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Effects of dividing attention during encoding on perceptual priming of unfamiliar visual objects

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Abstract

According to the distractor-selection hypothesis (Mulligan, 2003), dividing attention during encoding reduces perceptual priming when responses to non-critical (i.e., distractor) stimuli are selected frequently and simultaneously with critical stimulus encoding. Because direct support for this hypothesis comes exclusively from studies using familiar word stimuli, the present study tested whether the predictions of the distractor-selection hypothesis extend to perceptual priming of unfamiliar visual objects using the possible/impossible object-decision test. Consistent with the distractor-selection hypothesis, Experiments 1 and 2 found no reduction in priming when the non-critical stimuli were presented infrequently and non-synchronously with the critical target stimuli, even though explicit recognition memory was reduced. In Experiment 3, non-critical stimuli were presented frequently and simultaneously during encoding of critical stimuli; however, no decrement in priming was detected, even when encoding time was reduced. These results suggest that priming in the possible/impossible object-decision test is relatively immune to reductions in central attention and that not all aspects of the distractor-selection hypothesis generalize to priming of unfamiliar visual objects. Implications for theoretical models of object-decision priming are discussed.

In everyday life, people frequently divide their attention between two or more tasks, such as viewing an art exhibit while conversing on the cell phone. Simulating this experience, a typical divided attention experiment presents subjects with information for which their memory will later be tested (the critical target stimuli) while at the same time having subjects perform a secondary task (also called a distractor task). This secondary task is meant to reduce the amount of attention they can allocate to the information being presented. Importantly, subjects are required to respond to both the critical target items and the non-critical items, such that the perceptual analysis and conscious perception of the critical target stimuli are always guaranteed and only later (central) stages of information processing are affected.

Studies have repeatedly shown that dividing attention in this manner decreases later explicit memory for the critical target information, as measured on tests of recall and recognition (Baddeley, Lewis, Eldridge, & Thomson, 1984; Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Fiske & Schneider, 1984; Norman, 1969). Dividing attention also appears to decrease conceptual priming, a type of implicit memory, though typically to a lesser degree than explicit memory (e.g., Light, Prull, & Kennison, 2000; Mulligan, 1997, 1998; Mulligan & Hartman,

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1996). *Priming* refers to a change in the ability to classify, identify, or produce an item due to prior exposure that does not require conscious awareness of the prior exposure (Tulving & Schacter, 1990). Dividing attention is thought to decrease both conceptual priming and explicit memory because attention is vital for encoding and elaborating the semantic properties of a stimulus, which similarly enhances both types of memory.

Perceptual priming, by contrast, does not benefit from the semantic analysis of stimuli, but reflects an improvement in the processing of the physical, surface-level properties of stimuli that have been encountered previously. Consequently, one would expect divided attention manipulations to have little effect. Yet, the available empirical evidence is mixed, with some studies reporting decrements in perceptual priming when attention is divided during encoding (Mulligan, 2002, 2003; Mulligan & Hornstein, 2000) and other studies not (e.g., Gabrieli et al., 1999; Mulligan, 1998; Mulligan & Hartman, 1996; Parkin & Russo, 1990; Russo & Parkin, 1993; Schmitter-Edgecombe, 1996a, 1996b).

Mulligan and colleagues (2000, 2003) proposed a theoretical framework within which to understand why dividing attention might variably impact perceptual priming. This hypothesis, called the *distractor-selection hypothesis*, holds that “when distractors [i.e., non-critical, secondary task stimuli] require frequent responses and targets [i.e., critical stimuli later tested in priming task] are presented simultaneously, then the process of selecting a response to the distractor is most likely to disrupt memory encoding of the target” (Mulligan, 2003, pg. 273). This disruption in the encoding processes, in turn, is thought to produce a decrement in perceptual priming. On the contrary, when responses to non-critical stimuli are made infrequently, perceptual priming is thought to remain intact. Note that although Mulligan uses the term “distractor” to refer to secondary task stimuli to which subjects must respond, the current manuscript uses the term “non-critical stimulus” or “secondary task stimulus” because in the older attention literature, the term “distractor” usually referred to an unattended stimulus that is to be ignored. The term “primary task” in this manuscript refers to the encoding task that presents the stimuli for which priming is later tested.

The foundation for the distractor-selection hypothesis is the *central-bottleneck model* (Pashler, 1994, 1998). According to this model, memory encoding, memory retrieval, and response selection (mapping from stimulus identity to the required response) all rely on the same central amodal bottleneck. In Pashler's (1994, 1998) view, this bottleneck is a structural feature of a brain region or network that limits how many processes that region/network can concurrently perform. All processes that rely on this bottleneck have to be performed in a serial manner, such that a bottleneck-dependent process (process B) cannot be performed while another process (process A) is occupying the bottleneck. According to the distractor-selection hypothesis, selecting the appropriate responses to non-critical stimuli while critical target items are being presented reduces the availability of the bottleneck for encoding processes, which reduces later perceptual priming.

Importantly, the evidence directly supporting the distractor-selection hypothesis comes exclusively from studies using word-identification priming. However, in order to arrive at a general framework for describing the effects of dividing attention on perceptual priming, it is important to examine the conditions outlined in the distractor-selection hypothesis for different types of stimuli and priming tests. Therefore, the goal of this study was to investigate whether aspects of the distractor-selection hypothesis generalize to perceptual priming of unfamiliar visual objects. The primary reason that the effects of attention on perceptual priming might be different for words compared to novel nonverbal stimuli is that in the case of the former, priming is based to a large degree on modifications of existing representations, whereas in the case of the latter, priming is mediated largely by newly acquired representations (e.g., Bowers, 1994, 1996; Dorfman, 1998; Henson, Shallice, & Dolan, 2000; Schacter, Cooper, & Delaney, 1990). The building of new representations, however, is a process that takes time and might require more attention than the reactivation of existing traces. This is supported by a recent neuroimaging study that showed differential time courses of neural repetition effects for familiar and globally unfamiliar visual objects (Soldan, Zarahn, Hilton, & Stern, 2008): The familiar objects demonstrated a rapid decrease in fMRI response with repetition, whereas the unfamiliar stimuli showed a more gradual decline in activity across presentations. In addition, priming effects obtained under full attention are generally smaller for novel stimuli than familiar objects (e.g., Bowers, 1994; Goshen-Gottstein & Ganel, 2000; Stark & McClelland, 2000). Therefore, it is conceivable that reducing attention during encoding might disrupt perceptual priming of novel objects under conditions that would not affect perceptual priming of words. Consistent with this hypothesis, dividing attention has been shown to eliminate lexical decision priming for pseudowords but not words (Smith & Oscar-Berman, 1990).

Examining the effects of attention on perceptual priming of unfamiliar stimuli is theoretically important from another perspective. It has the advantage that semantic or conceptual processes, which are known to be sensitive to attentional manipulations, do not (or only minimally) influence the observed priming effects. Thus, when an effect of attention is observed in a perceptual priming task using unfamiliar stimuli, one can be more confident that it reflects the disruption of perceptual encoding processes, rather than conceptual ones. As such, studies using unfamiliar stimuli may provide a somewhat “cleaner” measure of the modulatory effects of attention on perceptual encoding processes than studies using familiar stimuli.

To our knowledge, only one prior study has investigated how reducing attention at encoding affects perceptual priming for unfamiliar visual objects (Ganor-Stern, Seamon, & Carrasco, 1998). This study, however, used a selective attention manipulation, not a divided attention manipulation. In selective attention studies, attention is directed away from the critical stimulus or the relevant features of a critical stimulus by having subjects respond to an irrelevant dimension of the critical stimulus or to a different stimulus altogether. A relevant stimulus dimension in this context refers to a stimulus feature that needs to be processed or attended to in order to obtain priming. For example, the color of a word would be an irrelevant stimulus dimension in studies of word identification priming, which requires the processing of word identity, but not color during encoding. Consequently, selectively attending to the color of a word during encoding reduces word identification priming (Mulligan, 2002). In the study by Ganor-Stern et al. (1998), subjects were asked to make a perceptual judgment about two visual stimuli that flanked the objects for which priming was later tested. No responses were made toward the objects and no instructions were given for the objects. In divided attention manipulations, by comparison, a response to the critical stimulus (or its relevant dimension) is always required, thereby ensuring the conscious perception of the critical stimulus and its relevant dimensions.

Importantly, selective attention manipulations can affect not only central amodal stages of information processing, as do divided attention manipulations, but also pre-central, modality-specific processing stages (e.g., Luck & Vecera, 2002; Marois & Ivanoff, 2005). In other words, unattended stimuli or features of stimuli may be filtered out at an earlier, pre-attentive level, particularly when presentation times are short, leading to the truncated perceptual analysis of stimuli and subsequent reduction in perceptual priming. As a result, as pointed out by Mulligan & Hornstein, 2000, selective-attention manipulations are generally more effective in reducing perceptual priming than divided attention manipulations (also see Mulligan, 2002). More importantly, any deficits in performance observed with selective attention manipulations are difficult to interpret from an information-processing perspective, as it is unclear which stages of stimulus processing were disrupted by the manipulation (early/modality-specific, late/central, or both). Note that the distinction between early, modality-specific aspects of attention and late, modality non-specific attention plays a central theme in many models of attention

(Corbetta & Shulman, 2002; Johnston, McCann, & Remington, 1995; Kastner & Pinsk, 2004; Maddox, 2002; Posner & Petersen, 1990), underscoring the importance of differentiating their effects on memory.

