

Value-Based Choice, Contingency Learning, and Suicidal Behavior in Mid- and Late-Life Depression

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ABSTRACT

BACKGROUND: Suicidal behavior is associated with impaired decision making in contexts of uncertainty. Existing studies, however, do not definitively address whether suicide attempters have 1) impairment in learning from experience or 2) impairment in choice based on comparison of estimated option values. Our reinforcement learning model-based behavioral study tested these hypotheses directly in middle-aged and older suicide attempters representative of those who die by suicide.

METHODS: Two samples (sample 1, $n = 135$; sample 2, $n = 125$) of suicide attempters with depression ($n_{\text{attempters}} = 54$ and 39, respectively), suicide ideators, nonsuicidal patients with depression, and healthy control participants completed a probabilistic three-choice decision-making task. A second experiment in sample 2 experimentally dissociated long-term learned value from reward magnitude. Analyses combined computational reinforcement learning and mixed-effects models of decision times and choices.

RESULTS: With regard to learning, suicide attempters (vs. all comparison groups) were less sensitive to one-back reinforcement, as indicated by a reduced effect on both choices and decision times. Learning deficits scaled with attempt lethality and were partially explained by poor cognitive control. With regard to value-based choice, suicide attempters (vs. all comparison groups) displayed abnormally long decision times when choosing between similarly valued options and were less able to distinguish between the best and second-best options. Group differences in value-based choice were robust to controlling for cognitive performance, comorbidities, impulsivity, psychotropic exposure, and possible brain damage from attempts.

CONCLUSIONS: Serious suicidal behavior is associated with impaired reward learning, likely undermining the search for alternative solutions. Attempted suicide is associated with impaired value comparison during the choice process, potentially interfering with the consideration of deterrents and alternatives in a crisis.

Keywords: Decision making, Depression, Expected value, Reinforcement learning, Reward, Suicide

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Our society tends to view the decision to end one's life as strategic (1). Yet, clinicians more commonly observe that suicide follows a limited consideration of the current crisis, alternative solutions, and deterrents (2). In retrospect, survivors usually regret their suicide attempt (3). These observations inform the general hypothesis that in a crisis, people vulnerable to suicide do not optimally incorporate moment-to-moment experiences into their decisions along with their values, goals, and prior knowledge. For example, precipitating stressors that may appear relatively inconsequential to the clinician (e.g., an argument) can trigger a suicidal act, temporarily overshadowing the more significant deterrents (e.g., traumatizing one's family). Explaining this phenomenon merely as a manifestation of impulsivity fails to capture the uncertainty and confusion characteristic of a suicidal crisis. More precise explanations may include poor integration of recent experiences with prior experience and values and improper

comparison of the worth of alternative options when making the choice. Reinforcement learning (RL) models of neural computation (Box 1) distinguish between these two explanations; disrupted learning of expected value (hypothesis 1 [H1]) depends on the medial orbitofrontal/ventromedial prefrontal cortex (vmPFC) (4), whereas impaired ability to compare learned values while making a choice (hypothesis 2 [H2]) maps to the lateral orbitofrontal cortex and, more generally, to the lateral PFC (5).

In people who have attempted suicide, laboratory studies using the Iowa Gambling Task (IGT), a decision-making task involving both learning of action values and value-based choice, support the general hypothesis of impaired decision making (6,7). The IGT, however, cannot differentiate between impairments in action value learning and impairments in value comparison. Specific evidence for the impaired value learning hypothesis (H1) is mixed, with suicide attempters showing

Box 1. Key Terms

Expected value: In economics, a measure of benefit associated with an option expressed in a theoretical common currency used to compare disparate goods. In animal learning, expected reward is associated with an action or a stimulus (associative strength). It is thought to be represented in the human ventromedial prefrontal cortex.

Reinforcement learning: Statistical account of learning wherein the discrepancy between the actually received reward and the expected reward (prediction error) is the learning signal, used to update expected value. The goal of reinforcement learning is to estimate the values of available options from experience and to maximize reward.

Value-based choice: Selection of actions informed by their values. Choices require greater cognitive effort when action values are close. Choices can be exploitative (favoring options with known high value) or exploratory (sampling lower-value alternatives, typically under uncertainty).

deficits on a probabilistic reversal learning task (8) and in some (9), but not all [meta-analysis: (7)], studies of deterministic learning using the Wisconsin Card Sorting Task. The hypothesis of impaired value comparison (H2) is supported by impairment in suicide attempters on the Cambridge Gambling Task (10), which does not require learning. Cambridge Gambling Task deficits in these patients have been also linked to disrupted value representations in the vmPFC (11). Indirect support for this hypothesis comes from a growing number of studies where suicide attempters show altered value-based decision making in contexts that do not involve uncertainty (e.g., delay discounting), tests of biases and heuristics, and social decision making (12–15). In summary, while our understanding of the neurocomputational mechanisms of impaired decision making in suicidal behavior is limited, there is preliminary support for impairments in both learning and value-based choice.

To test these hypotheses conclusively, we assessed learning (H1) and value-based choice (H2) in two nonoverlapping samples of suicide attempters with a three-armed bandit task differentially sensitive to these functions (5). Our initial analysis of learning (H1) examined the impact of one-back reinforcement on behavior. Our primary analysis examined how past reinforcement was encoded (H1) and how learned values affected current choices (H2). We first estimated learned expected value and prediction errors (PEs) using an RL model fitted to choices and reinforcement history. To avoid circularity, we then examined how decision times (DTs), a process index independent of inputs to the RL model, were modulated by recent reinforcement (H1) and previously learned values (H2). Decision field theory predicts slower responses on difficult trials involving a small difference between values (16). We used this slowing as an index of the influence of previously learned values on the current choice (H2). At the same time, we examined whether learning (H1) from recent reinforcement was altered in suicide attempters, as indexed by DT modulation by rewards and absolute PEs (17). This analysis of DTs enabled us to assess how reinforcement modulated the decision process and not merely its outcome (i.e., the choice).

