Commentary

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Decay Versus Interference: A New Look at an Old Interaction

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A question that has been fought over for at least 80 years is whether memory traces decay with time or interfere with one another (McGeoch, 1932). This question is central to interpretations of forgetting and memory capacity and to understanding the design of the human cognitive architecture. There are two camps, which take turns declaring victory (e.g., there is "no temporal decay in verbal short-term memory," proclaim Lewandowsky, Oberauer, & Brown, 2009; "time causes forgetting from working memory," respond Barrouillet, De Paepe, & Langerock, 2012).

Often lost in the fog of battle is evidence that decay and interference are both at work, with decay more subtle than interference but no less common. Berman, Jonides, and Lewis (2009) made this point when they went "in search of decay in verbal working memory" and ultimately found it when they pooled data across experiments (Berman et. al., Fig. 7). Small but robust decay effects can be measured by controlling interference across conditions (Altmann & Gray, 2002) rather than trying to eliminate it (Reitman, 1974). There is also the theoretical argument that decay plays a functional role in cleaning up episodic detritus (Altmann & Gray, 2008), which suggests that decay effects should be pervasive.

In the study reported here, we asked whether this perspective—that large interference effects and small decay effects pervasively coexist—could bring new clarity to the results of a classic study that helped shape and still influences the debate. Waugh and Norman (1965) used a probe-digit procedure, in which a list of digits was presented for study, and memory was tested with a probe that indicated which digit to recall. The last digit of the study list was the second occurrence of the probe, and the target for recall was the digit that followed the first occurrence of the probe. Interference was indexed by the number of items between the target and the end of the list. Decay was indexed by presentation rate.

Waugh and Norman's (1965) data appear in Figure 1. There was a large effect of number of interfering items but no effect of presentation rate (1 item/s vs. 4 items/s). The authors did not test the interaction of these factors—and although the interaction invited comment initially (Broadbent, 1971; Massaro, 1970; Shallice, 1967, as cited in Craik, 1971), it then slipped beneath the waves. Meanwhile, the large interference effect evolved into textbook evidence for an interference-only perspective (e.g., Ashcraft & Radvansky, 2010; Galotti, 2008).

And yet, the interaction (see Fig. 1)—which is highly significant[1]—is exactly what one would expect if interference and decay interacted to influence recall. Early items benefit if presentation is fast because memory for them is less decayed at test, and late items benefit if presentation is slow because memory for early items is more decayed at test and thus generates less proactive interference.

To demonstrate this point, we developed a simple formal model based on existing memory theory (Anderson, Bothell, Lebiere, & Matessa, 1998). Decay is represented by the following equation:

$$A(t) = -0.5 \ln(t), \tag{1}$$

where $A(t)$ is the activation of an item at test when it is t seconds old. The age of the last item, t_{last}, is a free parameter, which—together with the presentation rate—binds the ages of earlier items. Interference is represented by the following equation:

$$p(j) = \frac{e^{A(t_j)/s}}{\sum_i e^{A(t_i)/s}}, \tag{2}$$

where $p(j)$ is the probability of retrieving element j, A is activation from Equation 1, s is activation noise, and the summation is over all list items.

We assumed two additional mechanisms. The first is priming of the target by the probe at test, in the amount of activation r. This is necessary to overcome the competition for retrieval implied by Equation 2 and is consistent with a contiguity effect in which recall of one target predicts increased recall of its successor (Kahana, 1996). Second, we assumed extralist interference. Presentation rate was blocked, so extralist interference