Like Ganor-Stern et al. (1998), the present study investigated the effects of dividing attention on priming in the *possible/impossible object-decision test*. In this test, subjects are asked to judge whether previously presented (i.e., old) and not previously presented (i.e., new) line drawings of unfamiliar figures are structurally possible or impossible (see Figure 1 for examples of possible and impossible object). Priming has been demonstrated consistently for possible objects, but not impossible objects, in the form of greater classification accuracy and/or faster reaction times for old than new items (e.g., Schacter & Cooper, 1993; Schacter et al., 1990; Uecker et al., 1997; for a discussion why priming for impossible objects is not observed under standard test conditions, see Ratcliff & McKoon, 1995; Schacter & Cooper, 1995; Seamon & Carrasco, 1999; Williams & Tarr, 1997). In addition, studies that have measured priming in terms of the signal detection measures of bias and sensitivity have demonstrated increases in sensitivity, as well as consistent changes in the bias to respond “possible” for old compared to new objects (Marsolek & Burgund, 2005; Ratcliff & McKoon, 1995; Soldan, Mangels, & Cooper, 2006; Williams & Tarr, 1997).

Because of the dearth of research on the effects of dividing attention on perceptual priming of unfamiliar stimuli, Experiments 1 and 2 of the current study examined the effects of a standard secondary task, the digit-monitoring task, on perceptual priming of unfamiliar objects. This task has been used in a variety of divided attention studies and been shown to reduce priming on perceptual explicit test of memory and conceptual priming tests, but not on the perceptual priming tests of word identification and word fragment completion (e.g., Mulligan, 1998; Mulligan & Hartman, 1996). According to the distractor-selection hypothesis, perceptual priming should not be reduced when attention is divided using the standard digit-monitoring task because the secondary-task stimuli require infrequent responses (typically every 8 − 14 sec) and are typically not presented in synchrony with the critical target stimuli. Experiments 1 and 2 tested whether this prediction generalizes to perceptual priming of unfamiliar visual objects. In Experiment 1 the encoding phase was immediately followed by the test phase (as is typical of many priming studies), whereas in Experiment 2, a 20 min delay was imposed between the encoding and tests phases.

We reasoned that even if there is no deficit in priming in the divided attention encoding condition in Experiment 1, the delay may reveal that the memory representations formed under divided attention are in fact more vulnerable to the effects of interference and decay than the representations formed under full attention. This possibility is supported by the finding that priming in the possible/impossible object-decision test deteriorates in older adults over a 20 min period, but remains intact for up to 1 week in young adults (Stern et al., 2000). This finding is of relevance to the current study because older adults tend to show deficits in central or executive attention relative to young adults (e.g., Braver et al., 2001; Verhaeghen & Cerella, 2002) and it has been argued that aging reduces attentional resources available at encoding (Anderson & Craik, 2000; Craik, 1982; Craik & Byrd, 1982). Consequently, it is possible that priming in young adults similarly deteriorates over time when the stimuli are encoded under divided attention.

Finally, Experiment 3 tested whether the two conditions described by the distractor-selection hypothesis to be most likely to produce deficits in perceptual priming are indeed *sufficient* to reduce perceptual priming. Thus, according to Mulligan (2003), perceptual priming is most likely to be disrupted when (a) critical target and non-critical stimuli occur in synchrony, and (b) subjects make frequent responses to the non-critical stimuli during encoding of the critical target stimuli. Although Mulligan (2003) showed that the presence of one of these conditions is sufficient to reduce perceptual priming in the word-identification test, it is unclear whether their presence is *sufficient* to reduce perceptual priming in other tasks where the contribution of conceptual processes is minimized.

Examining the effects of dividing attention on priming in the possible/impossible object-decision test has implications not only for the distractor-selection hypothesis but for understanding the dependence of implicit memory processes on central aspects of attention more generally. Thus, if an effect of dividing attention is observed in Experiment 1, this would suggest that the formation of novel visual representations may be strongly dependent not only on visual attention, but also on capacity-limited central mechanisms that are also important for explicit memory and conceptual priming. It would also suggest that perceptual priming of novel visual objects is more heavily dependent on central attention than perceptual priming of familiar words. Alternatively, if dividing attention does not affect priming in Experiments 1 and 2, but reduces priming in Experiment 3, this would support the view that perceptual priming is dependent on central attention at the time of encoding, but less so than conceptual priming and explicit memory (which would be expected to be reduced under these conditions). One possibility is that there may be a gradient in the reliance of different types of memory tests on central attention, with perceptual priming being the least dependent, followed by conceptual priming, recognition memory, and recollection. If no effect of dividing attention is found in Experiment 1, 2, and 3, it may suggest that the encoding of structural information of visual objects is less dependent on central attention than the encoding of lexical or orthographic information that is thought to support perceptual priming of words. Finally, as explained in more detail in the general discussion, understanding whether and how divided attention influences priming in the possible/impossible object-decision test also has implications for theoretical models of object priming and representation.

Experiment 1

Method

Participants—Eighty-one students (58 females, 33 males) from Columbia University participated in exchange for course credit or payment of $5. All subjects in this and the subsequent experiments were between the ages of 18 and 30 years and reported normal or corrected-to-normal vision. The data from one participant were excluded from the analyses because of failure to follow the instructions for the object-decision test. Of those subjects whose data was included in the analyses, 48 completed the possible/impossible object-decision test and 32 were given an old/new recognition test. The recognition test was administered to ensure that the attentional manipulation indeed produced a decrement in explicit memory performance.

Materials—The stimuli used for the object-decision test consisted of 96 line drawings of unfamiliar objects (48 possible and 48 impossible). *Possible objects* are drawn in such a way that they could exist as three-dimensional (3D) objects in the real world, while *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 addition, five practice objects (three possible and two impossible) were inserted at the beginning of each encoding and test phase. The same five practice objects were used for all practice trials and all participants. All objects were presented as black drawings with a uniform gray background on an iMac computer. They subtended a visual angle of approximately 10° when viewed from a distance of 50 cm. In order to ensure that each object appeared equally often in each experimental condition (i.e., encoded full attention, encoded divided attention, and new), the set of 96 test objects was randomly divided into four groups of 12 possible objects and four groups of 12 impossible objects. These eight groups were then combined into eight different lists that were rotated through participants. Each list contained 12 possible and 12 impossible objects that were encoded under full attention, 12 possible and 12 impossible objects that were encoded under divided attention, and 24 new possible and 24 new impossible objects.

A separate pilot study was conducted to establish the inter-subject agreement about the possible/impossible nature of the objects, as well as the subjective complexity of each object. Complexity ratings were collected in order to assess potential interactions between attention and object complexity, as prior research reported that subjective object complexity is a better predictor of priming in the object-decision test than the possible/impossible status of the object (Carrasco & Seamon, 1996). Both ratings tasks were completed by the same 20 subjects and administered in separate blocks. The presentation of objects within each block was randomized and the order of task performance was counterbalanced across participants. Subjects were given unlimited time to complete each task. In the possible/impossible classification task, subjects were asked to classify all 96 objects as possible or impossible. On average, participants classified 96% of the possible objects as "possible" (range = 70 − 100%, SD = 7.9) and 94% of the impossible objects as "impossible" (range = 45 − 100%, SD = 11.0). With the exception of seven possible and five impossible objects, classification agreement was at least 90% for all objects. An Analysis of Variance (ANOVA) showed that classification accuracy did not differ for possible and impossible objects ($F < 1$).

Subjective object complexity was measured using the same procedure as Carrasco and Seamon (1996). Subjects were asked to rate how complex or intricate each object appeared to them using a seven-point scale, where 1 meant "low complexity" and 7 meant "high complexity." The complexity ratings were comparable to those of Carrasco and Seamon (1996). Impossible objects were rated as more complex than possible objects, $F(1, 94) = 287.07$, $p < 0.0001$, MSE = 0.62. The mean complexity rating for possible objects was 2.9 (range = 1.8 − 4.1, SD = 0.45), and that for impossible objects was 4.9 (range = 3.1 − 6.2, SD = 0.65). Next, the sets of 48 possible and 48 impossible objects were each divided into three groups of 16 objects, based on whether they were of high, medium, or low complexity. Based on these groups, a new within-subjects variable with three levels, *complexity*, was created, that could be included in the analysis of the accuracy data. Because the object lists used for counterbalancing purposes were created randomly, without taking into account object complexity, the number of high, medium, and low complexity objects in each experimental condition (new vs. encoded full vs. encoded divided) within a given participant was not identical. However, because the object lists were rotated across participants, each of the 16 high, medium, and low complexity objects appeared equally often in each condition in the experiment.