METHODS AND MATERIALS**Study Design: Overview**

We sought to sample individuals maximally representative of those who die by suicide. Given that older and middle-aged adults are at the highest risk for suicide and that attempt-to-death ratios decrease from 100:1 during young adulthood to around 2:1 during old age (18), our study enrolled middle-aged

and older suicide attempters with current major depression. To isolate decision process alterations associated with suicidal behavior, we included comparison groups of nonsuicidal patients with depression and patients with depression and serious suicidal ideation but no history of attempt. Furthermore, to test for a dose–response relationship between decision process deficits and suicidal behavior, we examined whether they scaled with the medical seriousness (lethality) of suicide attempts. Finally, the second sample was retested in a state of partial recovery from depression, potentially revealing the stability of decision deficits. This second experiment involved an additional manipulation separating long-term learned value from transient effects of reward magnitude.

Sample and Its Characterization

Overall, 260 adults aged 42 to 82 years (sample 1, $n = 135$) and aged 47 to 79 years (sample 2, $n = 125$) (Supplemental Tables S1 and S2; see Procedures for sample descriptions) participated in a longitudinal study of suicidal behavior in late-life depression (19). Participants provided written informed consent, and all study procedures were approved by the University of Pittsburgh Institutional Review Board. Participants were selected into one of four groups: suicide attempters with depression, suicide ideators with depression, nonsuicidal patients with depression, and healthy control participants. They were recruited at a psychogeriatric inpatient unit, at a late-life depression clinic, through primary care, and through community advertisements in Pittsburgh, Pennsylvania (15,19).

Suicide attempters with depression had a history of a self-injurious act with the intent to die within a 1-month period of completing the study assessments or had a history of a past suicide attempt with strong current suicidal ideation at the time of study enrollment. Suicide attempt history was verified by a psychiatrist (AYD or KS) using all available information: participant's report, medical records, and collateral information from the treatment team, family, and friends. Significant discrepancies between these sources led to exclusion from the study. The medical seriousness of attempts was assessed using the Beck Lethality Scale (20); for participants with multiple attempts, data for the highest-lethality attempt are presented. In total, 22 participants in sample 1 and 11 participants in sample 2 had at least one high-lethality attempt (Beck Lethality Scale score ≥ 4). High-lethality attempts resulted in coma, need for resuscitation, unstable vital signs, penetrating wounds of abdomen or chest, third-degree burns, or major bleeding. None of the participants had documented brain

damage from a suicide attempt. A review of medical records suggested that such damage could not be ruled out in 7 of 54 attempters in sample 1 and in 2 of 36 attempters in sample 2. In sensitivity analyses, we excluded these individuals. Suicidal intent associated with the most lethal attempt was assessed using Beck's Suicide Intent Scale (20). Suicidal ideators with depression, included to identify specific correlates of suicidal behavior, had suicidal ideation with a specific plan but no lifetime history of attempt. Individuals with a passive death wish or transient or ambiguous suicidal ideas were excluded from this group. Nonsuicidal older adults with depression were included in the study as a comparison group to identify an association between suicidal thoughts or behavior beyond the effects of depression. Nonsuicidal participants with depression had no lifetime history of self-injurious behavior, suicidal ideation, or suicide attempts based on the clinical interview, review of medical records, Structured Clinical Interview for DSM (SCID)/DSM-IV, and a score of 0 on the Hamilton Rating Scale for Depression (17 items) suicide item. Healthy control participants had no lifetime history of psychiatric disorders, as determined by the SCID/DSM-IV. All participants except for healthy control participants had a SCID/DSM-IV diagnosis of unipolar nonpsychotic major depression and a score of 14 or higher on the 17-item Hamilton Rating Scale for Depression at study entry. We excluded individuals with clinical dementia (previous diagnosis or score < 24 on the Mini-Mental State Examination) or a history of neurological disorder, delirium, or sensory disorder that precluded the performance of a learning task. Clinical, cognitive, and psychological characterization is detailed in [Supplemental Methods](#).

Procedures

Sample 1 participants met all inclusion criteria but refused or were ineligible for the functional magnetic resonance imaging study and so completed the task once (experiment 1) at study baseline. A nonoverlapping sample 2 first completed the same version of the task outside of the scanner (experiment 1) and once during functional magnetic resonance imaging scanning at follow-up (experiment 2; mean of 114 days after baseline; imaging results will be reported separately) ([Figure 1](#) [top] and [Supplemental Tables S1 and S2](#)).

RL Task and Model

Participants completed a 300-trial three-armed bandit task ([Figure 1](#), middle), which is shown to be sensitive to the effects of medial ventral prefrontal lesions on value-based choice and to the effects of lateral ventral prefrontal lesions on value learning in macaques (5,21) and humans (4).

To estimate expected value and PE for participants at every trial based on their reinforcement and sampling history, we used a Q-learning model implemented using the variational Bayesian approach in MATLAB, version 2016b (The MathWorks, Inc., Natick, MA) (22). The details of these models can be found in the [Supplemental Methods](#). The variational Bayesian approach yields robust and precise estimates of not only individual model parameters but also evolving hidden states, that is, expected value. We used an empirical Bayesian procedure leveraging the parameter estimates of an entire sample to constrain the estimates for individuals to reduce the risk that parameters for

poorly performing participants would be misestimated (estimation was blinded to group membership; details in [Supplemental Methods](#)) (23).

We leveraged several methodological advances to expand on our earlier findings (8,11). First, earlier studies of probabilistic learning in suicide did not explicitly separate the long-term value of options from more transient effects of reward magnitude. Thus, to isolate specific impairments in the computation of learned value, experiment 2 separately manipulated long-term value and reward magnitude. Second, to obtain more precise estimates of model parameters and hidden states (option values), we employed a robust Bayesian approach to RL model fitting. Third, to obtain independent inference regarding group differences in learning and value comparison, we examined the coupling of model-estimated signals and DTs not used in model fitting.

