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On the relationship between repetition priming and recognition memory: Insights from a computational model ☆

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Abstract

A single-system model of repetition priming and recognition memory is presented, which is conceptually similar to signal-detection theory. Key assumptions of the model are (a) that the same memory source contributes to both priming and recognition performance and (b) that variance of the noise associated with priming measures is greater than recognition. To test the model, four experiments were conducted examining the effects of a manipulation of attention at study on priming and recognition performance. The model predicted that (1) effects of attention will be observed on priming and recognition, albeit larger for recognition, (2) the magnitude of priming will not exceed recognition in any condition, and (3) priming and recognition performance will be weakly correlated. Predictions (1) and (2) were confirmed by the experiments, and some evidence for (3) was obtained, providing support for the model.

Keywords: Repetition priming; Recognition; Attention; Implicit; Computational model

Introduction

The relationship between repetition priming and recognition memory has played an important role in the development of theories of memory. Repetition priming refers to a change in identification, detection or production of an item (e.g., a word) as a result of prior exposure to the same or a similar item. For example, in a perceptual identification task, items are presented extremely briefly and priming can be shown if a greater proportion of old (previously studied) items are identified relative to new (non-studied) items (e.g., Jacoby & Dallas, 1981). Priming is often compared with performance in recognition tasks in which participants attempt to discriminate between old and new items.

An influential view is that priming and recognition are mediated by functionally independent and neurally distinct implicit/procedural and explicit/declarative memory systems respectively (Gabrieli, 1998; Squire, 1994). Consistent with this view, many dissociations between priming and recognition have been reported. For example, priming can be spared in amnesic individuals despite severely impaired recognition performance relative to normal adults (e.g., Graf, Squire, & Mandler, 1984; Hamann & Squire, 1997a, 1997b). The reciprocal dissociation of intact recognition memory and impaired priming has also been reported in

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individuals with occipital lobe damage (Gabrieli, Fleischman, Keane, Reminger, & Morrell, 1995; Keane, Gabrieli, Mapstone, Johnson, & Corkin, 1995), constituting a double dissociation between priming and recognition in these individuals and amnesics. Furthermore, functional dissociations have also been reported in controls, for example, deeper levels of processing of study items can effect recognition memory but have little or no effect on priming (e.g., Jacoby & Dallas, 1981; for reviews see Richardson-Klavehn & Bjork, 1988; Roediger & McDermott, 1993).

Contrary to the multiple-systems view, single-system accounts of priming and recognition explain dissociations such as these in terms of the unique ways in which different memory tasks make demands on a common underlying system (Buchner & Wippich, 2000; Kinder & Shanks, 2001, 2003; Shanks & Perruchet, 2002). For example the simple recurrent network (SRN) model, a single-system connectionist model of priming and recognition (Kinder & Shanks, 2001, 2003), has been shown to account for the double dissociation shown in amnesics and occipital-lobe-damaged individuals. Kinder and Shanks (2003) assumed that amnesics have a generalised learning deficit and that occipital lobe damaged individuals have a deficit of visual processing. The presentation of items in the perceptual identification task was simulated by inputting them to the SRN in degraded form relative to recognition. A double dissociation emerged from the SRN through the way that these factors interacted with the encoded memory representation. Similarly, in normal adults, other single-system models have been successful in accounting for functional dissociations (see Shanks, 2005; Shanks & Perruchet, 2002; Shanks, Wilkinson, & Channon, 2003; Zaki, Nosofsky, Jessup, & Unverzagt, 2003).

In this article, we add to the single-system account of priming and recognition by considering whether the effects of an attentional manipulation at study on priming and recognition can be accounted for by a single-system computational model. In the past, manipulations of attention at study have produced patterns of priming and recognition performance that may be challenging for a single-system account and we now briefly review some of this evidence.

Effects of attention on priming and recognition

Recognition performance for less-attended study items is typically impaired compared to attended items. For example, if participants must perform a concurrent task during the study phase, if attention is diverted away from a target to a different spatial location, or if working memory is loaded during the study phase, then recognition performance is typically impaired relative to non-divided attention conditions. The evidence regarding the influence that attentional manipulations at study have on priming, however, is mixed. Some studies have dissociated priming and recognition with attentional manipulations, finding effects on recognition but none on priming (Jacoby, Woloshyn, & Kelley, 1989; Kellogg, Newcombe, Kammer, & Schmitt, 1996; Mulligan & Hartman, 1996; Parkin, Reid, & Russo, 1990; Parkin & Russo, 1990; Russo & Parkin, 1993; Schmitter-Edgecombe, 1996a, 1996b; Szymanski & MacLeod, 1996; Wolters & Prinsen, 1997). Many of these studies have used dual-task manipulations at study (see below). In contrast, studies that have found effects on priming (Bentin, Moscovitch, & Nirhod, 1998; Berry, Shanks, & Henson, 2006; Crabb & Dark, 1999; Crabb & Dark, 2003; Eich, 1984; Hawley & Johnston, 1991; Johnston & Dark, 1985; MacDonald & MacLeod, 1998; Mulligan, 2002, 2003; Phaf, Mul, & Wolters, 1994; Rajaram, Srinivas, & Travers, 2001; Stone, Ladd, Vaidya, & Gabrieli, 1998; Stone, Ladd, & Gabrieli, 2000) often use selective attention manipulations at study. But despite this inconsistency, it is fairly clear that attentional effects are weaker on priming than on recognition.

Considering dual-task manipulations, Parkin et al. (1990), for example, required participants to carry out a sentence verification task (decide whether visually presented sentences made sense) under full- or divided-attention conditions at study. In the full attention condition, participants simply carried out the verification task. In the divided attention condition, participants carried out the verification task but also monitored a series of tones, occurring randomly every 3–7 s, and indicated for each one whether it was high, medium or low in pitch. Recognition performance was impaired by the manipulation, whereas priming in a word-fragment completion task was significant and unaffected by the study manipulation. This dissociation was interpreted by Parkin et al. (1990) within the implicit-explicit memory distinction to suggest that priming (a form of implicit memory) does not depend on attention at encoding, but recognition (a form of explicit memory) does. Similar conclusions from dissociations such as this have been drawn by other researchers (e.g., Kellogg et al., 1996; Parkin & Russo, 1990; Szymanski & MacLeod, 1996; Wolters & Prinsen, 1997).

This finding is typical of studies that manipulate attention at study by requiring participants to perform some concurrent task (e.g., tone-monitoring, digit-monitoring, performing addition sums, or maintaining a string of digits in working memory). Under these types of study conditions, priming has been found to be unaffected relative to full-attention conditions as measured in perceptual priming tasks such as word-fragment-completion (Mulligan, 1998; Mulligan & Hartman, 1996), fame-judgments (Jacoby et al., 1989), picture-fragment completion (Parkin & Russo, 1990), word-stem completion (Schmitter-Edgecombe, 1999; Wolters & Prinsen, 1997), lexical decision (Kellogg et al., 1996), and perceptual identification (Mulligan, 2003, Experiment 1; Schmitter-Edgecombe, 1996a, 1996b; but see Mulligan, 2003, Experiments 2–4).

Other studies finding dissociations have employed Stroop manipulations at study, where either the word (full attention condition) or the colour of the text (reduced-attention condition) is named at study. For example, Szymanski and MacLeod (1996) found no effect of attention on priming in a lexical decision task despite impaired recognition performance, and took this result to support the distinction between implicit and explicit memory. However, it should be noted that Stone et al. (1998) did not replicate this result with a perceptual identification task, and instead found that priming in this task was severely reduced in the colour naming condition relative to the word-naming condition (see also Mulligan & Hornstein, 2000; Rajaram et al., 2001). Stone et al. (2000) also found similar effects with this study manipulation for word-fragment completion and for preference priming tasks. Effects from the Stroop task are therefore mixed.

Other studies have used manipulations of selective attention, in which attention is diverted from the target stimulus to distractor stimuli that are presented synchronously at study. For example, Phaf et al. (1994) presented a pair of words, one to the left and one to the right of fixation, on each study trial. After a 200 ms delay, one of the words was cued with an arrow and participants were instructed to read this word aloud. The offset of the stimulus display was triggered by the onset of the vocal response. In subsequent perceptual-identification and word-stem completion tasks, significant priming for cued and uncued (non-arrowed) words was obtained, but priming for uncued words was less than that of cued words. Similarly, other studies using selective attention manipulations have reported decrements in priming as measured by tasks such as lexical decision (Bentin et al., 1998), perceptual identification (Crabb & Dark, 1999, 2003; Mulligan & Hornstein, 2000, Experiment 4; Mulligan, 2002, Experiment 2), the homophone spelling task (Eich, 1984), perceptual clarification (Johnston & Dark, 1985), word-stem completion (Crabb & Dark, 1999), naming latencies (MacDonald & MacLeod, 1998), and contrast judgments (Berry et al., 2006). Thus, with regard to functional dissociations, the evidence suggests that selective attention manipulations are more likely to have effects on priming, whereas dual-task manipulations are more likely to produce dissociations. We return to this possible difference between selective and dual-task manipulations in the General Discussion.