Procedure—All participants were initially told that they were participating in a visual perception experiment in which they would be making judgments about unfamiliar objects. No mention was made of the subsequent memory tests. Each participant completed two encoding phases: one under full attention and one under divided attention. The order of the full and divided attention encoding conditions was counterbalanced across subjects. In both encoding phases, participants first viewed the five practice objects, followed by 12 possible and 12 impossible critical objects that were presented twice for 4 sec, each time in a different random order. Participants were instructed to judge whether each object appeared to be facing primarily to the left or to the right. Although there is no objectively right or wrong answer to this question, these encoding instructions require subjects to process the objects' global 3D structure and have previously been shown to elicit reliable priming of possible objects (e.g., L.A. Cooper & Schacter, 1992; Schacter & Cooper, 1993). Participants were told to carefully examine each object for the entire duration it was on the screen to be able to make an accurate left/right judgment. Participants used the 'z' and '/' keys to indicate their left and right answers, respectively. Each trial was initiated by pressing the space bar, after which a fixation cross was displayed in the center of the screen for 350 ms. Next, the experimental image was presented for 4 sec and following its offset, participants entered their response. Note that this stimulus presentation time is relatively long compared to perceptual priming paradigms using familiar stimuli. Previous studies, however, have shown that a single short exposure (1 sec) does not produce priming in this task, whereas additional exposure time (up to 20 sec) or stimulus presentations (up to 4) beyond the minimum necessary to elicit priming do not enhance the magnitude of priming (Schacter, Cooper, Delaney, Peterson, & Tharan, 1991).

In the divided attention condition, subjects were given the left-right encoding instructions and simultaneously performed the digit-monitoring task. This task required participants to monitor a series of single-digit numbers presented on a tape player at a rate of 1 digit/per sec. Subjects were told to report the occurrence of three odd digits in a row by repeating these digits aloud in the same order in which they had occurred. The presentation of the digits and objects was not synchronized and critical three-digit sequences occurred approximately every 12 sec. This corresponds to a standard implementation of the task. The experimenter recorded missed sequences and errors. Participants were instructed to divide their attention equally between the two tasks and to perform both tasks as well as they could. They were given 1 min of practice with the digit-monitoring task alone before the start of the visual encoding phase. This also served as a baseline measure of digit-monitoring performance under full attention. There was a 1−2 min delay between the first and second encoding phase during which participants were given instructions for the next phase. In the full attention condition, subjects performed the left/right encoding task and were told to ignore the digits presented over the tape player.

Immediately after the second encoding phase, participants were given instructions either for the surprise old/new recognition test or the possible/impossible object-decision test. Subjects who took the *object-decision test* were asked to decide whether briefly presented objects were possible or impossible. They were told to respond as quickly and as accurately as possible by pressing the ‘z’ and ‘/’ keys for *possible* and *impossible* objects, respectively. Each trial was self-initiated by pressing the space bar and began with a fixation cross that was displayed for 150 ms and followed by a blank screen for 100 ms. Then, the same 5 practice objects followed by the 96 test drawings (48 old and 48 new) were presented randomly for a duration of 32 ms each. Subjects who completed the *old/new recognition test* were asked to decide which objects they had seen before in either the full or divided attention encoding phases and which ones were new. If they remembered having seen the object, they were to press the ‘z’ key; if they did not see the object, they had to press the ‘/’ key. Each object was presented for up to 5 sec, or until subjects made a response. Trials were self-initiated by pressing the space bar, after which a fixation cross was displayed for 350 ms, followed by the test image. The same five practice images were presented first, in random order, followed by the random presentation of the 96 test objects. At the end, all participants were debriefed about the purpose of the study.

Data Analysis—All analyses for this and the subsequent experiments were conducted treating both subjects and objects as the random variable. Because the pattern of results was the same, only the analyses across subjects are reported here. An alpha-level of 0.05 was adopted for all analyses. The data were analyzed using ANOVAs and significant effects were followed up with appropriate post-hoc tests corrected for multiple comparisons using the Holm-Bonferroni correction. Analyses involving independent variables with more than 2 levels were corrected for violations of the sphericity assumption using the Greenhouse - Geisser corrected *p*-values. Preliminary analyses indicated that there were no significant interactions between order and encoding status and no reliable interactions between complexity and encoding status in any of the experiments. As this indicates that neither order nor object complexity influenced priming of possible and impossible objects, the analyses reported below collapsed across these variables to increase the power to detect an effect of attention. Nonetheless, post-hoc analyses across experiments were performed to assess complexity effects in a larger sample (see comparison across experiments).

Priming was measured both in terms of accuracy (percent correct) and in terms of the signal detection theory (SDT) measures of sensitivity (d_L) and bias (C_L). 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"). We used d_L and C_L rather than the more traditional measures of d' and β (Snodgrass & Corwin, 1988) to facilitate comparison to previous studies of possible/impossible object-decision priming (Marsolek & Burgund, 2005; Williams & Tarr, 1997). Both d_L and C_L are based on logistic distributions and are functionally equivalent to d' and β. The signal detection measures were included because two theoretical accounts of performance in the possible/impossible object-decision test heavily focus on changes in bias effects with prior exposure to the objects (Ratcliff & McKoon, 1995; Williams & Tarr, 1997). Thus, in order to test if dividing attention differentially affects bias and sensitivity in this task, it is important to evaluate them separately (see general discussion). Reaction time data are not reported because there were no reliable effects of attention or encoding on response times.

Results

Digit-monitoring task—In the divided attention condition, subjects correctly identified 88% of the digit sequences, compared to 100% when they performed the task alone [$t = 6.17$, $p < 0.0001$]. Digit monitoring performance did not differ for subjects who completed the object decision test compared to those who were administered the old/new recognition test [$F(1, 76) < 1$].

Object-decision test—Table 1 shows the mean classification accuracy, bias, and sensitivity scores for old and new possible and impossible objects in the two attention conditions. An ANOVA on classification accuracy was performed with object type (possible vs. impossible) and encoding status (encoded full vs. encoded divided vs. new) as within subject variables. The only significant effect was the object type by encoding status interaction [$F(2, 94) = 4.13$, $p = 0.02$]. Planned comparisons indicated significant priming for possible objects in the full attention condition [$t(47) = 3.07$, $p = 0.01$], and the divided attention condition [$t(47) = 3.15$, $p = 0.01$]. A direct comparison of the magnitude of priming for possible objects in the full and divided attention conditions revealed no significant difference [$t = 0$]. There was no priming for impossible objects in either attention condition [both $p > 0.4$].

The magnitude of priming for possible objects was relatively small in the full attention condition (i.e., 6.3%), which potentially limits our ability to detect decreases in priming in the divided attention condition. The priming effect was relatively small in part because classification accuracy for new possible objects was at or close to ceiling for many subjects. Therefore, we directly compared the magnitude of priming for possible objects encoded under full and divided attention when only subjects with classification accuracies of 85% or lower were included in the analysis. This cutoff for inclusion was chosen because it excludes all subjects close to ceiling, while leaving the majority of subjects in the analysis (approximately two-thirds). There was significant priming for possible objects in the full [$M = 10.14\%$, $t(29) = 3.52$, $p<0.005$] and divided [$M = 9.03\%$; $t(29) = 3.16$, $p<0.005$] attention conditions and the difference in the magnitude of priming did not approach significance [$t < 1$]. There was no priming for impossible objects [both $p > 0.3$]. When the cutoff was lowered to 75% ($N=17$), priming rose to 16.9% and 16.4% in the full and divided attention conditions, respectively (both $p < 0.0005$), suggesting even when priming effects under full attention are large, priming effects under divided attention do not differ.

An ANOVA on sensitivity scores showed a main effect of encoding status [$F(2, 94) = 3.47$, $p = 0.04$]. Post-hoc helmert contrasts indicated higher sensitivity for previously presented objects compared to new objects [$F(1, 47) = 7.52$, $p = 0.009$], but no difference between objects presented in the full or divided attention conditions [$F(1, 47) = 0.09$, $p = 0.8$]. For bias scores, there was a marginal effect of encoding status [$F(2, 94) = 3.05$, $p = 0.055$. More negative C_L values indicate more bias to respond "possible". Thus, helmert contrasts showed that the bias to respond "possible" was greater for encoded objects relative to new objects [$F(1, 47) = 7.50$, $p = 0.009$], but there was no difference in bias for objects encoded under full or divided attention [$F(1, 46) = 0.27$, $p = 0.6$].

***Old/new* recognition test—**The percentage of hits and false alarms in the recognition test are displayed in Table 2. An ANOVA on corrected recognition scores (hits – false alarms) with encoding status (full vs. divided) and object type as variables revealed significantly lower recognition performance for objects encoded under divided attention than under full attention [$F(1, 31) = 19.02$, $p = 0.0001$]. In addition, recognition memory was lower for possible than for impossible objects [$F(1, 31) = 4.47$, $p = 0.04$]. Using d' or d_L as dependent variables yielded comparable results.

Discussion

In summary, Experiment 1 showed that dividing attention during left/right encoding of possible and impossible figures using the standard implementation of the digit-monitoring task substantially reduced explicit recognition memory for the objects, but had no effect on possible/impossible object-decision priming. There were comparable levels of priming, as measured by classification accuracy, for possible objects encoded under full and divided attention and no priming for impossible objects. Furthermore, the ability to discriminate between possible and impossible objects, as measured by sensitivity, and the bias to respond "possible" similarly increased for objects presented under full and divided attention compared to new objects.

