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The decision neuroscience perspective on suicidal behavior: evidence and hypotheses

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Abstract

Purpose of review—Suicide attempts are usually regretted by people who survive them. Furthermore, addiction and gambling are over-represented among people who attempt or die by suicide, raising the question whether their decision-making is impaired. Advances in decision neuroscience have enabled us to investigate decision processes in suicidal people and to elucidate putative neural substrates of disadvantageous decision-making.

Recent findings—Early studies have linked attempted suicide to poor performance on gambling tasks. More recently, functional MRI augmented with a reinforcement learning computational model revealed that impaired decision-making in suicide attempters is paralleled by disrupted expected value (expected reward) signals in the ventromedial prefrontal cortex. Behavioral studies have linked increased delay discounting to low-lethality/poorly planned attempts, multiple attempts, and the co-occurrence of attempted suicide and addiction. This behavioral tendency may be related to altered integrity of the basal ganglia. By contrast, well-planned, serious suicide attempts were associated with intact/diminished delay discounting. One study has linked high-lethality suicide attempts and impaired social decision-making.

Summary—This emerging literature supports the notion that various impairments in decision-making – often broadly related to impulsivity – may mark different pathways to suicide. We propose that aggressive and self-destructive responses to social stressors in people prone to suicide result from a predominance of automatic, Pavlovian processes over goal-directed computations.

Keywords

suicide; delay discounting; reinforcement learning; social decision-making; ventromedial prefrontal cortex

Introduction

The problem of suicide has occupied thinkers since at least the classical antiquity, seen chiefly as a moral dilemma. Plato (Laws, IX) viewed suicide as an act of cowardice and

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Conflicts of interest

None

laziness unacceptable in the polis, but allowed for exceptional circumstances such as moral corruption, a judicial order, extreme misfortune or shame. The stoics, on the other hand, felt that suicide was justified whenever life was not naturally flourishing (Cicero, III) or even when one was not living well (Seneca, Letters; all cited in [1]). What these disparate positions have in common is the consideration of suicide as a decision that has consequences for oneself and others. (Table 1)

At the same time, clinicians have long observed that the decision to commit suicide is often made after a limited and shallow consideration of the current crisis, possible consequences, and alternative solutions [3]. Indeed, suicide attempts are usually regretted by people who survive them [4]. Modern accounts of suicide such as Williams' entrapment theory [5] and Baumeister's view of suicide as an escape from the aversive self [6], see it as a flight from irresolvable problems. Suicide is precipitated by mood disorders, addiction and psychosis. However, compared to other individuals with these conditions, patients prone to suicide seem to differ in the way they consider their situation and the options available to them. Herman Hesse's phrase "temptation of suicide" [7] conveys the intuition that, from a certain narrow perspective, suicide may appear rewarding, not unlike gambling or drug use. This notion manifests in themes of pleasant relief and control in suicide notes [8].

One is more likely to succumb to this temptation when biases or distortions in decision-making obscure the consequences (e.g., impact on the family or foreclosed opportunities) and alternatives to suicide (seeking help, waiting). This view is supported by at least three converging lines of evidence. First, suicide is associated with gambling [9] and addiction [10], behaviors that are defined by disadvantageous decisions. Second, individuals with a history of suicide attempt display altered decision-making in the laboratory [11–18]. Third, imaging and deep brain stimulation studies link suicidal behavior to disruptions of decision-related signals in cortical-basal ganglia circuits [19–25]. The aforementioned undermines the alternative belief — embraced by many, judging by the societal acceptance of assisted suicide for the mentally ill [26] — that suicide is often rational and that a reasonable person would opt for it under dire circumstances.

What exactly is different about the decision-making of suicidal individuals? Given the wide variation in the expression of suicidal behavior across diagnoses, personality configurations, and age groups, a more realistic question may be: Are there subgroups characterized by distinct decision-making abnormalities? Further, what differences in brain structure and/or function explain these deficits? Below, we present hypotheses and selected evidence to address these questions. While research on decision processes offers a new perspective on suicide, important complexities presently remain beyond its scope, including culture, attachment, and male predominance. Studies reviewed below included patients with mood disorders, which account for the majority of suicides. Mechanisms underlying suicidal behavior in psychosis are likely different [27], and decision-making in suicidal patients with psychosis has not been investigated, although deficits in reward learning and decision-making are prominent in schizophrenia [28–30].

