Rational analysis of the adaptive and predictive nature of memory

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In his target article, Klein (2013) makes the important point that many approaches to studying memory neglect the function of memory, in particular its capacity to help predict the future. Here, we complement Klein's argument in two ways. First, we point to an existing and well-developed research program that formalizes a functional approach to memory, exploring its adaptive nature. Second, we illustrate how this approach can be applied to analyze regularities in social interactions, which memory might exploit to predict future interactions.

John R. Anderson and colleagues (Anderson & Milson, 1989; Anderson & Schooler, 1991, 2000; Schooler & Anderson, 1997) developed the rational analysis of memory, in which they argued that much of memory performance, including forgetting, might be understood in terms of adaptation to the structure of the environment. The first key assumption of the rational analysis is that environmental stimuli make informational demands on the cognitive system that are met by retrieving memory traces associated with those stimuli. The second assumption is that the memory system acts on the expectation that environmental stimuli tend to reoccur in predictable ways; the pattern of past encounters can, thus, predict the future need of information. The third assumption is that the memory system makes most accessible those traces that it predicts will be most useful in the future. Consequently, memory performance should reflect the patterns with which environmental stimuli occur and reoccur in the environment. For instance, more recently encountered stimuli will likely be encountered again. An adaptive memory system should make information about those stimuli more accessible because it is more likely to be needed. Conversely, the longer time interval since the last encounter, the less likely the information will be needed in the future, and so it can and should be forgotten.

The rational analysis of memory has been incorporated into the declarative memory system of ACT-R, a formal cognitive architecture that models a broad range of cognitive tasks from subitizing (Peterson & Simon, 2000) and list learning (Anderson, Bothell, Lebiere, & Matessa, 1998) to the emergence of cooperation in the prisoner's dilemma game (Kim, 2011) and the neural underpinnings of working and declarative memory (Borst & Anderson, 2013). In ACT-R, the accessibility of a memory trace equals its activation level, which corresponds to its predicted probability of being needed. A functional view of memory, therefore, lies at the heart of a thriving cognitive science research program that provides a formal, integrated theory of cognition (Anderson, 2007; http://act-r.psy.cmu.edu).

As an example of the assumed relation between past and predicted future occurrence of an object, consider the time since one has last encountered an object in the world (*recency*). Forgetting functions describe how memory retention declines with recency. Memory retention typically declines as a power function with longer time intervals since encountering an object (Figure 1a). Anderson and Schooler (1991) investigated whether this regularity in memory might reflect a statistical property of human environments. They found, in fact, that forgetting functions match patterns of word use. Specifically, encounter rates of words in the *New York Times* headlines (Figure 1b) and patterns of adult speech to children both show similar power functions with recency. Statistical patterns of past encounters seem to provide powerful predictors of future encounters—and memory functions seem to exploit these regularities in the environment to bet on future needs of information.

Anderson (1990) based the notion of rational analysis on an evolutionary perspective on cognition, incorporating evolutionary optimization in his framework. This approach, thus, not only offers an explicit adaptive perspective on the predictive nature of memory, but, like Klein's (2013) argument, it also has had an evolutionary foundation since its inception.[1] This explicitly evolutionary approach, then, provides a clear starting point for Klein's broader thesis that various aspects of memory (beyond the retention memory highlighted in the rational analysis) have adaptive function potentially geared toward predicting the future.

Another important domain in which memory might exploit statistical regularities in the environment to predict the future is social contact. Specifically, given the social nature of humans, it may be beneficial to predict whom from one's social environment one is likely to encounter again. Meeting, chatting with, and emailing other people requires the retrieval of information about them. Might memory use statistical regularities in social contact to predict future encounters? To test this possibility, we analyzed records of individual social contact (including email, face-to-face interactions, phone calls, and letters) across a period of 739 days (Pachur et al., 2013). Figure 1c shows that, similar to Anderson and Schooler's (1991) analyses of word use, the recency of previous social contact predicted probability of future contact in a power-law-like manner (Figure 1c). Patterns observed in memory and word usage can, thus, also be observed in social contact—and reflections of these patterns in memory could be used to predict social contact.

