

Evaluating Models of Object-Decision Priming: Evidence From Event-Related Potential Repetition Effects

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This study was designed to differentiate between structural description and bias accounts of performance in the possible/impossible object-decision test. Two event-related potential (ERP) studies examined how the visual system processes structurally possible and impossible objects. Specifically, the authors investigated the effects of object repetition on a series of early posterior components during structural (Experiment 1) and functional (Experiment 2) encoding and the relationship of these effects to behavioral measures of priming. In both experiments, the authors found repetition enhancement of the posterior N1 and N2 for possible objects only. In addition, the magnitude of the N1 repetition effect for possible objects was correlated with priming for possible objects. Although the behavioral results were more ambiguous, these ERP results fail to support bias models that hold that both possible and impossible objects are processed similarly in the visual system. Instead, they support the view that priming is supported by a structural description system that encodes the global 3-dimensional structure of an object.

Keywords: event-related potential, perceptual, implicit memory, structural description system

Much research over the last decade has focused on identifying the neural mechanisms underlying the behavioral phenomenon of *priming*—a change in the ability to classify, identify, or produce an item due to prior exposure (Tulving & Schacter, 1990). Priming is thought to occur independent of the ability to consciously remember previously encountered information and is typically assessed using indirect or *implicit* tests of memory. It can be further subdivided into two classes: *perceptual priming*, which is modality specific and is not affected by semantic or elaborative encoding, and *conceptual priming*, which is not modality specific and does depend on the degree of semantic processing of an item. Considerable evidence from neuropsychological and neuroimaging studies has accumulated showing that distinct brain regions are involved in perceptual priming, conceptual priming, and the conscious recollection of information (for a recent review of neuroimaging studies of priming, see Henson, 2003).

One well-characterized perceptual priming paradigm that has been used to study the nature of visual object representation is the

possible/impossible object-decision test developed by Cooper, Schacter, and colleagues (e.g., Cooper & Schacter, 1992; Schacter, Cooper, & Delaney, 1990a, 1990b). During the encoding phase of this paradigm, participants are exposed to a series of unfamiliar line drawings, half of which depict structurally possible figures and half structurally impossible figures. *Possible objects* are drawn in such a way that they could exist as three-dimensional (3D) objects in the real world, whereas *impossible objects* contain subtle surface and edge violations that make it impossible for them to be rendered as coherent 3D structures (see Figure 1). In the test phase, participants are presented with both previously presented (old) and new possible and impossible objects and are asked to classify them as either structurally possible or impossible. Priming has been demonstrated consistently for possible objects in the form of greater classification accuracy for old than new test items. By contrast, priming is not typically found for impossible objects (e.g., Liu & Cooper, 2001; Schacter & Cooper, 1993; Schacter et al., 1990a; Schacter, Cooper, Delaney, Peterson, & Tharan, 1991; Schacter, Cooper, Tharan, & Rubens, 1991; Schacter, Cooper, & Valdiserri, 1992; Uecker et al., 1997; however, for examples of negative priming, see Penney, Mecklinger, Hilton, & Cooper, 2000; Ratcliff & McKoon, 1995; Seamon & Carrasco, 1999; Williams & Tarr, 1997). In addition, subjects' performance on the object-decision test has been shown to be stochastically independent of performance in an explicit old/new recognition test, in which subjects are asked to discriminate between old and new objects (Schacter et al., 1990a; Schacter, Cooper, Delaney, et al., 1991—but see Poldrack, 1996, for problems associated with testing for stochastic independence).

Based on a number of behavioral studies, three different theories have been put forward to account for performance in the object-decision test. In this article, we refer to these models as the *structural description system* (SDS) account (e.g., Schacter et al., 1990a, 1990b), the *general bias* model (McKoon & Ratcliff, 1995;

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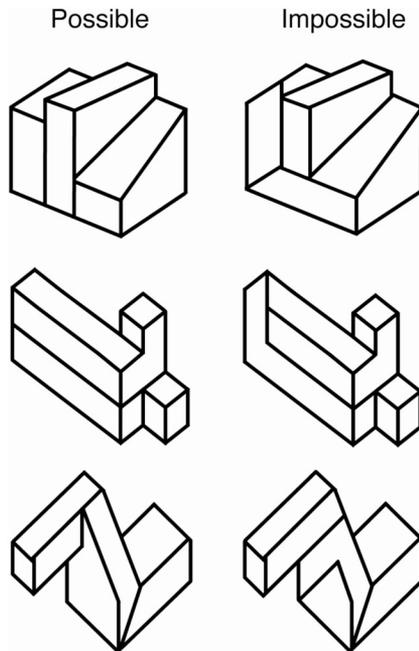


Figure 1. Examples of the matched possible and impossible stimuli used in this study.

Ratcliff & McKoon, 1995), and the *structure-extraction bias* view (Williams & Tarr, 1997). As of yet, behavioral manipulations alone have not provided unequivocal support for any one of these theories. Therefore, in this study we examined some of the neural processes related to object priming performance in an attempt to provide further information regarding this debate. As explained in more detail later, these theories differ in their view of how the visual perceptual system processes possible and impossible objects during encoding, as well as the relationship between initial encoding and subsequent object-decision priming. The aim of the present investigation was to provide a test of these theories by evaluating encoding-related neural activity and its relationship to object-decision priming using event-related potentials (ERPs).

The excellent temporal resolution of ERPs is well suited to this endeavor because one can differentiate early perceptual effects from later explicit recognition effects and postperceptual decision processes (e.g., Curran, Tanaka, & Weiskopf, 2002; George, Jemel, Fiori, & Renault, 1997; Henson, Rylands, Ross, Vuilleumier, & Rugg, 2004; Schendan & Kutas, 2003; Schott, Richardson-Klavehn, Heinze, & Düzel, 2002). Our analysis was focused on early latency effects because perceptual priming is considered to be a relatively automatic and fast process that occurs before the semantic analysis of a stimulus has taken place. Of particular interest to us were the posterior P1, N1, and N2 ERP components. These waveforms have previously been implicated in various aspects of perceptual processing of objects, including visual attention (Mangun, 1995; Taylor, 2002), global–local processing of hierarchical visual stimuli (Han, He, & Woods, 2000; Han, Liu, Yund, & Woods, 2000), implicit visual categorization (Curran et al., 2002; Vogel & Luck, 2000), structural encoding of global configurations (Eimer, 2000; Itier & Taylor, 2002, 2004), and object-selection mechanisms (Schendan & Kutas, 2002; Tallon-

Baudry, Bertrand, Delpuech, & Pernier, 1997). Although none of the three theories of object-decision performance that we are testing make explicit predictions about the way in which these ERP waveforms might be modulated, we believe that the predictions derived for each one are reasonable and fair.

In order to assess encoding-related neural activity and how it relates to object-decision priming, the present study took advantage of the finding that priming occurs only when the objects are presented for several seconds at encoding. Total presentation time can be distributed across multiple exposures, although additional exposures beyond the minimum necessary to induce priming do not increase the magnitude of priming (e.g., Schacter, Cooper, Delaney, et al., 1991; Seamon & Carrasco, 1999). Therefore, we presented each object twice during the encoding phase for 4 s each, a method used in previous studies to elicit reliable priming for possible objects (e.g., Hilton et al., 2002; Uecker et al., 1997). This repetition paradigm enabled us to use potential changes in the neural signal from the first to the second presentation of an object (ERP repetition effect or repetition priming) as an index of encoding-related modulations that may or may not be predictive of subsequent object-decision priming. As described later, the three models make different predictions about both repetition effects that might be observed in the ERPs and the relationship of these changes to subsequent priming performance. This approach is analogous to so-called differences due to later memory (DM) studies of declarative memory in which items presented at encoding are sorted according to whether they were remembered or forgotten on a subsequent memory test (Mangels, Picton, & Craik, 2001; Paller, Kutas, & Mayes, 1987; for reviews see Friedman & Johnson, 2000; Paller & Wagner, 2002). We focused on the encoding phase of the experiment, rather than the object-decision test phase, because we wanted to examine how the visual system processes these objects when subjects are not explicitly thinking about their possible/impossible status. In addition, the ERPs recorded during encoding are not subject to retrieval biases and motor or attentional processes associated with making a speeded response.

In evaluating the relationship between encoding-related neural activity and subsequent object-decision priming, it is important to note that there are multiple ways in which priming performance can be assessed. That is, in addition to percentage change in reaction time (RT) and accuracy for previously presented items versus new items, one can also define priming in terms of the signal detection theory (SDT) measures of bias and sensitivity. As was pointed out by Williams and Tarr (1997), correct “possible” responses can be considered as hits and incorrect “possible” responses as false alarms. Likewise, correct “impossible” responses can be treated as correct rejections, and incorrect “impossible” responses as misses. In this framework, *sensitivity* corresponds to the ability to discriminate between the distributions of possible and impossible items, whereas *bias* refers to the degree to which subjects use one type of response (i.e., “possible”) more than another response (i.e., “impossible”). As elaborated below, the concepts of bias and sensitivity play an important role in differentiating the structural description and bias theories of object-decision priming, even from a purely behavioral perspective. Therefore, we evaluate the behavioral priming results from the present study using both conventional priming and SDT measures.

In what follows, we first briefly review each of the three theories and their supporting evidence. Then, we describe both (a) the specific behavioral and neural predictions we believe each theory would make with regard to repetition effects for possible and impossible objects during encoding and (b) the relationship of these effects to behavioral performance in the object-decision test (i.e., percentage of change in RT, accuracy, bias, and sensitivity). In the present study, we reasoned that testing specific predictions that can be derived from each theory might yield results that would shed light on the mechanisms underlying possible/impossible object-decision priming.

The SDS explanation of performance in the object-decision test is based on a series of studies that have demonstrated double dissociations between performance on the implicit (object possibility) and explicit (old–new recognition) tests. These double dissociations have been produced by using study-to-test object transformations (Cooper, Schacter, Ballesteros, & Moore, 1992; Schacter, Cooper, & Treadwell, 1993), or manipulating the encoding instructions, such that they varied in the emphasis they placed on processing an object's local two-dimensional (2D) features, global 3D structure, or semantic associations (e.g., Schacter & Cooper, 1993; Schacter et al., 1990a). In addition, older subjects and patients with amnesia show normal priming in the object-decision test (at least when tested immediately), despite impaired recognition performance (Schacter, Cooper, Tharan, & Rubens, 1991; Schacter et al., 1993; Schacter et al., 1992). These findings led Schacter and Cooper to conclude that priming in the possible/impossible object-decision test is supported by a *perceptual representation system* (PRS) that can function independent of episodic memory (Tulving & Schacter, 1990). Moreover, because priming in the object-decision test is only observed for possible objects, not for impossible objects, they conjectured that priming depends on a representation of an object's global 3D structural description as well as the relations among the object's component axes. These structural descriptions are computed by the SDS, a subsystem of the PRS.

Although the parts of impossible objects can be represented in the SDS, globally coherent structural descriptions, by definition, cannot be generated for impossible objects. As a result, priming in the object-decision test is seen for possible objects only. This view is supported by the finding that only encoding tasks that require subjects to process the objects' global 3D structure produce priming of possible objects in the object-decision test (Schacter & Cooper, 1993; Schacter et al., 1990a; but see Ganor-Stern, Seamon, & Carrasco, 1998). Thus, according to the SDS account, there is a fundamental difference in the way that possible and impossible objects are processed when subjects are engaged in a structural encoding task and it is this difference that results in the differential priming effects observed in the object-decision test.

