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P R E S S

A unitary signal-detection model of implicit and explicit memory

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Do dissociations imply independent systems? In the memory field, the view that there are independent implicit and explicit memory systems has been predominantly supported by dissociation evidence. Here, we argue that many of these dissociations do not necessarily imply distinct memory systems. We review recent work with a single-system computational model that extends signal-detection theory (SDT) to implicit memory. SDT has had a major influence on research in a variety of domains. The current work shows that it can be broadened even further in its range of application. Indeed, the single-system model that we present does surprisingly well in accounting for some key dissociations that have been taken as evidence for independent implicit and explicit memory systems.

Implicit and explicit memory

A popular view of memory is that there are functionally and neuroanatomically distinct explicit and implicit memory systems in the brain [1,2]. Explicit (declarative) memory is thought to be accessible to awareness, whereas the contents of implicit (non-declarative) memory are unconscious. The majority of evidence in favour of this 'multiple-systems' view has attempted to show that performance on particular tasks, thought to be driven by either implicit or explicit memory, can be dissociated from one another. The two most commonly compared tasks measure long-term repetition priming (henceforth priming, taken to index implicit memory) and recognition (taken to index explicit memory). Priming refers to a change in behavioural response to a stimulus after re-exposure. This change often takes the form of an improvement in performance, such as shorter identification times, or increased identification rates of stimuli presented in degraded form. Recognition refers to the capacity to judge whether an item has been previously encountered in a particular context.

Given the large amount of research that has been conducted over the past 20 years (for a review of the topic see Ref. [3]), it is surprising that there are few computational models that have been applied to both implicit and explicit memory. Computational models offer many benefits: they promote theoretical transparency and can be used to generate quantitative predictions that can be tested. Furthermore, they can often indicate alternative interpretations of dissociations [4–6]. Here, we propose that many dissociations between priming and recognition, which, on

the surface, seem indicative of multiple-memory systems, are in fact not inconsistent with a single-system account. To illustrate, we review recent work that we have conducted with a simple (and easy-to-implement) single-system model. The model extends signal-detection theory (SDT) of recognition (Box 1) to priming (and also to fluency, another traditional implicit memory phenomenon) [7,8] (Figure 1). A single memory-strength signal drives priming and recognition in the model but, crucially, this signal is subjected to independent sources of non-memorial noise for each task. Even if ultimately shown to be inadequate, we believe that our exploration of a single-system model demonstrates the value of using formal models in implicit and explicit memory research.

Simulating dissociations
Functional dissociations

Consider the often reported dissociation that a manipulation affects recognition but has little or no effect on priming. In normal adults, examples of variables that produce this result are depth of processing manipulations (e.g. making a semantic versus non-semantic judgment about a word at encoding) [9,10] or attentional manipulations (e.g. encoding words with or without a concurrent distractor task) [11]. A common interpretation of this dissociation is that explicit memory is selectively influenced by the manipulation, whereas implicit memory is not. Often, in cases in which a (similar but smaller) effect is also detected on priming, the effect is explained by saying that the priming measure is 'contaminated' with explicit memory. Both of these interpretations postulate more than one memory system (or source of memory) to explain the dissociation.

The single-system model can explain this type of dissociation by postulating only one source of memory [8]. In the model, each item in the test phase is associated with a single memory strength value (f) that is sampled from a normal distribution, the mean of which is assumed to be greater for old (studied) than new (unstudied) items. The value of f of an item is used to generate its recognition judgment and its priming measure. Crucially, this value of f is combined with one randomly sampled noise value for each task. These sources of noise are independent of the memory signal and can, therefore, be conceptualized as non-memorial influences on task performance.

The functional dissociation described earlier can be produced by the model if it is assumed that the variance of the noise associated with the priming task (perceptual

SDT [26] has played an important part in theories of recognition (see Ref. [27] for a review). In standard signal-detection models of recognition, old (studied) and new (non-studied) items are represented as overlapping Gaussian distributions on a single 'strength of evidence' continuum (Figure I). Because of the influence of the study phase, the mean strength of the old item distribution is assumed to be greater than that of new items. Typically, a participant is assumed to decide whether an item is old or new by assessing its strength relative to a decision criterion located at some point along this continuum. If the strength of the item exceeds the criterion then it will be judged old, otherwise it will be judged new.