Delay discounting: short-sightedness and present focus in unplanned suicidal acts

Suicide is a rejection of one's entire personal future, often in response to distress that is likely to be impermanent. Such myopia in suicidal people is associated with trait impulsivity [31,32]. A more precise hypothesis is that people prone to suicide are averse to delays and over-value immediate outcomes. Such a preference may render the escape from current suffering more subjectively valuable than the rest of one's life. The notion of *subjective value* is central to understanding how our brain converts disparate inputs, such as delay and magnitude of rewards, into a single currency, enabling us to choose among alternative options. The degree to which humans discount the value of delayed outcomes differs across people, with high discount rates (lower willingness to delay gratification) associated with trait impulsivity, addiction and attention deficit-hyperactivity disorder [33,34]. Does this association extend to suicide? This is plausible, yet not all suicidal acts are impulsive and many serious ones are well-planned [35–38]. Thus, we hypothesized that higher delay discounting would be selectively associated with suicidal acts that are not premeditated. We reasoned that while the impulsiveness of a suicide attempt is not necessarily explained by trait impulsivity [35–38], delay discounting may be more specifically related to characteristics of suicidal behavior because it taps directly into how individuals compare options available at different time points, such as immediate relief vs. working on an alternative solution, or attempting suicide immediately vs. taking time to prepare the attempt. In our study of people with late-life depression, individuals with a history of less medically serious and poorly planned suicide attempts displayed high delay discounting (i.e., a preference for smaller immediate rewards). High discount rates (unwillingness to delay) were also seen in people with suicidal ideation and no history of attempt. Interestingly, those who had trouble re-paying their debts displayed higher delay discounting, suggesting that financial problems – usually seen as a cause of suicidal behavior – may reflect a history of short-sighted decisions [39]. By contrast, people who had made more serious and better planned suicide attempts had an intact and even exaggerated ability to delay gratification (Fig. 1; [40]). Was lower delay discounting in people with serious and well-planned suicide attempts a pathological tendency? Low delay discounting has been described in obsessive-compulsive personality disorder (OCPD [41]) and restricting-subtype anorexia [42]. Interestingly, older adults with a history of better-planned suicide attempts displayed a blunted lateral prefrontal response to the difference in subjective value between the immediate and the delayed option in a subsequent fMRI study [43]. One intriguing possibility is that patients with OCPD, restricting-type anorexia or premeditated suicide attempts, who strive for excessive control over their life, are insensitive to the intrinsic value of time, or opportunity cost [44,45], investing excessive time in behaviors that should be abandoned in favor of better alternatives.

The association between delay discounting and suicidal behavior was replicated in a contemporaneous study of adolescent girls with multiple suicide attempts [46] and among people with addiction who had attempted suicide [47]. Increased delay discounting in suicide attempters may resolve once the suicidal crisis subsides [48], indicating the presence of a state component. High delay discounting in older suicide attempters may also reflect

disrupted structural integrity of the basal ganglia [19], and a subsequent study related high delay discounting to lower integrity of corticostriatal connections [49]. Further, in older people with depression, subjective paralimbic value signals in the posterior cingulate cortex and precuneus during delay discounting were moderated by trait impulsivity [43], confirming that, as suggested earlier, paralimbic value representations are a key neural correlate of individual differences in impulsivity [50].

Disrupted computation of expected value in the vmPFC

Suicide is often seen as a strategic, deliberate choice [51]. Yet, clinicians know that the last straw in a suicidal crisis can be surprisingly minor: an argument, a problem at work, a bill. Deterrents that are seen as important at other times become overlooked, suggesting that suicidal individuals may not be able to estimate the consequences – or expected value – of events and their own actions. Consistent with these clinical observations, suicide attempters are often impaired in their ability to make dynamic decisions based on moment-to-moment feedback in an uncertain, dynamic environment [13,14,16,20]. Early studies found suicide attempters to make poor decisions on the sensitive, but not mechanism-specific, Iowa Gambling Task (see [16] for a meta-analysis). Subsequent behavioral studies aimed to dissect the decision-making of suicide attempters and uncover specific biases. One of these biases is the neglect of critical information in decisions [12,14,52]. An early example of this behavior was seen on the Cambridge Gambling Task (CGT), which does not involve learning. The CGT resembles roulette in that one is asked to make a bet on one of two outcomes or ‘colors’, but the probability of outcomes is manipulated from 6:4 to 9:1 and shown explicitly to the subject. Yet, instead of betting on the color in the majority, older depressed suicide attempters – but not suicide ideators – chose the minority color on about ¼ of the trials, ignoring the odds [12]. Another instance was seen on the probabilistic reversal learning (PRL) task, where one is initially presented with two options of which the first is frequently rewarded (80%) and the second, infrequently rewarded (20%). After 40 trials, the reinforcement contingency is reversed unbeknownst to the subject. On this task, one needs to trade off staying with the previously reinforced stimulus despite occasional misleading (probabilistic) feedback and switching when a true reversal occurs. Suicide attempters were unimpaired in initial learning, but failed to learn the new contingency after the reversal. They either switched away from the newly reinforced option after a single instance of misleading negative feedback or perseverated in selecting the previously rewarded option, neglecting subsequent negative feedback [14]. The neglect of decision-relevant information in suicide attempters resembles deficits in value-based decision-making in patients with behavioral variant of frontotemporal dementia [53–55] where the ventromedial prefrontal cortex (vmPFC; Fig. 2a) is selectively affected, and in humans [56,57] and other primates [58] with vmPFC lesions. This is not surprising, since in human imaging studies expected value in general (Fig. 2b; see [59] for a meta-analysis) and learned value in particular (Fig. 2c; see [60] for a meta-analysis) has been consistently mapped to the vmPFC (also see [61] for a comparative review of animal electrophysiological and lesion experiments vis-à-vis human imaging studies). These observations lead to the hypothesis that, in individuals prone to suicidal behavior, the neglect of both (i) decision-relevant information in the laboratory

and (ii) the deterrents or alternative solutions in a suicidal crisis is paralleled by disrupted expected value signals in the vmPFC.