Priming in the absence of recognition

Another pattern of priming and recognition performance that may be challenging for a single-system model to explain are reports of priming for less-attended items occurring in the absence of recognition in normal adults (e.g., Bentin et al., 1998; Eich, 1984; Johnston & Dark, 1985; Merikle & Reingold, 1991; Vuilleumier, Schwartz, Duhoux, Dolan, & Driver, 2005). This type of finding is also evidence for what is arguably a defining characteristic of implicit memory—that its contents are not accessible to awareness (Schacter, 1987). Studies that have obtained this dissociation have typically employed selective-attention manipulations of attention at study. For example, in an early study by Eich (1984), participants shadowed prose presented to one ear in a dichotic listening task. To the non-shadowed ear, pairs of words were presented, consisting of a homophone and a context word, such as TAXI-FARE, which was intended to bias the meaning of the homophone to its less common meaning. At test, participants were presented with old or new homophones and were asked to make a recognition judgment or to spell the word. Recognition memory was at chance for the non-shadowed homophones, but participants were more likely to spell them in their less common form (i.e., FARE rather than FAIR) than would be expected by chance, which suggests an unconscious influence of memory.

A similar finding was obtained by Merikle and Reingold (1991) using a visual analogue of Eich's study phase. They presented pairs of words visually, one above the other, for brief durations at study. On each trial, attention was diverted away from one of the words to the other word by cuing one word with arrows and requiring this word to be read aloud by participants. At certain points in the test phase, priming for uncued words in a contrast judgment task was found to be greater than recognition memory, which was at chance (Merikle & Reingold, 1991; but see Berry et al., 2006). Bentin et al. (1998) presented pairs of words on each trial but cued one of the pair members by presenting it in a certain colour. They also found priming for uncued words in a lexical decision task when recognition memory was close to chance. A finding of priming in the absence of recognition seems inconsistent with a single-system account (but see Whittlesea & Price, 2001): if priming and recognition depend on the same memory representation, and recognition tasks are more sensitive to this representation, then priming should not occur when there is no recognition memory.

Correlations between priming and recognition

Another finding that is often regarded as evidence for separate priming and recognition systems is that performance between the two tasks is very weakly or not correlated (Ostergaard, 1992; Parkin & Russo, 1990; Tulving, 1999). This would appear difficult for a single-system model to explain; if priming and recognition depend on the same memorial representation then why is it often the case that performance is not correlated? Ostergaard (1992) has suggested that only a small proportion of the variance in priming task performance is due to memory, and that priming task performance may be affected by many more non-memorial processes than recognition, a task which is considered to be a relatively pure measure of memory. As a result, correlations between priming and recognition performance will be low or close to zero, even though they may depend on the same memorial representation. One purpose of this study is to investigate correlations between priming and recognition both empirically and in a model in which it is assumed that only a small proportion of variance is due to memory.

In summary, manipulations of attention have produced three types of results that may be challenging for a single-system model (a) effects of attentional manipulations on recognition but not priming, (b) priming in the absence of recognition, and (c) lack of correlations between performance on priming and recognition tasks. In the next section we present a simple model of priming and recognition that does not incorporate an implicit–explicit distinction. We then report experiments in which attention was manipulated at study to examine the effects on recognition (with old/new judgments) and priming in the perceptual identification task. Finally, we show that the single-system model can account for the experimental findings.

Perceptual identification was used as the priming task because (a) it has been evaluated favourably as a perceptual implicit memory task (Roediger & McDermott, 1993), (b) it has been reported to have a reliability that is higher than many other implicit memory tasks (Buchner & Wippich, 2000), (c) the task is frequently used to compare priming with recognition performance, and (d), as we detail in the Methods section, perceptual identification performance can be measured using the same response metric as recognition performance.

Although there are obvious differences in the manner of presentation of stimuli in each task (i.e., in degraded form vs. not degraded), and also in the type of response (i.e., production of a word vs. old/new), measuring performance using the same response metric serves to increase the comparability of the tasks. This is advantageous because when the tasks are not directly comparable (e.g., in terms of response metric, or retrieval cues), it could always be argued that dissociations between the tasks are artefacts of the task differences. For the above reasons, we regard dissociations between recognition and priming in the perceptual identification task as particularly compelling evidence for multiple memory systems and therefore use these tasks in this study.

A single-system model of priming and recognition

The model presented here is conceptually very similar to standard signal detection models of recognition judgments (Pike, 1973; Ratcliff & Murdock, 1976; Stretch & Wixted, 1998), and extends previous work with this type of model (Shanks, 2005; Shanks & Perruchet, 2002; Shanks et al., 2003). It should be noted here that the model is not one of the priming and recognition tasks themselves, but of the influence of memory on them. The model assumes that, at test, both old and new items are associated with a variable called familiarity f. f is a normally distributed random variable:

$$f \sim N(\mu, \sigma_f) \qquad (1)$$

which, because of prior exposure, is assumed to have a greater mean value for old items (μ_{old}) than for new items (μ_{new}). For a given item, the same value of f contributes to both recognition and priming tasks (which is what makes it a single-system model). The difference between recognition and priming tasks concerns the amount of decision noise in each task. The judgment made during a recognition task depends on the variable J_r:

$$J_r = f + e_r \qquad e_r \sim N(0, \sigma_r) \qquad (2)$$

where e_r is another normally distributed random variable with mean of zero and standard deviation of σ_r that represents task-specific sources of noise in the recognition task. Likewise, the judgment made during a priming task like perceptual identification depends on the variable J_p:

$$J_p = f + e_p \qquad e_p \sim N(0, \sigma_p) \qquad (3)$$

where e_p is an independent source of noise to e_r and σ_p is the standard deviation of the task-specific sources of noise in the priming task. For the present purposes, we restrict the measure of priming to accuracy in a perceptual identification task (though other linear transformations of J_p can be used to simulate reaction times instead, e.g., Shanks et al., 2003). This is because we want to be able to compare performance on the priming and recognition tasks using exactly the same metric.

To simulate accuracy in recognition, J_r is compared against a criterion value, C. If the value of J_r for a given item exceeds the criterion, then the item will be called "old", otherwise the item will be called "new". In principle C is free to vary, however, for the sake of simplicity, the criterion used here is set to the midpoint between the means of the old and new familiarity distributions, i.e., $(\mu_{new} + \mu_{old})/2$.

The simulation of accuracy in the perceptual identification task is slightly different to that of recognition. First, a constant T is added to the value of J_p for each item presented at test, where T represents a boost in familiarity resulting from the presentation of the item in degraded form at test. Boosting the familiarity of the test item, regardless of its old/new status, is similar to the manner in which the effects of perceptual identification exposures are simulated in other models such as REMI (Schooler, Shiffrin, & Raaijmakers, 2001) and the counter model (Ratcliff, Ratcliff, & McKoon, 1997). T is temporary in the sense that, after the test trial has been simulated, J_p returns to its previous value. To determine the participant's response, the presented item's value of J_p is compared to the values of J_p of all of the other N items in the test phase of the Experiment being simulated, plus an extra N items representing non-test items (which have J_p values that are derived in an identical manner to new items). The extra N items are supposed to represent the other words in a participant's vocabulary (albeit crudely). In other words, a competition takes place in parallel between all items in the participant's vocabulary, and the item with the greatest value of J_p is output for response (Nosofsky, 1985; Thurstone, 1927).[1]

Despite their different mechanisms, identification trials, like recognition trials, can still be classified using signal detection terms: In identification, the subject's goal is to accurately identify each item. Sensitivity to the influence of memory can be shown in the task if the proportion of correct identifications to old items is greater than new items. Thus, if the item being presented is old and is also chosen as output for a response, then the item is classified as a hit (because a positive response, in the form of a correct identification, is made to an old item). If the item being presented is new and is also chosen to be output as a response, then the item is classified as a false alarm (because a positive response is made to a new item).

Unlike the absolute criterion that is employed in the simulation of the recognition data, the decision process in identification uses a relative criterion (because whether an item is output for a response depends on the J_p values of the other items that are being compared). Other models of identification also use a relative criterion. For example, there are some similarities between our model of identification and the counter model designed by Ratcliff et al. (1997). The counter model simulates the identification process using counters to represent words. When a word is flashed for perceptual identification, counts are accumulated in the counters according to the perceptual evidence from the flash and also from random noise. The counter which surpasses the maximum of the others by a criterion number of counts is output for response.

The counter model, and also other models of identification, for example, REMI, designed by Schooler et al. (2001), give detailed accounts of the mechanisms involved in identification, and can account for a range of priming results. For example, both the counter model and REMI can take into account the effects of visual similarities between items, a factor which affects identification performance (e.g., Ratcliff et al., 1997). The model presented here, however, is not intended as a detailed mechanistic account of the processes involved in perceptual identification: By simulating the influence of memory upon task performance, the model is intended to serve primarily as an avenue through which the common f variable can be mapped onto both a recognition and an identification response.

Note that the calculation of J has been framed in terms of sequential drawing from two distributions (first from the old/new familiarity distribution, then from the task-specific noise distribution) to illustrate the conceptual distinctions in the model. The model as presented above applies when the old items that appear in priming and recognition tasks are identical: the only difference in the calculation of J for each task is the addition of task specific noise to an item's value of f. However, when the items that appear in each task are different (i.e., as is the case in the experiments reported below in which there is no repeat presentation of items across test phases), the values of f in each task can be considered independent of one another. In other words, the values of J can be simulated by drawing from a single normal distribution for priming, and a single normal distribution for recognition:

$$J_{\mathrm{r,old/new}} \sim N(\mu_{\mathrm{old/new}}, \mathrm{sqrt}(\sigma_{\mathrm{f}}^2 + \sigma_{\mathrm{r}}^2)) \quad (4)$$

$$J_{\mathrm{p,old/new}} \sim N(\mu_{\mathrm{old/new}}, \mathrm{sqrt}(\sigma_{\mathrm{f}}^2 + \sigma_{\mathrm{p}}^2)) \quad (5)$$

Importantly, though this formulation of the model may look like a dual-system instantiation, this interpretation would be a mistake; there is no scope in this model for experimental manipulations to affect the distributions of familiarity independently for each task (i.e., the mean of the old item familiarity distributions are the same for each task in this model). Put differently, this description of the model leaves open the possibility that an experimental manipulation could affect μ_{old} differently in Eqs. (4) and (5), yet this is precisely what our single-system precludes. Our reference to the model in this paper as a single-system model reflects our conceptual framework for memory—that is that the same memory representation mediates performance in priming and recognition tasks.