These results extend previous findings using verbal material by showing that perceptual priming of novel visual objects remains intact when attention is divided using the digit-monitoring task (Mulligan, 1998, 2003; Mulligan & Hartman, 1996). The present findings are consistent with the distractor-selection hypothesis, which predicts no decrement in perceptual priming when responses to non-critical stimuli are required infrequently and the presentation of critical and non-critical stimuli does not occur in synchrony.

Experiment 2

Although similar levels of priming were found under full and divided attention in Experiment 1, it is possible that the memory representations that supported priming in the divided attention condition are more vulnerable to the effects of decay than the representations that supported priming under full attention. In other words, does priming for novel objects encoded under divided attention persist over time? Previous research has shown that priming for possible objects persists for at least one week. This may not be the case when attention is divided at encoding. Unlike priming for familiar stimuli, priming for novel stimuli requires the creation of new representations. It is possible that these new representations are less stable when they were established with limited attentional resources.

The rationale for examining the persistence of priming over time is provided by the finding that healthy older adults show normal priming in the possible/impossible object-decision test when tested immediately after encoding (Schacter, Cooper, & Valdiserri, 1992), but not when tested after a 20 min delay (Stern et al., 2000). Given that normal aging is thought to be associated with a reduction in central attentional resources or processing capacity (e.g., Anderson & Craik, 2000; Craik, 1982; Craik & Byrd, 1982), we hypothesized that the perceptual representations acquired by young subjects under divided attention might similarly deteriorate over time. This hypothesis was tested in Experiment 2 by introducing a 20 min delay between the encoding and test phases of the experiment. Additional support for the hypothesis that dividing attention during encoding might have similar effects on perceptual priming as normal aging comes from the finding that dividing attention and normal aging can have very similar effects on explicit memory performance (e.g., Anderson, Craik, & Naveh-Benjamin, 1998; Anderson et al., 2000; Castel & Craik, 2003; Craik, 1982; Dehon, 2006; J. M. Jennings & Jacoby, 1993), though differences are sometimes noted (e.g., Castel & Craik, 2003).

Method

Participants—Fifty-two students (33 females, 19 males) from Columbia University and Barnard College participated in this experiment in exchange for class credit or payment of $5. Four of these subjects were excluded from the analyses: three because their performance in the object-decision test did not differ from chance and one because of equipment failure. Subjects were randomly assigned to either the full or the divided attention conditions and encoding-to-test delay was manipulated within subjects.

Materials—The materials were identical to those used in Experiment 1.

Procedure—The procedure was the same as that used for subjects who completed the object-decision test in Experiment 1, except that attention was manipulated between subjects and a delay of 20 min was inserted between the first and second encoding phase. Thus, participants in both attention conditions viewed one set of 24 possible and impossible objects 20 min before the object-decision test, and another set of 24 objects immediately before the test. To ensure that activity during the delay period was constant across participants, they were administered a number of standard verbal neuropsychological tests. These tests were completed in the same order by all subjects and consisted of the: Selective Reminding Task (SRT), Nelson Adult Reading Test (NART), verbal fluency test (CFL), and the Letter-Number Sequencing sub-test of the WAIS III. As there was no relationship between the performance on these tests and performance in the possible/impossible object-decision test, they are not described in further detail.

Results

***Digit-monitoring* task—**Participants in the divided attention condition correctly identified 82% of the digit sequences during the first (delayed) encoding phase and 90% during the second (immediate) encoding phase [$t(23) = 3.02$, $p = 0.006$]. This represents a significant decrement in performance relative to performance under full attention (i.e., single task practice phase), both $p < 0.0005$].

Object-decision test—Subjects mean classification accuracy, bias, and sensitivity can be found in Table 3. For the accuracy data, a repeated measures ANOVA was performed with object type and study condition (studied immediate vs. studied delayed vs. new) as within subjects variables and attention as a between subjects variable. Overall accuracy was higher in the divided than in the full attention group [$F(1, 46) = 4.90$, $p = 0.03$]. The effect of study condition was significant [$F(2, 92) = 6.90$, $p = 0.002$, as was the interaction between study condition and object type [$F(2, 92) = 3.17$, $p = 0.05$]. However, attention did not interact with study condition [$p > 0.25$]. Separate ANOVAs for possible and impossible objects revealed no significant effects for impossible objects [all $p > 0.25$]. For possible objects, by contrast, there was an effect of study condition [$F(1, 46) = 8.33$, $p = 0.0003$], but again no interaction with attention [$p > 0.6$]. By post-hoc t-test, priming for possible objects was significant under full and divided attention at both the immediate and the delayed test [all $p < 0.05$]. Moreover, there was no difference in the magnitude of priming for possible objects in the immediate and delayed study conditions when the objects were encoded under full attention [$t(23) = 1.05$, $p = 0.30$]

or divided attention [$t(23) = 0.0$, $p = 0.99$]. When we excluded subjects performing close to ceiling for new possible objects (> 85%), the overall magnitude of the priming effect for possible objects was greater but it did not vary as a function of attention in either the immediate [M full = 13.54, SD = 19.79; M divided = 10.53%, SD=17.14; $t(29) = 0.45$, $p>0.6$] or delayed [M full = 8.68, SD = 12.49; M divided = 10.97%, SD = 15.42; $t(29) = 0.43$, $t > 0.6$] encoding conditions.

As in Experiment 1, there was an effect of study condition on sensitivity [$F(2, 92) = 11.30$, $p < 0.0001$], but no interaction with attention [$F(2, 92) = 0.01$, $p > 0.9$]. Sensitivity was higher for previously presented objects than for new objects [$F(1, 46) = 31.14$, $p <0.0001$, but did not differ in the immediate and delayed study conditions [$F(1, 46) = 0.18$, $p = 0.67$]. There was also an effect of study condition on bias [$F(2, 92) = 4.05$, $p = 0.02$], but no interaction with attention [$F(2, 92) = 0.34$, $p = 0.7$]. Like sensitivity, the bias to respond possible increased for studied relative to new objects [$F(1, 46) = 8.66$, $p = 0.005$], but did not differ as a function of delay [$F(1, 46) = 1.08$, $p = 0.31$]. By post-hoc t-test, the magnitude of priming, as measured by sensitivity or bias, did not differ in the immediate and delayed study condition for objects encoded under full attention (both $p > 0.2$) or under divided attention (both $p > 0.7$).

Discussion

The central finding from Experiment 2 is that even after a delay of 20 minutes, comparable levels of priming were obtained for possible objects encoded under full and divided attention. There were no effects of encoding or attention on performance of impossible objects. As in Experiment 1, both the ability to discriminate between possible and impossible objects (i.e., sensitivity) and the bias to call an object “possible” increased for previously presented objects compared to new objects. However, neither sensitivity, nor bias was influenced by attention or delay.

These findings suggest that at least for delays of up to 20 min, the representations that support priming in the possible/impossible object-decision test, even when acquired under divided attention, are relatively immune to the effects of memory decay. In this regard, perceptual priming of novel objects appears to operate like priming of familiar objects. For example, Parkin and Russo (1993) showed that perceptual priming of familiar pictures in the fragmented picture completion task was comparable for pictures encoded under full and divided attention following a 2-hour delay. The present results also suggest that the loss of priming in older participants at delays of 20 min or more may not stem from age-related deficits in central attentional resources at encoding.

The results from Experiments 1 and 2 are both consistent with the distractor-selection hypothesis, which predicts that perceptual priming should not be disrupted by a secondary task with infrequent response requirements and non-synchronized presentations of primary and secondary task stimuli. However, according to the distractor-selection hypothesis, when the critical and non-critial items do occur in synchrony or the non-critical items require frequent response selection during encoding of critical stimuli, deficits in perceptual priming are likely to occur. Consistent with the view, Mulligan (2003) showed that both an auditory and a visual version of the digit-monitoring task reduced word identification priming when the critical target words and non-critical stimuli were presented synchronously, even though responses to non-critical stimuli occurred infrequently (about every 8 sec). When response selection to non-critical stimuli occurred frequently (every 1 sec), precise synchrony of critical and non-critical stimuli was not necessary to reduce word identification priming (Mulligan, 2003).

The results of Mulligan (2003) appear to suggest that either synchrony of primary and secondary task stimuli or frequent response selection to secondary task stimuli during encoding of critical stimuli is sufficient to impair perceptual priming on the word-identification test.

Because the distractor-selection hypothesis was meant to provide a framework for understanding the apparent inconsistencies in the literature regarding effects of dividing attention on perceptual priming it is important to examine if these findings generalize to other stimuli and tasks. Therefore, Experiment 3 of the current study tested whether the presence of both of these conditions is sufficient to reduce perceptual priming in the possible/impossible object-decision test.

Experiment 3

The encoding task of Experiment 3 was identical to Experiments 1 and 2, but a different secondary task was used. There were several reasons for choosing a different secondary task in Experiment 3 rather than adapting the digit monitoring. First and foremost, we needed a task that would allow for a high response rate on each trial. This would not be possible with the digit monitoring task because in this task a series of stimuli must be presented across several trials before a response would be required and an actual response would probably only occur every 2 to 6 trials. Second, we wanted a secondary task that requires access to the central processing bottleneck not only in terms of its response selection demands but also in terms of the cognitive processes invoked by this task. According to Pashler's (1994) central bottleneck model, however, holding a concurrent memory load probably does not interfere with access to the central processing bottleneck. Third, we intended to implement a secondary task in which accuracy could be monitored on a trial-by-trial basis to ensure that subjects were indeed attending to the non-critical items.