The following predictions can be generated and tested for the SDS model of object-decision priming. Behaviorally, the SDS account predicts priming in the form of accuracy or RT improvements for old possible objects, but not for old impossible objects. In terms of SDT, prior exposure should increase discriminability for old objects compared with new objects but should have no effect on bias. The reason is that performance for old possible objects increases, whereas performance for old impossible objects does not change. However, occasional increases in the bias to call old objects "possible" have been reported under standard condi-

tions and were attributed to the influence of familiarity on object-decisions (Schacter & Cooper, 1995).

With respect to the neural predictions, the SDS account would postulate that some pattern of ERP repetition effects might be observed for possible objects, whereas a subset of these effects would be anticipated for impossible objects. Because possible and impossible objects share many visual features, such as object parts and contours, repetition effects may also occur for impossible objects. However, because possible objects contain additional information that is not available for impossible objects (i.e., global structural descriptions), the SDS model would predict that at least one additional repetition effect would occur for possible objects only. Any repetition effect(s) that occurred exclusively for possible objects would be expected to occur after potential effect(s) common for both object types because parts-based structural descriptions have to be available before global structural descriptions can be computed. Nonetheless, even the repetition effects exclusive for possible objects should be evident at a relatively early perceptual level. Moreover, the SDS model predicts that there will be significant correlations between the magnitude of ERP repetition priming effects exclusive to possible objects (and likely, therefore, to represent global structural information) and the magnitude of behavioral priming for possible objects (RT, accuracy, and sensitivity) on the subsequent object-decision task. It would not predict such correlations to occur for impossible objects, because priming on the object-decision test is thought to rely on global structural descriptions, which cannot be generated for impossible objects. Finally, the magnitude of any ERP repetition effect would not be expected to correlate with bias.

A different account of priming in the possible/impossible object-decision test, and of memory-systems approaches to priming in general, has been provided by Ratcliff & McKoon (1995, 1996, 1997, 2000; McKoon & Ratcliff, 1995, 2001). According to their general bias model, priming in the object-decision test reflects two processes. First, there is a bias to call all previously seen objects "possible," and second, there is explicit memory for information about the objects that influences object-decision performance. Presumably, the bias to call all familiar objects "possible" exists because in the real world people encounter only structurally possible 3D objects. In the object-decision test, this bias results in greater classification accuracy for previously seen possible objects (the positive priming effect) and reduced classification accuracy for familiar impossible objects (because subjects' tendency to say "possible" is the incorrect response for impossible objects). However, negative priming for impossible objects is not observed in the standard object-decision test because it is offset by explicit memory for specific object configurations that cue the subject as to whether the object is possible or impossible. This explicit information is available for both object types and improves object decisions for all studied items. With regard to impossible objects, when the explicit memory is combined with the bias to respond "possible," the two processes cancel each other out, resulting in zero priming. For possible objects, the bias and explicit memory combine to produce robust positive priming.

To support their model, Ratcliff and McKoon (1995) used a variety of retrieval manipulations designed to eliminate or reduce the purported influence of explicit memory on object-decision performance. Although it was never demonstrated that these manipulations directly reduced explicit memory, they did produce the

predicted bias pattern in benefits (for possible objects) and costs (for impossible objects). One of these manipulations—the inclusion of *matched objects* in the test phase of the experiment—was also used in the present study. Matched objects are identical to objects presented in the encoding phase, except for one feature that has been manipulated to change the object's global 3D structure from possible to impossible, or vice versa. For the purpose of this article, the term *matched possible* object refers to a possible test object presented in its impossible version during encoding. Analogously, a *matched impossible* object is an impossible test object that was shown in its possible version at encoding. Theoretically, when matched objects are included at test, subjects cannot assume that a given test object is possible or impossible simply because it looks familiar or because they explicitly remember having seen the object in its possible or impossible version during the encoding phase. The general bias model predicts that once this influence of explicit retrieval is removed, there should be priming of possible test objects (both old and matched) and negative priming of impossible test objects (both old and matched). The SDS model, by contrast, holds that explicit memory has no effect on object-decision performance and, therefore, priming should still be evident only for old possible objects even when matched objects are used at test.

In addition, Ratcliff and McKoon's (1995) model would predict that with the influence of explicit memory reduced or removed by including matched objects, differential performance between possible and impossible objects would be driven solely by a bias to call all old objects possible relative to new objects, rather than any change in sensitivity. In their formulation of the general bias model, Ratcliff and McKoon did not specify a single mechanism by which this bias emerges, however. Rather, they posited that it might be due to a number of factors, including a shift in a response criterion or a modification of high-level visual processes. For the purpose of the current investigation, we adopted the most straightforward interpretation of the model, which posits that bias, whether resulting from processes occurring at encoding, retrieval, or both, influences both object types to the same extent. In other words, the general bias model can be interpreted to hold that possible and impossible objects are not differentially processed during encoding. Therefore, unlike the SDS model, the general bias model would predict that any ERP repetition effects observed during the encoding phase, as well as any observed relationship to subsequent object-decision performance, should be the same for both possible and impossible objects. More specifically, if the bias is only operating during retrieval (i.e., the object-decision test), there should be no correlations between encoding-related neural changes and subsequent object-decision test performance. If, however, the bias is influenced by events at encoding, the relationship between the encoding-related activity and object-decision priming should be the same for both object types. In addition, when the influence of explicit memory is reduced or eliminated by the presence of matched objects, encoding-related neural activity may correlate with bias, but not with sensitivity, because bias would be the only mechanism operating during the object-decision test. Because bias positively affects object-decision performance for possible objects, one would also expect to find positive correlations between ERP repetition effects at encoding and accuracy or RT for possible objects. For impossible objects, the same repeti-

tion effects should correlate negatively with accuracy or RT because bias reduces performance for these items.

The structure-extraction bias model of object-decision priming, proposed by Williams and Tarr (1997), concurs with the general bias model in the belief that object-decision performance results from a combination of explicit memory and bias. However, these researchers attributed this bias to constraints in the way that objects are perceptually processed by the visual system rather than to an artifactual response bias. Specifically, they argued that when an object is first encountered, its possible "parts" are extracted and processed by the *structure-describing* system. When the object is encountered again during the object-decision test, these repeated possible parts will be processed more efficiently due to a *structure-extraction* bias—a perceptual mechanism that is biased to process the *possible parts* of an object. Because this bias operates preferentially on possible parts, impossible features of a familiar object will not be processed more efficiently. Because possible objects contain more possible parts or information than impossible objects, the system will be more biased to call them "possible" than impossible objects—leading to more priming for possible than impossible objects. Thus, the structure-extraction bias model holds that there is a difference in how possible and impossible objects are processed during encoding but that this difference is a matter of degree, not kind. The key result in support of the structure-extraction model is that the influence of bias decreases systematically with the number of structural violations present in an object at encoding. Indeed, Williams and Tarr found that the bias to respond "possible" was largest for objects encoded as possible figures, somewhat less for objects encoded with one structural violation, and smallest for objects encoded with three structural violations. Unlike the SDS view, this model does not assume that global, axis-based structural descriptions are represented in addition to parts-based structural information. Instead, it holds that objects are represented in a strictly parts-based manner.

With regard to the present study, the structure-extraction bias view predicts that any ERP repetition effects should occur for both possible and impossible objects. However, to the extent that a given ERP repetition effect indexes a facilitation of the parts-based structural analysis of the object, one would expect a larger repetition effect for possible than impossible objects (i.e., greater amplitude or latency modulation). The reason is that possible objects contain more valid structural information that can be primed than do impossible objects but do not differ from them categorically. Furthermore, although the structure-extraction bias view, like the general bias model, predicts positive priming of old and matched possible test objects and negative priming of old and matched impossible test objects, these views differ somewhat with regard to the relative magnitude of these effects. Specifically, the magnitude of the positive priming effect for old possible objects (change in accuracy or RT) should be slightly larger than the magnitude of the negative priming effects for old impossible objects and matched objects.

This subtle difference in the degree of positive and negative priming derives from the notion that when possible objects are presented at both encoding and test, there is maximal overlap in valid structural information and, therefore, maximal bias to call an item "possible." Yet, for impossible objects, the bias to call the object "possible" is somewhat reduced because of the smaller number of possible components available for priming. This will

lead to more positive priming for old possible objects compared with negative priming for old impossible objects. As a result, there will be a small increase in sensitivity for old compared with new objects and a small decrease in sensitivity for matched objects. Despite these differences in sensitivity, the bias to call objects “possible” should increase to the same extent for both old and matched objects relative to new ones. Therefore, with regard to the ERP predictions, the structure-extraction bias model would predict that the degree to which ERP components were modulated by repetition would correlate with sensitivity for possible objects only, but that any correlations with bias should be the same for both object types.

To summarize the behavioral predictions made by the three models, we note that the SDS model would predict that prior exposure would lead to priming of possible objects only, no change in bias, and an increase in sensitivity for old but not matched objects compared with new objects. In contrast, both of the bias models predict priming of old and matched possible test objects and negative priming of old and matched impossible test objects. In addition, both bias models would anticipate that prior exposure increases subjects’ bias to call old and matched objects “possible.” Furthermore, prior exposure should have either no effect on subjects’ sensitivity for the possible/impossible discrimination (general bias model) or a small increase in sensitivity for old objects and a small decrease for matched objects (structure-extraction bias model).

With regard to neural predictions, the SDS model would predict that ERP repetition effects would be observed for possible objects, whereas either none or a subset of these effects would be observed for impossible objects. In addition, one or more of the potential repetition effects that are exclusive to possible objects might be related to sensitivity or priming of possible objects, as measured by RT or accuracy, on the subsequent object-decision test. In contrast, the bias models would predict the same overall pattern of ERP repetition effects for possible and impossible objects, although the structure-extraction model also would predict that some of these effects would be larger for possible than impossible objects. Both bias models also would predict that any correlation between ERP repetition effects during encoding and subsequent object-decision test performance, as measured by accuracy, RT, and bias, would be the same for both possible and impossible objects. Finally, although the general bias model does not predict a relationship between ERP repetition effects and sensitivity, the structure-extraction model would predict such a correlation for possible objects.

Given the specificity of these models with regard to their behavioral and neural predictions, the results from the present studies may elucidate how globally coherent and incoherent 3D objects are represented in the visual system and answer fundamental questions about how modulations of activity within this system can implicitly influence behavior over time.

Experiment 1: Left/Right Encoding

Method

Participants. Twenty-four (11 female and 13 male) neurologically and psychologically healthy Columbia University students between 18 and 30 years of age were paid for their participation in this experiment. All reported being right-handed, having normal or corrected-to-normal vision,

and having normal depth perception. The data of 3 of these participants were excluded from the analysis because they had less than 16 artifact-free ERP trials in one or more of the encoding conditions (a minimum of 16 ERP trials per condition is generally considered to be sufficient for this type of investigation; Rugg et al., 1998).