An important feature of this model is that the variance of the noise associated with priming tasks

[1] In principle, T could also be added to the value of J_r for each item presented during a recognition test trial, increasing the comparability of the ways in which priming and recognition performance is simulated. However this is not necessary: it would have no effect on simulated recognition performance because both the old and new distributions would be shifted by a constant amount.

is typically greater than that associated with recognition tasks, i.e., $\sigma_p > \sigma_r$. This is because performance in priming tasks, in general, is believed to be influenced by a larger range of non-memory-related factors than is recognition performance (Kinder & Shanks, 2001, 2003; Ostergaard, 1998). In support of this, the reliability coefficients associated with performance in priming tasks are often found to be less than those of recognition tasks (Buchner & Brandt, 2003; Buchner & Wippich, 2000; Meier & Perrig, 2000). As we will show in our simulations, this assumption is important for the model to reproduce a wide range of results. For example, one straightforward prediction is that the recognition task will be more sensitive to f than the priming task.

In Experiments 1–4, attention was manipulated at study by diverting it away from one member of a pair of visually presented words and towards another. The effects of attention at study are simulated in the model by varying the familiarity of old items, i.e., the value of μ_{old} is greater for attended than unattended items. Given that priming depends on the same familiarity value as recognition, effects of attention on priming are predicted, albeit not necessarily of the same magnitude (because of the differences in variance of the noise distributions associated with each task). The greater noise variance for priming tasks also means that it is unlikely (given a finite number of trials) that one will observe priming in the absence of recognition, for example, for unattended items. Finally, the model predicts a correlation between priming and recognition, though this correlation can be weak, depending on the variances of the task-specific noise (σ_r and σ_p) relative to the variance and difference in means of the familiarity distributions (σ_f and μ_{new} vs. μ_{old}). Robust evidence contradicting these predictions would falsify the model.

Experiments 1–4

In each of the following experiments, pairs of words were presented for 500 ms, one above the other, on each study trial. Arrows cued one of the pair, which was to be read aloud. At test, cued or uncued (non-arrowed) words from the study phase were presented together with new (unstudied) words in either a perceptual identification priming task or an old/new recognition task.

Priming and recognition for cued and uncued words was tested between participants in Experiment 1 and within-participants in Experiment 2. In Experiment 3, priming and recognition were also tested for uncued words that were presented four times at study (uncued-4 words). In Experiment 4, priming and recognition were tested within-participants for uncued words only.

General methods

We first describe the general method of Experiments 1–4, later giving details of the differences between each experiment.

Participants

The participants in the following experiments were recruited from a psychology subject database, reported having normal or corrected-to-normal vision, reported English as their first language, and were paid for their participation. There were 45 participants in Experiment 1 (n priming = 23, n recognition = 22), 26 in Experiment 2 (n priming/recognition = 12, n recognition/priming = 14), 46 in Experiment 3 (n priming/recognition = 23, n recognition/priming = 23), and 24 in Experiment 4 (n priming/recognition = 12, n recognition/priming = 12).

Materials and design

Each experiment was run on a computer in a sound-dampened cubicle. The experimental software was written in Visual Basic 6.0 and used ExacTicks v1.1 (Ryle Design, 1997) to achieve millisecond accuracy.

The stimuli in this and subsequent experiments were low frequency 6-letter nouns (with a frequency of occurrence of one per million in Experiment 1, 1–5 per million in Experiment 2, and 1–8 per million in Experiments 3 and 4; Kucera & Francis, 1967). All word stimuli were presented in white 26 pt Arial font against a black background. The stimuli were arranged into lists for each experiment: one list for each stimulus type (cued, uncued, and new in Experiments 1, 2 and 4; cued, uncued, new and uncued-4 in Experiment 3) in each test phase. The assignment of lists to each type of stimuli was counterbalanced across subjects according to a Latin square.

On each study trial, pairs of words were presented. One member of the word pair was cued and the other was not. There were 48 target trials (trials that contained stimuli that would later appear at test) in Experiment 1, 72 in Experiment 2, 240 in Experiment 3, and 108 in Experiment 4.

The trials of each test phase were arranged into three blocks. In Experiments 1 and 2, each block contained an equal number of cued, uncued and new item trials. In Experiment 3, an equal number of cued, uncued and uncued-4 words were presented in each block, but because of the extra type of old stimuli (uncued-4), there were twice as many new word trials in a block as there were a given type of old stimuli trials. In Experiment 4 there were an equal number of uncued and new words in each block. No indication of block transitions was given to participants. The selection of the stimuli to be presented in each block of each experiment and the order in which items were presented was randomly determined.

Thus, in Experiment 1, there were 48 trials in total for each type of stimulus; in Experiment 2, there were 36 trials for each type of stimulus; in Experiment 3 there were 24 trials for each type of study item (cued, uncued, and uncued-4) and there were 48 trials for new items; and in Experiment 4 there were 54 trials in total for each type of study item.

Procedure

Each participant was seated approximately 100 cm from the monitor at the beginning of every experiment. At the start of the study phase, a white fixation dot (measuring 0.4 cm in diameter and subtending approximately 0.23° of visual angle) was displayed at the centre of a black background. Participants were told to initiate each trial when they were looking at the fixation dot by pressing the ENTER key. After a trial was initiated, the fixation dot was replaced by a 200 ms blank field. The target display consisting of a pair of words was then presented for 500 ms. One word was presented 0.6 cm (0.34°) above the fixation point and one 0.6 cm (0.34°) below. Each word pair consisted of a cued and uncued word chosen randomly from the appropriate list. The cued word appeared an equal number of times above and below the fixation point and this position was randomly determined for each study trial.

Each 6-letter word was approximately 3.4 cm long (1.9°) and 0.6 cm high (0.34°). The entire stimulus display measured approximately 3.2 cm (1.83°) vertically and 6 cm (3.43°) horizontally on the screen. One word of the pair was cued by a pair of arrows, and each arrow measured 0.5 cm (0.28°) in length and was located approximately 0.8 cm (0.46°) from the end of the cued word. Participants were required to read out the cued word; both accuracy and speed were emphasised in the study instructions. Study phase responses were audio-recorded to be later checked for accuracy.

A 2000 ms unfilled interval followed the target display after which the fixation dot reappeared to indicate to the participant that they could initiate the next trial. In Experiments 1, 2 and 4, trials were self-initiated in this way; in Experiment 3, however, study trails were automatically initiated by the computer: after the fixation dot had been presented for 500 ms, the sequence of events for the next trial was automatically initiated. This procedure was adopted in Experiment 3 because of the larger number of study trials relative to the other experiments and an automated study phase constrained the total study phase completion time. The first and last trials of the study phase (4 trials in Experiment 1, and 8 trials in Experiments 2–4) acted as primacy and recency filler trials, and none of these filler stimuli later appeared in the test phase.

On each trial of the recognition test a study-phase or new word was presented. Beneath this word the question "Is this word OLD or NEW? Press O or N" was displayed in blue 14 pt MS Sans Serif font. Participants were told in the instructions that an "old" word could be a cued or an uncued word from the first phase, and they were also informed of the relative proportions of old and new words. Participants who performed the recognition task after the priming task were told that none of the words they were about to make decisions for were presented in the priming stage and were also reminded as to the nature of the first stage. When the O or N key was pressed the display was replaced with a 1200 ms blank field and then the next word was displayed.

The task used to measure priming was a perceptual identification task. On each trial, an uncued or new word was presented very briefly. A single trial consisted of (a) the words "Get Ready" presented centrally in blue 12 pt MS Sans Serif font for 1000 ms, (b) a blank field for 2000 ms, (c) a white '+' fixation sign for 500 ms, (d) a blank field for 500 ms, (e) the target word at the same location as the fixation sign for 33 ms, and (f) a mask consisting of a row of '########'s for 500 ms. The participant's task was to then identify each target word by typing it on the keyboard.

General analysis

All study responses were later checked for study errors (incorrectly naming the uncued word instead of the cued word on a single trial). The error rate in each experiment was practically zero and no further analysis of the study responses was conducted.

Comparing recognition and priming using the same metric

In order to compare the priming and recognition tasks with the same metric, performance was measured as the hit rate minus the false alarm rate (henceforth Hits-FAs). This metric of sensitivity was chosen because it is simple and makes few assumptions (Snodgrass & Corwin, 1988); scoring the data instead using equal-variance signal detection theory did not affect the qualitative pattern of results.[2,3] In the recognition task, the hit rate (proportion of old words judged "old") and false alarm rate (proportion of old words judged "new") were calculated for each stimulus type (i.e., cued/uncued) for every participant. In the priming task, identification attempts to cued, uncued and new words at the first exposure duration (33 ms) were classified as either a "hit" (a positive response, in the form of a correct identification of an old word), or a "false alarm" (a correct identification of a new word), and the hit and false alarm rates were calculated accordingly.