Learning: Initial Analyses

We first looked for group differences in responses to reinforcement outside of the RL framework. To examine whether recent reinforcement had a differential effect in suicide attempters, we tested whether they were less likely to repeat a choice after a reward (vs. omission) on the last trial. These effects were estimated using binary logistic mixed models implemented by the lme4 package (24) in R 3.3.3 (25).

Main Analysis: DT Signatures of Value-Based Choice and Contingency Learning

These analyses employed linear mixed-effects models implemented in the lme4 package (24), modeling a random intercept of subject. Critically, this analysis was independent from RL model estimation, which did not use DTs. Trials with DT < 200 ms or DT > 4000 ms, comprising <4% of data, were removed (26). Following Ratcliff (27), DTs were inverse transformed (the results were the same using raw DTs). We used the maximum value available on a trial (V_{max}) as our measure of long-term value affecting choice (see [Supplemental Methods](#) for rationale). To separate trial difficulty (indicated by V_{max}) from whether the last choice was exploratory (low value) or exploitative (high value), the difference between the last chosen value and V_{max} , termed V_{choice} , was incorporated into analyses. V_{choice} was zero when the best option was chosen (exploitation) and became negative when an inferior option was chosen (exploration). The final model was

$$\frac{1}{DT_t} = \frac{1}{DT_{t-1}} + t + \text{switch}_t + \text{reward}_{t-1} + V_{choice_{t-1}} + |\text{prediction error}_{t-1}| + V_{max_{t-1}} + \text{reward}_{t-1} \times \text{Group} + |\text{prediction error}_{t-1}| \times \text{Group} + V_{max_{t-1}} \times \text{Group}$$

where t indicates the current trial and $t - 1$ indicates the previous trial.

Sensitivity and Exploratory Analyses

We ascertained that group differences detected in our main analysis were not explained by the following confounds (included as covariates): demographic characteristics (particularly education), cognitive control, global cognitive function, comorbid conditions (anxiety and addiction), depressive severity, possible brain damage from suicide attempts, and exposure to