A controversial issue in recognition memory research is whether there are qualitatively distinct familiarity and recollection processes in recognition. Familiarity is thought to be context-free, whereas recollection involves retrieval of specific details of the study episode. In an influential dual-process model, familiarity is represented as a continuous strength variable (as in standard SDT) and recollection is represented as an independent high-threshold component [28]. Methods have been proposed to enable one to obtain separate estimates of familiarity and recollection (e.g. analysis of receiver operating characteristics and remember and know judgments). However, the dual-process model has been challenged by 'single-process' SDT models, in which recognition is based upon a single dimension of memory strength and the variance of old and new item strengths are unequal (e.g. Refs [27,29]; although see Ref. [30]). The unidimensional SDT model has been successful in accounting for a wide range of data previously taken to support the dual-process model.

Given the success of SDT in accounting for recognition, it seems logical to extend SDT to account for implicit memory phenomena such as repetition priming. According to some dual-process theories of recognition, repetition priming is one basis of familiarity [9,18]. Understanding the extent to which implicit memory can be accounted for by SDT will therefore have implications for theories of recognition.
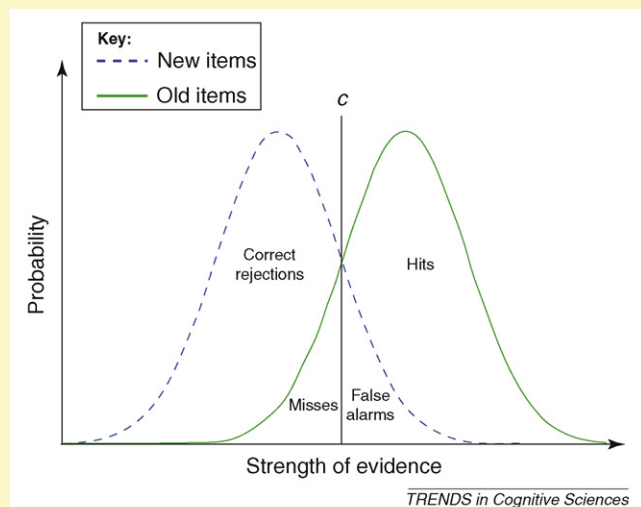

Figure I. Standard SDT of old and new recognition judgments. *c* represents the decision criterion. Items to the right of *c* will be judged old, and those to the left of *c* will be judged new. An old item is classified as a hit if judged old, or a miss if judged new; a new item is classified as a false alarm if judged old, or a correct rejection if judged new.

memory strength (i.e. increase the difference between mean f values for old and new items) will be less likely to affect priming than recognition. In sum, this dissociation can arise in the model because the memory signal in priming is overshadowed by a higher degree of noise.

The assumption that the variance of the noise associated with priming is typically greater than that associated with recognition leads the model to make another interesting prediction: when tasks are comparable and performance is measured on the same response metric, it predicts that the sensitivity (e.g. d') of priming tasks cannot exceed that of recognition. Evidence against this prediction would therefore constitute evidence against the model; it would also support the notion that the content of memory supporting priming is unconscious (Box 2).

Other kinds of functional dissociations have been taken to support the multiple-systems view. For example, changes in modality between study and test can produce larger reductions for priming than for recognition, whereas generating versus reading an item at study can improve recognition, but impair priming (see Ref. [3]). Particularly compelling is the demonstration of such crossed double dissociations in parallel with associations between priming and recognition tasks (e.g. Ref. [14]) – so-called 'reversed associations' [15].