Given that some participants found the priming task more difficult than others, only participants who made at least 5 correct identifications at 33 ms were included in the subsequent analysis. By this criterion, in Experiment 1, one participant was excluded from the analysis and hence the total n for the priming group was 22. The majority of participants were well above this criterion (median = 65 out of 144 possible correct identifications at 33 ms, range: 17–114). In Experiment 2, two participants were excluded from the analysis (both from the priming/recognition task-order group) and hence the total N was 24 (median = 59.5 out of 108, range: 14–92). Four participants were excluded from Experiment 3 (all four identified zero words correctly) and hence the total N was 42 (median = 71.5 out of 120, range: 32–115). No participants were excluded in Experiment 4 according to this criterion (median = 44.5 out of 108 in the test phase, range: 8–93).

Split-half correlations

Split-half correlations were used as reliability estimates of performance in the recognition and priming tasks (e.g., Buchner & Wippich, 2000). For every participant, two halves of the task were created by assigning odd number trials to the first half and even numbered trials to the second half. Following Buchner and Wippich (2000), Hits-FAs could then be calculated for each type of study word for both halves of the task. The split-half correlations were estimated as the Pearson correlations between these summary scores.

An α level of 0.05 was used for statistical tests, and t-tests were two-tailed. Tests involving repeated-measure factors with more than two levels were corrected for non-sphericity using the Greenhouse-Geisser correction.

Experiment 1

This experiment was run using a standard version of the perceptual identification task, in which the duration of each test word was gradually increased in duration until the participant identified it correctly. More specifically, the initial duration of test words was 33 ms (two screen refreshes at 60 Hz), and if the participant did not type the test word correctly, it was repeated with durations incremented by 16.6 ms until the participant identified it correctly (after which the next trial began). Performance in this task was scored as the proportion correct at the shortest duration (33 ms). The perceptual identification (priming) and recognition tasks were run on different groups of participants, to minimise interference between tasks. The data from this first experiment were used to set many of the free parameters of the model (see Simulations section).

Results

Inspection of the upper-left panel of Fig. 1 indicates that the attentional manipulation had a large effect on Hits-FAs for recognition but a much smaller effect for priming. This was confirmed by a 2 (recognition, priming) × 2 (cued, uncued) mixed ANOVA, which yielded a significant interaction between these factors, $F(1, 42) = 113.29$, $p < .001$. Simple effects analyses revealed that there were significant effects of the attentional manipulation on both recognition, $t(21) = 15.90$, $p < .001$, and priming, $t(21) = 6.84$, $p < .001$. Simple effects analyses also confirmed that, for cued words, recognition task performance was greater than priming performance, $t(42) = 11.91$, $p < .001$, whereas for uncued words, priming and recognition task sensitivity did not

[2] The choice to measure priming and recognition with Hits-FAs did not affect the conclusions of any of the experiments in this article, and the results for d' were also calculated. When sensitivity was analysed with d', the qualitative patterns of results in Experiments 1–4 were the same, except for the following: In analysis of Experiment 2, the task was found to significantly interact with the task order (priming/recognition, recognition/priming), $F(1, 22) = 4.61$, $p = .043$. However, the interaction between the two factors was still significant for each task-order group (Fs > 26.57, ps < .001). A further difference in the analysis of Experiment 2 was that the correlation between priming and recognition performance for cued items approached significance, $r(23) = .39$, $p = .057$, consistent with the prediction of the model. Furthermore, calculation of sensitivity by d' allowed us to calculate each subject's criterion, C. As assumed in the model, the mean value of C (calculated from the cued hit rate and false alarm rate for each task in Experiments 1–3, and from the uncued hit rate and false alarm rate for each task in Experiment 4) did not significantly differ between tasks for any experiment (Experiment 1–3, ts < 1; Experiment 4, $t(23) = 1.49$, $p = .15$).

[3] Note that, when sensitivity is measured by d', there is an analytic solution for the sensitivities predicted by the model for the recognition task. Because we assumed that f is a normally distributed variable and that $\sigma_{f,\,old}$ and $\sigma_{f,\,new}$ are equal, d' for the recognition task is equal to $\mu/\mathrm{sqrt}(\sigma_f^2 + \sigma_r^2)$. However, we chose to analyze sensitivity using Hits-FAs because we do not necessarily wish to make the same assumptions in our analysis of the data (plus an analytic solution for the identification task is not so tractable).

significantly differ, $t(42) = 0.28$, $p = .78$. Further analysis revealed that both priming and recognition of cued words exceeded the chance level of performance (Hits-FAs = 0; priming, $t(21) = 8.48$, $p < .001$; recognition, $t(21) = 20.16$, $p < .001$) as did that of uncued words (priming, $t(21) = 2.64$, $p < .05$; recognition, $t(21) = 3.12$, $p < .005$). The hit and false alarm rates are shown separately in Fig. 2.[4]

Conventional analysis of priming in terms of test word duration

To check that the effect of attention on priming was reproduced when the perceptual identification task was analysed in a more conventional manner, the final exposure duration before the word was correctly identified was also analysed. The % priming for cued words and uncued words was calculated as $100 \times$ (mean final new word exposure duration−mean final old word exposure duration)/mean final new word exposure duration. A paired *t*-test on the % priming scores for cued and uncued words revealed that there was a significantly larger amount of priming for cued words ($M = 14.93\%$, $SE = 1.35$) than uncued words ($M = 2.64\%$, $SE = 1.38$), $t(21) = 8.71$, $p < .001$. Additional analysis indicated that the amount of priming was significantly greater than chance (0%) for cued words, $t(21) = 11.10$, $p < .001$, and approached significance for uncued study words, $t(21) = 1.91$, $p = .07$. Thus, the pattern of results from the more conventional analysis of the perceptual identification task agreed with those from the sensitivity (Hits-FAs) analysis at a single duration (33 ms).

Split-half correlations of recognition and priming

The split-half correlation for cued words in the recognition task was greater than chance (0), $r(21) = .72$, $p < .001$, indicating that recognition performance for these words was reliable. In contrast, the split-half correlation for uncued words did not exceed that expected by chance, $r(21) = -.08$, $p = .73$. This suggests that performance was more reliable when sensitivity was greater.

However, the split-half correlation in the priming task was not reliably greater than chance for either cued, $r(21) = .12$, $p = .60$, or uncued, $r(21) = -.10$, $p = .65$, words. This indicates that performance was generally not reliable in the priming task, even when priming was greater than chance.

Experiment 2

Given that the sensitivity analysis for the priming task in Experiment 1 agreed with the more conventional analysis of test word duration, the remaining experiments measured sensitivity of priming using only a single, fixed duration of test words (33 ms). This also had the advantage of increasing the comparability of the priming and recognition tasks because each test item was only presented once. Experiment 2 was a replication of Experiment 1, but with the test factor run within- rather than between-participants. This also allowed us to look at correlations across participants between performance on the priming and recognition tasks. To avoid repetition effects at test, different words were used in the priming and recognition tasks, i.e., one half of the studied words were tested in the priming task, while the other half were tested in the recognition task. To counterbalance any task order effects, half of the participants performed the priming task first, while the other half performed the recognition task first.

Results

The upper right panel of Fig. 1 shows the sensitivity in each task and indicates a very similar pattern of results to those of Experiment 1, namely a large effect of the manipulation of selective attention on recognition and a much smaller one on repetition priming. A 2 (recognition, priming) $\times$ 2 (cued, uncued) $\times$ 2 (test order: priming/recognition, recognition/priming) ANOVA revealed that firstly, neither the main effect of trial order ($F < 1.00$) nor any of its interactions were significant ($Fs < 2.27$, $ps > .15$), indicating that whether priming or recognition was the first or second test phase did

4 Priming was also compared to recognition when analysed at the 50 ms exposure duration rather than the 33 ms duration. The reason for this was to check that the qualitative pattern of results did not differ when identification responses were scored at a different exposure duration. A 2 (cued, uncued) $\times$ 2 (priming, recognition) ANOVA revealed significant main effects of cuing, $F(1, 42) = 193.27$, $p < .001$, task, $F(1, 42) = 128.30$, $p < .001$, and also a significant interaction, $F(1, 42) = 84.58$, $p < .001$. As was observed at the 33 ms exposure duration, priming for cued words ($M = 0.12$, $SE = 0.03$) was significantly greater than priming for uncued words ($M = -0.004$, $SE = 0.02$), $t(21) = 3.42$, $p = .003$. Priming was significantly greater than chance for cued items, $t(21) = 3.70$, $p = .001$, but, unlike the analysis conducted at the 33 ms duration, there was no significant priming for uncued items, $t(21) = .22$, $p = .83$. Split-half correlations were also calculated for identification performance scored at the 50 ms exposure duration. The split-half correlation for cued words was not reliably greater than chance for cued, $r(21) = -.09$, $p = .69$, or uncued words, $r(21) = -.22$, $p = .32$. This pattern of results, with the exception of the null priming effect for uncued items, is in accord with the analysis conducted at the 33 ms exposure duration. The results are also in agreement with the results for priming when collapsed across Experiments 1–4 (see Summary of Experimental Results section).

