Sampling memory to make profitable choices

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A computational model explains how memories of past rewards guide value-based choices. Incorporating behavioral and functional MRI evidence, the findings indicate that 'sampling' from individual memories of past rewards influences choices.

When faced with a buffet table of oysters, you may need to choose whether and to what degree you will indulge. This decision is based on your estimation of whether or not eating the oysters will lead to a rewarding outcome. In such instances, it seems obvious that our decision will be informed by our past experiences. What is less obvious, however, is in exactly what way we use our memories of past experiences to guide current decisions. An intuitive idea that has dominated decision-making research for many years is that we store something like a running average of our experiences ("I tend to be fine after eating oysters"), weighting recent experiences more heavily[1]. The next time we need to make the same decision, we 'load' this norm-based expectation to guide our decision. Researchers studying value-based decision-making have fine-tuned this basic idea over the years, generating detailed computational models that can powerfully explain variability in how human subjects actually respond in these situations (though, typically, without using oysters)[2,3].

In a pair of studies that elegantly integrate behavioral and neuroimaging evidence[4,5], Bornstein and colleagues challenge this traditional view of decision-making by introducing a different computational model that better explains how memories for past experiences influence present decisions. In contrast to the idea that decisions are based on a running average of outcomes, Bornstein and colleagues argue that decisions are largely influenced by memories of individual experiences from the past ("One time when I had oysters I became sick") or even contextually relevant experiences from the past ("One time, after having oysters at this very restaurant, I became sick"). According to this alternative view, there is no need to store or continuously update a running average of outcomes; rather, we only need to form memories for individual events and their outcomes, and we then retrieve—or 'sample'—these memories whenever we need to make a decision[6–8].

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To adjudicate between various theoretical accounts of decision-making, researchers typically have subjects play some kind of decision-making game (think gambling in Las Vegas, but computerized and less debaucherous). They then generate computational models that explicitly parameterize potential influences on decisions. These models can then be applied to subjects' actual choices to quantify how well the model fits the pattern of choices that subjects made. In an initial experiment, Bornstein and colleagues[4] developed a model based on the idea that individuals sample from remembered experiences to make choices. In the experiment, subjects chose which of four slot machines to play. Each machine had a different payout rate (between 0 and 100 points) that slowly varied over time. Subjects decided which slot machine to play on each trial, and models were fit to subjects' patterns of choices. As a first step, the researchers asked whether the new sampling model better explained behavior than the traditional, running-average model.

If subjects' choices are predominantly based on a running average of outcomes, then their responses should follow a predictable pattern, with temporally distant experiences having very little influence on current choices. Alternatively, if subjects sample individual past events, then temporally distant experiences should occasionally have a strong influence (**Fig. 1a**). In other words, subjects would be expected to occasionally play a slot machine that had a big payout long ago. When the sampling and running average models were fit to each subject's behavioral choices, the sampling model provided a superior fit for every subject. And when the models were then applied to a functional MRI (fMRI) dataset using the same task, the sampling model also better explained fluctuations in neural responses than did the running-average model.

While these initial findings suggest that sampling powerfully explains choice behavior, the researchers went a step further, conducting a separate behavioral study in which they experimentally manipulated, on a trial-by-trial basis, whether individual episodes from the past were active in memory. This allowed them to causally test whether memories of a single past experience influence current choices. In this version of the experiment, subjects chose between two slot machines and received images of various monetary rewards. Critically, however, these payouts were coupled with images of arbitrary, trial-unique objects (for example, a picture of a coffee mug) that would later be used to remind subjects of individual trials.

To test whether memories of individual events biased current decisions, the memory cues (for example, the coffee mug) were shown to subjects just before another slot machine trial (**Fig. 1b**). The prediction was that subjects' choices—that is, which slot machine to play—would be influenced by the reminded event. For example, if subjects were reminded of a past trial where the first slot machine yielded a big payout, then subjects should be more likely to choose the first slot machine on the current trial. As predicted, subjects' decisions were robustly influenced by these reminders. In fact, reminders of these temporally distant experiences had an influence on choices that was comparable in magnitude to the influence of outcomes two or three trials ago. In other words, the reminders effectively revived past rewards, thereby influencing current choices. Thus, the results of the first study strongly hinted that subjects' current decisions were being influenced by the retrieval of individual past events, whereas the second study provides causal evidence that bringing individual past events to mind influences current decisions.

In a separate but closely related paper[5], Bornstein and colleagues further extended the idea of sampling to consider the influence that context has on decisions ("Should I eat oysters from this restaurant?"). As in the previous study[4], subjects again made choices that were associated with probabilistic rewards (in this case, choosing between decks of cards that had different probabilities of paying out $10). Again, trials were associated with specific images that were later used to remind subjects of the rewards received on that trial. However, every trial was now also associated with one of several scene images—for example, a picture of a beach (**Fig. 1c**). These scene images can be thought of as 'rooms' that provided context for each trial. Critically, each room was associated with different, time-varying payout probabilities for each deck of cards, so that the room itself conveyed information about the odds of winning from each deck.