Stimuli. A total of 160 novel line-drawn objects (80 pairs) served as experimental stimuli (see Figure 1 for examples). The two members of an object pair were matched, or almost identical, except that one member depicted a structurally possible object—one that could exist in three dimensions—and the other a structurally impossible object—one that could not be rendered in 3D. The two members of a pair were matched on several objective complexity criteria: They had the same silhouette (outline), number of visible surfaces, lines (± 1), line segments, (± 1), and vertices (± 1). This is important because concerns have been raised that differential priming effects for possible and impossible objects are due, at least in part, to differences in object complexity (Ganor-Stern, Seamon, & Carrasco, 1998; Seamon & Carrasco, 1999). Interparticipant agreement about the possible or impossible nature of each object was very high as assessed in a prior pilot study with an additional 24 participants: 96% for possible (range = 77%–100%) and 92% for impossible objects (range = 77%–100%). All objects were drawn in black on a uniform gray background and subtended a visual angle of approximately 7°.

Procedure. The experiment consisted of an encoding phase during which electrophysiological indices of repetition were assessed, followed by a test phase that served to inform the extent to which repetition supported behavioral object-decision priming. During the encoding phase, subjects viewed 40 unique objects: 20 possible and 20 impossible from different object pairs. The total number of stimuli presented at encoding was limited to 40 because pilot data have shown that behavioral priming effects are smaller and less reliable when 50 or more objects are presented. After all objects had been shown once, the entire set was repeated in a different random order without a break between the first and second presentation. This constituted the second encoding experience of each item and, as is explained in more detail below, served as the basis of the ERP repetition effect. On average, 40 items, or 4.5 min, intervened between the first and second presentation of an item. Participants were instructed to indicate whether each object appeared to be facing primarily to the left or to the right by pressing one of two designated keys. Although there is no objectively right or wrong answer to this question, this orienting task requires subjects to process the global 3D structure of the object and has been previously shown to produce robust priming for possible objects in the object-decision test (Cooper & Schacter, 1992; Schacter & Cooper, 1993; Schacter et al., 1990a). No mention was made of the distinction between the two types of objects nor of the subsequent object-decision test. Participants self-initiated each trial by pressing the space bar, after which they saw a blank screen for 1,500 ms, followed by a 500-ms fixation cross, and an object for 4 s. Participants entered their left/right responses after the offset of each object, precluding meaningful analysis of RT to this decision.

In the test phase, all of the objects from the encoding phase, and their matched versions, as well as 40 new objects (20 possible and 20 nonmatching impossible), were presented in an intermixed series. As stated earlier, the purpose of including the matched objects was to reduce the potential contribution of explicit memory to object-decision performance. The order of presentation of the encoded and matched versions of an object was counterbalanced between participants, such that one member of an object pair was presented in the first half of the test and the other member in the second half. The subject’s task was to decide whether each object was structurally possible or impossible. Both speed and accuracy were emphasized. Participants self-initiated each trial by pressing the space bar. Next, they saw a blank screen for 1,500 ms, followed by a 500-ms fixation cross, and then the object. Each object remained on the screen until subjects made their response, or until 2 s had elapsed, whichever occurred sooner. Responses made after 2 s or before 300 ms were counted as errors. The

assignment of objects to encoding status was counterbalanced across participants, such that each object occurred equally often as an old, matched, and new object in the experiment.

Electrophysiological recording and analysis. The electroencephalograph (EEG) was recorded at standard sites (International 10/20 System) using 64 tin electrodes embedded in an elastic cap. Eye movements and blinks were recorded with electrodes placed 1 cm lateral to the outer canthi (LO1/LO2) and over the infraorbital ridge (IO1/IO2). They were later modeled and compensated for using 3–4 ocular source components (BESA 5.1; MEGIS Software GmbH, Gräfelfing, Germany). Epochs that contained muscle or skin potential artifacts were rejected. Activity from all electrodes was sampled at a rate of 500 Hz analogue to digital (A/D) with a bandpass of 0.01–50 Hz. All channels were initially referenced to CZ and then converted to an average reference offline, a method of referencing EEG data that is preferred by the Society for Psychophysiological Research (Picton et al., 2000). All electrode impedances were kept below 5 k Ω .

Although continuous EEG was recorded during both the initial presentations of the objects (encoding phase) and the object-decision phase of the experiment, the present study focused on encoding-related neural activity and its relationship to behavioral priming. Therefore, only analyses pertaining to the encoding phase of the experiment are included.¹ For each participant, baseline-corrected, artifact-free trials time locked to the onset of a stimulus were averaged across the experimental conditions from 100 ms before stimulus onset until 1,000 ms thereafter. The ERPs were then averaged across participants for each condition. The mean trial count for each condition was 19 (range = 16–20) and did not differ across conditions.

An alpha level of .05 was adopted for all statistical analyses. Effects were evaluated with analyses of variance (ANOVAs), and Greenhouse–Geisser corrections were applied where appropriate. Significant main effects and interactions were followed by post hoc contrasts and Tukey's honestly significant difference pairwise comparisons. Unless stated otherwise, only significant effects using corrected probability values are reported below.

In as much as our primary interest concerned neural changes occurring at the perceptual level, the analyses concentrated on early latency effects (before 300 ms) at posterior electrode sites. For well-defined peaks (P1, N1), peak amplitude was used as a dependent variable; otherwise, mean amplitude was used. Peak amplitudes for a given subject corresponded to the highest amplitude occurring within a \pm 30-ms time window around the peak of the corresponding waveform in the grand mean; peak latencies were quantified as the corresponding time point of maximal deflection. To examine the effects of stimulus repetition on latency and amplitude, we conducted a series of ANOVAs with object type (possible vs. impossible) and presentation (first vs. second) as factors. Unless stated otherwise, these analyses were conducted on 8 of the 10 lateralized electrodes shown in Figure 3 (O1, O2, PO3, PO4, P3, P4, P5, and P6), with laterality (left vs. right) and site (occipito-parietal [O1, O2, PO3, and PO4] vs. parietal [P3, P4, P5, and P6]) as additional factors. Significant interactions involving electrode, laterality, and site are not mentioned unless they also involved the factors of object type or presentation.

In those cases in which we did find a significant effect of presentation on either amplitude or latency, we proceeded to test whether this ERP repetition effect was related to behavioral priming on the subsequent object-decision test. To do so, we correlated the magnitude of the ERP repetition effects on amplitude or latency of a given component with the magnitude of the four behavioral priming effects (RT, accuracy, sensitivity, and bias) separately for possible and impossible objects. The magnitude of the ERP repetition effect was determined by computing an index of relative increase in amplitude or latency from first to second presentation of an object: difference/sum ($[\text{presentation 1} - \text{presentation 2}]/[\text{presentation 1} + \text{presentation 2}]$). Unlike a simple difference score, this measure takes into account differences in the absolute value of responses between individual subjects, which can be rather substantial for ERPs. It also takes into

account the direction of change, irrespective of whether the actual waveform is positive or negative. In order to obtain a relatively stable measure of the repetition effect for a particular ERP component, we calculated correlations using the average ERP repetition effect across the entire group of parietal (P3, P4, P5, and P6) or occipital electrodes (O1, O2, PO3, and PO4), given that no interactions between electrode and repetition effects emerged. For the behavioral priming measures, the same index of increase was computed separately for possible and impossible objects to make the behavioral and neural priming effects comparable.

In addition, in those cases in which reliable repetition effects occurred for possible, but not impossible objects, we conducted a power analysis to determine whether the experiment had sufficient power to detect an effect in impossible objects that is smaller in size than the effect observed for possible objects. This analysis is important in differentiating between the structure-extraction bias model and the SDS model. The former predicts that all repetition effects should occur for both object types and that at least one of them should be smaller, but not absent, for impossible compared with possible objects, whereas the SDS model predicts that at least one repetition effect should occur for possible objects only. The analyses reported subsequently are based on the peak-to-peak amplitude of a particular repetition effect, rather than the peak amplitude, although the pattern of results is the same for both. In order to determine whether the experiment had sufficient power to detect a repetition effect for impossible objects that is smaller in size than the effect observed for possible objects, we established an objective, though somewhat arbitrary, a priori criterion for quantifying smaller effect sizes. We settled on a criterion of two thirds, that is, a repetition effect for impossible objects is smaller than a repetition effect for possible objects if it is two thirds of the effect size of possible objects or smaller.

We arrived at this criterion based on two considerations. First, according to the structure-extraction model, the amount of priming for an object is determined by the "amount" of valid structural information. Although the model does not provide an explicit quantification of how the effects of adding or deleting possible parts should influence priming, we reasoned that because the objects in this experiment were well matched and differed by only one or two structural features, one would not expect very large differences in the effect sizes between the two types of objects. Second, we used the effect sizes of the behavioral priming effects reported by Williams and Tarr (1997) and those observed in this experiment as estimates for potential neural effect sizes. Williams and Tarr (Experiment 1) reported that the priming effect for old impossible objects with three structural violations was approximately 60% of the priming effect for old possible objects. Because the impossible objects in the current experiment had fewer structural violations, one would expect even more priming for them. The behavioral results from this experiment confirm this estimate. The average effect size (for accuracy and RT combined) for old impossible objects was approximately 70% of the effect size for old possible objects.

¹ There are two reasons for not including the test-phase data. First, unlike the encoding data, the test-phase data are subject to retrieval and postperceptual decision biases associated with the possible/impossible decision that may influence the ERPs recorded in response to the objects. Therefore, they do not allow for as direct an examination of visual perceptual processes as do the encoding data. Second, the trial counts for the ERP data were quite low in some participants because accuracy was below 100% in most or all conditions. If we applied the strategy of excluding participants who had trial counts of less than 16 in all conditions to our retrieval data, as we did for the encoding data, we would eliminate too many participants for a meaningful analysis. Moreover, those that were left would have roughly equivalent trials in studied and nonstudied conditions for possible and impossible objects, which would effectively mean that they were demonstrating little or no priming as measured by accuracy or bias.

Thus, although our criterion is somewhat arbitrary, we believe that it represents a somewhat conservative estimate of the effect size of the neural repetition effect one may expect for impossible objects in this experiment. In any case, adopting a quantitative (rather than qualitative) criterion does provide a means of more rigorous statistical testing, as well as a value that can be further evaluated in subsequent studies.

Results

Behavioral results (object-decision test). Preliminary analyses showed that subjects' accuracy and RT did not vary as a function of order, that is, whether the old or matched version of an object was presented first during the object-decision test. Hence, we collapsed across this factor for all subsequent analyses.

Object classification RT and accuracy data are presented in Figure 2 (top and middle panel, respectively). An ANOVA with RT as the dependent variable and object type (possible vs. impossible) and encoding status (old, matched, new) as within-subject factors revealed a main effect of object type, $F(1, 20) = 9.41$, meaning that subjects were faster in classifying possible compared with impossible objects. There was also a significant interaction between object type and encoding status, $F(2, 40) = 6.51$, $\epsilon = .93$. To further investigate this interaction, we conducted two post hoc contrasts: new versus old and new versus matched. The first contrast confirmed a significant interaction between object type and encoding status, $F(1, 20) = 12.27$. Follow-up t tests demonstrated significantly faster RTs for old compared with new possible objects, $t(20) = -4.63$, $p < .001$, but no effect of prior exposure on impossible objects, $t(20) = 0.99$. The second contrast showed that the interaction between encoding status and object type was not reliable for matched objects, $F(1, 20) = 2.31$, $p > .1$, even though priming for matched possible objects was statistically significant by post hoc comparison, $t(20) = -2.64$, $p < .05$.