A task that satisfied all three of our requirements was visual mental rotation. This task required subjects to determine whether two flanking digits, one presented to the left and one to the right of the object, were identical or mirror images of one another. Presentations of objects and digits were synchronized to ensure that response selection occurred during object encoding. The response frequency in the mental rotation task was relatively high with approximately 1 response every 1.2 sec (see results) and thus comparable to the response frequencies reported by Mulligan (2003). The process of mentally rotating an image has been shown to require access to the central bottleneck mechanism (Band & Miller, 1997; Ilan & Miller, 1994; J. R. Jennings, van der Molen, & Debski, 2003; Ruthruff, Miller, & Lachmann, 1995). Hence, it would be difficult to argue that any failure to find an effect of dividing attention in the present experiment was the result of low demands of the secondary task on central attentional resources.

Although a mental rotation task has not been used in studies directly supporting the distractor-selction hypothesis (Mulligan, 2003; Mulligan & Hornstein, 2000), it is still appropriate for testing what aspects of the distractor-selection hypothesis generalize to experimental paradigms other than word-identification priming. The reason is that the type of secondary task and the modality in which attention is modulated are thought to play little role in determining the effects of dividing attention on perceptual priming according to the distractor-selection hypothesis. Consistent with this view, Mulligan (2003) showed that an auditory and a visual version of the digit-monitoring task, a tone discrimination task, and a visual flanker task performed during word encoding produced similar decrements in word-identification priming, provided that response frequency to non-critical stimuli was high and/or critical and non-critical items were presented synchronously.

Experiment 3 also tested whether reducing the time available for object encoding increases the impact of dividing attention on perceptual priming, as suggested by Ganor-Stern et al. (1998). These authors showed that when possible and impossible objects were presented 5 times for 1 sec during encoding, reducing attention using a selective attention manipulation eliminated a negative priming effect for impossible objects (i.e., lower accuracy for encoded than new impossible objects), but had no effect on perceptual priming for possible objects.

When the objects were presented only 3 times for 1 sec at encoding, perceptual priming for possible objects was also reduced. However, because that study used a selective attention manipulation, which can affect both early and late processing stages, it is unclear whether those results extend to divided attention manipulations, where both primary and secondary task stimuli must be processed, such as that used in the present study.

In addition to using a divided rather than a selective attention manipulation, Experiment 3 of the present study improves upon several methodological aspects of the study by Ganor-Stern et al. (1998) to facilitate interpretation of the results. First, Ganor-Stern et al. (1998) manipulated attention between subjects, while the current experiment manipulated attention within subjects. This ensures that any differences between the full and divided attention conditions cannot be attributed to baseline differences between the experimental groups, as each subject serves as his or her own control. Second, Ganor-Stern et al. (1998) projected the object images on a screen and tested subjects in groups of up to 5, which would have prevented them from tightly controlling for visual angle. In this experiment, subjects were tested individually on a computer. Third, subjects in Ganor-Stern et al.'s (1998) study were given 4 sec to mark their responses on paper. This means that response latencies could not be monitored and were likely to be quite long. This is potentially problematic because long response latencies, compared to short ones, are more likely to be influenced by deliberate, strategic processes than by more automatic processes. However, it is the latter, not the former type of processes which are assumed to underlie perceptual priming. Fourth, Ganor-Stern et al. (1998) used different objects sets for the encoded and new conditions, rather than rotating objects across the experimental conditions. This means that item specific effects could have influenced their results. Fifth, Ganor-Stern et al. (1998) used a secondary task without objectively correct response categories. This means that accuracy in the secondary task could not be assessed and that subjects could have used different response criteria and strategies to perform the task, which are potentially associated with differential processing and attentional demands. In the current experiment, accuracy could be validly assessed on all trials of the secondary task. Finally, Ganor-Stern et al. (1998) observed reliable negative priming for impossible objects in both the 3 sec and the 5 sec full attention conditions, which was eliminated when attention was reduced. Although this suggests that reducing attention in the 5 sec encoding condition did reduce perceptual priming, this finding is difficult to interpret because reliable negative priming for impossible objects is not generally observed under standard test conditions. In the current study, more standard procedures, like those used in the original experiments by Schacter and Cooper were implemented to reduce the likelihood of observing atypical effects in the full attention condition.

Method

Participants—The data from 64 subjects were analyzed for Experiment 3. Half of them participated in the long encoding condition (two object exposures of 4 sec each) and half in the short encoding condition (one 4 sec exposure). The data from 6 additional subjects were excluded from the analysis because their performance in the object-decision test did not differ reliably from chance. All subjects were Columbia University or Barnard College students and participated either for course credit or payment of $10.

Materials—The possible and impossible objects were the same as in Experiment 1. The stimuli for the secondary tasks (i.e., mental rotation) consisted of two single digits flanking the object to the left and right. The digits 0 and 8 were not used because they are symmetrical about their vertical axis, and therefore identical in their normal and mirror-reflected presentations. The digit 9 was not used because it is identical to 6 when rotated 180 degrees. Each digit subtended approximately 8 degrees of visual angle when viewed at a distance of 50 cm. See Figure 2 for an illustration.

Procedure—The manner of presentation of the possible and impossible objects during the encoding and test phases of this experiment were identical to that of Experiment 1, with one exception: Subjects in the long encoding condition viewed the objects twice for 4 sec each, as in Experiments 1 and 2, whereas subjects in the short encoding condition were given a single 4 sec exposure. This represents a 50% reduction in encoding time, but still leaves sufficient encoding time for priming to occur. (A minimum of 2 or 3 sec appears to be necessary to obtain significant priming for possible objects when the number of items to be encoded is less than half of that in the present study (Ganor-Stern et al., 1998; Schacter, et al., 1991). Priming in the full attention condition was not expected to be affected by this encoding time manipulation, as possible/impossible object-decision performance has been shown to be equivalent after one and four 5-sec exposures to the left/right encoding task (Schacter et al., 1991). Also note that prior research indicates that distributing total encoding time over multiple exposures appears to have the same effect on possible/impossible object-decision priming as using a single long exposure (Schacter et al., 1991).

As in Experiment 1, attention was manipulated within subjects and the order of the full and divided attention encoding blocks was counterbalanced across subjects. There was no delay between the two encoding blocks. In the full attention encoding condition, subjects only performed the left/right encoding task. In the divided attention condition, subjects simultaneously performed the mental rotation task. The mental rotation task was implemented as a continuous-performance task, such that a new pair of digits was presented as soon as subjects responded to them, while the same object remained on the screen for the duration of the 4 sec trial. At the end of the trial, the object and the digits disappeared from the screen and subjects rated whether the object was primarily facing to the left or to the right. This ensured that selecting responses to the digits took place during encoding of the objects.

The two flanking digits were generated randomly and always represented the same number. Subjects were instructed to decide whether they were mirror-reflections of one another or not, irrespective of the digits' rotation in the horizontal plane. Subjects were asked to press the ‘z’ key if neither of the two digits or both digits were reflected across their vertical axis, indicating that they were “the same”. Alternatively, if only one of the two digits was reflected across its vertical axis, then they pressed the ‘/’ key, to indicate that the two digits were “different”, or mirror-reflections of one another (see Figure 2 for an example of a “different” trial). On each trial it was randomly determined, for each digit, whether it appeared in its canonical orientation, or “mirror-reversed” (reflected across the vertical plane), and how much it was rotated in the horizontal plane. The two digits were never rotated more than 60 degrees from their upright position, either clockwise (60 degrees) or counter-clockwise (300 degrees). The angle of rotation varied in 15-degree increments. These parameters were used as they permitted subjects to respond frequently while keeping accuracy relatively high. Greater angles of rotation significantly reduced accuracy and response frequency, as determined in a pilot experiment.

Subjects were asked to respond as quickly and accurately as possible to the digits while the object was on the screen. They were encouraged to respond to as many digits as possible, while paying enough attention to the objects to be able to accurately rate their left/right orientation at the end of the trial. Subjects were given 10 dual-task practice trials at the beginning of the divided-attention encoding phase using the same 5 practice objects as in the full attention condition. Immediately prior to the divided attention practice phase, subjects completed 40 digit-only trials to establish a full attention baseline rate of responding. The first 10 of these trials served as practice items and were not included in calculation of the baseline response rate. The trial structure of the digit-only trials was identical to the divided attention condition, with the exception that instead of an object, a fixation cross was displayed.

Results

Mental Rotation Task—Table 4 displays subjects' accuracy and response frequency in the mental rotation task under single and dual task conditions. Response frequency was calculated by dividing the stimulus presentation time (i.e., 4 sec) by the number of responses during that time window. For the long encoding condition, we averaged over the first and second presentation of stimuli. Because encoding time had no significant effect on mental rotation performance or on object-decision performance (see below), the data were collapsed across this variable for display purposes in all tables and figures. The mental rotation data were analyzed using repeated-measures ANOVA, with task (single vs. dual-task performance) as a within-subjects variable and encoding group (short vs. long) as a between-subject's variable. For accuracy, there were no significant effects or interactions (all $p > 0.5$) and for response frequency there was a main effect of task [$F(1, 62) = 76.71$, $p < 0.0001$]. This indicates that accuracy did not differ under single and dual task conditions, but response frequency decreased significantly under dual compared to single task performance for both encoding groups.