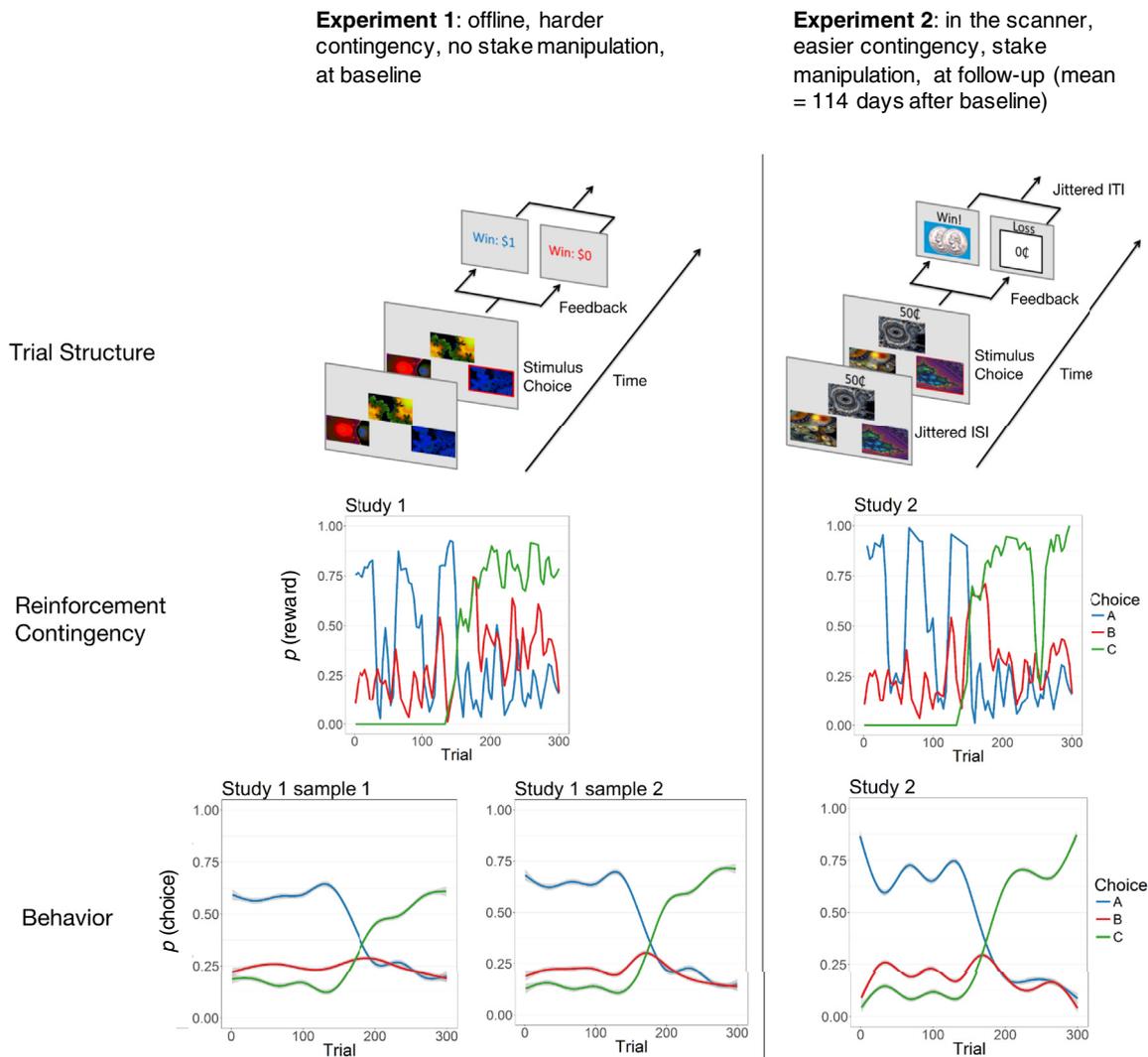


Figure 1. Procedures, samples, and task. *Top: Summary of Experiments.* Both samples completed experiment 1, while only sample 2 completed experiment 2. *Trial Structure:* The options, three novel fractal stimuli, were presented on the screen of a tablet (experiment 1) or on a back-projection screen (experiment 2) using E-Prime. Their location in each trial was randomized in a triangle pattern. The participants selected one option using the arrow keys (experiment 1) or a response glove (experiment 2). Win/loss feedback was then displayed for 1500 ms, followed by an intertrial interval (ITI). To dissociate learned value, which integrates reinforcement across multiple trials, from reward magnitude, in experiment 2 we independently manipulated the amount at stake at each trial (10c, 25c, or 50c). The stake was presented before the choice, making it clear to the participants that while the win/loss outcome depended on their choice, the amount won did not. In experiment 2, the choice feedback and ITIs were jittered, sampled from exponential distributions with means of 4000 and 2920 ms, respectively. *Reinforcement Contingency:* Curves depict probability of reward by stimulus over 300 trials. Both experiments used similar contingencies [modified from (5)]. The contingency was easier for experiment 2. *Behavior:* Curves represent the probability of choosing a given stimulus, aggregated for the entire sample (means and error bands are estimated by LOESS regression). ISI, interstimulus interval.

antidepressants (including augmenting agents), antipsychotics, sedative/hypnotics, and opioids. Next, we verified that results were robust to model fit or fitting procedure (individual vs. empirical Bayesian RL model parameter estimation). Finally, we sought to rule out alternative explanations stemming from collinearity between reward on the previous trial and long-term value and from confounding of between-person and within-person effects of value due to individual differences in learning.

Our exploratory analyses examined the patterns of value-based choices in suicide attempters using expected value estimates from the RL model. Such analyses should be interpreted

with caution given that RL model parameters were originally fit to the same choices. Thus, we did not rely on them for detecting group differences, but only for describing them qualitatively.

RESULTS

Group Characteristics

Across samples, suicide attempters were less educated than nonsuicidal comparison groups. Suicide attempters were similar to suicide ideators on all other measures while differing from nonsuicidal patients on depression severity and some

measures of impulsivity, especially in sample 1 (Supplemental Tables S1 and S2).

Learning, Preliminary Analysis: Behavioral Effects of Reinforcement on the Previous Trial

Across samples and experiments, participants learned the reinforcement contingency well (learning curves: Figure 1; statistics: Figure 2).

Across samples and experiments, suicide attempters were less responsive to reinforcement on the previous trial. Specifically, in both samples in experiment 1, suicide attempters differed from healthy control participants and suicide ideators, but only in sample 1 did they differ from nonsuicidal patients with depression. In experiment 2, suicide attempters differed from nonsuicidal patients with depression and suicide ideators, but not from healthy control participants (see Follow-up Analysis: Exploratory Versus Exploitative Choices in Suicide Attempters for one possible explanation). A combined analysis of both samples in experiment 1 revealed that sample 1 was generally less sensitive to reinforcement (sample \times reward, $B = 0.64$, $SE = 0.09$, $p < 10^{-11}$), which may reflect its lower education level. In the combined sample, suicide attempters were less sensitive to reinforcement than all comparison groups ($z > 5.12$, $p < 10^{-6}$).

Learning, Preliminary Analysis: Effects of Attempt Lethality

Across samples and experiments, high-lethality attempters were less responsive to reinforcement than healthy control participants, nonsuicidal patients with depression (albeit marginally in sample 2, experiment 1), and suicide ideators. In addition, in experiment 2 high-lethality attempters were more impaired than low-lethality attempters (Figure 3).

Learning: DTs

Larger unsigned PEs were followed by longer DTs in both samples in experiment 1 but not in experiment 2 (Figure 4, green), with no consistent group differences. Rewards versus omissions slowed DTs across samples and experiments (Figure 4, red). Suicide attempters slowed down more after a reward than healthy control participants (across samples and experiments), suicide ideators (only in experiment 1, both samples), and nonsuicidal patients with depression (only in experiment 2).

Value-Based Choice: DTs

Choices are more difficult when the values of options are close. Accordingly, DTs were longer on such trials (indicated