The model has not yet been applied directly to these dissociations; however, they could be explicable by a simple extension of the model to two or more distributions of memory strengths. One distribution could reflect an amodal, conceptual memory signal, whereas others could reflect modality-specific memory signals. When combining the signals from these different sources to make a decision, recognition tests might typically place more emphasis on the conceptual signal, whereas priming tests might place more emphasis on modality-specific signals. This could explain the earlier described dissociations between recognition and priming which are produced by changes in modality of presentation between study and test, or by reading versus generating items at study. Importantly, however, none of these memory signals would correspond to an explicit or implicit memory system *per se*; under other conditions (e.g. different task instructions), recognition decisions could be more heavily influenced by a modality-specific memory signal, and priming decisions could be more heavily influenced by an amodal memory signal. This proposal resembles the 'transfer appropriate conceptual–perceptual processing' account that has also questioned the implicit–explicit memory systems account (e.g. Ref. [16]).

In sum, as others have pointed out (e.g. Refs. [12,15]), many functional dissociations do not necessarily imply distinct implicit and explicit memory systems.

Amnesia

Damage to the medial temporal lobe (MTL)/hippocampal regions results in amnesia and impairments in recognition, but leaves priming relatively unaffected (compared with controls). This striking dissociation is often considered to be the most compelling evidence for the multiple-systems view. From a multiple-systems perspective, it indicates that the MTL is the site of an explicit memory system that drives recognition but not priming (see also Box 3).
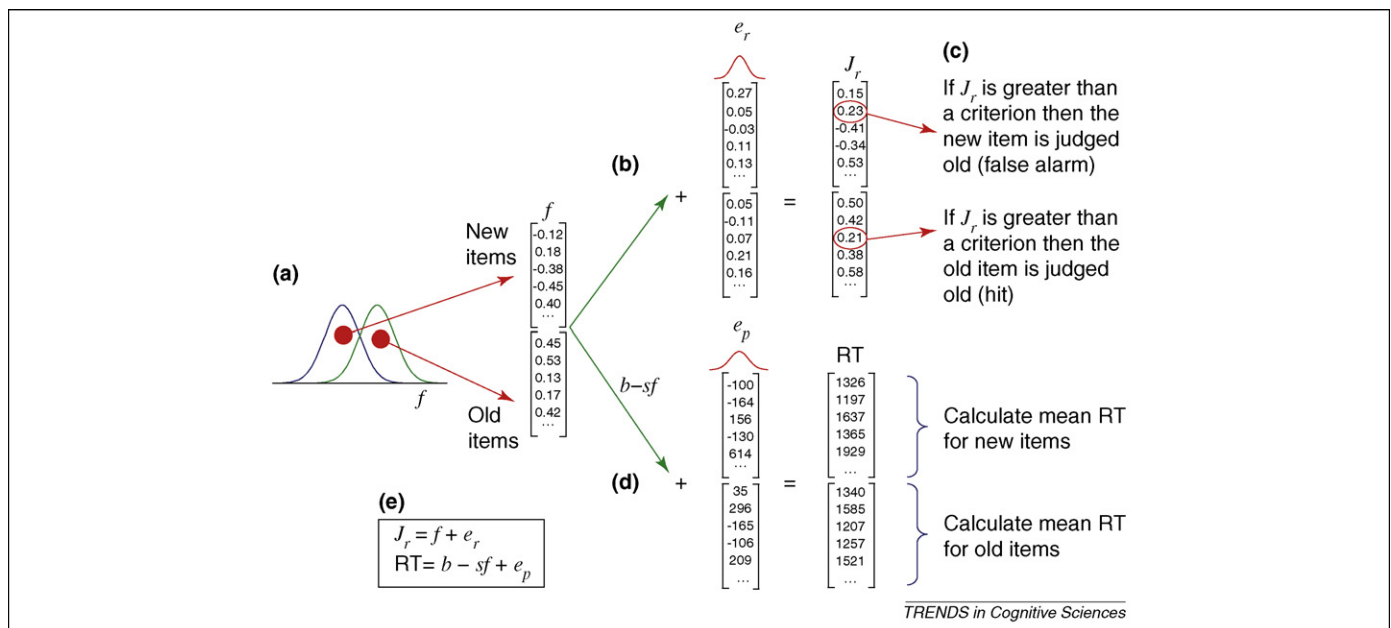
identification) is usually greater than that of recognition. This assumption is supported by the typically lower inter-trial reliability of priming tasks, compared with recognition [12] (Figure 2a), and is consistent with the view that the influence of non-memorial factors is greater in priming tasks than in recognition [13]. From this assumption it follows that manipulations which increase overall