An ANOVA with object-decision accuracy as the dependent variable also showed a main effect of object type, $F(1, 20) = 17.09$, indicating that subjects classified possible objects more accurately than impossible objects. There was an interaction between object type and encoding status, $F(2, 40) = 14.66$, $\epsilon = .96$. Post hoc contrasts (new vs. old and new vs. matched) showed that the interaction between object type and encoding status was significant for old objects, $F(1, 20) = 16.39$, but not for their matched mates, $F(1, 20) = 0.67$. Follow-up pairwise comparisons revealed higher accuracies for old possible objects compared with new possible objects, $t(20) = 3.41$, $p < .01$, and lower accuracies for old compared with new impossible objects, $t(23) = -3.31$, $p < .01$.

We chose to express bias and sensitivity in terms of C_L and d_L , respectively, rather than the traditional measures of d' and β , in order to make our results directly comparable to those of Williams and Tarr (1997). C_L and d_L are based on logistic distributions and are functionally equivalent to d' and β , which are based on normal distributions. More negative C_L values indicate a greater bias to use the "possible" response. As shown in Figure 2 (bottom panel), subjects were significantly biased to respond "possible" in all experimental conditions, as indicated by bias scores that were significantly less than zero (all $ps < .05$). Furthermore, there was a main effect of encoding status (old vs. new vs. matched) on bias, $F(2, 40) = 11.88$, $\epsilon = .98$. Follow-up t tests indicated that relative to new objects, the bias to respond "possible" increased for old objects, $t(20) = -4.16$, $p < .001$, but did not change for matched

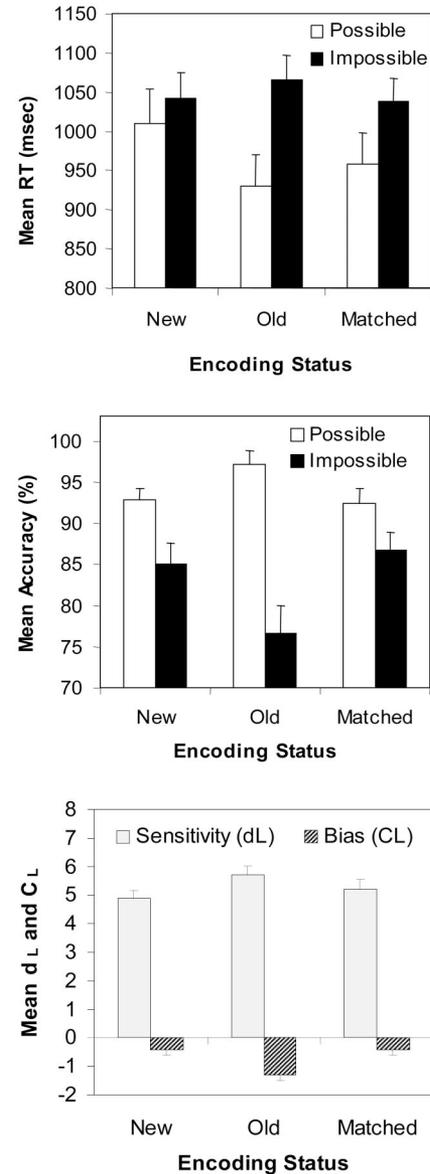


Figure 2. Behavioral results from Experiment 1. Object-decision performance as a function of encoding status: mean classification reaction time (RT; top panel), accuracy (middle panel), and bias and sensitivity (bottom panel) for new, old, and matched test objects. Error bars represent the standard error of the mean. msec = milliseconds.

objects, $t(20) = -0.11$. An ANOVA on sensitivity (d_L) scores produced a marginal effect of encoding status, $F(2, 40) = 2.88$, $p < .09$, $\epsilon = .93$. Sensitivity increased for old compared with new items, $t(20) = 2.25$, $p < .05$, but did not change for matched objects, $t(20) = 0.68$.

In summary, subjects were both more accurate and faster in classifying previously seen possible objects compared with new possible objects, indicating reliable priming. For impossible objects, prior exposure had no effect on RTs and produced a decrease in accuracy (i.e., negative priming). Although there was some evidence for faster RTs for possible objects studied in their im-

possible versions, this effect was not reliable. In addition, subjects were biased to use the “possible” response for all items, and this bias increased for old but not matched objects relative to new objects. Overall, subjects’ performance benefited from prior exposure to the objects, as indicated by an increase in sensitivity for old compared with new items.

Electrophysiological results. Figure 3 shows the ERPs for the first and second presentation of possible (top panel) and impossible objects (bottom panel). For the P1, there were no significant effects of object type or presentation on peak latency, which averaged 106 ms ($SD = 14$) across conditions. However, the peak amplitude of the P1 was larger over the right than the left hemisphere, $F(1, 20) = 7.78$. The second presentation of an object elicited higher P1 amplitudes than the first presentation, $F(1, 20) = 7.20$. These effects were qualified by a four-way interaction between object type, presentation, site, and laterality, $F(1, 20) = 6.28$. Follow-up analyses revealed that the effect of presentation was significant for impossible objects at both the occipital, $F(1, 20) = 5.18$, and parietal, $F(1, 20) = 5.17$, sites, bilaterally. By contrast, repetition enhancement for possible objects was found only at the parietal electrodes in the right hemisphere, $F(1, 20) = 4.96$, not in the left hemisphere, $F(1, 20) < 1$, or at the occipital electrodes, $F(1, 20) < 1$.

Next, we analyzed the effect of object type and presentation on the P1 relative to the peak of the immediately preceding negative wave, the C1 or C50. The C1 has traditionally been interpreted to represent the initial activation of primary visual cortex, V1 (Di Russo, Martinez, Sereno, Pitzalis, & Hillyard, 2002; Hillyard & Anllo-Vento, 1998; Martinez et al., 1999, but see Foxe & Simpson, 2002, for evidence that extrastriate regions contribute to the latter phase of the C1). It is sensitive to the location of stimuli in the visual field but generally impervious to the effects of stimulus category, familiarity, and top-down attention (Di Russo, Martinez, & Hillyard, 2003; Martinez, Di Russo, Anllo-Vento, & Hillyard, 2001, but see Pourtois, Grandjean, Sander, & Vuilleumier, 2004; Seeck et al., 1997). Therefore, we would not expect the C1 to be modulated by either object type or presentation in the present study, as sensory characteristics of possible and impossible objects were comparable both with each other and across presentations. Nonetheless, we did observe a trend for smaller C1 amplitudes for the second compared with the first presentation of objects, particularly for impossible objects ($ps > .07$). Given that this was not a robust effect and not predicted by the previous literature, we do not attempt to interpret it further. However, in recognition that even marginal C1 differences could influence measurement of the subsequent P1, we conducted a peak-to-peak analysis of the P1 relative to the C1. Of interest, this analysis did not reveal any significant effects or interactions (all $ps > .1$). In other words, the effect of stimulus repetition on the P1 was no longer reliable once the P1 amplitude was measured relative to the C1 amplitude, $F(1, 20) = 1.92$, $p = .18$.

The N1 peaked approximately 184 ms ($SD = 15$) poststimulus. For N1 latency, we did not find any significant effects or interactions involving object type or presentation (all $ps > .1$). Regarding amplitude, the N1 was larger over the right hemisphere than over the left hemisphere, $F(1, 20) = 5.44$, as well as over the parietal cortex than over the occipito-parietal cortex, $F(1, 20) = 23.14$. Furthermore, there was a marginal effect of presentation, $F(1, 20) = 4.31$, $p = .051$, and an interaction between object type and

presentation, $F(1, 20) = 7.26$. Post hoc comparisons, collapsed across the laterality and site, indicated that the amplitude of the N1 increased from first to second presentation for possible objects, $t(20) = -3.30$, $p < .01$, but did not change for impossible objects, $t(20) = -0.53$. Moreover, there was no difference in the initial amplitude for possible and impossible objects, but after repetition possible objects elicited larger N1 amplitudes than impossible objects, $t(20) = 3.59$, $p < .005$. The same pattern of results was obtained when the N1 amplitude was measured relative to the P1 amplitude.

A power analysis indicated that the effect size of the N1 repetition effect for possible objects was small (Cohen’s $d = 0.34$), and the power to detect an effect of this magnitude was moderate (.47). Because the variance for possible and impossible objects was the same, the power to detect a repetition effect of equal magnitude in impossible objects was the same as for possible objects. However, we would have had relatively low power to detect a repetition effect for impossible objects that was two thirds the size of the effect for possible objects.

Next, we ran Pearson product-moment correlations between the magnitude of the N1 repetition effect for possible objects and behavioral priming at test. We opted to use the peak-to-peak amplitude measure, as this would reduce any variability in the N1 amplitude that was related only to the amplitude of the preceding P1. There was a positive correlation between accuracy priming for possible objects and the amount of N1 repetition enhancement over the parietal cortex ($r = .61$, $p < .005$, uncorrected), the site where the N1 effect was largest. Thus, for possible objects, the greater the increase in N1 amplitude from first to second presentation during encoding, the more accuracy priming the subject would demonstrate during the possible/impossible object-decision test phase. Because of the presence of an outlier, the same correlation was computed excluding that particular subject, and a non-parametric (Spearman) correlation was performed (see Figure 4, top panel). The resultant coefficients were smaller, but still significant ($r = .47$, $p < .05$; Spearman’s $\rho = .49$, $p < .05$, both uncorrected). Similarly, as shown in Figure 4 (bottom panel), there was a positive correlation between the magnitude of the N1 repetition effect for possible objects over parietal cortex and object-decision priming for possible objects, as measured by RT ($r = .45$, $p < .05$; Spearman’s $\rho = .53$, $p < .05$, both uncorrected). In contrast, for impossible objects, there was no correlation between the amount of change in N1 amplitude from first to second presentation and object-decision performance (all $ps > .1$). At the occipital sites, there were no significant correlations between behavioral and neural priming for either possible or impossible objects. Nor were there any significant correlations with sensitivity or bias (all $ps > .1$) over either parietal or occipital cortex.

