency $\times$ Condition interaction, $F_{1,22}=4.4$, $MSE=9671$, $\eta_p^2=.17$, $p=.048$, showing larger priming for LSF than HSF, and no significant 3-way interaction, $F_{1,22}<1$. However, the relative role of LSF and HSF may depend on task demands (Oliva & Schyns, 1997). It is possible that HSF priming might occur in a task that required discrimination among similar exemplars of a category (Collin & McMullen, 2005; Archambault et al., 2000; Schyns et al., 2002) rather than the basic-level categorization task that we employed. Indeed, such task differences might explain the difference in findings from a previous study (de Gardelle & Kouider, 2009). The findings regarding the relative role of LSF and HSF priming should require additional work to sort out. Importantly, however, our findings show that when the visibility of LSF and HSF images is equated, LSFs can activate relevant, flexible representations to facilitate recognition.

Our finding of viewpoint generalization with FS and LSF primes is consistent with previous research revealing viewpoint-invariant performance during early stages of processing (Harris et al., 2008; Hamm & McMullen, 1998; Murray, 1998). The viewpoint invariance we observed may stem from the fact that the range of viewpoint that we tested was significant but limited (up to 60°) and that all main visual features of the objects were clearly shown in most of our stimuli (e.g., Biederman & Gerhardstein, 1993; but see Hayward & Tarr, 1997). Nonetheless, even though the exact image details vary, a blurry image containing global shape information is sufficient to facilitate subsequent recognition of an object across slight viewpoint changes.

We also found that similar global shapes led to comparable priming effects for identical and visually similar exemplars for FS and LSF primes, although the local features of the visually similar exemplars were quite distinct. While semantic information can be extracted from an image relatively quickly (e.g., Potter, 1975; Dell'Acqua & Grainger, 1999), it appears insufficient to facilitate recognition of briefly presented exemplars that are visually distinct in shapes. It is possible that during early stages of processing, recognizing objects based on matching general visual features of LSF representations is more efficient than relying on semantic processing, and that the visual and semantic processes may rely on different neural substrates, for instance the orbitofrontal cortex (Bar et al., 2006) and the right fusiform (Koustaal et al., 2001; Simons et al., 2003) are more involved in visual processing, whereas the inferior frontal cortex (James & Gauthier, 2004) and the left fusiform (Koustaal et al.,

2001; Simons et al., 2003) are more involved in semantic processing. Future research should further clarify the temporal dynamics of the frontal-temporal areas that may be involved in the processing of visual and semantic information for prediction and recognition (Ghuman et al., 2008; Grill-Spector et al., 2006; Segaert et al., 2013).

Taken together, our results suggest that LSF information is important in activating a ‘visual gist’ to facilitate subsequent processing. The results demonstrate that the flexible nature of this representation allows for generalization across adjacent views of an object and across differences between exemplars of a category. By utilizing a generic representation, the visual system appears to take advantage of the nature of LSF information and uses this information to generate predictions in a fast and flexible manner.

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Figure 1.

Sample prime and target objects (left) and the trial sequence of the priming task (right). The prime objects could consist of full spectrum (FS), low spatial frequency (LSF) or high spatial frequency (HSF) information. LSF and HSF filtered images were first normalized for comparable visibility in a separate experiment. The image contrast here has been adjusted for illustration purpose. In the “object” trials, the target objects could be identical to the prime objects but varied in orientation (in the *Viewpoint* experiment), or they could be exemplars from the same category as the prime object (in the *Exemplar* experiments), or they could be completely different objects from the prime objects. In each “non-object” trial, the target image showed an abstract 3D sculpture.

Figure 2.

Correct response times (RT) across Spatial Frequency and Viewpoint conditions (left) and across Spatial Frequency and Exemplar conditions (right). Error bars represent the 95% confidence intervals of the 3×4 interaction.

Table 1

Mean sensitivity (d') on the object/sculpture judgment task across the spatial frequency conditions in the *Viewpoint* and *Exemplar* experiments. Standard error of the mean is shown in the parentheses.

	Full Spectrum (FS)	Low spatial frequency (LSF)	High spatial frequency (HSF)
<i>Viewpoint</i> experiment	3.38 (.12)	3.27 (.09)	3.35 (.11)
<i>Exemplar</i> experiment	3.04 (.12)	2.84 (.06)	2.99 (.11)