Figure 1. Single-system model of recognition, priming and fluency. The same memory strength variable (familiarity, *f*) is assumed to drive recognition, priming and fluency, but crucially, this variable is subjected to independent sources of random noise for each task. It is important to note from the outset that the model is simply a model of the influence of memory on task performance and is not a comprehensive model of the mechanisms involved in the tasks. The following steps are performed to simulate recognition, priming and fluency performance for one simulated subject: **(a)** each item at test is assumed to be associated with a memory strength variable called familiarity, *f*, which is a normally distributed, random variable. Because of prior exposure, old items are assumed to have a greater mean *f* than new items. A single value of *f* is independently sampled for each new and old item from the relevant distribution. **(b)** To simulate recognition data, each value of *f* is combined with some normally distributed random noise (e_r) (with zero mean) to produce a 'strength of evidence' value (J_r) for each item. **(c)** Every item is then classified according to whether its value of J_r is greater or less than a criterion of evidence that needs to be exceeded in order for an old judgment to be made. If the value of J_r exceeds the criterion, the item will be judged old and if J_r falls below the criterion then it will be judged new. For the sake of simplicity, we have previously assumed that the criterion is located midway between the mean values of the old and new *f* distributions (although in principle it is free to vary). The proportion of hits and false alarms can then be calculated, which form the basis of the performance measure for the recognition task (e.g. *d'*, *Pr* etc.). **(d)** Performance in the priming task (in this case identification RTs in the continuous identification with recognition [CID-R] task, see Figure 2b) is simulated in a very similar manner. Crucially, because this is a single-system model, the *same* value of *f* is used to generate the value of J_r of an item and its identification RT. RT is assumed to be a decreasing function of *f*. Thus, the model assumes that greater levels of *f* lead to a greater likelihood of an item being judged old and also to shorter identification RTs. However, an important difference in the generation of the priming data is that each value of *f* is combined with another independent source of normally distributed random noise (e_p) (also with a zero mean). Priming can then be calculated as the difference in the mean RT to new and old items; the fluency effect is calculated as the difference between the mean RT to items judged new, versus judged old. RTs can also be sorted and compared according to the recognition response (i.e. hit, miss, correct rejection and false alarm) (Figure 2d). **(e)** The generation of J_r and the RT can be summarized with two equations. The parameters *b* and *s* in the equation for RTs are chosen simply to ensure that RTs are generated between approximately the correct limits. The data in the figure were generated by using the parameter values from simulation study 1 in [7]. Other transformations of *f* can be used for other priming tasks, for example, perceptual identification [8] or the sequential reaction time task (an implicit learning task) [23].

Furthermore, Conroy *et al.* [17] recently showed that fluency effects (the tendency for items judged old to have shorter identification reaction times [RTs] than items judged new in a gradual clarification task, similar to the one in Figure 2b) are also relatively normal in amnesics (Figure 2c). To the extent that fluency can give rise to a feeling of familiarity and be used as a basis of recognition (as hypothesized by e.g. Refs [9,18]), Conroy *et al.* [17] reasoned that fluency from priming should contribute to recognition performance in amnesia. However, the amnesics in their study showed impaired (and in one exceptional case, no better than chance) recognition performance, even though their fluency and priming effects were relatively normal. Conroy *et al.* [17] took this as evidence that priming and fluency do not contribute to recognition and that the sources of memory driving priming and recognition are independent.