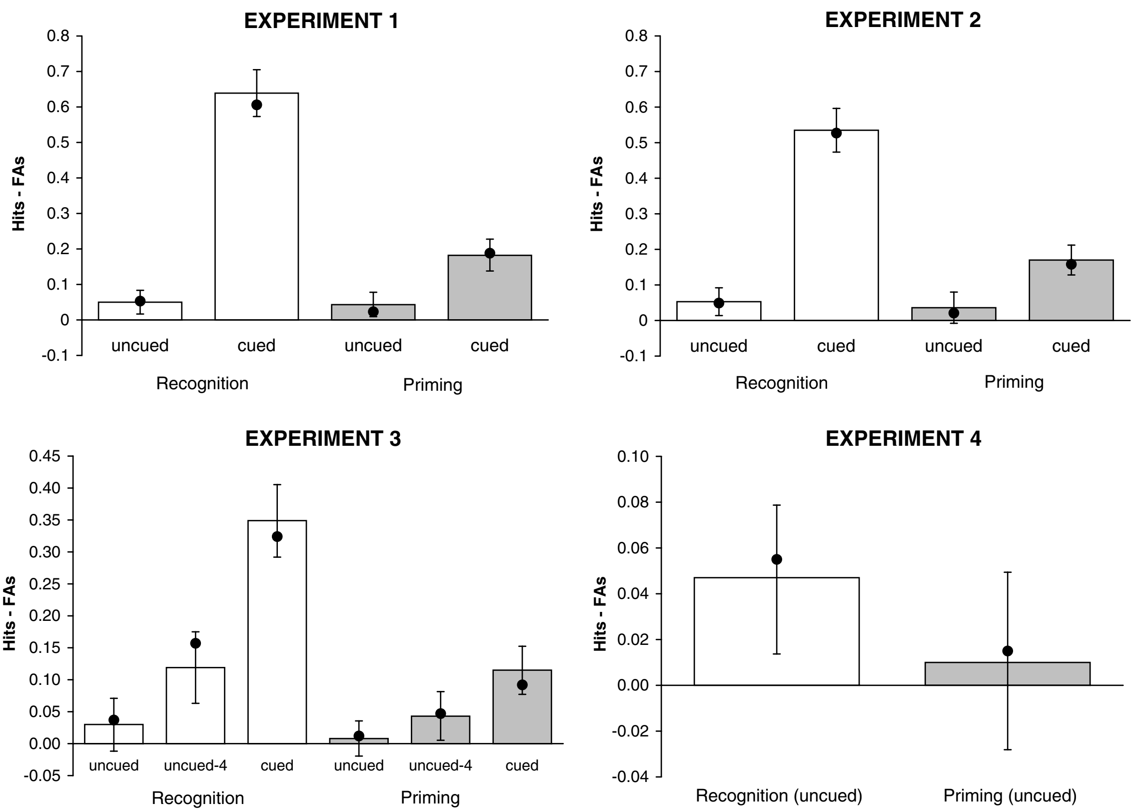

Fig. 1. Mean sensitivity (Hits-FAs) of the priming and recognition task as a function of cuing in Experiments 1–4. In the recognition task, participants decided whether each study word was old or new; in the priming task, participants attempted to identify briefly presented old and new words. Bars indicate experimental data (error bars indicate 95% confidence intervals), closed-circles indicate model results, FA = false alarms.

not result in any significant difference in performance. Secondly, like Experiment 1, a significant cuing × task interaction, $F(1, 22) = 57.69$, $p < .001$, was obtained. Furthermore, simple effects analyses indicated that cuing had effects on both recognition, $t(23) = 12.58$, $p < .001$, and priming, $t(23) = 5.03$, $p < .001$. Simple effects analyses also indicated that for cued words, sensitivity was greater in the recognition task than the priming task, $t(23) = 11.34$, $p < .001$, whereas for uncued words, sensitivity did not differ in the recognition and priming tasks, $t(23) = -.58$, $p = .57$. Recognition of uncued words was significantly greater than that expected by chance (Hits-FAs = 0), $t(23) = 2.80$, $p = .01$, but, unlike Experiment 1, priming of uncued words was not, $t(23) = 1.70$, $p = .10$.

Split-half correlations of recognition and priming

Like in Experiment 1, the split-half correlation for cued words in the recognition task was greater than chance, $r(23) = .50$, $p = .012$, but the correlations for uncued words in the recognition task, $r(23) = -.17$, $p = .43$, and for cued and uncued words in the priming task ($r(23) = -.04$, $p = .86$ and $r(23) = -.18$, $p = .40$, respectively), did not exceed chance (though in this case, it should be remembered that overall sensitivity for uncued words in the priming task was not reliably greater than zero).

Correlations between recognition and priming

Given that priming and recognition tasks were performed for each subject, we could now look at correlations between the two tasks. A Pearson correlation was performed on overall performance scores for cued and uncued words in each task. The correlation did not exceed chance for either cued, $r(23) = .21$, $p = .32$, or uncued, $r(23) = -.05$, $p = .83$, words.

Experiment 3

Given that priming performance was so low for uncued words in Experiment 2, we added a further condition in Experiment 3 in which some uncued words

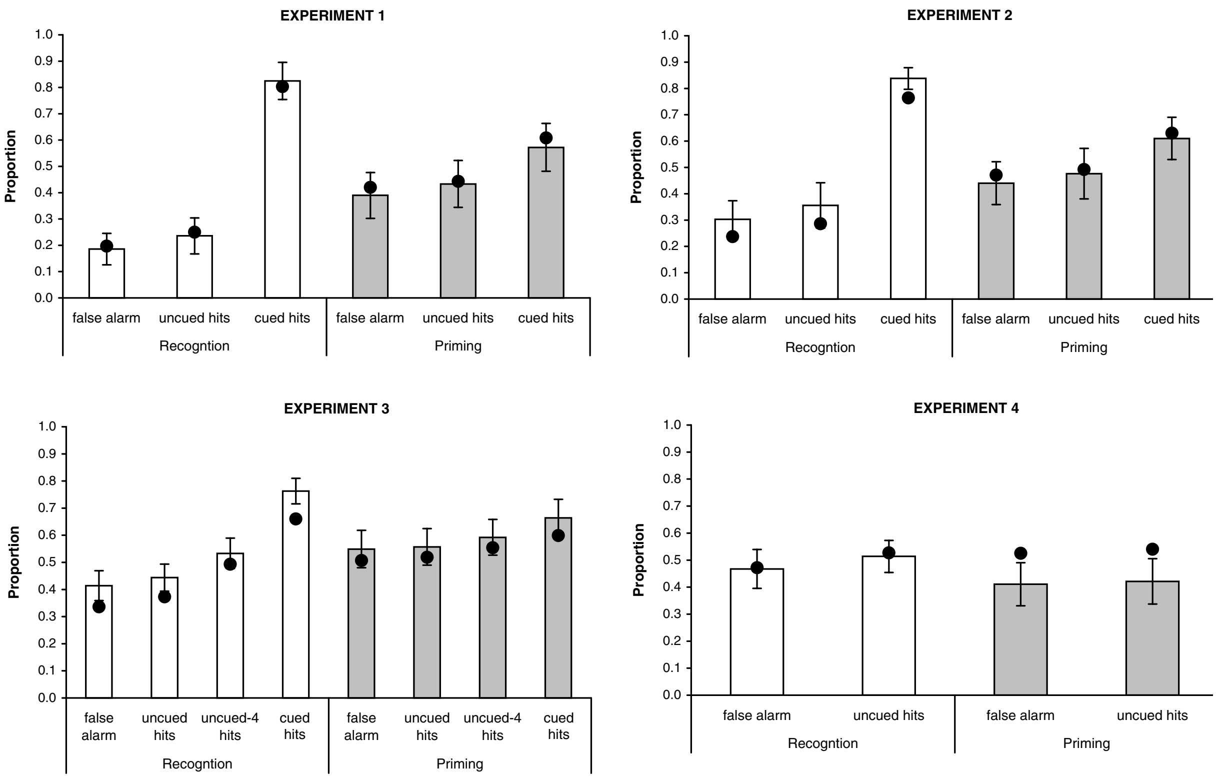

Fig. 2. Mean proportion of old responses (Recognition task) and mean proportion of correct identifications (Priming task) as a function of test item type in Experiments 1–4. Bars indicate experimental data (error bars indicate 95% confidence intervals), closed-circles indicate model results.

were repeated multiple times during study. Repetition of items presented for study can increase the magnitude of priming and recognition (e.g., Ostergaard, 1998). However, it is not clear what the effect will be when the repeated items are not in the focus of attention, and whether the effects upon priming and recognition will be parallel. Therefore an "uncued-4" condition was added, corresponding to words presented four times as uncued words at various intervals across the course of the study phase (each time with a different cued word). At least two study trials intervened before an uncued-4 word was repeated. This inclusion of uncued-4 words also required extra filler words to act as cued words on the trials in which uncued-4 items were presented. None of these filler items appeared in the test phases.

Results

Sensitivity performance is shown in the bottom left panel of Fig. 1. Four presentations improved performance for uncued words in both priming and recognition tasks, and more so for the recognition task. Performance was analysed with a 2 (recognition, priming) $\times$ 3 (cued, uncued, uncued-4) $\times$ 2 (test order: priming/recognition, recognition/priming) mixed ANOVA. Unlike Experiment 2, there was a significant interaction of task order and type of task, $F(1, 40) = 6.29$, $p < .05$. This interaction reflected greater sensitivity of the recognition task when it was performed first than when it was performed second, $F(1, 40) = 5.27$, $p < .05$ (the sensitivity of the priming task did not significantly differ with test order, $F < 1$). Moreover, the basic cuing $\times$ task interaction remained in the priming/recognition group, $F(2, 40) = 9.49$, $p < .001$, and also in the recognition/priming group, $F(2, 40) = 11.05$, $p < .001$. Given that this interaction was not obtained in any other experiment and that it does not change the overall pattern of results, we do not explore it further. No other effect involving the task order factor was significant, $F\text{s} < 1.8$, $p\text{s} > .19$.