Immediately following the N1, there was a second negative deflection, N2, over occipital and parietal-occipital scalp sites peaking at around 280 ms post stimulus onset. As shown in Figure 3, this wave appeared somewhat larger at medial than lateral posterior electrodes and also seemed to be modulated by stimulus repetition. An ANOVA on mean amplitude showed that there was a main effect of site, $F(1, 20) = 6.67$, such that the N2 was larger over occipito-parietal than parietal cortex. There was also an interaction between object type and presentation, $F(1, 20) = 6.67$, as well as a marginal interaction between site, object type, and presentation, $F(1, 20) = 3.31$, $p = .08$. Separate

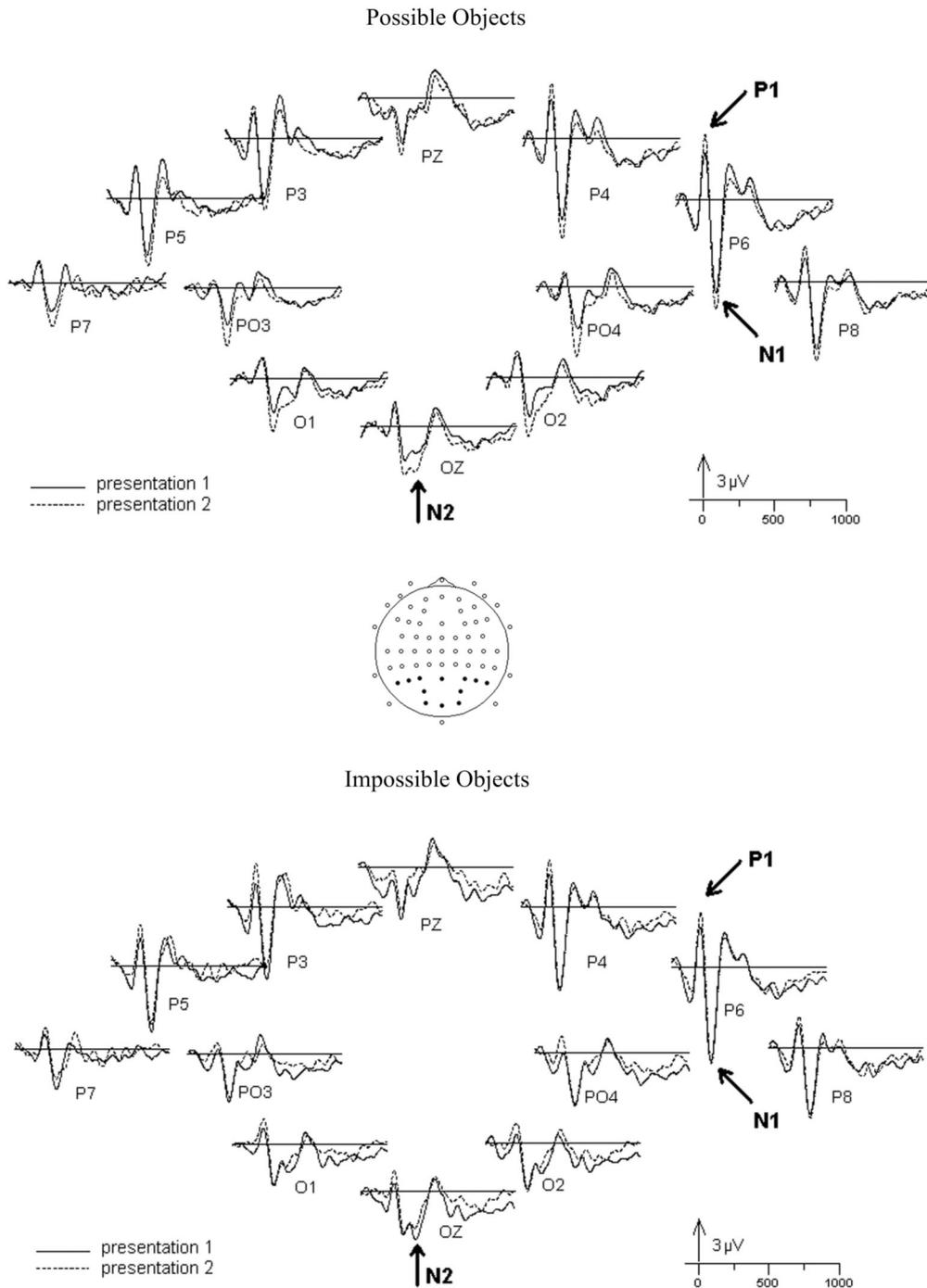


Figure 3. Event-related potential (ERP) results from Experiment 1. Grand mean average referenced ERPs for first and second presentations of possible objects (top panel) and impossible objects (bottom panel) at posterior electrodes.

ANOVAs for the occipital and parietal sites indicated that there were no reliable effects involving object type or presentation for the parietal electrodes (all p s > .1). By contrast for the occipital site, there was an Object Type \times Presentation interaction, $F(1, 20) = 6.85$. Post hoc t tests, collapsed across electrodes, revealed larger N2 amplitudes for repeated possible objects relative to their

first presentation, $t(20) = -2.20$, $p < .05$, but no effect of repetition on impossible objects, $t(20) = 1.43$, $p = .17$.

An analysis of the effect size of the N2 repetition effect for possible objects showed that the effect was small ($d = 0.29$), and our power to detect it was low (.37). However, the repetition effect for impossible objects was in the opposite direction as that for

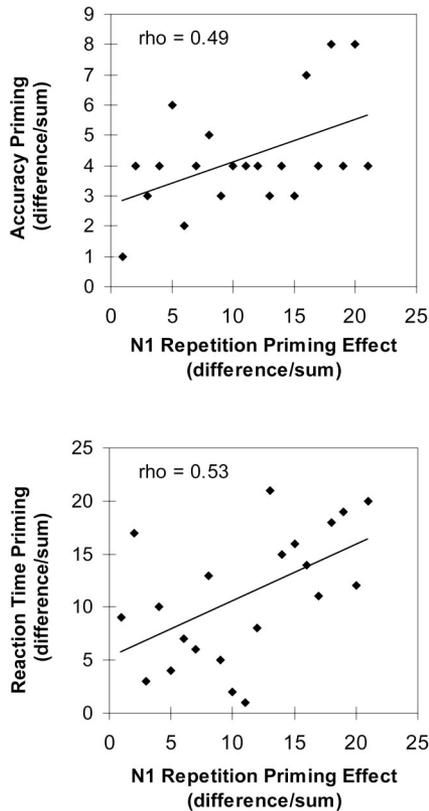


Figure 4. Scatter plots representing the correlations between behavioral and neural priming in Experiment 1. Top panel: Scatter plot representing the Spearman correlation between the magnitude of the N1 repetition priming effect for possible objects and behavioral priming for possible objects in the object-decision test, as measured by accuracy (top panel, $\rho = .49$, $p < .05$) and reaction time (RT; bottom panel, $\rho = .53$, $p < .05$). Neural repetition priming was computed by dividing the difference in peak-to-peak amplitudes between the first and the second presentation of possible objects from 150 to 210 ms by the sum of these two values (difference/sum). Behavioral priming was similarly measured as the difference in the percentage correct or RT for old compared with new possible objects divided by the sum of these values.

possible objects. That is, there was a nonsignificant trend for repetition suppression, rather than enhancement, for impossible objects. Because the bias models would have predicted the same type of effect (either repetition suppression or enhancement) for both object types, this is some evidence against both bias models, even though the power to detect an effect for impossible objects was low.

There were no significant correlations between the magnitude of the N2 repetition effect for possible objects, averaged over the occipital electrodes, and behavioral priming for possible objects, sensitivity, or bias (all $ps > .1$). Because there was no reliable effect of stimulus repetition at the parietal electrodes, correlations with behavioral performance were not assessed for the parietal sites.

Discussion

This study examined the neural correlates of repetition priming for possible and impossible objects during encoding in order to

elucidate the basis of the differential behavioral priming effects for possible and impossible objects in an object-decision task. Although the behavioral results did not adjudicate between the three theories of object-decision priming (SDS, general bias, structure-extraction bias) as clearly as did the ERP results, the ERP data provided fairly consistent support for the SDS model. When one is interpreting these results, however, it is important to keep in mind that the absence of a predicted effect does not falsify a model. On the other hand, the presence of contradictory effects can support one model over another.

First, we consider the behavioral results. In accord with the SDS and the structure-extraction models, but contrary to the predictions of the general bias model, there was an increase in sensitivity for old, compared with new, objects. Sensitivity did not change for the matched objects, which is also consistent with the SDS model, but not with the structure-extraction model, which predicted a decrease in sensitivity for the matched objects. However, other results were more in line with the bias models. Specifically, the inclusion of the matched objects produced a bias pattern of costs and benefits for old objects. That is, subjects were more accurate in classifying old possible objects and less accurate in classifying old impossible objects because of their bias to call all old objects “possible.” This shift in bias was reflected in more negative C_L values for old compared with new objects.

In addition, consistent with both bias models, but not with the SDS view, there was some, albeit not robust, evidence for a facilitation in subjects’ RTs for matched possible objects. This indicates that subjects benefited from the prior presentation of an impossible object when the same object was later presented in its possible version. However, other aspects of matched object performance distinguished between the two bias models. Specifically, we found that the magnitude of the effect for matched possible objects was smaller than that for old possible objects, a result that concurs with the predictions of the structure-extraction model, but not the general bias model. That is, according to the structure-extraction bias model, objects encoded in their impossible version (matched possible) should give rise to less priming than objects studied in their possible version (old possible) because of the smaller amount of valid structural information in impossible objects. Other effects of the matched objects failed to confirm either bias model. There was no change in the signal detection measure of bias or accuracy for the matched objects, and the change in RT occurred only for matched possible, but not matched impossible, objects.

According to the bias models, any familiar-looking object, whether it was originally seen in its possible or impossible version, should be subject to the bias. The reasons for not being able to replicate Ratcliff and McKoon’s (1995) and Williams and Tarr’s (1997) results are unclear. Like the present experiments, both groups of researchers have presented matched, old, and new objects to the same participants in the object-decision test phase and have found the predicted bias for matched objects (i.e., positive priming for matched possible figures and negative priming for matched impossible figures). It is possible that the addition of the matched objects in the present experiment did not have the desired effect of reducing explicit memory but rather altered some other aspect of processing that produced the bias for old objects, but not new objects matched to the old objects. Alternatively, the bias might be based not on stimulus familiarity but on some other

mechanism that operates specifically on those objects that were presented at encoding and not on their matched counterparts. Further research is necessary to discriminate between these and other alternatives. Nonetheless, although a shift in bias for previously encountered objects would not have been predicted by the SDS model, this finding is not necessarily problematic for that model if one assumes that participants' biases are based on decision criteria or other processes at the time of test, not on how the objects are perceptually processed at encoding (see Schacter & Cooper, 1995).

With regard to our ERP results, we found that repetition did not modulate the posterior P1 once its amplitude was adjusted for variability in the preceding C1. However, for the posterior N1 and N2, we found repetition enhancement for possible objects and no effect of repetition on impossible objects. Moreover, the size of the N1 repetition effect for possible objects over lateral posterior parietal cortex was positively correlated with the amount of priming for possible objects, as measured by accuracy and RT. There was no significant correlation between the change in N1 amplitude from first to second presentation of an impossible object and priming for impossible objects, as measured in terms of accuracy, RT, bias, and sensitivity.

We now consider how this overall pattern of ERP repetition effects relates to the three models of object-decision priming previously described. The observed ERP repetition effects are more consistent with an SDS-like perceptual system that differentially processes possible and impossible objects than with the general bias model or the structure-extraction bias model. The first main finding in support of the SDS model is that ERP repetition effects were observed exclusively for possible objects. This is suggestive of a system that is specialized for processing the global 3D structure of an object, not just its possible parts. Both of the bias models would have predicted repetition effects for both object types. However, whereas the general bias model would posit equal ERP repetition effects for possible and impossible objects, the structure-extraction bias model would have anticipated smaller but significant effects for impossible objects, reflecting the relative amount of possible features present in the impossible, compared with possible, objects. Thus, although no repetition effects were observed for impossible objects, the possibility that low power may have obscured smaller but significant differences for these objects makes it difficult to definitively discount the structure-extraction bias model.