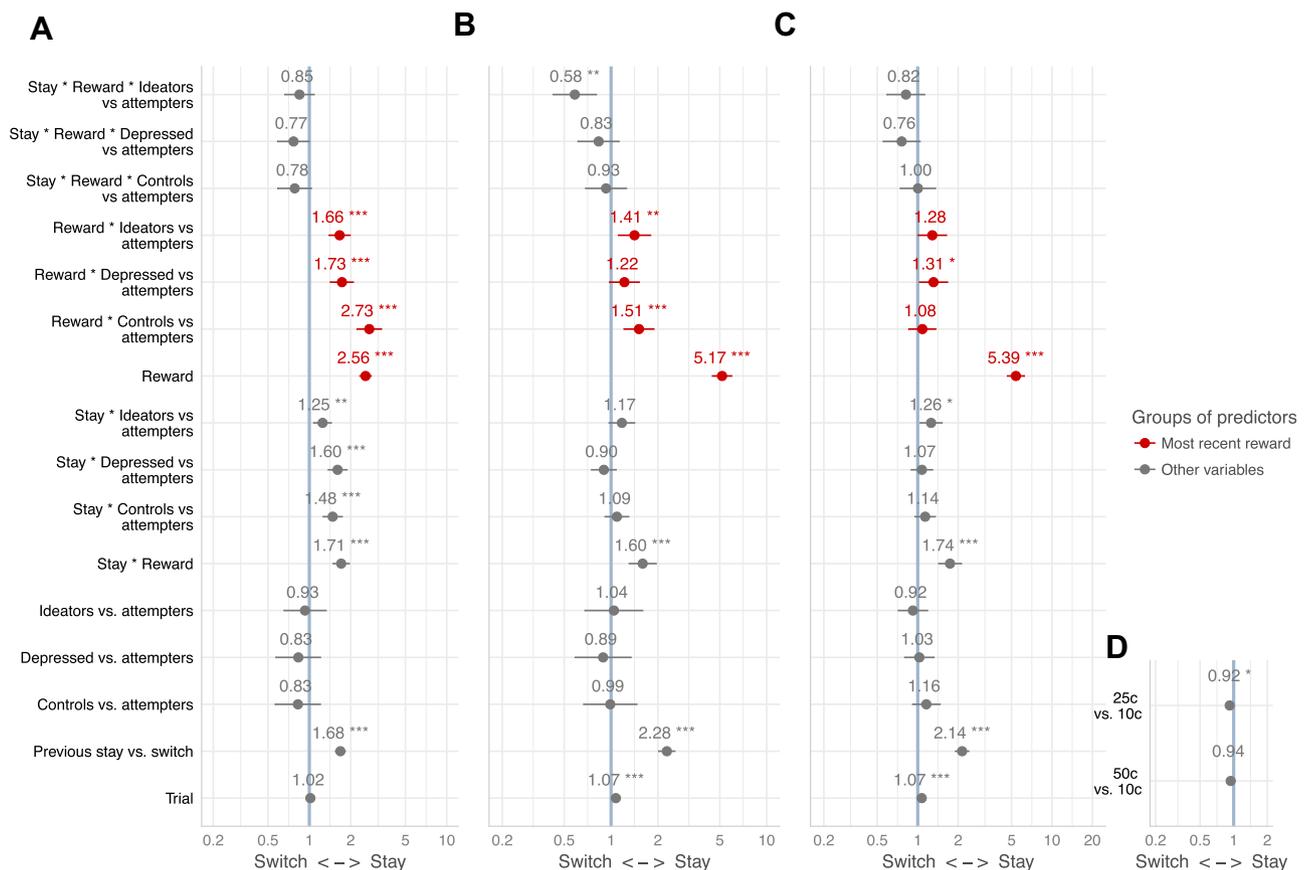


Figure 2. Learning: Effect of most recent reward on choice in suicide attempters (coefficients from binary logistic mixed-effects models predicting stay/switch choice) for sample 1, experiment 1 (A); sample 2, experiment 1 (B); and sample 2, experiment 2 (C). Suicide attempters are the reference group. “Reward” denotes whether the previous choice was reinforced regardless of reward magnitude, which was independently manipulated [stake effect shown in panel (D)] but was irrelevant to whether one should stay with the same choice. Central dot and horizontal lines denote estimated regression coefficient and 95% confidence interval. The x-axis shows the log odds of switching vs. staying. * $p < .05$, ** $p < .01$, *** $p < .001$.

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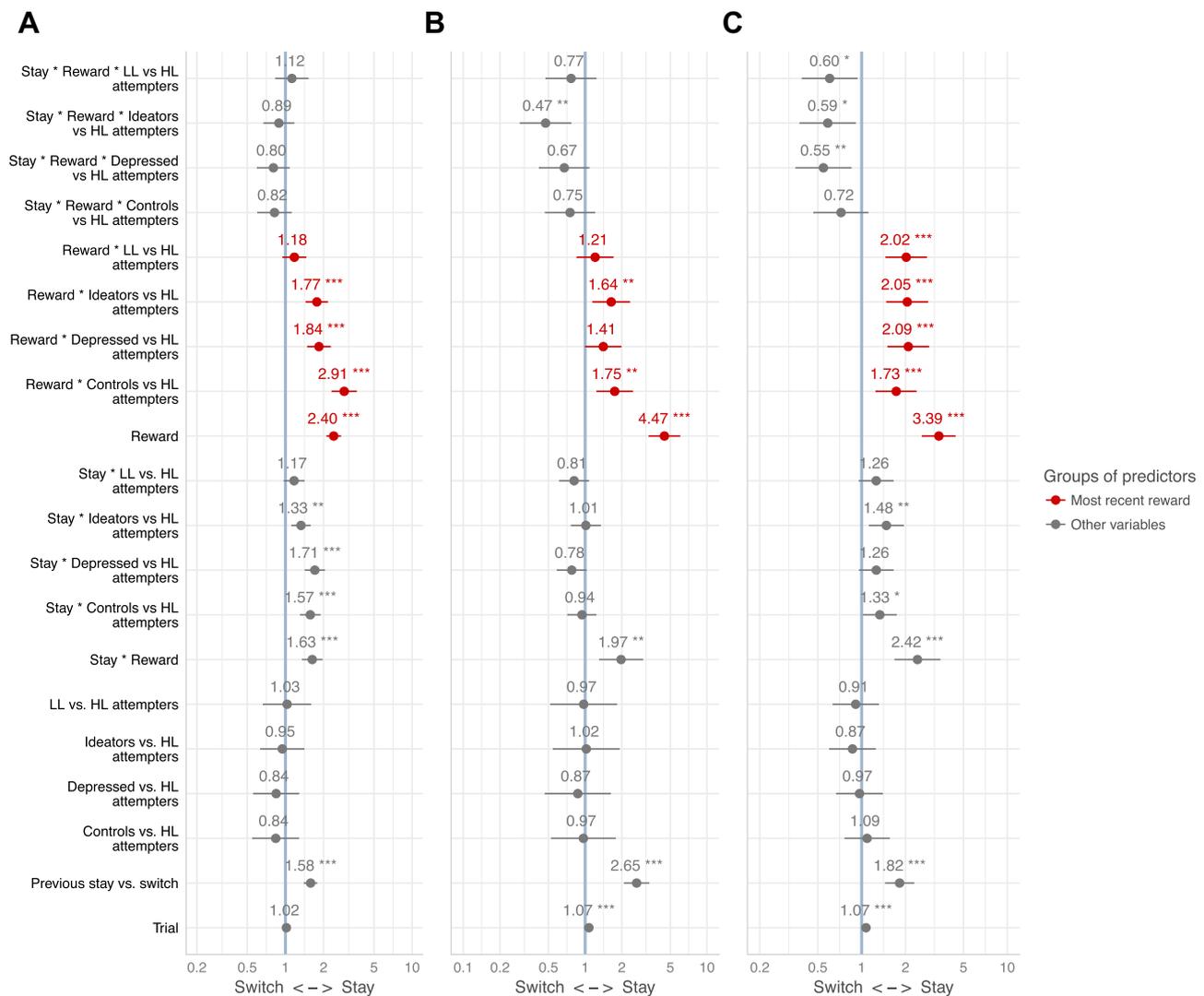