Object-decision test—Subjects mean classification accuracy, bias, and sensitivity in Experiment 3 are shown in Table 5. Accuracy in the possible/impossible object-decision test was analyzed with repeated-measures ANOVA with object type and encoding status as within subject variables and encoding time as a between subjects variable. As in the previous experiments, classification accuracy was higher for possible than for impossible objects [$F(1, 62) = 23.98$, $p < 0.0001$]. There was a main effect of encoding status [$F(2, 124) = 3.64$, $p = 0.03$] and an object type by encoding status interaction [$F(2, 124) = 6.59$, $p = 0.002$]. There was no main effect of encoding time and no interactions between encoding time and encoding status, indicating that this variable did not affect priming [all $p > 0.26$]. Post-hoc *t*-tests (collapsed across encoding time and order) revealed significant priming for possible objects under full [$t(63) = 4.43$, $p < 0.0001$] and divided attention [$t(63) = 3.82$, $p = 0.0009$], but no difference between these two conditions [$t(63) = 0.71$, $p = 0.48$]. There was no priming for impossible objects [both $p > 0.29$]. When the analysis was limited to subjects with classification accuracy of 85% or lower for new possible object, highly significant priming for possible objects occurred in the full attention condition ($M = 11.5\%$; $SD = 13.47$, $t(39) = 5.38$, $p < 0.0001$] and in the divided attention condition [$M = 9.17$; $SD = 14.69$; $t(40) = 3.95$, $p = 0.0005$) but there was no difference between the two conditions [$t(39) = 1.02$, $p > 0.3$].

The analysis of sensitivity scores showed an effect of encoding status [$F(2, 124) = 11.51$, $p < 0.0001$]. Post-hoc helmert contrasts indicated that sensitivity was higher for previously encoded objects [$F(1, 62) = 13.48$, $p = 0.0005$], but did not differ for objects encoded under full and divided attention [$F(1, 62) = 0.87$, $p = 0.36$]. Similarly, there was an effect of encoding status on bias [$F(2, 124) = 7.62$, $p = 0.0009$]. Post-hoc contrasts showed that the bias to respond “possible” increased for objects presented during encoding relative to new objects [$F(1, 62) = 15.68$, $p = 0.0002$], there was no difference in bias for objects viewed under full and divided attention [$F(1, 62) = 0.21$, $p = 0.65$].

Analysis across experiments: Effects of object complexity

None of the experiments in this study found an effect of object complexity on priming, even though we used some of the same objects as Carrasco and Seamon (1996). To confirm the absence of a complexity effect on priming, an analysis averaging across Experiments 1 and 3 was performed (N = 112). Contrary to the findings by Seamon and Carrasco, neither priming of possible or impossible objects was affected by object complexity, as indicated by a non-significant interaction between encoding status and complexity ($p = 0.7$). There was no priming for impossible objects of low, medium, or high complexity under full or divided attention (all $p > 0.36$), but priming of possible objects at all levels of complexity (all $p < 0.05$). Mean priming scores as a function of complexity are shown in Table 6.

Power Analysis

Because none of the divided attention manipulations in the three experiments reported here had an effect on priming, we examined the possibility that our experiments lacked sufficient power to detect such effects. To do so, we used the divided attention effect on recognition in Experiment 1 as a basis for computing statistical power in the possible/impossible object-decision test. We based this approach on the finding that the size of the divided attention effect in Mulligan's (2002) experiments was approximately the same on priming as on recognition memory. In the present study, the effect size of dividing attention on corrected recognition memory (i.e., proportion of hits minus false alarms), averaging across possible and impossible items was $d = 0.69$. The power to detect an effect this size on priming of possible objects was greater than 0.95 in each of the three experiments (N = 48 in Experiment 1, N = 24 in Experiment 2, and N = 64 in Experiment 3; alpha = 0.05, directional test). The power to detect an effect just half this size ($d = 0.34$), which would be considered a relatively small effect, was $d = 0.76$ in Experiment 1, $d = 0.50$ in Experiment 2, and $d = 0.86$ Experiment 3. Averaging across attention conditions in Experiment 2, the power to detect an effect of delay (d = 0.34) on priming for possible objects was 0.85. Finally, in the short encoding condition of Experiment 3, where we would have predicted the largest effect of attention, the power to detect an effect on priming of the size observed in the recognition test of Experiment 1 was 0.98 and the power to detect an effect half this size was moderate at 0.60 (N = 32, alpha = 0.05, directional test). This suggests that we had moderate to large power in all three experiments to detect an effect of attention on priming.

Discussion

The results form Experiment 3 showed that reducing attention within the visual modality using a secondary task with frequent response selection demands during stimulus encoding did not affect priming in the possible/impossible object-decision task. Equivalent priming of possible objects was obtained in the full and divided attention conditions and there was no priming for impossible objects in any condition. As in Experiments 1 and 2, exposure to possible and impossible objects in the left/right encoding task increased sensitivity and the bias to respond “possible” compared to non-encoded test objects. Again, there was no difference in sensitivity and bias for objects encoded under full and divided attention. Experiment 3 also demonstrated that reducing the time available for object encoding from a total of 8 to 4 sec had no effect on possible/impossible object-decision performance in either the full and divided attention conditions.

Taken together, these results demonstrate that perceptual priming of previously unfamiliar 3D objects is surprisingly impervious to the effects of dividing attention during encoding. A single exposure to a novel object while attention is divided produces similar levels of priming as multiple presentations to such an object under full attention.

The absence of an interaction between attention and encoding time suggests that selective (Ganor-Stern et al., 1998) but not divided attention manipulations may be sensitive to differences in encoding time. This would be consistent with the finding that selective attention manipulations appear to be more likely to produce deficits in perceptual priming than divided attention manipulations (see Mulligan, 2003 for a discussion of this issue). A potential reason could be that in situations where attention is directed away from the criical stimulus or stimulus dimension (i.e., selective attention), reducing encoding time increases the probability that early perceptual processing (such as structural encoding) of the critical stimuli is disrupted. In divided attention studies, by comparison, subjects are required to process the critical stimulus (dimension), such that reductions in encoding time are unlikely to have an impact on the early perceptual analysis of the critical target stimuli. In other words, decreasing encoding time in selective attention studies may have the effect of truncating perceptual processing, and as such affect perceptual priming via a different mechanism than dividing attention.

It is also possible that a further reduction in encoding time to 3 sec in the present study would reduce priming. Note though that 2 or 3 sec appear to be necessary to obtain priming for possible objects under full attention, leaving a relatively small window for the encoding time by attention interaction to emerge (D. L. Schacter et al., 1991). Also, Mulligan (2003, Experiment 2) showed that dividing attention reduced word identification priming when encoding time was as long as 2900 ms, suggesting that the 4000 ms used in this study is not unusually long, given the unfamiliar nature of the stimuli. Finally, the difference between the present results and those obtained by Ganor-Stern et al. (1998) may be related to the many procedural differences across the two studies, which were described before.

With respect to the distractor-selection hypothesis, Experiment 3 indicates that the two conditions thought to be most likely to disrupt memory encoding and subsequent perceptual priming (i.e., synchronous presentations of primary and secondary task stimuli and frequent response selection during critical stimulus encoding) are *not sufficient* for reducing perceptual priming in the possible/impossible object-decision task. These findings are important as they suggest that key predictions of the distractor-selection hypothesis do not generalize to some perceptual priming paradigms.

General Discussion

This study examined how dividing attention during encoding affects perceptual priming of unfamiliar visual objects in the possible/impossible object-decision test. Experiment 1 showed that priming was not affected when attention was divided using the traditional digit-monitoring task, which requires frequent updating of working memory but infrequent response selection and uses non-synchronized presentations of primary and secondary task stimuli. Explicit recognition memory, however, was reduced by the same attentional manipulation. Experiment 2 replicated the results from Experiment 1 and further showed that priming effects for novel objects encoded under divided attention are relatively stable over time, at least for up to 20 min. As such, the data from Experiments 1 and 2 extend prior research using verbal material or familiar objects and suggest that perceptual priming of novel visual objects is not more susceptible to the division of attention than perceptual priming of familiar stimuli. The results from Experiments 1 and 2 are also consistent with the distractor-selection hypothesis, which posits that perceptual priming should not be impaired when a secondary task has infrequent response requirements and non-synchronous presentations of critical and non-critical items.

However, not all predictions of the distractor-selection hypothesis appear to generalize to perceptual priming of novel 3D objects. Experiment 3 demonstrated that frequent response selection to non-critical stimuli during object encoding and synchronized presentations of objects and non-critical items are not sufficient for decreasing perceptual priming in the possible/impossible object-decision test. While this finding does not invalidate the distractor-selection hypothesis, it indicates that additional conditions must be met (besides frequent and simultaneous response selection to non-critical stimuli) in order for a secondary task to have an effect on perceptual priming.