Is it necessary to interpret the results of Conroy *et al.* [17] in terms of independent systems or sources of memory, or can they be explained by a single-system account? As shown in Figure 2c, the model successfully simulated this dissociation by assuming that there was a greater degree of variability in the underlying memory signal, and also in the assessment of that signal (e.g. greater variability in the

placement of the decision criterion from trial-to-trial) in amnesics, relative to controls. The model even predicted a priming effect as recognition approached chance (the model can therefore simulate a similar pattern to that of the severely amnesic patient E.P. [19]). Because noise is incorporated into the model, this dissociation can counter-intuitively be simulated even though the same strength variable is assumed to drive priming, recognition and fluency.

Patients with right-occipital lobe lesions have been shown to exhibit the opposite dissociation to amnesics (i.e. impaired priming and intact recognition, reviewed in Ref. [2]). This dissociation was initially taken as evidence for the existence of a visual implicit memory system in this occipital region; however, later work with similar patients has called into question this evidence (e.g. Ref. [20]). In sum, the striking dissociation between priming and recognition in amnesia is not inconsistent with the single-system model.

Within-item/group dissociations and stochastic independence
A common practice in priming and recognition research is to select a subset of items from the test phase that
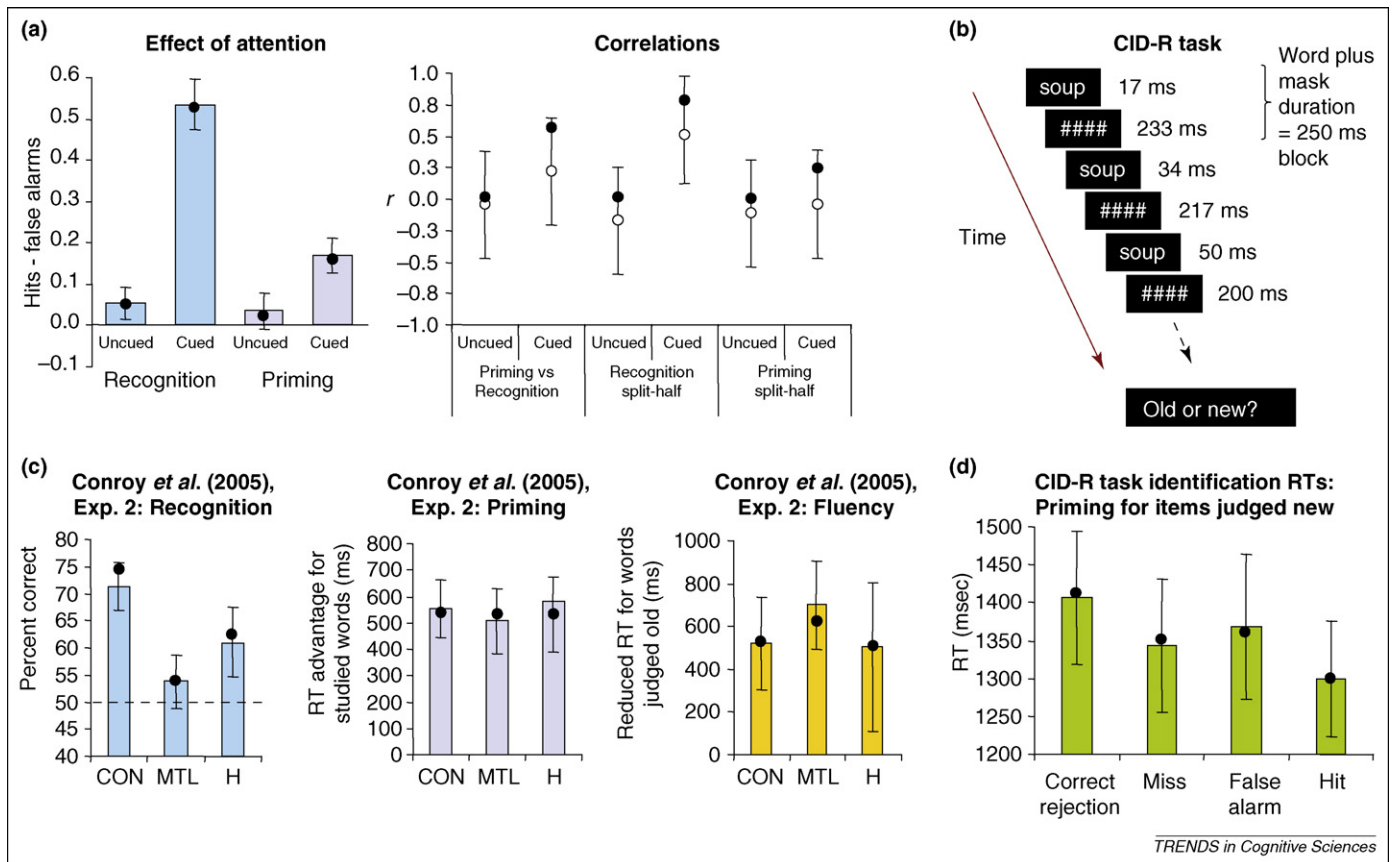
Figure 2. Surprising results accounted for by the model. **(a)** Sensitivity (hits minus false alarms) of recognition and priming tasks to the familiarity of attended (cued) and less-attended (uncued) study items (left panel) (from Ref. [8]). Pairs of items were presented for 500 ms at encoding and one item of the pair was cued with arrows for overt naming (i.e. cued), the other was not (i.e. uncued). The effect of the attentional manipulation was much greater for recognition than priming (as measured with a perceptual identification task) (bars indicate data, error bars denote 95% confidence intervals). This result was simulated by assuming that the variance of the noise associated with the priming task is greater than that of the recognition task (black circles denote simulation results from 10 000 simulated participants, in this and all other panels of the figure). This assumption was supported by measures of the inter-trial reliability of each task (in most cases greater for recognition, as indicated by split-half correlations, see right panel. White circles denote data). Despite being driven by the same strength variable, the model also fit the low correlations observed between priming and recognition in the task (right panel). **(b)** In a trial of the CID-R task [21], a stimulus is flashed for longer and longer durations. A mask is presented immediately after each presentation, giving the appearance of a gradually clarifying stimulus. When used at test, an old