Like Experiments 1 and 2, a significant interaction was found between cuing and task, $F(2, 80) = 20.52$, $p < .001$. Simple effects analysis showed that there was an effect of cuing on priming, $F(2, 82) = 18.01$, $p < .001$, and on recognition performance, $F(2, 82) = 84.05$, $p < .001$. Sensitivity was significantly greater in the recognition task than in the priming task for cued words, $t(41) = 6.90$, $p < .001$, and uncued-4 words, $t(41) = 2.20$, $p = .03$, but not uncued words, $t(41) = .84$, $p = .41$.

Recognition performance was superior for uncued-4 words than uncued words (presented once), $t(41) = 3.91$, $p < .001$, but recognition performance for uncued-4 words, however, was significantly worse than for cued words, $t(41) = 7.65$, $p < .001$. Similarly, priming was (marginally) significantly greater for uncued-4 words than uncued words, $t(41) = 1.88$, $p = .07$, but priming for uncued-4 words was significantly less than that of cued words, $t(41) = 3.72$, $p < .001$. Although the effect of repetition of uncued words was numerically greater for recognition than priming, a 2 (priming, recognition) × 2 (uncued, uncued-4) ANOVA indicated a non-significant interaction between these factors, $F(1, 41) = 2.58$, $p = .12$. Thus, repeating uncued words four times had the effect of increasing the magnitude of *both* priming and recognition.

Further analysis revealed that priming and recognition performance for uncued words did not exceed chance (priming, $t(41) = .59$, $p = .56$; recognition, $t(41) = 1.44$, $p = .16$). Performance for uncued-4 words, however, was significantly greater than chance in both tasks (priming, $t(41) = 2.30$, $p = .03$; recognition, $t(41) = 4.30$, $p < .001$), as was performance for cued words (priming, $t(41) = 6.15$, $p < .001$; recognition, $t(41) = 12.42$, $p < .001$).

Split-half correlations of recognition and priming

Like in Experiments 1 and 2, the split-half correlation for cued words in the recognition task was greater than chance, $r(41) = .54$, $p < .001$, as it was also for uncued-4 words, $r(41) = .50$, $p < .001$. The split-half correlations for cued and uncued-4 words were not significant in the priming task however, $r(41) = .11$, $p = .50$, and $r(41) = .01$, $p = .94$. Finally, the split-half correlations for uncued words were not reliable in either the recognition, $r(41) = .21$, $p < .19$, or priming, $r(41) = -.11$, $p = .49$, tasks (though again, this is in the context of an overall sensitivity that was not reliably greater than zero in either case).

Correlations between recognition and priming

Similar to Experiment 2, overall performance for priming and recognition was not significantly correlated for cued words, $r(41) = -.01$, $p = .95$, or uncued words, $r\ (41) = -.10$, $p = .54$, and was also not significant for uncued-4 words, $r(41) = -.06$, $p = .73$.

Experiment 4

An inconsistency across experiments thus far is that priming for uncued words was obtained in Experiment 1 but not in Experiments 2 or 3. In Experiment 4 we investigated this further by only presenting uncued words at test. This was because we wondered whether the presence of cued (attended) words at test might influence the strategies used by participants in the priming task. Even though participants in the priming task were not told that study items were being presented, it is possible that once a participant realised that some of the items are old in the priming task (which is more likely when cued items are presented at test) they then tried to perform the task by attempting to remember items from the study phase. This action could result in interference and possibly deplete the sensitivity of the priming task. Thus, in this experiment, we tested whether priming for uncued words could be obtained when there was no interference possible from cued words.

Results

Sensitivity performance is shown in the bottom right panel of Fig. 1. Like Experiment 2, recognition of uncued words was greater than priming. A 2 (recognition, priming) × 2 (task order: priming/recognition, recognition/priming) mixed ANOVA revealed no effects of task-order (both *F*s < 1). There was a trend for the sensitivity of the recognition task to be greater than that of the priming task, but the main effect of task did not reach significance, $F(1, 22) = 2.66$, $p = .12$. Further analysis revealed that performance in the recognition task was significantly greater than chance, $t(23) = 2.90$, $p < .01$, while repetition priming was not, $t(23) = .60$, $p = .55$.

Split-half correlations of recognition and priming

Like Experiments 1–3, the split-half correlation for uncued words in the priming and recognition tasks were not greater than chance, $r(23) = -.31$, $p = .14$, and $r(23) = -.04$, $p = .87$, respectively.

Correlations between recognition and priming

In contrast to Experiments 1–3, priming and recognition performance for uncued words was found to be significantly correlated in Experiment 4, $r(23) = .44$, $p < .05$.

Summary of experimental results

In relation to the three hypotheses in the Introduction: (1) all four experiments showed a reliable effect of attention on priming, i.e., greater priming for cued than uncued words, (2) no experiment showed reliable priming for uncued words when recognition performance was at chance (i.e., no experiment showed greater performance in the priming than recognition task), (3) there were no significant correlations between priming

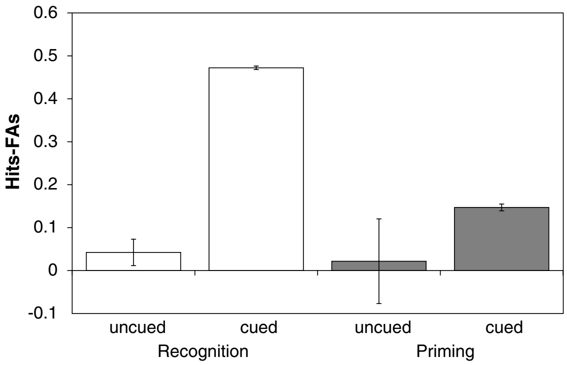

Fig. 3. Mean sensitivity (Hits-FAs) of the priming and recognition task as a function of cuing, collapsed across Experiments 1–4 (error bars indicate 95% confidence intervals).

and recognition for cued or uncued words in Experiments 1–3, although priming and recognition for uncued words was significantly correlated in Experiment 4.

Furthermore, (4) all experiments showed a greater effect of attention on recognition than priming, (5) split-half correlation estimates of performance in the priming task did not exceed chance for any type of study word in Experiments 1–4, even when overall performance was greater than chance, and (6) split-half correlation estimates of performance in the recognition task did exceed chance for cued words in Experiments 1–3 (and uncued-4 words in Experiment 3), but never for uncued words.

The combined Hits-FAs data for cued (Experiments 1–3) and uncued-once stimuli (Experiments 1–4) are presented in Fig. 3. Similarly, combined reliability measures were calculated, and the collapsed data confirmed the pattern of reliability observed in each experiment: the split-half correlation for cued words in the recognition task was greater than chance, $r(87) = .71$, $p < .001$, but the correlations for uncued words in the recognition task, $r(111) = .004$, $p = .96$, and cued or uncued words in the priming task, $r(87) = .13$, $p = .27$, and $r(111) = -.10$, $p = .32$, respectively, did not exceed chance. Also similar to the general pattern of findings across experiments, the correlation between priming and recognition performance collapsed across experiments was not significant for cued words, $r(87) = .15$, $p = .23$, or for uncued words, $r(87) = -.06$, $p = .61$.

A single-system model of priming and recognition: Simulations

In a previous section, we introduced a single-system model of recognition and priming as has been used in previous studies (Shanks & Perruchet, 2002). For present purposes, we can simplify this model by setting $\mu_{\text{new}} = 0$ and $\mu_{\text{old}} = \mu$, with no loss of power (i.e., μ represents the difference in the means of the old and new distributions). However, we need to extend the model to include individual differences between participants, in order to simulate correlations across participants within and between the recognition and priming tasks. This was done simply by drawing a value of μ randomly from a normal distribution for each participant, i:

$$\mu_i \sim N(\mu, \sigma_\mu)$$

where σ_μ is the standard deviation of the mean familiarity across participants.

We also need to separate values of μ_i for cued and uncued old items. This was achieved by assuming that increases in familiarity owing to attention at study scale the mean familiarity of cued, $f_{i,\text{c}}$, relative to uncued, $f_{i,\text{u}}$, items such that:

$$f_{i,\text{u}} \sim N(\mu_i, \sigma_\text{f})$$

$$f_{i,\text{c}} \sim N(\beta_\text{c}\mu_i, \sigma_\text{f})$$

where β_c is a new parameter.

The other parameters of the model (see Eqs. (1)–(3)) are the standard deviation of the distribution of familiarity values across items, σ_f, the standard deviation of the noise associated with the recognition task, σ_r, the standard deviation of the noise associated with the priming task, σ_p, and also the temporary increase in strength associated with the presentation of an item in degraded form in the perceptual identification task, T. To reduce the degrees of freedom in the model, the values of σ_f and σ_r were constrained to be equal, given that the important factor is the size of σ_p relative to σ_f and σ_r (Eqs. (4) and (5)). There were also a priori constraints that $\mu_i > 0$, i.e., that one presentation at study increases familiarity, even when uncued, and that $\beta_\text{c} > 1$, i.e., that cuing during study (selective spatial attention) increases familiarity. Finally, the criterion, C, for recognition was fixed (for a given participant) as the midpoint of the weakest and strongest distributions of familiarity in a given experiment. In other words, C_i was fixed as $C_i = \beta_\text{c}\mu_i/2$ in Experiments 1–3, and as $C_i = \mu_i/2$ in Experiment 4. This was because our main concern was to reproduce the basic pattern of sensitivity results (Hits-FAs), rather than fitting the hit and false alarm rates as closely as possible, for which allowing C to vary across subjects (and/or conditions and tasks) would have helped.