Specifically, if it is correct that the mechanism by which frequent and contemporaneous response selection to non-critical items disrupts perceptual priming is by reducing access of the critical target to central-bottleneck dependent encoding processes, then increasing the reliance of a secondary task on central processes would be expected to increase the likelihood that perceptual priming is disrupted. This might be accomplished by increasing the difficulty of the secondary task, or by increasing the degree to which the secondary task, independent of its response selection demands, depends on central bottleneck-dependent processes. Thus, "cognitively-demanding" perceptual processes have been shown to require access to the central bottleneck and, therefore, would also be expected to interfere with central encoding operations. These include the manipulation of visual images (Jennings, van der Molen, & Debski, 2003; Reisberg, 1983; Ruthruff, Miller, & Lachmann, 1995) and difficult perceptual judgements (McCann & Johnston, 1989). Likewise, secondary tasks that strongly rely on memory retrieval and other response-related processes might reduce perceptual priming, as these processes have been shown to require access to the central processing bottleneck (Pashler, 1998; Band & Miller, 1997; Ilan & Miller, 1994; Jennings, van der Molen, & Debski, 2003; Ruthruff, Miller, & Lachmann, 1995). Future research is necessary for determining whether the manner in which a secondary task interferes with central processing is important in determining the effect of a secondary task on different types of perceptual priming tests and stimulus material. For example, the frequency and synchrony of response selection appear to be very important for word-identification priming but less so for possible/impossible object-decision priming.

It is important to note that although the three experiments reported here represent null findings regarding the effects of attention on perceptual priming, the results nonetheless provide new and important insights into the mechanisms mediating perceptual priming. In fact, to our knowledge, this is the first study to examine how dividing attention affects perceptual priming of unfamiliar visual objects. Based on the prior research using unfamiliar stimuli in perceptual priming tasks, one would have predicted a greater sensitivity to attentional manipulations for unfamiliar stimuli. Specifically, priming effects tend to be smaller for unfamiliar than familiar stimuli (e.g., Bowers, 1994; Goshen-Gottstein & Ganel, 2000; Stark & McClelland, 2000), suggesting that the memory representations mediating these priming effects are not very stable or robust and, by inference, more susceptible to reductions in attention. Furthermore, relatively long encoding times appear to be necessary to obtain priming for unfamiliar items, suggesting that considerable processing must occur at encoding to obtain later priming and that manipulations that impair these encoding processes (e.g., dividing attention) significantly impair priming. Finally, the study by Smith and Oskar-Berman (1990) indicated a greater vulnerability of pseudowords than words to the effects of dividing attention on lexical decision priming. This further supported the view that priming of unfamiliar objects would be very sensitive to the reduction of attention at encoding.

The results, however, appear to indicate that even strong divisions of attention that typically impair conceptual priming do not have an impact on perceptual priming of novel 3D objects. Such a finding could be sensible from an evolutionary perspective. Being able to quickly compute the structure of objects, whether familiar or not, is extremely helpful when interacting with the world. As such, perceptual priming of objects may represent a mechanism by which to optimize the perception of and responses to repeatedly occurring events in the environment even when attention is limited. Being able to quickly read or name words or pseudowords, by contrast, may be useful in modern societies, but would not confer an evolutionary advantage because pseudowords are not typically encountered and do not convey any meaningful information. Similarly, the lack of priming for structurally impossible objects may be related to the fact that these items are not typically encountered in daily life and, consequently, processed qualitatively differently than structurally possible objects (See Habeck et al., 2006; Schacter et al., 1995; Soldan, Mangels, Cooper, 2006; Soldan et al., 2008 for neuroimaging evidence for qualitatively different processing of possible and impossible objects).

The results from this study also have implications for theoretical accounts of performance in the possible/impossible object-decision test. Several theoretical models have been proposed to explain the finding that possible but not impossible objects show priming in the standard version of this test (Carrasco & Seamon, 1996; Marsolek & Burgund, 2005; Ratcliff & McKoon, 1995; Schacter et al., 1990; Williams & Tarr, 1997). According to Ratcliff and McKoon (1995), this differential priming effect can be explained by a model in which retrieval from explicit memory during the object-decision test phase plays an important role. Specifically, task performance is thought to be mediated by two processes: a bias to respond "possible" to all previously encoded objects and episodic memory for previously encoded object features. The bias increases classification accuracy for familiar possible objects and decreases classification for familiar impossible objects compared to new possible and impossible objects, whereas episodic memory improves classification accuracy for both stimulus types. Thus, when the effects of bias and explicit memory are combined, there is no change in classification accuracy for encoded compared to new impossible objects and a robust enhancement in classification accuracy for encoded possible objects. Consistent with this proposal, Ratcliff and McKoon (1995) showed that manipulations during the object-decision test phase that presumably reduce retrieval from explicit memory reveal the predicted bias pattern of responding.

Consistent with Ratcliff and McKoon's (1995) two-process model, the present study found that encoding of possible and impossible objects enhanced the bias to respond "possible" in all experiments. However, dividing attention during encoding had no effect on object decision performance, whether measured in terms of accuracy, bias, or sensitivity, even though it substantially reduced explicit memory for both types of objects (Experiment 1). These data do not support Ratcliff and McKoon's (1995) two-process model, which would have predicted an increase in bias in the divided compared to the full attention encoding condition. One important difference between the experiments reported in this study and those reported by Ratcliff and McKoon is that Ratcliff and McKoon (1995) used retrieval manipulations to decrease explicit memory, thus precluding a direct comparison between their results and the present ones. Notably though, Ratcliff and McKoon (1995) provided no measure that episodic memory was indeed reduced by their manipulations, leaving open the possibility that their results can be attributed to effects other than explicit memory (for a discussion of this issue, see Schacter & Cooper, 1995 and the reply by McKoon & Ratcliff, 1995).

The results from this study, however, are consistent with a host of prior studies documenting dissociations between possible/impossible object-decision priming and explicit recognition tests using encoding manipulations (e.g., Schacter & Cooper, 1993; Schacter et al., 1990), study-to-test object transformations (L. A. Cooper, Schacter, Ballesteros, & Moore, 1992; Schacter, Cooper, & Treadwell, 1993), a selective attention manipulation (Ganor-Stern et al., 1998), and subject populations with impaired episodic memory (Schacter, Cooper, Tharan, & Rubens, 1991; Schacter et al., 1993; Schacter et al., 1992). Based on these dissociations, Schacter, Cooper, and colleagues interpreted the differential priming effects of possible and impossible objects to arise from the operation of a *structural description system*, a perceptual mechanism that can operate independently of episodic memory and is specialized for processing the three-dimensional (3D) structure of visual objects. Although possible parts of impossible objects are thought to be processed by and represented in the structural description system, priming in the possible/impossible object-decision test is thought to depend on access to information about the global organization of object parts (D. L. Schacter et al., 1991). Because impossible objects lack a globally coherent 3D geometry, possible/impossible object-decision priming can be observed for possible but not impossible objects, according to this model. Although this model was not directly evaluated in this study, the present results are consistent with it.

The findings from this study also bear on a third model of possible/impossible object-decision priming. Carrasco and Seamon (Carrasco & Seamon, 1996; Seamon & Carrasco, 1999) proposed that the magnitude of priming in the possible/impossible object-decision test depends on the subjective complexity of the objects: as object complexity decreases, priming increases, both for possible and for impossible object. Priming for impossible objects is not typically observed because they tend to be much more complex than possible objects, as measured by subjective ratings and objective criteria. When Carrasco and Seamon equated the subjective complexity of possible and impossible objects at a moderate level, they found priming for both item types. These findings led Carraco and Seamon to conclude that the priming of impossible objects is either based on parts-based structural descriptions or that the structural-description system is capable of representing global structural descriptions of both possible and impossible objects, provided the objects are not highly complex.

The present results found no support for the view that object complexity affects priming in the possible/impossible object-decision test: similar priming was observed for possible objects at all levels of complexity and no priming occurred for impossible objects at any level of complexity. The reason for the discrepancy between the present results and those by Carrasco and Seamon are unclear, but could be related to the small number of stimuli in the studies by Seamon and Carrasco. Thus, the low complexity impossible objects for which priming was observed consisted of only 5 objects (Seamon & Carrasco, 1999) or 6 objects (Carrasco & Seamon, 1996). When the number of objects is this low, it becomes increasingly likely that item-specific effects influence the results. Given that Carrasco and Seamon did not rotate their stimuli through the different experimental conditions to restrict the influence of such item specific effects, it is possible that their findings do not generalize to other low complexity impossible objects. The present study included a greater number of stimuli and rotated them through the experimental conditions, thus minimizing item-specific findings. This strongly suggests that possible/impossible object-decision priming is not influenced by object complexity, at least within the range examined here, and that the effects of dividing attention during encoding on priming are the same for objects of varying complexity.

In conclusion, perceptual priming of unfamiliar 3D objects does not appear to be more vulnerable to the reduction of attention at encoding than perceptual priming of familiar items. Although priming of familiar and unfamiliar objects was not compared directly, strong divisions of attention that affect conceptual, but not perceptual implicit memory of familiar stimuli also did not affect possible/impossible object-decision priming. Furthermore, this study indicates that the effects of dividing attention during encoding on perceptual priming of unfamiliar objects are not solely a function of the response frequency to non-critical stimuli during encoding of critical target stimuli and the synchrony of critical and non-critical stimulus presentations, but that other factors must play an important role.