Figure 3. Learning: Effect of most recent reward on choice in high-lethality (HL) and low-lethality (LL) suicide attempters (coefficients from binary logistic mixed-effects models predicting stay/switch choice) for sample 1, experiment 1 (**A**); sample 2, experiment 1 (**B**); and sample 2, experiment 2 (**C**). HL suicide attempters are the reference group. Group sizes for LL versus HL suicide attempters were 32 low and 22 high in sample 1 and 28 low and 11 high in sample 2. Effects of reward at stake are not shown (reported in Figure 2D). Central dot and horizontal lines denote estimated regression coefficient and 95% confidence interval. The x-axis shows the log odds of switching vs. staying. * $p < .05$, ** $p < .01$, *** $p < .001$.

by low V_{max} (Figure 4, blue). In experiment 1, this slowing was less pronounced in the less educated sample 1 than in sample 2 (sample \times value, $B = -0.119$, $SE = 0.028$, $p < .001$) (Figure 4A, B).

Across samples and experiments, suicide attempters exhibited greater slowing on difficult low- V_{max} trials compared healthy control participants and suicide ideators. In sample 2 (both experiments), suicide attempters differed from non-suicidal patients with depression (no significant difference in sample 1).

DTs: Effects of Attempt Lethality

Learning. Mirroring high-lethality attempters' diminished behavioral sensitivity to one-back reinforcement, their DTs also

slowed more after rewards and slowed less after larger absolute PEs, differing from low-lethality attempters in experiment 1 (both samples) but not in experiment 2 (Supplemental Table S7).

Value-Based Choice. There were no consistent differences in sensitivity to expected value between high- and low-lethality attempters.

Follow-up Analysis: Exploratory Versus Exploitative Choices in Suicide Attempters

Our analysis of DTs suggested that suicide attempters struggled when choosing between options with close values. How did this difficulty affect their choices? An optimal choice policy

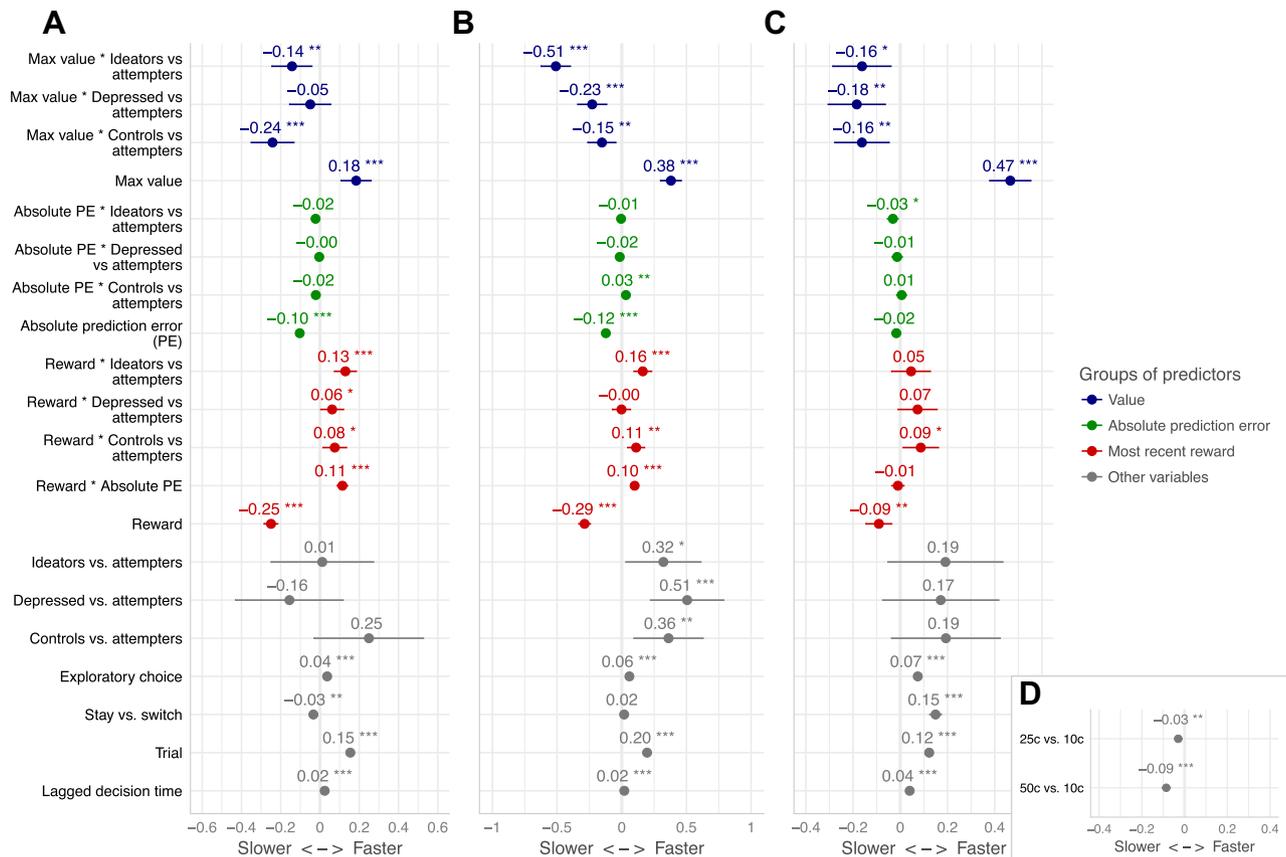


Figure 4. Modulation of decision times by value and current reinforcement (standardized coefficients from linear mixed-effects models) for sample 1, experiment 1 (A); sample 2, experiment 1 (B); and sample 2, experiment 2 (C). “Max value” is the value of the best available option (higher values correspond to easier choices). “Reward” denotes whether the previous choice was reinforced regardless of reward magnitude, which was independently manipulated [stake effect shown in (D)]. “Exploratory choice” is the difference in value between the chosen and best available option. Central dot and horizontal lines denote estimated regression coefficient and 95% confidence interval. The x-axis shows the decision times (arbitrary units). * $p < .05$, ** $p < .01$, *** $p < .001$. PE, prediction error.