Notably, the ERP repetition effects for possible objects found at the N1 and N2 were not reliably observed for the earliest visual potentials (C1 and P1), which have been localized to striate and lateral extrastriate cortex (BAs 18 and 19), respectively (Di Russo, Martínez, Sereno, Pitzalis, & Hillyard, 2001). This suggests that at the initial stages of visual analysis, possible and impossible objects are processed in a similar manner. These processing steps may encompass the analysis of the object's outline, contours, and component parts, including local 3D structural information. Following this analysis, additional computations seem to be performed for possible objects that are not (or cannot be) performed for impossible ones, such as the construction of a global 3D structural description. This is consistent with the idea that longer lasting neural plasticity in the visual system (i.e., in the order of minutes rather than seconds) is typically observed for higher order perceptual processes, not earlier (lower level) ones. Thus, evidence

from functional magnetic resonance imaging (fMRI) has shown little or no plasticity in early visual areas (V1, V2, V3, and V4) concerned with the analysis of contours and form (e.g., Buckner et al., 1998; Grill-Spector et al., 1998). By contrast, robust effects of stimulus repetition are typically found in higher order visual areas that are primarily activated by whole objects, rather than scrambled objects or 2D textures, such as the lateral occipital complex, fusiform gyrus, and the inferior temporal cortex (e.g., Lerner, Hendler, Ben-Bashat, Harel, & Malach, 2001; Lerner, Hendler, & Malach, 2002; Vuilleumier, Henson, Driver, & Dolan, 2002).

Another major piece of evidence in support of the SDS model is the correlation between the N1 repetition effect for possible objects and later behavioral priming for possible objects, but not impossible ones. Both of the bias models hold that any relationship between repetition effects at encoding and subsequent object-decision performance should be evident for both object types. Of importance, the finding that this correlation is specific to possible objects lends support to the idea that the N1 repetition enhancement reflects the building of a perceptual representation that underlies the improvement in object-decision performance found for possible, but not impossible, objects. Finally, this correlation provides the first direct evidence that the differential manner in which the brain analyzes these objects is associated with the behavioral priming effects observed in the object-decision test.

Experiment 2: Tool/Support Encoding

Taken together, the results from Experiment 1 generally support the SDS model of object-decision priming. The neural data in particular were more consistent with the SDS model in that they directly contradicted predictions made by either bias model interpretation. Experiment 2 was conducted to determine whether our results would replicate when a different encoding task was used that also requires the structural analysis of objects. If the observed pattern of ERP repetition effects (i.e., repetition enhancement for possible objects, no effects for impossible objects) generalizes to different structural encoding tasks, it would strengthen the view that these effects reflect processes associated with the analysis of an object's global 3D structure. On the other hand, should the results not replicate with a different structural encoding task, the observed repetition effects may reflect processes associated specifically with the left/right encoding task. That is, the decision as to whether an object faces to the left or to the right could potentially require different operations for possible and impossible objects, and these may be related to the differential priming effects in the object-decision test. To rule out this possibility, participants in Experiment 2 performed a tool/support judgment on the objects during the encoding phase; all other aspects of the experiment were identical to those of Experiment 1. Although this is a functional encoding task, it also requires the analysis of an object's 3D structure and has previously been shown to produce object-decision priming of a similar magnitude to that associated with the left/right encoding task (Schacter & Cooper, 1993).

Method

Participants. Twenty-one Columbia University students (11 women and 10 men) participated in this experiment. They were compensated at a rate of \$5 per 30 min. Four of these subjects were excluded from the

analyses presented below because of low trial counts (<16 trials in one or more encoding condition) due to artifacts. All subjects were between 18 and 30 years of age and reported being right-handed, being neurologically and psychologically healthy, having normal or corrected-to-normal vision, and having normal depth perception.

Procedure. The procedure was identical to that of Experiment 1, except for the instructions subjects were given during the encoding phase of the experiment. In this experiment, subjects were asked to indicate whether a particular object was best used as a tool (e.g., to perform such functions as scooping, cutting, or pounding) or for support (e.g., stepping, sitting, or leaning on it). As in the left/right task, subjects were told to pay careful attention to each object and to use all of the allotted time (4 s) to view the object and consider its functional role. All other aspects of the experiment were identical to those of Experiment 1.

Results

Behavioral results. As is evident from Figure 5, the behavioral results were essentially identical to those of Experiment 1. The order of presentation (i.e., whether the old or the matched version of an object appeared first in the object-decision test) had no effect on test performance (all $ps > .098$), and the results were collapsed across this variable. For object-decision RT, there was a marginal effect of object type, indicating that possible objects were classified faster overall than impossible objects, $F(1, 16) = 4.37, p = .053$. In addition, there was a main effect of encoding status, $F(2, 32) = 4.17, \epsilon = .93$, and an interaction between object type and encoding status, $F(2, 32) = 10.56, \epsilon = .81$. Post hoc contrast (new vs. old and new vs. matched) showed that the interaction was significant only for old objects, $F(1, 16) = 18.95$, but not for matched objects, $F(1, 16) = 1.68, p > .2$. Pairwise comparisons between old and new objects indicated no difference in RT for old and new impossible objects, $t(16) = 1.38, p = .19$, but significantly faster RTs for old possible objects relative to new possible objects, $t(16) = 4.77, p < .0005$. Indeed, all 17 subjects had numerically faster RTs for old than new possible objects.

As in Experiment 1, subjects were not only faster but also more accurate when classifying possible objects compared with impossible objects, $F(1, 16) = 4.61$. Furthermore, there was an interaction between object type and encoding status, $F(2, 32) = 5.66, \epsilon = .94$. As with RT, this interaction was significant for possible objects, $F(1, 16) = 8.78$, but not for matched ones, $F(1, 16) = 0.38$. Whereas classification accuracy was higher for old than new possible objects, $t(16) = 2.34, p < .05$, it did not differ for old and new impossible objects, although there was a nonsignificant trend for lower classification accuracy for old compared with new impossible objects, $t(16) = -1.78, p = .095$.

The objects' encoding status also affected subjects' sensitivity (d_L), $F(2, 32) = 4.70, \epsilon = .97$, and bias (c_L), $F(2, 32) = 6.18, \epsilon = .88$. Participants' sensitivity in discriminating between possible and impossible objects increased for old relative to new objects, $F(1, 16) = 8.78, p < .01$, but did not change for matched compared with new objects, $F(1, 16) = 0.84$. Likewise, subjects' bias to call an object "possible" was greater for old than new objects, $F(1, 16) = 10.51, p < .01$, and remained the same for matched objects, $F(1, 16) = 0.00$, in comparison to new ones. Of importance, subjects were not significantly biased to call new or

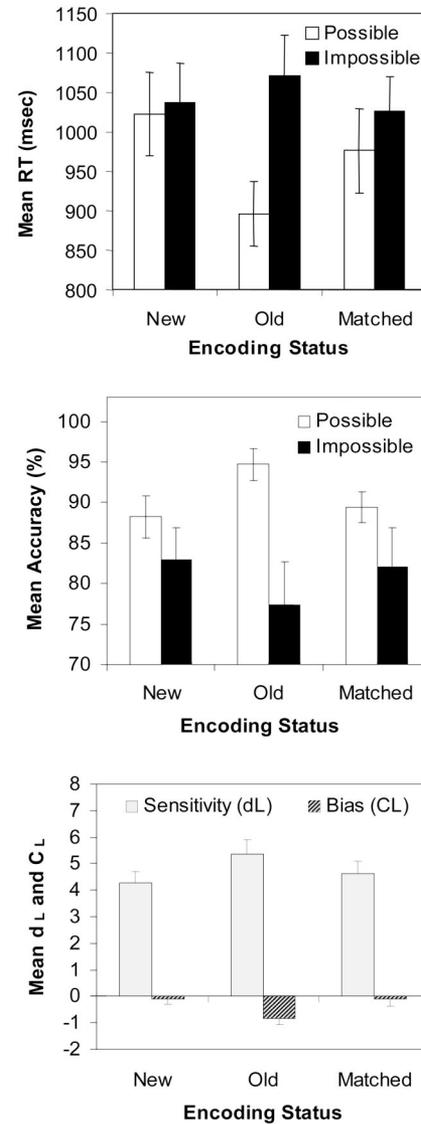


Figure 5. Behavioral results from Experiment 2. Object-decision performance as a function of encoding status: mean reaction time (RT; top panel), mean classification accuracy (middle panel), and mean bias and sensitivity (bottom panel) for new, old, and matched test objects. Error bars represent the standard error of the mean. msec = milliseconds.

matched objects "possible." That is, their decision criterion did not differ significantly from zero (both $ps > .5$). Participants did, however, have a strong tendency to call old objects "possible," $t(16) = 3.16, p < .01$.

Electrophysiological results. The data from Experiment 2 were analyzed in the same fashion as those from Experiment 1. As can be seen in Figure 6, the overall morphology of the ERPs was quite similar to that in Experiment 1. An ANOVA of the latency of the P1, which peaked at 114 ms ($SD = 13$), showed a significant three-way interaction between laterality, site, and presentation, $F(1, 16) = 4.91$. However, separate ANOVAs for the occipital and parietal sites revealed no significant effects or interactions involving object type and presentation (all $ps > .08$). Likewise, for P1

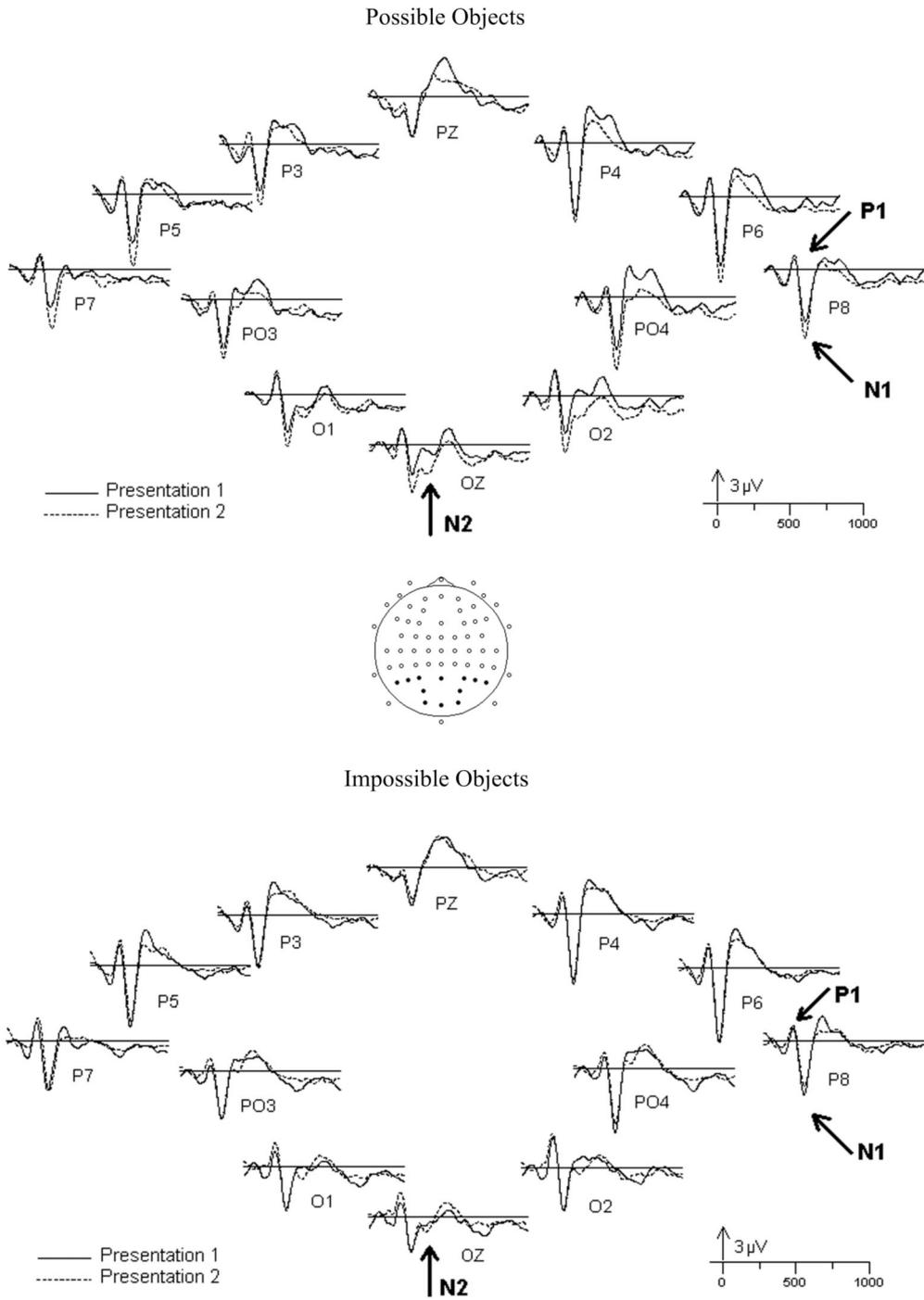


Figure 6. Event-related potential (ERP) results from Experiment 2. Grand mean average referenced ERPs for first and second presentations of possible objects (top panel) and impossible objects (bottom panel) at posterior electrodes.