or new recognition judgment can be obtained after each identification, permitting recognition and identification RTs (which form the basis of the priming and fluency measures) to be measured concurrently for each item. **(c)** An application of the model to amnesic data from Ref. [17]. Recognition, priming and fluency were measured in two amnesic groups (MTL and hippocampal [H]; see following explanations) and a control (CON) group in a gradual clarification paradigm, similar to the CID-R task. The H group had damage to hippocampal regions, and the MTL group had more extensive MTL lesions. Despite severely impaired levels of recognition relative to controls (left panel, broken line indicates chance performance), the amnesic groups showed relatively normal priming (middle panel) and fluency effects (right panel). The model simulated this dissociation by assuming that there is a greater amount of variance in the underlying strength variable and also in the assessment of that variable (e.g. greater variability in the placement of the decision criterion from trial-to-trial) in amnesics, relative to controls. Greater severity of amnesia (in the MTL versus H group) was associated with greater levels of variability. The model also predicted priming and fluency effects even though recognition was very close to chance in the MTL group. (Bars denote data from Ref. [17]; error bars denote 95% confidence intervals in the CON group and patient range in the MTL and H groups.) **(d)** Identification RTs classified according to recognition outcome in normal participants in the CID-R task (from Ref. [7]). Priming for items not recognized (indicated by shorter RTs for misses versus correct rejections) was found in the data and was also predicted by the model. (Bars denote data from Ref. [7], error bars denote 95% confidence intervals.) A demonstration of this simulation can be found at the first author's website: http://www.homepages.ucl.ac.uk/~ucjtcjb/resources.htm. Adapted, with permission, from Refs [7,8,17].

were not recognized, and to then show that a priming effect still exists for these items (e.g. Ref. [21]). It might then be concluded that the sources of memory that drive priming and recognition are independent because, if the same source of memory drives priming and recognition, why would priming occur for particular items in the absence of recognition? This result happens to fall quite naturally from the single-system model. In SDT, old items judged new (misses) are items whose strength falls below the decision criterion (Box 1); however, the strength of misses will still tend to be greater than the strength of new items judged new (correct rejections), simply because the mean strength of old items is typically greater than new items. In the single-system model (Figure 1), identification RTs are inversely related to

strength, and so the identification RTs to misses will tend to be shorter than those of correct rejections (Figure 2d). Thus, counterintuitively, it is simply not the case that priming for unrecognized items is indicative of multiple sources of memory.