needs to balance exploiting high-value options and exploring uncertain, previously undersampled alternatives (28). Because one of the three options throughout most of the task was inferior in value, undersampled, and thus more uncertain (Figure 1), we could determine to what extent participants’ choices were exploratory (sampling the uncertain, lowest-valued option) versus exploitative (sampling the best or second-best option). We focused on win-switch choices, which normatively should be motivated by exploration. We examined the value of participants’ choices, controlling for the highest available value and for whether the preceding choice was exploratory. Across samples and experiments, the comparison groups were more likely to explore the most uncertain, lowest-value option on win-switch trials. Suicide attempters favored the second-best option; the value of their choice was consistently above chance (Figure 5, black horizontal line) ($t > 6.68$, $p < .0001$).

Sensitivity Analyses

We verified that group differences in sensitivity to expected value were unaffected when controlling for possible

confounds: demographics, cognitive function, medication exposure, severity of depression, and possible brain damage from suicide attempts (see Supplemental Results: Sensitivity Analyses; Supplemental Tables S8–S16). Group differences in sensitivity to recent reinforcement were less robust to inclusion of the above variables. Notably, controlling for cognitive control abolished group differences in postreward slowing and poor cognitive control predicted diminished slowing (Supplemental Table S9).

Furthermore, we ascertained that our main results were robust to individual differences in RL model fit (Supplemental Table S11), transformations of DTs, possible confounding between expected value and one-back reinforcement, removal of covariates, and effects of between-subject differences in expected value (see Supplemental Results: Sensitivity Analyses; Supplemental Tables S18–S22).

DISCUSSION

Our RL model-based study of decision making in attempted suicide aimed to describe deficits potentially underlying the inability to find alternative solutions and consider deterrents in

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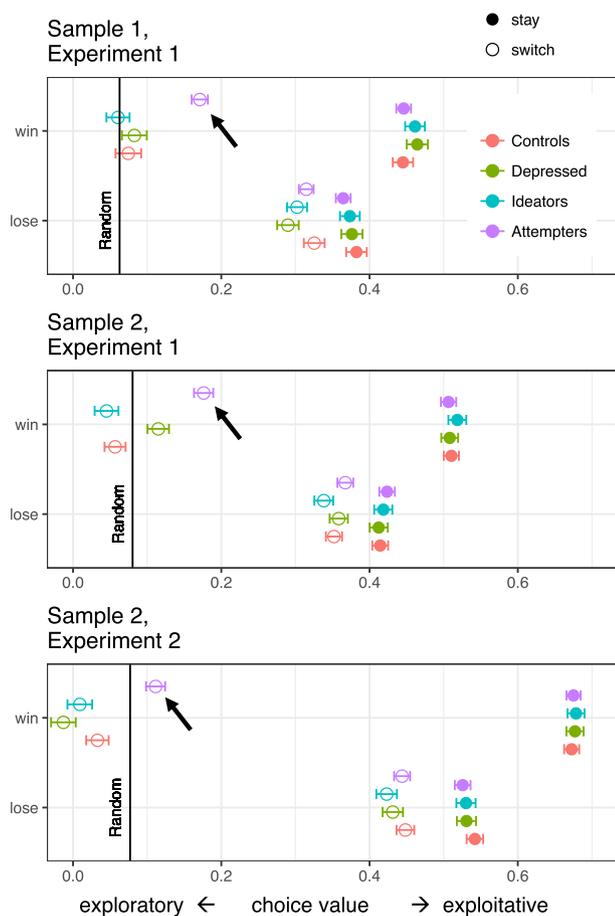


Figure 5. Win-switches in suicide attempters: Value of chosen option as a function of preceding reward and stay/switch. Estimated marginal means from a linear mixed-effects model predicting the expected value of participants' choice based on whether the previous choice was rewarded and repeated are shown (stay [filled circles]/switch [open circles]). The black vertical line indicates the expected value of a random choice given that it is a win-switch (mean of the second-best and worst options). Exploratory choices lie near or to the left of this line. The value of suicide attempters' win-switch choices (black arrows) is consistently higher than chance, suggesting that they favored the second-best option over the undersampled worst option. These statistics should be taken with caution since RL models were fitted to the same choices, shown for illustration.

a suicidal crisis. We hypothesized the existence of deficits in learning from experience and in the ability to choose optimally among actions given their values. Both hypotheses were supported (Table 1).

Value-Based Choice

In analyses of value-based choice, suicide attempters displayed abnormally extended DTs when choosing between similarly valued options (Figure 4) and a tendency to confound the best and second-best options, revealed in their preference for the second-best option on win-switch trials (Figure 5). In short, suicide attempters struggled to distinguish between options that were close in value. This excessive—rather than

lacking—modulation of DTs by long-term values could not be explained by task-unrelated fluctuations, poor effort, or distraction. These group differences were robust to controlling for cognitive control, estimated premorbid IQ, and general cognitive ability as well as medication exposure and possible brain damage from suicide attempts.

Our findings provide a bridge between data on decision making in attempted suicide and the basic literature on its specific neurocomputational substrates, particularly impaired functioning of the vmPFC. Poor IGT performance in previous studies could result from both impaired learning and value comparison or even from broader cognitive impairment. Lesion studies suggest that the core value comparison component of IGT performance depends on the vmPFC; conversely, the neural substrates of other aspects of IGT performance overlap significantly with those of cognitive control in the lateral PFC and the dorsal anterior cingulate (29). Human and monkey lesion studies have mapped value comparison deficits on the three-armed bandit task of the type seen here to the medial orbitofrontal cortex/vmPFC (4,21), also implicated in our earlier functional magnetic resonance imaging study of expected value in suicide attempters (11). Taken together, this evidence points toward impaired value comparison as a specific cognitive correlate of suicidal behavior, likely involving the vmPFC. Furthermore, value comparison deficits may be the primary factor underlying attempters' poor IGT performance.