peak amplitude, there were no significant main effects or interactions involving object type and presentation (all $ps > .07$). Furthermore, when the P1 amplitude was analyzed relative to the C1 amplitude, the only effect was a marginal interaction between laterality, site, and presentation, $F(1, 16) = 3.96, p = .06$. How-

ever, separate ANOVAs for the occipital and parietal sites again produced no significant effects (all $ps > .1$). These results confirm the findings from Experiment 1 by demonstrating that the P1 was not reliably modulated by stimulus repetition. In addition, contrary to Experiment 1, the C1 was not reliably modulated by object type

or presentation (all $ps > .1$), suggesting that the marginal effect in Experiment 1 was probably not reliable.

The N1 reached its peak amplitude at about 182 ms poststimulus ($SD = 14$) and was maximal over right parietal cortex (see Figure 6). An analysis of its latency produced only one significant effect: a four-way interaction between site, object type, presentation, and electrode sites, $F(1, 16) = 5.60$. To further explore this interaction, separate ANOVAs were performed on parietal and occipito-parietal sites. For the parietal electrodes, there were no significant effects, whereas for the occipital electrodes, we found an interaction between object type, presentation, and electrode, $F(1, 16) = 5.87$. However, when separate ANOVAs were conducted for individual electrodes, no reliable effects emerged (all $ps > .07$). Unlike latency, the peak amplitude of the N1 was modulated by stimulus repetition, as evidenced by an interaction between object type and presentation, $F(1, 16) = 6.51$. As in Experiment 1, possible objects presented for a second time elicited larger N1 amplitudes compared with their first presentation, $t(16) = 2.97$, $p < .05$. At the same time, the N1 for impossible objects was not modulated by repetition, $t(16) = 0.54$. In addition, although the amplitude of the N1 did not differ for possible and impossible objects during their initial presentation, $t(16) = 0.92$, $p > .3$, it was larger for possible than impossible objects at second presentation, $t(16) = 2.52$, $p < .05$. The same pattern of results emerged when the peak-to-peak amplitude was used as the dependent measure.

A power analysis showed that the effect size of the N1 repetition effect was very small (0.18) and the power to detect it was low (.21). Consequently, we did not have sufficient power to detect an even smaller effect in impossible objects.

As displayed in Figure 7, the magnitude of the N1 repetition enhancement effect for possible objects at the parietal electrodes correlated with RT priming for possible objects ($r = .64$, $p = .005$, uncorrected; Spearman's $\rho = .72$, $p = .0012$, uncorrected). Thus, the more the peak-to-peak amplitude of the N1 increased from the

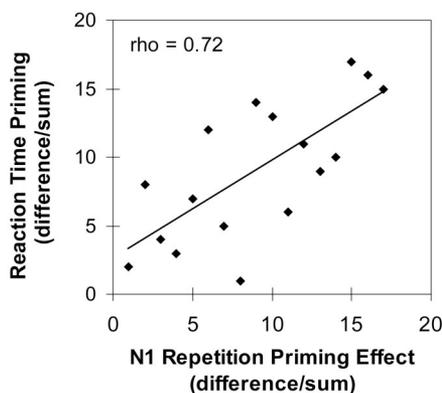


Figure 7. Scatter plot representing the Spearman correlation between the magnitude of the N1 repetition priming effect for possible objects and behavioral priming for possible objects in the object-decision test in Experiment 2, as measured by reaction time ($\rho = .72$, $p < .0005$). Neural repetition priming was computed by dividing the difference in peak-to-peak amplitudes between the first and the second presentation of possible objects from 150 to 210 ms by the sum of these two values (difference/sum). Behavioral priming was similarly measured as the difference in RT for old compared with new possible objects divided by the sum of these values.

first to the second presentation of possible objects, the greater the improvement in object-decision RT for those objects compared with new possible objects. Other behavioral measures of priming (accuracy, bias, and sensitivity) did not exhibit such a correlation with the N1 repetition effect. Of importance, the observed correlation was again specific to possible objects, as the magnitude of N1 repetition for impossible objects did not correlate with any behavioral measures of priming for impossible objects (all $ps > .25$).

As in Experiment 1, we identified a second, smaller negative wave mostly over occipital electrodes. This N2 peaked at approximately 280 ms. An ANOVA on mean amplitude (averaged from 240 to 340 ms) showed an interaction between site, object type, and presentation that approached significance, $F(1, 16) = 4.17$, $p = .057$, as well as an interaction between laterality, object type, and presentation, $F(1, 16) = 12.64$. Follow-up analyses indicated that there were no significant effects for the parietal site. By comparison, for the occipital site, there was an interaction between laterality, object type, and presentation, $F(1, 16) = 10.83$. Additional analyses provided evidence for repetition enhancement of the N2 over the right, but not the left, occipital cortex for possible objects, $t(16) = 4.40$, $p < .001$. There was no effect of repetition for impossible objects, $t(16) = 1.05$, $p = .31$. The effect size of the N2 repetition effect for possible objects was moderate ($d = 0.46$), as was our power to detect this effect (.60). The power analysis also indicated that we had low to moderate power (.35) to detect a smaller repetition effect in impossible objects (i.e., two thirds of the effect size of possible objects). Finally, the magnitude of the N2 repetition effect over right occipital cortex was not correlated with any of the behavioral measures of priming for either possible or impossible objects.

Discussion

Both the behavioral and the ERP results observed in Experiment 2 were largely identical to those from Experiment 1. We found reliable behavioral priming in the object-decision test for old possible objects, both in terms of RT and accuracy, but not for matched possible objects. Object-decision performance for old and matched impossible objects did not change as a function of prior exposure, although there was a trend for lower classification accuracy for old than for new impossible objects. Overall, object-decision performance improved for previously seen objects, as indicated by an increase in sensitivity for old objects. Sensitivity did not change for matched objects. At the same time, subjects' bias to call previously encountered objects "possible" was larger for old than new and matched objects, which did not differ from one another. Thus, as in Experiment 1, the behavioral data did not clearly differentiate between the three models of object-decision priming. However, the evidence in favor of the SDS model and contrary to the bias models was somewhat stronger in Experiment 2 because there was no effect at all on performance of the matched objects, compared with a small effect on RT for matched possible objects in Experiment 1.

Neurally, object repetition during encoding enhanced the posterior N1 and N2 ERP components for possible but not impossible objects and had no effect on the posterior P1. The results from the power analysis showed that for the N1, we did not have sufficient power (at $\alpha < .05$) to detect a smaller repetition effect in impos-

sible objects. For the N2, we had low to moderate power to detect such an effect. Thus, we cannot rule out the possibility that there were repetition effects for impossible objects but that we lacked the power to detect them. Nonetheless, because we replicated both the N1 and N2 repetition effects for possible objects across two experiments and did not find reliable effects for impossible objects in either experiment, it appears that these effects are occurring exclusively for possible objects.

Of importance, we replicated the correlation between the magnitude of the N1 repetition enhancement for possible objects and RT priming for possible objects. This correlation indicated that the more the N1 amplitude increased from the first to the second presentation of a possible object, the more RT priming subjects showed for old possible objects. As in Experiment 1, this correlation was present at the posterior parietal electrodes, but not the occipital sites. In contrast to Experiment 1, however, the N1 repetition effect did not correlate with priming measured in terms of accuracy.

Because the same ERP repetition effects emerged with two different structural encoding tasks, they are likely to reflect processes associated with the fundamental visual analysis of the objects, rather than strategic, task-related processes that may differ for possible and impossible objects. Therefore, taken together, the results from these two experiments strongly support the notion that objects with a globally coherent 3D structure are processed differently by the visual system than objects that can only be represented in a parts-based manner. Moreover, this difference appears to account for the differential priming effects for possible and impossible objects in the object-decision test. These findings are in agreement with the SDS model of object-decision priming, which predicts distinct neural repetition effects for structurally possible and impossible objects. The data are incompatible with both the general bias model and the structure-extraction bias model because they predict a similar pattern of ERP repetition for both object types.

General Discussion

This study used evidence from ERPs to test the validity of three models of priming in the possible/impossible objects decision test: the SDS model, general bias model, and structure-extraction bias model. Unlike previous studies on this subject, which examined neural activity during the object-decision test phase, we examined the change in the neural signal from the first to the second presentation of the objects during the encoding phase (i.e., repetition priming) and the extent to which it predicted behavioral priming in the object-decision test. This approach permitted us to investigate the neural response to structurally possible and impossible objects when subjects were not actively thinking about the possible/impossible nature of the objects and may not even have been explicitly aware of the distinction. This way, we hoped to minimize the influence of any decision biases that may arise during the object-decision test phase and affect processing of the objects. Using this strategy, we wanted to elucidate whether there is a direct link between basic differences in perceptual processing of these objects and subsequent priming behavior.

Across two experiments, we found relatively early latency (180–280 ms) ERP repetition effects over posterior cortex for possible but not impossible objects and a correlation between the magnitude of one of these effects and subsequent priming in the

object-decision test. These results are consistent with the SDS model, according to which priming is supported by global 3D structural descriptions. To our knowledge, this study also presents the first evidence specifically linking neural activity at the time of encoding to subsequent behavioral priming in a perceptual task.

In a previous ERP study of possible/impossible object-decision priming, Penney et al. (2000) reached a similar conclusion about the validity of the SDS model, even though they measured brain activity during the test phase of the experiment. These authors reported more positive waveforms for old compared with new possible objects from 500 to 700 ms poststimulus over centroparietal scalp and no repetition effects for impossible objects. The authors interpreted these results as consistent with the view that the brain encodes the global structural information about novel objects in a unitized form via an SDS. However, although the repetition effect for possible objects might indeed index processes related to perceptual priming, its timing and topography also overlap with processes related to explicit recollection (the parietal P300 component; e.g., Allan, Wilding, & Rugg, 1998; Düzel, Yonelinas, Mangun, Heinze, & Tulving, 1997; Mecklinger, 2000). This interpretation of their finding is strengthened by the fact that recognition performance was better for possible than impossible objects in a parallel explicit old/new recognition experiment.