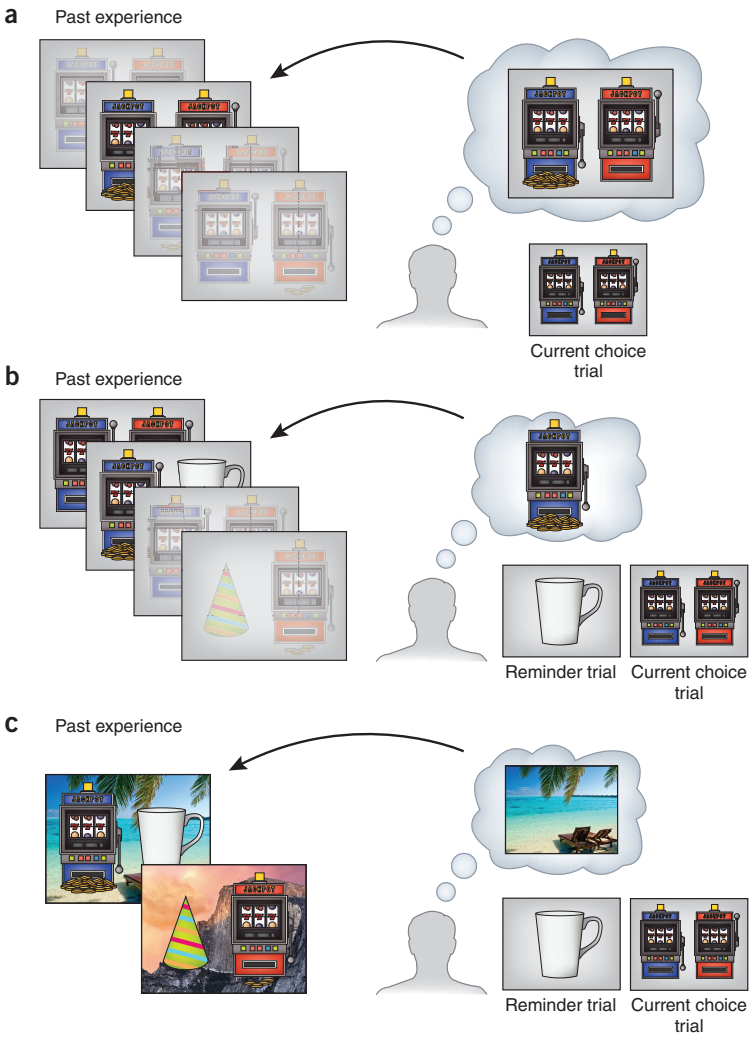

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Figure 1 Memory sampling and choice behavior. (**a**) According the hypothesis of memory sampling, a subject's choice on a current trial is influenced by retrieval of a single memory for the outcome associated with a past choice. For example, in deciding which slot machine to play, a subject may choose the blue slot machine based on a sampled memory of previously receiving a high payout when playing the blue slot machine. Bornstein *et al.*[4,5] show that a computational model based around the idea of memory sampling provides a better fit to subjects' pattern of choices than does a more traditional model that assumes that choices are based on a running average of the payouts associated with each slot machine. (**b**) To test whether memories for individual events from the past can influence current choices, Bornstein *et al.*[4,5] 'tagged' each event with an arbitrary, trial-unique picture (for example, a coffee mug) and then used these tags to remind subjects of past choices and rewards. They found that these reminders influenced subjects' current choices. For example, a reminder of a past trial associated with a high payout from the blue slot machine increased the likelihood that subjects would select the blue slot machine on the current trial. (**c**) Extending the idea of sampling, Bornstein and Norman[5] show that reminding subjects of a particular trial from the past also activates the context in which that choice and reward occurred. For example, if subjects are reminded of a trial that occurred in 'room A,' sampling is biased to draw from other trials experienced in that same room (as opposed to trials from 'room B'). Using fMRI, Bornstein and Norman[5] provide further evidence that retrieved context influences choices, showing that patterns of brain activity associated with a past context are in fact reinstated when making current choices. Critically, the degree of this reinstatement of past context predicts how strong an influence context has on current choices.

Based on the aforementioned study[4], it was anticipated that subjects would be influenced by the rewards received on the reminded (past) trial. However, the new question was whether these reminders would also produce an influence from the reminded context. In other words, did reminding subjects of a trial that occurred in the beach room lead them to choose cards as if they were back in that room? In an initial behavioral study, subjects' choices were influenced both by the reminded trial (as in the prior studies) and the reminded context. In fact, the reminded context had an even stronger influence than the reminded trial. This finding refines the idea of sampling by showing that context influences which memories will be sampled.

In a follow-up study, subjects performed the same card task but this time during fMRI scanning. Ingeniously, fMRI data were used as a covert index of the degree to which subjects activated the context associated with each reminded trial: activation in scene-selective brain regions was taken as evidence for reinstatement of reminded contexts. Not only did reminders activate scene-selective cortex but the strength of scene activation—an index of context memory—predicted the degree of influence that the reminded context had on decisions. Thus, the fMRI data provided a window into the sampling process in action.

Collectively, these findings shake up some long-held ideas about how past experiences influence current decisions, providing compelling evidence that decisions are shaped by retrieval of individual memories for past rewards—even rewards that occurred long ago. However, these findings also raise several provocative questions. For example, what factors beyond context might influence the probability of a memory being sampled during choice behavior? While the present findings consider the role of memory in activating past rewards, an intriguing possibility is that past rewards may themselves influence which memories are most likely to be sampled[9]. Also, the very act of sampling a memory raises the possibility that the sampled memory may be altered—either strengthened or weakened[10]. As illustrated by these questions, the findings of Bornstein and colleagues[4,5] bring together two often disparate literatures, memory and decision-making, and are likely to inspire future research that considers this important interplay.

COMPETING FINANCIAL INTERESTS
The authors declare no competing financial interests.

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