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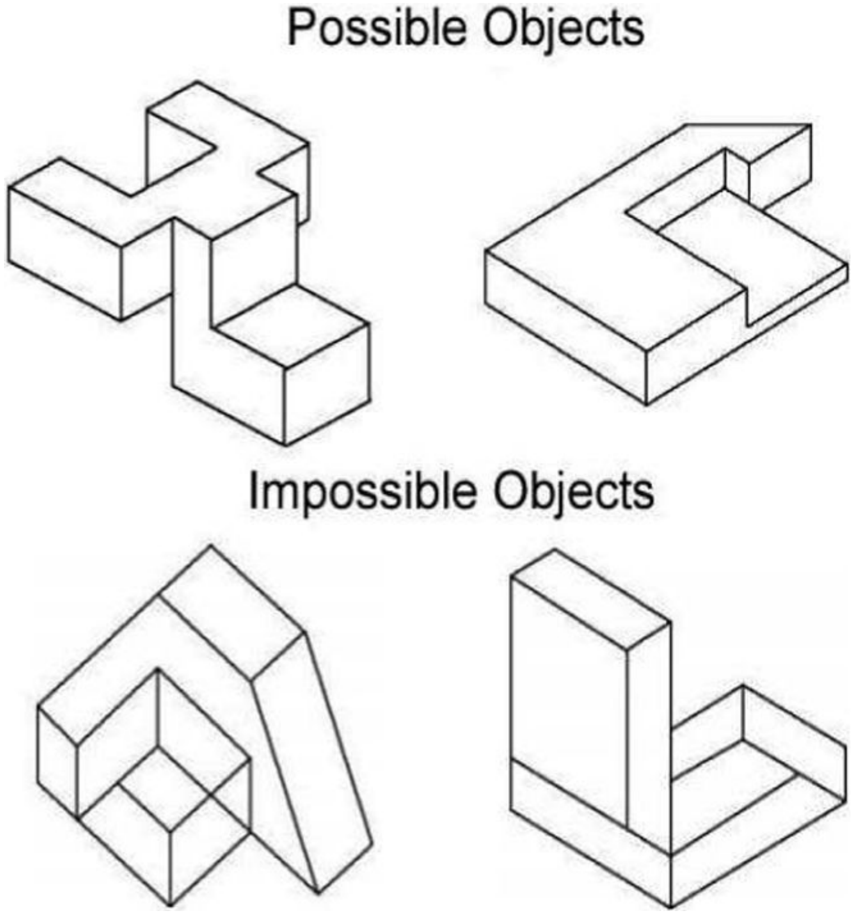

Figure 1.
Examples of possible and impossible figures used in this study.

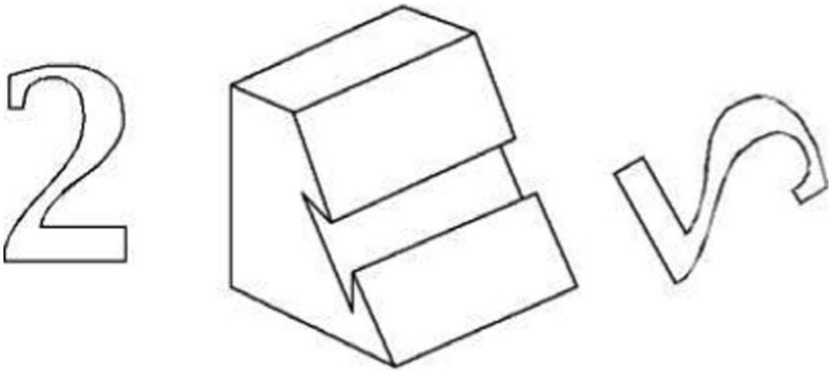

Figure 2.

Experiment 3: Example display of objects and digits in divided attention condition.

Table 1

Experiment 1: Mean object-decision accuracy and signal detection measures. Standard error of the mean appears in parentheses. In the divided attention condition, subjects performed the digit-monitoring task.

	Old Objects		**New Objects**
	Full Attention	**Divided Attention**	
Percent Correct			
Possible objects	82.1 (2.4)	82.1 (2.3)	75.9 (2.8)
Impossible objects	76.6 (2.8)	76.0 (2.6)	78.3 (2.2)
Signal-detection measure			
Sensitivity (D_L)	3.7 (0.3)	3.6 (0.3)	3.0 (0.2)
Bias (C_L)	−0.2 (0.2)	−0.3 (0.2)	0.0 (0.1)
Priming (old — new)			
Accuracy - possible objects	6.3 (2.0)	6.3 (2.0)	
Accuracy - impossible objects	−1.7 (2.3)	−2.3 (2.3)	
Sensitivity (D_L)	0.7 (0.3)	0.6 (0.3)	
Bias (C_L)	−0.3 (0.1)	−0.3 (0.1)	

Table 2

Experiment 1: Mean old/new recognition performance for object viewed under full and divided attention. Standard error of the mean appears in parentheses. In the divided attention condition, subjects performed the digit-monitoring task.

	Old Objects		**New Objects**
	Full Attention	**Divided Attention**	
Possible objects			
Percent “old” responses	64.1 (4.3)	46.1 (3.7)	19.7 (2.8)
Hits — false alarms	44.3 (5.7)	26.4 (4.0)	
Impossible objects			
Percent “old” responses	60.9 (3.4)	45.3 (3.1)	24.6 (3.2)
Hits — false alarms	36.3 (4.1)	20.7 (2.9)	

Table 3

Experiment 2: Mean object-decision accuracy and signal detection measures. Standard error of the mean appears in parentheses. In the divided attention condition, subjects performed the digit-monitoring task.

	Old Objects		New Objects
	No Delay	20-min Delay	
Full Attention			
Proportion Correct			
Possible objects	89.9 (2.5)	87.2 (3.1)	81.9 (3.1)
Impossible objects	76.7 (3.2)	78.5 (2.8)	79.0 (2.2)
Signal-detection measure			
Sensitivity (d_L)	4.3 (0.5)	4.1 (0.4)	3.0 (0.2)
Bias (C_L)	−0.7 (0.2)	−0.5 (0.2)	−0.2 (0.1)
Priming (old — new)			
Accuracy — possible objects	8.0 (3.2)	5.2 (2.2)	
Accuracy — impossible objects	−2.2 (2.7)	−0.5 (2.5)	
Sensitivity (D_L)	1.3 (0.5)	1.1 (0.4)	
Bias (C_L)	−0.5 (0.2)	−0.3 (0.2)	
Divided Attention			
Proportion Correct			
Possible objects	81.6 (3.4)	81.6 (2.8)	72.9 (3.3)
Impossible objects	77.1 (2.8)	78.5 (2.7)	73.3 (3.0)
Signal-detection measure			
Sensitivity (d_L)	3.6 (0.4)	3.5 (0.3)	2.4 (0.3)
Bias (C_L)	−0.3 (0.2)	−0.2 (0.2)	−0.1 (0.2)
Priming (old — new)			
Accuracy — possible objects	8.7 (3.2)	8.7 (3.1)	
Accuracy — impossible objects	3.8 (3.1)	5.2 (2.2)	
Sensitivity (D_L)	1.2 (0.4)	1.1 (0.3)	
Bias (C_L)	−0.3 (0.2)	−0.2 (0.1)	

Table 4

Experiments 3: Mean accuracy and response frequency in mental rotation task. Standard errors of the mean are given in parentheses.

	Accuracy (%)	**Response Frequency**
Single task baseline	88.7 (1.0)	4.0 (0.1)
Dual task encoding	88.5 (1.1)	3.4 (0.1)

Table 5

Experiment 3: Mean object-decision accuracy and signal detection measures. Standard error of the mean appears in parentheses. In the divided attention condition, subjects performed the mental rotation task.

	Old Objects		**New Objects**
	Full Attention	**Divided Attention**	
Percent Correct			
Possible objects	84.9 (1.7)	83.7 (1.9)	77.5 (1.8)
Impossible objects	69.1 (2.6)	67.8 (2.6)	69.8 (2.1)
Signal-detection measure			
Sensitivity (D_L)	3.6 (0.3)	3.4 (0.3)	2.6 (0.2)
Bias (C_L)	−0.5 (0.1)	−0.6 (0.1)	−0.2 (0.1)
Priming (old — new)			
Accuracy - possible objects	7.4 (1.7)	6.2 (1.6)	
Accuracy - impossible objects	−0.7 (1.8)	−1.9 (1.8)	
Sensitivity (D_L)	1.0 (0.2)	0.8 (0.2)	
Bias (C_L)	−0.3 (0.1)	−0.4 (0.1)	

Table 6

Complexity analysis across Experiments 1 and 3: Mean priming scores (percent correct old — new) for possible and impossible objects as a function of subjective object complexity, averaging across Experiments 1 and 3 (N = 112). Standard error of the mean appears in parentheses.

	Old Objects	
	Full Attention	**Divided Attention**
Possible objects		
Low complexity	5.1 (2.1)	5.2 (2.0)
Medium complexity	7.3 (2.8)	9.9 (2.7)
High complexity	5.2 (2.3)	6.2 (2.2)
Impossible objects		
Low complexity	2.2 (2.8)	0.0 (2.8)
Medium complexity	0.4 (2.5)	−2.2 (2.4)
High complexity	−1.1 (2.8)	−1.4 (2.9)