For Experiment 1, this left 6 free parameters: μ, σ_μ, β_c, $\sigma_\text{f}(=\sigma_\text{r})$, T, and σ_p. There were 10 degrees of freedom in the data (hit rate for cued words, hit rate for uncued words and false alarm rate for new words, for each of the priming and recognition tasks, plus split-half reliability measures for cued and uncued words for each of the recognition and priming tasks). The values of the parameters are shown in Table 1.

Table 1
Parameters of the model

Symbol	Meaning	Value			
		Exp. 1	Exp. 2	Exp. 3	Exp. 4
σ_f	Standard deviation of familiarity distributions (new/cued/uncued)	**0.2**	0.2	0.2	0.2
σ_r	Standard deviation of noise associated with recognition (constrained to equal σ_f)	0.2	0.2	0.2	0.2
σ_p	Standard deviation of noise associated with priming	**1.0**	1.0	1.0	1.0
μ	Mean familiarity of uncued items	**0.065**	**0.055**	**0.033**	**0.04**
σ_μ	Standard deviation of mean of uncued items across subjects	**0.03**	0.03	0.03	0.03
β_c	Proportional increase in mean of cued relative to uncued items	**8.33**	8.33	8.33	—
β_{u4}	Proportional increase in mean of uncued-4 relative to uncued items	—	—	4	—
T	Increase to target item strength within an identification trial	**2.8**	2.8	2.8	2.8

Note: Exp. = Experiment. Bold indicates that the parameter was varied to fit the data; a dash indicates that this condition was absent from the experiment.

The data were simulated using the same number of trials as in the test phases of the experiments (48 trials per stimuli type in Experiment 1, 36 in Experiment 2, 24 trials for cued, uncued and uncued-4 items and 48 trials for new items in Experiment 3, and 54 in Experiment 4), and using 10,000 simulated subjects. The large number of participants means that the error bars on the simulation results are negligible. The simulation results are shown for hit and false alarm rates in Fig. 2 (and also for the derived measure, Hits-FAs, in Fig. 1) and for the correlations in Fig. 4. The error bars on the experimental data are 95% confidence intervals. It can be seen that the model results lie within these intervals for all cases in Experiment 1.

The model was then applied to Experiment 2. The same parameter values were kept from Experiment 1, except for μ which was decreased from 0.065 to 0.055 (which decreased the mean familiarity of both uncued and cued items, given that they are related by the scaling factor β_c). This change could be justified by the longer study and test lists (i.e., longer retention interval for a given word) in Experiment 2, and possibly the different participants. With the exception of the hit rate for cued items in the recognition task, the model reproduced all of the hit and false alarm rates, and split-half measures of reliability, which were within the empirical range, providing further support for the robustness of the model. Furthermore, the model also reproduced the low correlations between priming and recognition tasks when tested across subjects (see Fig. 4), which were numerically greater for cued than uncued items, even though their confidence intervals overlapped zero in both cases (see Summary of Simulations section for further discussion).

The introduction of uncued-4 items in Experiment 3 required the addition of a parameter, β_{u4}, which reflected the increase in mean familiarity of uncued items when they were presented four times relative to once, i.e., $f_{i,u4} \sim N(\beta_{u4}\mu_i, \sigma_f)$. However, to minimise degrees of freedom in the model, this parameter was fixed a priori as 4. There was a need to reduce μ from 0.055 to 0.033, which again could be justified by the much longer study and test lists in Experiment 3 than in Experiment 2 (240 study trials versus 72). Most importantly, the model reproduced the effect of attention and of repetition on Hits-FAs in both tasks (see Fig. 1). For the recognition task the model provided a fit to the hit rate for uncued-4 items, but the fits to the cued hit, uncued hit and false alarm rates were not as accurate as they were in Experiments 1 and 2 (see Fig. 2). It is evident that the fits would benefit from a more liberal value for the criterion C (which was constrained here), in order to increase both the hit and false alarm rates. Nonetheless, the model reproduced all of the hit and false alarm rates in the priming task, and also all of the split-half measures of reliability for both tasks. It also reproduced the correlations between priming and recognition, with the exception of the correlation between priming and recognition for cued items (see Fig. 4).

Finally, apart from the need to increase μ to 0.04 (which could again be justified in terms of the shorter study list length in Experiment 4 than Experiment 3, i.e., 108 study trials vs. 240), the same parameter values provided sufficient fits to all conditions in Experiment 4, except for the hit and false alarm rate in the priming task, which fell just outside of the empirical range.

Summary of simulations

The model fits the data according to the three hypotheses in the Introduction: (1) Given that study exposure (whether cued or uncued) increases familiarity, the model necessarily predicts that attention modulates priming, (2) given that priming and recognition rely on the same familiarity measure, priming can never be greater than chance when recognition is (truly) at chance; indeed, if the noise associated with priming tasks is greater than that associated with recognition tasks, priming performance can never exceed recognition performance, (3) given that, relative to recognition, only a

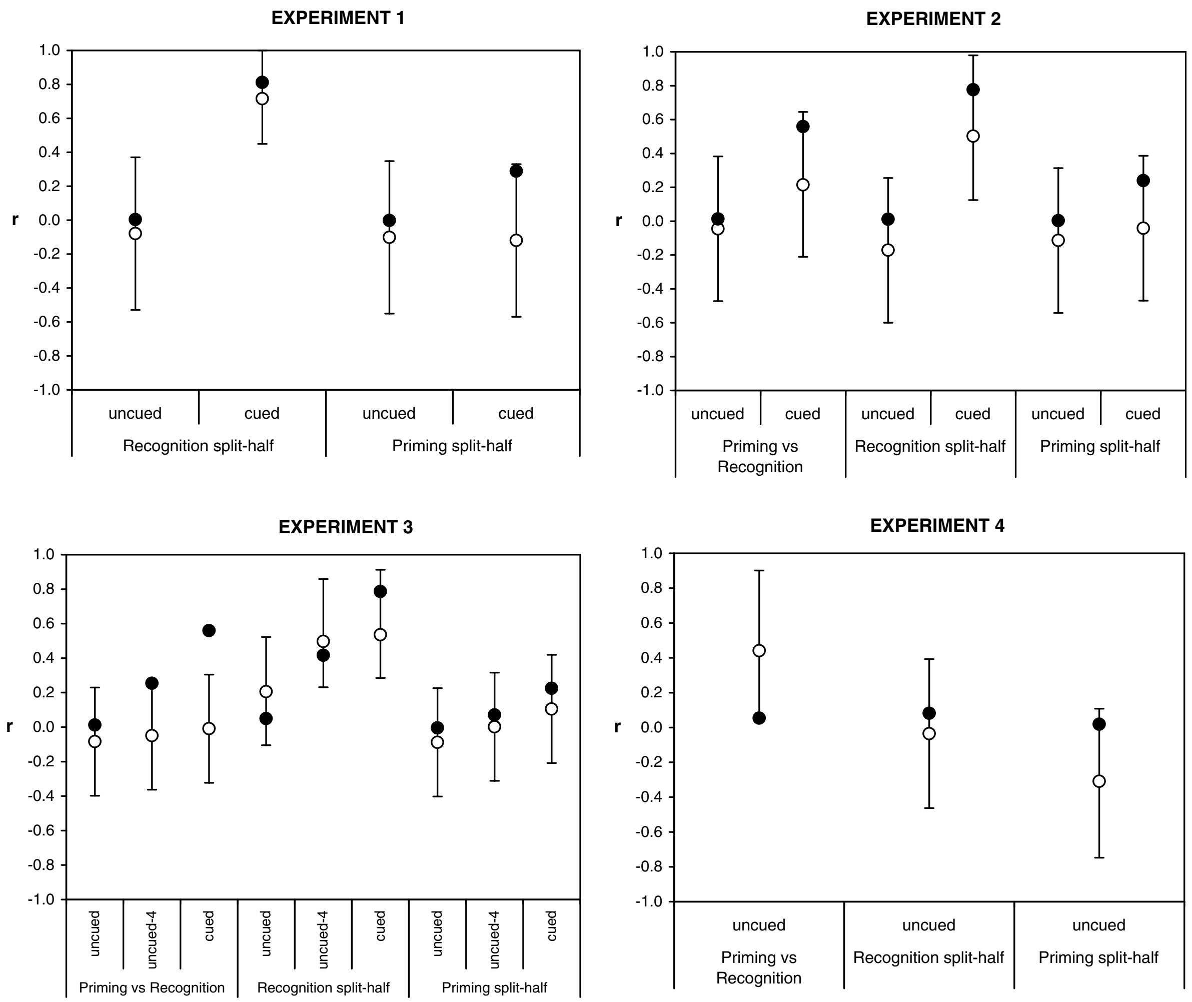

Fig. 4. Inter-task (priming vs. recognition) correlations (r) and split-half reliability estimates of priming and recognition tasks for Experiments 1–4. Open-circles indicate experimental data (error bars indicate 95% confidence intervals), closed-circles indicate model results.

small proportion of the variance in priming task performance is due to familiarity, the correlation between priming and recognition will be low; however, the model necessarily predicts a positive correlation between recognition and priming tasks, given that they depend on the same underlying familiarity signal.[5]

Furthermore, if the noise associated with priming tasks is greater than that associated with recognition tasks, the model predicts a greater effect of attention on sensitivity measures (e.g., Hits – FAs) for recognition than for priming, as was consistently found in Experiments 1–4. This is because sensitivity measures are a function of both the (i) difference in means of the old and new distributions and (ii) the spread of those distributions. This means that even though the difference in mean familiarity for cued/uncued and new items is equivalent in the single-system model, the spread of the final distributions used to make a decision (i.e., J in Eqs. (4) and (5)) is greater in the priming task when the noise is greater.