The reason why Penney et al. (2000) failed to find the same repetition effects at earlier waveforms as we did is less clear but could be the result of the large number of stimuli (128) presented during the encoding phase. As mentioned previously, prior behavioral studies in our laboratory using this paradigm indicate that priming effects are smaller and less robust when subjects are exposed to more than 50 items at encoding. This could be due to the fact that the SDS is load sensitive. Consequently, early perceptual ERP repetition effects may have been too small to be detected in Penney et al.'s (2000) study. Alternatively, the change in tasks from the encoding to the test phases of the experiment might have obscured potential repetition effects related to the visual analysis of the objects.

Two other ERP studies that investigated the effect of immediate repetition of structurally possible and impossible objects using a target detection task also reported rather different results (Penney, Mecklinger, & Nessler, 2001; Rugg, Soardi, & Doyle, 1995). Both studies reported repetition suppression effects over parietal and frontal cortex. These effects were present for both possible and impossible objects in Penney et al.'s (2001) study and for possible objects in the study by Rugg et al. (1995), who did not investigate the repetition effects for impossible objects. The latency of these effects ranged from 200 to 400 ms (Rugg et al., 1995) and 300 to 900 ms (Penney et al., 2001). Penney et al. (2001) argued that these repetition effects were indicative of facilitated processing of the objects, as both the frontal and parietal repetition effects represented reductions in neural activity for the second compared with the first presentation of items. However, interpreting the meaning of these repetition effects, as well as their relationship to models of object-decision priming or theories of object perception, is difficult because there were no intervening items between stimulus repetitions. As a result, it is unclear whether the observed ERP effects represented facilitation of some aspect of visual processing of the objects (perceptual priming), explicit recollection, changes in attention, or the reactivation of information in visual short-term memory.

Unlike the studies by Penney et al. (2000) and Rugg et al. (1995), the present experiment found repetition enhancement rather than a reduction in neural activity. Although fMRI studies of visual object repetition priming typically report repetition suppression, repetition enhancement is sometimes found (for a review, see Henson, 2003). The ERP literature is more mixed. With respect to ERP studies using immediate stimulus repetitions, researchers have reported both repetition enhancement of early visual components (before 300 ms) for pictures of everyday objects (Henson et al., 2004) and famous faces (Schweinberger, Pickering, Jentsch, Burton, & Kaufmann, 2002; Trenner, Schweinberger, Jentsch, & Sommer, 2004) and repetition reduction for unfamiliar faces (Campanella et al., 2000; Itier & Taylor, 2002; Schweinberger, Pfütze, & Sommer, 1995). However, when several items intervene between the first and second presentation of an item, as in the present study, ERP repetition enhancement is typically reported. For example, amplitude increases of early perceptual components have been found for repeated familiar objects (Doniger et al., 2001; Schendan & Kutas, 2003), unfamiliar faces (George, Jemel, Fiori, & Renault, 1997; Jemel, Calabria, Delvenne, Crommelinck, & Bruyer 2003), meaningless 2D shapes (George et al., 1997), and familiar 2D shapes (Curran et al., 2002). Whether stimulus repetition produces enhancement or suppression of neural activity is still a matter of debate but could be related to the type of stimulus, task, and the delay and number of intervening items between repetitions. Some authors have suggested that repetition reduction indexes more efficient processing of items with preexisting representations, whereas repetition enhancement, particularly for unfamiliar items, reflects the formation of novel representations (Fiebach, Gruber, & Supp, 2005; Henson, 2003; Wiggs & Martin, 1998). Our results are certainly consistent with this notion.

The finding that this ERP repetition enhancement was only present for possible objects indicates that parts-based structural descriptions and their neural representations are more resistant to long-term modifications by experience than are global structural descriptions. Indeed, this resistance may explain why structural representations of impossible objects appear more vulnerable to degradation over very short intervals. Although long-lasting priming (10 min to 1 week) can be observed for possible objects, priming for impossible objects has only been observed after very short intervals (up to 21 s; Hilton, Pavlicic, Cooper, Warren, & Stern, 2003). Recent evidence from fMRI confirms this interpretation (Zarahn, Hilton, Flynn, Cooper, & Stern, 2004). Use of a continuous priming design in which possible/impossible object decisions were made on individual objects four times within a window of 16 trials (21 s) resulted in detection of systematic changes in activation with the repeated exposure of possible objects across the four repetitions. No such changes were found with impossible objects.

The finding that the earliest effects of stimulus repetition for possible objects occurred at the N1 indicates that the preceding perceptual processes indexed by the P1 (and C1) were not modified by prior experience and did not differ for globally coherent and incoherent 3D objects. These processes might include image segmentation, contour perception, boundary completion, and principles of grouping. Although the extent to which the P1 is involved in the structural analysis of objects is difficult to ascertain, previous studies suggest that it does not seem to be sensitive to an object's global structure. For example, it is larger when attention is

allocated to local rather than global features of a hierarchical visual stimulus (Han, Fan, Chen, & Zhuo, 1999; Han, He, & Woods, 2000; Han, He, Yund, & Woods, 2001). Thus, given that neither stimulus repetition nor the global 3D structure of an object affected the P1, it appears as though subjects' initial allocation of attention to local object features did not differ for possible and impossible objects.

Previous studies of the posterior N1 component, which peaks between 150 ms and 200 ms, have shown that it is linked to implicit visual discrimination processes (Curran et al., 2002; Kiefer, 2001; Vogel & Luck, 2000). It is larger when subjects discriminate visual objects at the subordinate compared with the basic level of categorization (Tanaka, Luu, Weisbrod, & Kiefer, 1999) and when experts categorize objects in their domain of expertise (Tanaka & Curran, 2001). Large N1 amplitudes are also observed in response to visually presented words (e.g., Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999), for which we, as human beings, have developed great expertise and that we can discriminate at the subordinate level. In addition, the N170 is larger in response to faces than to other object categories (e.g., Bentin, Allison, Puce, Perez, & McCarthy, 1996; Eimer, 2000), which can also be viewed as a consequence of our expertise at recognizing faces and our ability to automatically recognize them at the subordinate level (Tanaka, 2001). Although the relationship between the N170 for faces and the N1 for objects is still being debated (e.g., Itier & Taylor, 2004; Rossion, Curran, & Gauthier, 2002), taken together, these findings suggest that the N1 is related to the cumulative visual experience we have in discriminating between instances of a particular stimulus category (Gauthier, Curran, Curby, & Collins, 2003; Rossion et al., 2002; Schendan, Ganis, & Kutas, 1998).

In the present experiment, the N1 repetition effect for possible but not impossible objects might be related to our extensive visual experience in recognizing 3D possible objects compared with our lack of experience in representing impossible objects. As a result, the repetition of possible objects increases our expertise with them more rapidly than does the repetition of impossible objects. This would explain the absence of an initial amplitude difference for possible and impossible objects. Given that the N1 is thought to be involved in the structural encoding of global configurations (Doniger et al., 2001; Eimer, 2000; Itier & Taylor, 2002, 2004), the reason for this faster rate of familiarization with possible objects could be due to the fact that these objects can be represented in a global structural format, whereas impossible objects can only be represented in a parts-based manner. Thus, the N1 repetition enhancement in this experiment seems to be indicative of facilitation in the global structural analysis of familiar compared with unfamiliar possible objects. This interpretation is strengthened by the correlation between the magnitude of this repetition effect and object-decision priming for possible objects.

Less is known about the processes underlying the N2 repetition effect over occipital scalp; however, recent studies have suggested that it might be related to later stages of object recognition. Prior studies have reported a posterior N2 to be larger for meaningful than for meaningless stimuli (Tallon-Baudry et al., 1997). The posterior N250 was proposed to be a marker of face recognition (Schweinberger et al., 2002), and it was shown to increase with repeated exposure to a face (Tanaka, Curran, Porterfield, & Collins, 2004). In addition, studies investigating perceptual closure

processes (the ability to join disjointed contour segments belonging to a single object) have shown that the amplitude of the N2, also called N_{CL} (for negativity associated with closure), tracks perceptual closure processes. Thus, when subjects are asked to recognize fragmented objects, the N2 builds incrementally and peaks when the subject is able to identify the objects (Doniger et al., 2000, 2001; Schendan & Kutas, 2002, 2003). It has been suggested that the N1 and the N_{CL} may reflect successive stages of object perception, with the N1 representing the structural analysis and the N_{CL} indexing structural as well as semantic processes (Doniger et al., 2001).

Others have proposed that the N_{CL} and the related frontal N350 reflect covert object selection processes, that is, the automatic search for a stored structural description of an object that matches a visual input image (Schendan & Kutas, 2002, 2003). Thus, in the current experiment the N2 repetition effect might be related to an automatic search in visual memory for previously seen possible objects. The reason that no N2 repetition effect was observed for impossible objects could be attributed to the absence of global structural descriptions and to the typically weaker recognition memory for impossible objects (e.g., Schacter, Cooper, Delaney, et al., 1991; Schacter & Cooper, 1993; Schacter et al., 1990a; Schacter et al., 1992).

As a more general point, these results highlight the usefulness of examining neural activity at encoding and its relationship to object-decision priming. Examining neural activity at encoding allows for a more independent assessment of perceptual processes, as it is not subject to the various contested postperceptual decision processes that come into play at the time of test. Although many studies have compared encoding-related neural activity for stimuli that were later remembered or forgotten (DM effects) on explicit tests of memory, no study to date has attempted to apply this type of strategy to a perceptual priming task. Although a few studies have explored the neural correlates of encoding of word-stem completion priming (Friedman, Ritter, & Snodgrass, 1996; Paller, 1990; Paller, Kutas, Shimamura, & Squire, 1987; Schott, Richardson-Klavehn, Heinze, & Düzel, 2002), this task has been shown to involve both perceptual and conceptual processes (Buckner, Koutstaal, Schacter, & Rosen, 2000; Thiel, Henson, Morris, Friston, & Dolan, 2001; Winocur, Moscovitch, & Stuss, 1996).

The dearth of research on perceptual priming and encoding might be attributable to the fact that one cannot directly compare encoding-related activity for primed and unprimed items using most experimental paradigms. The reason is that perceptual priming is typically measured as the difference in RT or accuracy for previously encountered compared with new items, the latter of which are not presented during the encoding phase, thereby precluding a direct comparison between the two types of items. This problem was circumvented by the possible/impossible object-decision test, in which priming is usually seen for one type of item (possible objects), but not the other (impossible objects), despite identical encoding conditions for both types of stimuli. As a result, one can compare neural activity during encoding for stimuli that produce priming with those that do not.

In conclusion, our results demonstrate that the visual perceptual system differentially encodes globally coherent and incoherent 3D objects. Specifically, it displays greater neural plasticity for 3D objects that can be represented as coherent wholes than for objects for which no stable 3D interpretation exists. Of importance, even

though our encoding instructions make no reference to the distinction between the two types of objects, this differential perceptual response was similar regardless of whether subjects were attending to left/right orientation or their functionality (tool/support). In addition, aspects of this differential perceptual response (N1) demonstrated a relationship to object-decision priming. Thus, these findings are in greater agreement with the SDS account of possible/impossible object-decision priming, according to which priming is based on the facilitation in the analysis of an object's global 3D structure, than with bias models. In future studies, it would be interesting to examine whether the ERP repetition effects for possible objects found in the present study would still be observed when the encoding task does not require subjects to process the objects' global 3D structure. If neural repetition effects are not found under these conditions, this would strengthen the interpretation that the effects observed in this study reflect processes concerned with the construction of the global 3D structure of an object.

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