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Modeling single versus multiple systems in implicit and explicit memory

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It is currently controversial whether priming on implicit tasks and discrimination on explicit recognition tests are supported by a single memory system or by multiple, independent systems. In a *Psychological Review* article, Berry and colleagues used mathematical modeling to address this question and provide compelling evidence against the independent-systems approach.

Cognitive psychologists expend enormous effort investigating the proposition that different cognitive phenomena reflect the contribution of separate neurophysiological systems. For example, much research rests on the notion that separate memory systems underlie priming on implicit tasks and discrimination on explicit recognition tests [1]. Behavioral and neurophysiological research methods have driven impressive progress in this area, but another powerful research tool – mathematical modeling – has been significantly under-utilized. In a recently published article, Berry, Shanks, Speekenbrink, and Henson [2] took a step in the direction of a more rigorous modeling approach. Their results demonstrate the promise of formal models for increasing the clarity of predictions, producing more appropriate interpretations of empirical patterns, and redefining research questions.

Berry *et al.* [2] focused on a task in which explicit and implicit memory could be compared within the same test. In this task, participants first identify a test item from a degraded stimulus that becomes clearer over time. Some of the test items have been presented in a previous list, and priming is obtained if these items are identified more quickly than non-studied items. Following the identification of a test item, participants decide whether or not the item was previously presented (i.e., whether it is 'old' or 'new'). In addition to the standard 'old'/'new' procedure, Berry *et al.* obtained recognition responses in terms of confidence ratings ranging from 1 (certain 'new') to 6 (certain 'old'), as well as responses in which participants indicated whether they specifically recollected studying an item or just found it familiar. To accommodate identification priming and accuracy in recognition, the authors developed signal detection models under a range of assumptions regarding the relationship between priming and conscious recognition.

At one extreme, a single-system model assumes that the same memory strength value drives priming and recognition memory. This single-system account makes strong and novel predictions. First, recognition and priming should be linked: even within old or new items, identification times should be faster for items called 'old' than items called 'new.' Consequently, there should be less priming for old items that are not recognized than for recognized items. Second, independent variables cannot have opposite influences on recognition and priming, and third, priming should not be observed in the absence of recognition.

At the other extreme, one version of a multiple-system model assumes that completely independent memory signals drive identification and recognition (we call this the independent-systems model). Within a stimulus class ('old' or 'new'), this model predicts that identification times should be equal for items receiving 'old' and 'new' judgments. The independent-systems model is free to separately vary the memory strength contributions to priming and recognition and therefore, unlike the single-system model, it can produce priming in the absence of recognition discrimination and vice versa.

Covering the middle ground between the single-system and independent-systems models is a model in which the contributions of memory to recognition and priming overlap somewhat but not completely (we call this the overlapping-systems model). Specifically, the memory strengths for identification and recognition are drawn from a bivariate Gaussian distribution with parameters for the mean identification strength, the mean recognition strength, and the correlation between the two strengths across items.

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To evaluate these models, the authors reported three experiments with college students, as well as previously published data from amnesic patients [3]. Results decisively precluded the possibility of independent systems. Even within 'old' and 'new' items, identification times were faster for words called 'old' versus words called 'new', for words recognized with a high versus a low level of confidence, and for words that participants claimed to consciously recollect versus words they claimed were merely familiar. Even amnesic patients showed numerical evidence of these effects. As the independent-systems model has no mechanism for producing this link, it must be rejected in favor of either the single-system model or the overlapping-systems model. The single-system model was often preferred by fit statistics that penalize for the number of model parameters (Akaike information criterion). However, one of the amnesic patients showed detectable priming with no discrimination on the recognition task, a result that is not possible under the single-system model.

Although Berry *et al*. [2] tested only one form of implicit memory and tests of others are needed (e.g., word fragment completion), their results are an important first step in simultaneously modeling implicit and explicit memory. Nevertheless, their work leaves ample room for further theoretical development. One important direction is to distinguish the single-system model from the overlapping-systems model with targeted manipulations that qualitatively (not just quantitatively) support one model and reject the other. A second important direction is to specify how the values of memory strength that drive identification and recognition are produced (i.e., develop a process model, [4,5]). Still another critical advance would be to develop a more realistic model of response times by moving to a sequential sampling decision model [6–9]. In their current form, the models suggested by Berry *et al*. do not address response times for recognition decisions and the simplistic linear function they use to map strength onto identification times cannot accommodate full response time distributions across a range of experimental variables and tasks. In many applications, models that can explain only accuracy or mean decision times have been profitably replaced with models that can explain both accuracy and full response time distributions (see [7] for a review).

The Berry *et al*. [2] article highlights two important messages that should influence the future of research on implicit and explicit memory. First, even if implicit and explicit memory can be dissociated in special situations, Berry *et al*.'s results demonstrate a profound overlap in the memory processes involved in priming and explicit recognition. This overlap should be accommodated theoretically (see the discussion in [10], p. 405). Second, Berry *et al*. show that future progress requires a more rigorous formal approach to theory than has previously characterized this domain. A modeling approach should direct attention away from simply establishing how many systems we can differentiate and toward a more important question: how do these systems work and how do they work together?

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Number, texture and crowding

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A recent study shows that selectivity for numerosity emerges as a natural property in deep networks of hierarchical generative models of visual perception. These results, together with recent conceptualizations of crowding and texture, suggest that the 'sense of number' is a fundamental visual property, independent of texture and seemingly related attributes.

Most adult humans can count. However, we also share an approximate non-verbal system with infants and other animals: a visual 'sense of number' [1]. We can visually estimate the numerosity of sets of items, with a margin of error which increases with set size, following 'Weber's law' (like most perceptual processes). Neurons tuned for number have been found in the higher reaches of the visual system of non-human primates [2]. Moreover, numerosity, like all primary sensory properties, is susceptible to adaptation: prolonged exposure to a more numerous visual stimulus makes the current stimulus appear less numerous and vice versa [3].

Surprisingly, there has been considerable resistance to the idea that number could be a visual attribute. Several

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