Of particular note is that the model produces values for the split-half measures of reliability in the priming

[5] Given the stochastic nature of the model, these statements are of course based on asymptotic performance (i.e., large numbers of trials). With a small number of trials, there is always the possibility that random fluctuations can cause an empirical result contrary to one or more of these statements. According to the model, such a finding would however not hold in the long run (i.e., would not be reproducible with sufficient numbers of trials).

task (Fig. 4) that are low enough to fit the data. The model always predicts a reliability greater than zero because a non-zero value for the difference in mean familiarity of old and new items (μ) always implies similar Hits – FAs for odd and even trials. However, the relatively large contribution of random noise from trial to trial in the priming task, σ_p, means that the reliability can be small. Nonetheless, one would predict that, with a greater number of trials (i.e., more powerful measure of split-half reliability), the reliability of both priming and recognition tasks would be significantly greater than zero for all types of item. The smaller noise in the recognition task explains the larger (and in many cases significant) reliability values for this task.

A similar argument applies to the non-significance of the between-task correlations in the present study: the model can predict correlations that are low enough to be difficult to detect given a statistical power comparable to that in the present study. Nonetheless, the significant, positive correlation that was found in one of the three experiments (Experiments 2–4) provides some support for the model's assumption that recognition and priming share a common distribution of familiarity.

General discussion

In this paper, we presented a single-system model of repetition priming and recognition memory, which embodies two core assumptions: (a) that a single memory strength variable (f) supports performance in priming and recognition tasks, and (b) that the noise associated with decisions in the priming task is greater than that associated with the recognition task. Three predictions of the model (as stated in the Introduction) were tested across four experiments that employed a manipulation of selective attention at study. Firstly, as predicted by the model, effects of attention were observed on both priming and recognition performance in Experiments 1–3: Priming and recognition were greater for cued words than uncued words. This result is in line with a number of other studies that found effects of selective attention at study on priming and recognition (Bentin et al., 1998; Berry et al., 2006; Crabb & Dark, 1999, 2003; Eich, 1984; MacDonald & MacLeod, 1998; Mulligan, 2002; Phaf et al., 1994) and is inconsistent with claims that manipulations of attention do not affect priming (e.g., Parkin & Russo, 1990).

Secondly, the model predicts that recognition is more sensitive to the underlying strength variable than is priming. It is therefore unlikely that priming will be found in the absence of recognition in an experiment (or that the magnitude of priming will be greater than that of recognition, when compared with the same response metric). In line with this prediction, priming for uncued, uncued-4 or cued words was never greater than recognition for such words in any of the four experiments. Indeed, recognition memory for uncued words occurred in the absence of reliable priming for these words (in Experiments 2, 3 and 4). Contrary to the predictions of the model, priming in the absence of recognition for less-attended items has been reported in some studies (e.g., Eich, 1984; Merikle & Reingold, 1991), yet the findings of some of these studies have proven difficult to replicate (e.g., see Berry et al., 2006). The present experiments do not directly address the findings from these studies; however, the results of all four of our experiments suggest that selective attention manipulations are unlikely to produce a pattern of priming greater than recognition, even when recognition is reduced (or is very close) to chance (e.g., for uncued words in Experiment 3).

Thirdly, the model predicted that priming and recognition performance will be correlated. In support of this prediction, a significant correlation for uncued items was observed in Experiment 4. However, in Experiments 2 and 3 (in which calculation of the correlation was also possible), performance between tasks for cued, uncued or uncued-4 words was not significantly correlated. Significant correlations between priming and recognition performance have been reported under some conditions (e.g., Ostergaard, 1998), however, it is more common for performance to be reported as uncorrelated (e.g., Parkin & Russo, 1990; Stark & McClelland, 2000). In the account presented here, because only a small proportion of the variance in priming measures is due to memory, correlations between performance in both tasks, when obtained, will be weak. A true correlation of zero would be evidence against the model in this paper. However, other single-system models have predicted zero correlations between priming and recognition (Kinder & Shanks, 2003), suggesting that even this finding is not indicative of multiple systems (see also e.g., Ostergaard, 1992).

Our experimental and simulation results, together with the results of a number of recent studies, converge on the notion that recognition tasks are generally more reliable measures of memory than are priming tasks (Buchner & Brandt, 2003; Buchner & Wippich, 2000; Meier & Perrig, 2000). The perceptual identification task, however, has been found by Buchner and Wippich (2000) to be reliable and to have a reliability that is comparable to recognition. In the present study, this pattern was not obtained: the perceptual identification task did not reliably measure memory for any stimulus type, even when the split-half reliability estimates were calculated for data collapsed across experiments. It is possible that this discrepancy in results is due to the greater power of Buchner and Wippich's (2000) study to detect reliability of the priming task, or it could be due to minor procedural differences between the perceptual identification tasks used (e.g., the presentation duration for all items in Buchner and Wippich's test was a pre-determined threshold for each participant).

A trend discernable from the reliability analysis is that in both the recognition and priming tasks, the split-half correlations are generally greater when sensitivity is higher (e.g., greater reliability estimates for cued items than uncued items). One could therefore propose that differences in task reliability could be solely explained by differences in task sensitivity. However, the significant split-half correlation of uncued-4 words for recognition in Experiment 3 counts against this proposal. The sensitivity (Hits-FAs) of uncued-4 items in recognition is similar in magnitude to (if not less than) cued items in priming in Experiments 1–3. Despite this similarity, the split-half correlation for uncued-4 items in recognition was significant, while those of cued items in the priming task of Experiments 1–3 are not. This supports the account presented in this paper: that the lower reliability of the priming task reflects greater noise variance associated with the priming decision than the recognition decision (without any difference in the underlying memory signals, or in the means of the familiarity distributions). In other words, some idiosyncratic difference of the priming task per se causes its reliability to be lower than that of recognition.

The account presented here could help to shed light on the different patterns of results from studies employing divided versus selective attention manipulations at study. As described in the Introduction, dual-task manipulations have been reported to affect recognition but not priming, whereas selective attention manipulations have been found to affect both. The model predicts that there will be effects of attention on both tasks and that they will be smaller on priming than recognition. However, if the effects of dual task manipulations are smaller than selective attention manipulations then it will be harder to detect effects on priming than recognition. A study by Mulligan (2003) suggests that this may actually be the case. Mulligan (2003) found that effects of dual-task manipulations on priming emerge when the difficulty of the secondary task is increased. In his Experiment 1, a digit monitoring secondary task (detecting sequences of 3 odd digits in a row) produced effects on recognition but not priming (in a perceptual identification task), reproducing the typical dissociation. However, when the difficulty of the secondary task was increased, either by making the presentation of distractors synchronous with the presentation of the target, or by increasing the frequency of responding at test (rather than only requiring responses when a target sequence was detected), effects on priming were found.

This account could also be applied to studies that have found that depth of processing manipulations at study can affect recognition but have no detectable effect on priming (e.g., Graf & Mandler, 1984; Graf, Mandler, & Haden, 1982; Jacoby & Dallas, 1981). Contrary to the early consensus that this variable has no effect on priming, the conclusions drawn from meta-analyses suggest that it does (Brown & Mitchell, 1994 ; see also Challis & Brodbeck, 1992; Roediger & McDermott, 1993, for similar conclusions), although the effect is clearly greater for recognition. The model could account for this finding quite readily: If it is assumed that deeper levels of processing of items lead to greater levels of f, then as f increases, recognition performance will increase at a greater rate than priming.

The key assumption of recognition being more sensitive than indirect tasks appears to contradict the idea, adopted either implicitly or explicitly by researchers, that priming tasks are more sensitive than recognition. This assumption follows quite straightforwardly from the reports that priming can occur in the absence of recognition in amnesics (e.g., patient E.P. in Hamann & Squire, 1997a, 1997b; Stark & Squire, 2000; though see Kinder & Shanks, 2001, 2003). However, the evidence concerning whether this pattern can be obtained in normal adults is equivocal. For example, Berry et al. (2006) attempted to replicate some compelling evidence for unconscious memory and, in contrast to the original findings (Merikle & Reingold, 1991), consistently found that the sensitivity of the recognition task was greater (or at least never less) than that of the priming task. Priming performance is regarded as being subject to more non-memorial influences than recognition and this may contribute to a lack of sensitivity in the priming tasks. Thus, we believe that it is reasonable to assume that the noise variance associated with priming tasks is greater than that of recognition (which results in their lower sensitivity).

Lastly, this model is not intended as a comprehensive model of priming and recognition. For example, it is unclear how the model in its current form could account for the finding that certain experimental manipulations selectively affect priming (such as study/test modality; for an overview see Richardson-Klavehn & Bjork, 1988). The model in its current form, however, is able to account for a range of sensitivity, task-reliability, and inter-task correlation results as we have shown. Furthermore, it is hoped that the principles that the model embodies will provide a basis for further exploration.

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