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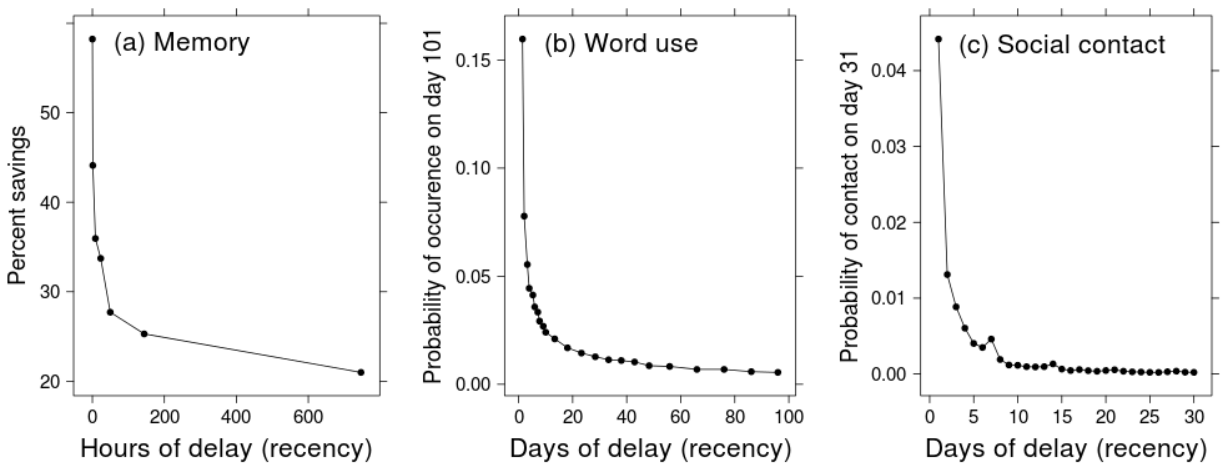

Figure 1: Memory, word use, and social contact patterns. (a) Ebbinghaus (1913) recorded the percent savings in memory retention (savings refers to the amount of studying saved when relearning) at different retention intervals (recency). According to Anderson and Schooler (1991) and Wixted and Ebbesen (1991), memory savings falls off as a power-law function with recency. (b) Anderson & Schooler also showed that the probability of a word appearing in a *New York Times* headline depended on the recency of the last time that word appeared. (c) Pachur et al. (2013) showed that, like memory retention and word use, the probability of social contact decreased as a power function of time since last contact. Panels (a) and (b) are redrawn from Anderson and Schooler (1991), and panel (c) is redrawn from Pachur et al. (2013).

Why might social contact be a particularly critical environmental force shaping cognition? For one, social contact patterns can influence the evolution of cooperation (Krasnow et al., 2013; Pachur et al., 2013). The evolutionary stability of many strategies in cooperative situations depends on the probability of future interaction (Axelrod & Hamilton, 1981; Nowak, 2006). Reciprocal strategies such as tit-for-tat (copying your partner's previous choice) and reputation-based strategies work only if future encounters are likely. Human memory may reflect patterns of social contact to predict the probability of future encounters of potentially cooperative partners. This perspective implies that cognition (memory) and decision making (cooperative strategies) may have co-evolved to match structures in the social environment.

In summary, the rational analysis of memory provides a theoretical foundation for Klein's (2013) contention that cognitive psychology should pay more attention to the functional basis of memory. Built with an evolutionary perspective in mind, this approach provides a formal framework for deriving quantitative predictions of both behavior and, through ACT-R, the underlying cognitive processes and corresponding neural correlates. We have proposed that social contact may be a key aspect of the environment to which our cognition has adapted. The more recently one has encountered a contact, the more likely one will encounter this person in the near future. This creates memory demands for retrieving information about these contacts, so memory should be adapted to cope with these demands. These patterns of social contact, then, have important implications for evolutionarily relevant problems such as cooperation. This combination of assessing the structure of the environment and the cognitive capacities of the actors conceptually bridges the historically mechanistic cognitive science approach and the typically more functional evolutionary approach. As proposed by Herbert Simon (1956), we will not understand the human mind without considering both cognition *and* the environment.

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Footnotes

1. It should be noted, however, that the rational analysis of memory does not require that the adaptation of memory to the statistical structure of the environment be an evolutionary adaptation; it could also be a result of adaptation over the lifespan of an individual.