A related prediction of the model concerns the relationship between the identification RTs to misses and false alarms when the difference between the mean strength values for old and new items is small versus large. When the difference is small, the model predicts that the identification RTs of false alarms will be shorter than those of misses. However, surprisingly, when the difference is large, the model predicts the opposite (i.e. shorter identification RTs to misses versus false alarms). This counterintuitive prediction arises because of the independent

Box 2. Establishing the existence of 'pure' implicit memory

Clear, replicable evidence for what is arguably a defining characteristic of implicit memory – that is, that its contents are not available to awareness – has proven difficult to establish [31–34]. Numerous methods for demonstrating unconscious memory have been proposed. One straightforward method is to show that priming occurs (at a group level) even though overall recognition performance is at chance. This dissociation would indicate that priming is caused by unconscious memory because explicit memory is absent. A well-known problem with this type of method is that it can be difficult to be certain whether the recognition test exhaustively indexes all of the memory that is available to awareness [31]. Furthermore, all too frequently, priming and recognition tasks have different retrieval cues, response metrics, susceptibilities to response bias, reliabilities etc., meaning that any dissociation found could potentially arise because of these differences (e.g. Refs [12,34]).

A more rigorous method, which has not been widely adopted, is the relative sensitivity approach [35]. This method requires that one first matches priming and recognition tasks on all extraneous characteristics and then compares the relative sensitivity (e.g. d') of the tasks. Implicit or unconscious memory is demonstrated whenever the sensitivity of the priming task is greater than the recognition task, even if performance on the latter is greater than chance (see Ref. [35] for details). Although a striking early demonstration of unconscious memory with this method [35] has been taken as proof of the existence of unconscious memory [3], we were unable to replicate this evidence [32].

Surely, if the construct of implicit memory is to be maintained, then clear, replicable evidence of its existence must be provided. Indeed, the lack of such evidence has led some to call for the term 'implicit memory' to be scrapped altogether [36]. This issue has also plagued the field of implicit learning for some time [31]. Because no one doubts that we can have memories that are conscious, if evidence for the existence of unconscious memory is not forthcoming, perhaps it is more parsimonious to assume that all forms of memory are accessible to consciousness.

Box 3. Neuroscientific evidence

Consistent with the multiple-systems view that implicit and explicit memory systems are neurally distinct (e.g. Ref. [2]), priming and recognition are, in most cases, associated with different patterns of brain activity. By using functional magnetic resonance imaging (fMRI) for example, retrieval from explicit memory is, in most cases, associated with haemodynamic response increases in prefrontal, parietal and medial temporal regions [37–39]. In contrast, priming is, in most cases, associated with haemodynamic response decreases in occipital, temporal and prefrontal regions [40]. This reduction in the haemodynamic response – a phenomenon referred to as repetition suppression – is thought to reflect increased processing efficiency, as also indexed by behavioural measures of priming [40]. Event related potential (ERP) studies also indicate that priming- and recognition-related activity at retrieval are associated with distinct time-courses and topographies (Ref. [41], although see Ref. [42]). These neural differences also extend to the encoding phase: subsequent priming and explicit memory are associated with distinct patterns of haemodynamic responses [43] and distinct electrophysiological responses [44].