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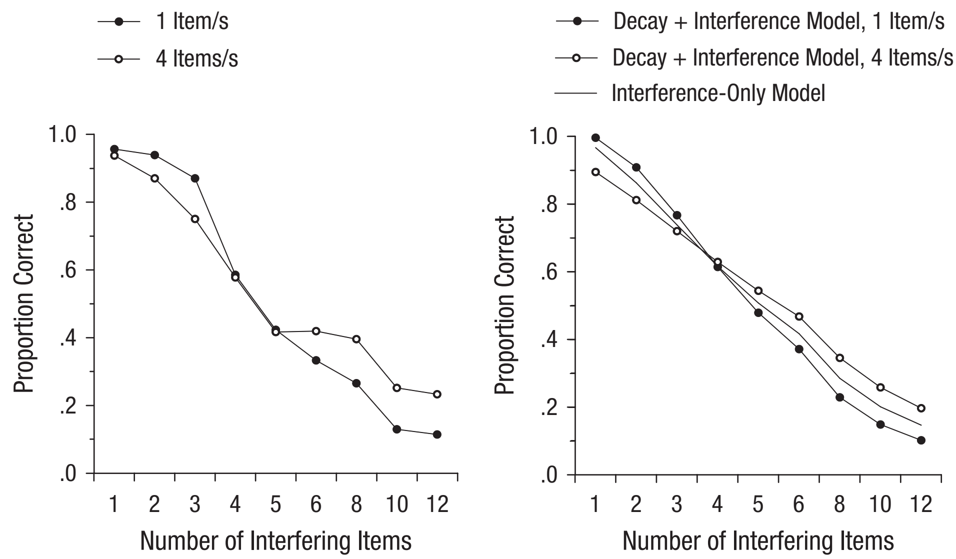

Fig. 1. Data from Waugh and Norman (1965) and fits of two models to the data. The left panel shows the proportion of correct responses in Waugh and Norman (1965), uncorrected for guessing, as a function of the number of interfering items and presentation rate. The right panel shows the maximum-likelihood fits of two models—decay plus interference and interference only—to the data. For the decay-plus-interference model, fits are shown separately for the two presentation rates. Presentation rate had no effect in the interference-only model.

should have been greater in the fast condition than in the slow condition because distractors from previous lists would have been more recent. We represented this factor with an extra distractor in the fast condition, estimating its activation E as a free parameter. With these mechanisms, the probability of recalling element j at each presentation rate is as follows:

$$p(j)_{\text{fast}} = \frac{e^{[r + A(t_j)]/s}}{e^{E/s} + \sum_i e^{A(t_i)/s}}, \tag{3a}$$

$$p(j)_{\text{slow}} = \frac{e^{[r + A(t_j)]/s}}{\sum_i e^{A(t_i)/s}}. \tag{3b}$$

We used maximum-likelihood estimation to fit these equations to Waugh and Norman's (1965) data, estimating four parameters (t_{last}, s, r, and E) from 18 data points. The likelihood function was the binomial distribution, with the model predicting the probability of an accurate response. The fit is illustrated in the right panel of Figure 1 ($\ln L = -85.3$). The model captures both the main effect of number of interfering items and its interaction with presentation rate.

We compared this model with one in which presentation rate had no effect and which therefore could not capture the interaction (see Fig. 1; $\ln L = -92.4$).[2] The Bayes factor computed from the log likelihoods for the two models favored the decay-plus-interference model by 1,274:1; values over 150:1 are considered "very strong" evidence (Wagenmakers, 2007, p. 791).

Of course, other time-based processes could account for the interaction of number of interfering items and presentation rate. For example, Massaro (1970) explained the interaction in terms of perceptual encoding, noting that presentation rate determines time available to process a stimulus. That said, memory is a functional system, and explaining any effect in isolation says little about how memory actually delivers information. A system-level focus suggests, for example, that some decay-like process is necessary to manage interference (Altmann & Gray, 2008), and detractors have yet to respond with their own account of how the system avoids grinding to a halt in the face of unmitigated buildup of interference. The prior theoretical odds for decay are therefore quite high (see also Schooler & Hertwig, 2005). The general point is that a functional, system-level focus (Newell, 1973) is an important way to drive memory theory, as well as a useful way to explore subtleties of archival data.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Supplemental Material

Additional supporting information may be found at http://pss.sagepub.com/content/by/supplemental-data

Notes

1. To test the interaction, we reconstructed the data from Waugh and Norman's (1965) subject-level plots. The interaction was significant, $F(8, 24) = 5.12$, $p = .001$. The reconstructed data are included in Data and Models in the Supplemental Material available online. Norman (1966) seems to have replicated the interaction (see Norman, 1966, Fig. 1) but again did not report statistics.
2. A description of this interference-only model is included in the Supplemental Material.

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