How might these deficits facilitate suicidal behavior? We view the choice between suicide and its alternatives as a temporally unfolding decision process (30,31). In a given crisis, the choice process may unfold over hours to weeks or longer (32). During this process, one drifts stochastically toward or away from an attempt depending on the perceived long-term value of life versus escape, shaped by recent experiences and deterrents. Whereas in retrospect survivors of attempted suicide typically judge its subjective value to be inferior to alternatives, that value can be temporarily overestimated in the confusion of a crisis. If suicide attempters indeed struggle to differentiate between close-valued options, they may be at risk for erroneously selecting suicide during periods of despair when its value approaches that of alternatives [cf. (33)]. To the extent that our findings are representative of real-life decision making, they reinforce the clinical notion that suicidal acts often arise in the setting of marked ambivalence and can potentially be prevented by measures such as means restriction, bridging interventions, and contingency planning. In general, they reinforce the accident prevention approach to suicide (33), and choice abnormalities can be viewed as a form of accident-proneness.

Learning

Our analyses of learning revealed that suicide attempters were less sensitive to one-back reinforcement, as indicated by both choices (Figures 2 and 3) and DTs (Figure 4 and Supplemental Table S7), suggesting a difficulty in learning the worth of actions from their outcomes. This effect was specific to the effects of reinforcement itself and not to whether reinforcement differed from what was predicted, given that

Table 1. Summary of Group Differences Across Samples and Experiments

Effect	Reference Group	Groups Differing From the Reference Group		
		Sample 1, Experiment 1	Sample 2, Experiment 1	Sample 2, Experiment 2
Learning				
Diminished behavioral sensitivity to reinforcement	Suicide attempters	C, D, I	C, I	D
	High-lethality attempters	C, D, I	C, I	C, D, I, LL
Exaggerated postreward slowing ^a	Suicide attempters	C, D, I	C, I	C
	High-lethality attempters	C, D, I, LL	C, I, LL	C, D
Choice				
Exaggerated slowing on low-value trials	Suicide attempters	C, I	C, D, I	C, D, I
Difficulty in distinguishing between close-valued options (exploratory analysis)	Suicide attempters	C, D, I	C, D, I	C, D, I

There were no differences between high- and low-lethality attempters in choice analyses.

C, healthy control participants; D, nonsuicidal patients with depression; I, suicide ideators; LL, low-lethality suicide attempters.

^aGroup differences were partially explained by cognitive control.

we found no group differences in DT slowing following absolute PEs (surprise). Deficits in learning scaled with suicide attempt lethality and were partially explained by cognitive control performance.

Interestingly, this pattern of group differences parallels that in earlier studies where high-lethality attempters displayed learning and cognitive control deficits (7,9,34,35). Performance on cognitive control and learning tasks relies on a network encompassing the dorsal anterior cingulate complex (29) and the lateral PFC (36). Furthermore, the learning deficits observed among attempters in our study resemble the effects of lateral orbitofrontal cortex/fronto-opercular lesions from earlier three-armed bandit studies (4,5). Altogether, impaired contingency learning in high-lethality attempters in suicide attempters is consistent with cingulo-opercular dysfunction, which may also have contributed to poor IGT performance in earlier studies.

In a crisis, the search for alternatives to suicide may be undermined by learning impairments that lead to a lack of awareness or confidence in available options. In addition, impaired learning and cognitive control make the search for alternative solutions more costly in terms of both time (37) and cognitive effort (38). It is thus possible that under such circumstances suicide gains appeal as a literal easy way out (39).

Correlates of Suicidal Behavior Versus Ideation

Most previous studies of the neurocognitive diathesis to suicide did not include a group of suicide ideators, leaving it unclear whether any deficits are selectively associated with suicidal behavior rather than ideation. In the few studies that did, most cognitive markers—IQ, memory, and attention—did not differentiate between suicidal behavior and suicidal ideation (20,40,41). The two exceptions are decision making and inhibition, although attempter/ideator differentiation is based on very few, mostly small, studies (8,10,14,34,42,43). Our study contributes substantially to this inquiry; both impaired value comparison and learning were implicated in acting on suicidal thoughts and not merely suicidal ideation.

Between-Sample Differences and Limitations

Across samples and experiments, suicide attempters displayed some form of altered sensitivity to reinforcement (Table 1). However, group differences in basic learning from one-back reinforcement were more prominent in the less educated sample 1, whereas group differences in sensitivity to long-term value were more pronounced in sample 2. This is likely due to better learning in sample 2 (Figures 2 and 4). In general, given the clinical heterogeneity of suicidal behavior and the modest group sizes, sampling variability is likely the main reason for our failure to replicate all findings. This sampling variability may also contextualize the generalizability of our findings. The retrospective case-control design of our study is susceptible to unobserved confounds even though we made every effort to measure observable confounds and examine their effects statistically. In particular, it was not possible to examine the effects of individual psychotropic medications. One should be cautious in extrapolating results to those who die by suicide, although the inclusion of high-lethality suicide attempters is reassuring in this respect. Finally, our models lacked a detailed account of the choice process, and future developments in the integration of RL with serial sampling choice models on multialternative tasks will likely yield additional insights into choice abnormalities in attempted suicide (44).

In summary, we found that suicidal behavior in mid- and late-life depression is associated with impaired ability to compare the values of alternative actions. In addition, medically serious suicide attempts are associated with deficient moment-to-moment learning from reinforcement. In a crisis, these low-level aberrations in decision processes likely undermine one's ability to search for alternative solutions and consider deterrents.

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The deidentified behavioral data and all codes used to obtain our results are publicly available at https://github.com/DecisionNeurosciencePsychopathology/bandit_pub.

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