These types of findings might be considered problematic for single-system views. However, only a few of these imaging studies have directly contrasted the neural correlates of implicit and explicit memory within the same paradigm (i.e. matching the experimental conditions). Of those that have, some compared the neural correlates associated with the contrast of misses versus correct rejections during a recognition memory test, hypothesized to reflect implicit memory, with those associated with the contrast of hits versus misses, hypothesized to reflect explicit memory [45,46]. As mentioned in the text however, misses are not necessarily a pure measure of implicit memory. Others have compared stimulus repetition effects across explicit or implicit memory tasks (e.g. Ref. [47]). The most compelling studies have compared implicit and explicit memory tasks that differ only in the instruction given to participants (e.g. within the word-stem completion paradigm), and furthermore measured priming and recognition on a trial-by-trial basis within each task [43,48]. However, even these studies have yet to meet more stringent criteria for dissociable patterns of brain activity associated with implicit and explicit memory; criteria analogous to those for a 'reversed association' [15], and that are important to allow for nonlinearities in measurements of neural activity [49]. Finally, it is worth mentioning that some have found commonalities in the neural correlates of the encoding processes leading to priming and recognition [50]. Future research will continue to illuminate the commonalities and potential differences in the neural processes underlying priming and recognition.

sources of noise in the model (see simulation study 2 in Ref. [7] for more details).

Another common practice in priming and recognition research is to look within a group of participants who (overall) perform above chance in recognition and find that there are individual participants who show priming even though their recognition performance is no better than chance. Priming in the absence of recognition in these participants invites the interpretation that their priming must be caused by another form of memory. Again, the presence of independent noise sources cautions against this, as Shanks [22] showed when applying a single-system model to an implicit learning paradigm (the sequential reaction time task, which involves responding to a visual cue that appears at different locations according to a particular sequence). The single-system model was shown to be able to reproduce this dissociation (see also Ref. [23]).

Finally, the presence of noise in the model enables it to explain another finding often taken to support multiple-systems views: priming and recognition performance is frequently not correlated (i.e. performance is often stochastically independent). Although the use of stochastic independence as evidence for multiple-systems is controversial [13,24], it seems important for the single-system model to account for such a common finding. As shown in Figure 2a, the model can indeed predict a weak correlation between priming and recognition, within the empirical range (see also Ref. [7]). Because of the independent sources of noise

associated with each task, it can seem as if there is a lack of relationship between priming and recognition, even though they are driven by the same memory signal (see also Ref. [5]). In sum, findings of priming within subsets of items or participants in which recognition is seemingly absent are compatible with the single-system model, as are findings of very low (often unreliable) correlations between priming and recognition.

Conclusions

The endeavour to obtain dissociations between priming and recognition has yielded many interesting findings. However, as we [7,8] and others [4–6] have shown, many dissociations can be explained without postulating independent memory systems or independent sources of memory. Formal models have been crucial in demonstrating this point, and we believe that they should be used to a greater extent to drive implicit and explicit memory research, as has been the case in theories of recognition (Box 1). The single-system model that we have discussed here is by no means exhaustive and many questions

Box 4. Outstanding questions

- Can other functional dissociations (such as those produced by changing presentation modality between study and test, or from reading versus generating items at encoding) be accounted for by the model, for example by introducing separate dimensions for modality-specific and modality-independent strength?
- Do regions of the brain associated with priming, recognition and fluency mirror *f* in the single-system model (Figure 1 in main text)?
- Can a multiple-systems version of the model be formulated? Can competing predictions of single- and multiple-system versions of the model be identified and tested? And, would a multiple-systems version be preferable to a single-system version as revealed by formal model comparison procedures that take into account the complexity of models?

remain for future research (Box 4). Although other models of implicit memory have been proposed, they have not been directly applied to dissociation evidence, and have tended to view priming and recognition in isolation (see Ref. [25]). As indicated by the success of our simulations, we believe that a good place to start in constructing models is with the assumption that the same memory signal drives priming, fluency and recognition. Regardless of whether the SDT modelling framework turns out to be the correct one for understanding implicit and explicit memory, we do believe that there is much to gain by using computational models to formalize and develop theories of implicit and explicit memory.

Acknowledgements

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