We tested this hypothesis in a functional MRI study of attempted suicide in late-life depression, using the PRL task [20]. To estimate value signals for every participant, we employed a reinforcement learning (RL) model. In RL, expected value is updated in each learning episode (e.g. trial) by the discrepancy between the previously expected and actually obtained outcome ([62,63]; see [64] for an introduction). Thus, by exposing the model to the same reinforcement history as the participant, we obtained unique estimates of learned value for each trial in every participant. We then used these estimates to map value representations in the brain. The advantage of computational model-based fMRI here is that it maps the latent process of learning, rather than merely registering responses to stimuli or experimental conditions. In control groups, value signals were represented in the vmPFC and other paralimbic cortical regions. In suicide attempters, vmPFC value signals were blunted (Fig. 2d). Furthermore, confirming a link to decision-making, the degree of blunting scaled with perseverative errors on PRL in the scanner and bets against the odds on CGT outside of the scanner. Finally, value signals were most blunted in patients who made the least planned suicide attempts and in individuals high in trait impulsivity [20]. A similar blunting of vmPFC value signals was described in youth with disruptive behavior disorders [65,66], raising the possibility that this may be a general feature of externalizing disorders. These intriguing findings require replication. Many questions remain: are these deficits specific to value that is learned in uncertain environments or do they extend to any choice situations, as suggested by CGT findings? Are abnormalities in value computation intrinsic to the vmPFC/mOFC [56–58] or a downstream consequence of disrupted ascending meso-striato-thalamic inputs [67]? The association of basal ganglia [19,21,23,68,69] with suicidal behavior points toward the latter possibility.

Social decision-making: Pavlovian-to-instrumental transfer

Although reasons for attempting suicide are complex and multiply determined, social stressors such as divorce, family discord, or perceived isolation often play a primary role [70–72]. Moreover, enhancing social connections is a key focus of many suicide prevention programs [73]. In some cases, suicide attempts are motivated by a desire to express anger or are linked with impulsive aggression [31,74,75], consistent with theoretical accounts emphasizing interpersonal hostility [76]. In others, suicide may be motivated by a desire to relieve perceived burden on others [77].

Regardless, individuals who attempt suicide appear to misestimate or misunderstand how to integrate interpersonal information in their decisions, as reflected in experiences of suicide loss survivors [78]. Loved ones of those who complete suicide often describe problems with interpersonal reactivity and difficulties in conveying social support. For example, in borderline personality disorder (BPD), individuals are interpersonally hypersensitive, often distorting social cues, forming extreme opinions of others, and misattributing malevolence to others' actions or even facial expressions [79]. Perceived quarrelsome behavior in close relationships enhances one's own quarrelsomeness, and this association is magnified in BPD

[80]. Such biases in social perception and representation may be proximal in precipitating suicidal crises.

Difficulties integrating social information in appraisals of self-worth or the quality of interpersonal relationships may be related to impairments in value-based decision-making in suicide more generally. For example, in an ultimatum game (where social cooperation is crucial), we have found that high-lethality suicide attempters tend to punish others for unfairness even though it is disadvantageous to their own winnings in the game [81]. From a decision-making perspective, there are two notable features of maladaptive social behaviors in suicide: behavioral insensitivity to adverse consequences [80–82] and heightened sensitivity to internal emotional state [80,81]. These are signature properties of the Pavlovian system, distinguishing it from the instrumental and deliberate decision-making systems involved in goal-directed action [83–86]. Thus, we view social triggers as potent Pavlovian conditioned cues that interfere with adaptive learning and decision-making. Aggressive, hostile and self-destructive reactions to social conflict correspond therefore to conditioned responses (CRs). The inflexibility of CRs and their sensitivity to internal state, but not to consequences of one's actions, promote rigid misestimates of social information, as well as self-destructive behaviors. Although there is strong evidence of Pavlovian biases in instrumental decisions (termed Pavlovian-to-instrumental transfer in the learning literature; see [87][88]), its extension to social decision-making in suicide is nascent. One major challenge for this direction will be to understand what is specific to social decision-making in suicide and what reflects broader disruptions in value-based decisions (for a related discussion in the normative literature, see [89]).

Conclusions

To the extent that suicidal behavior involves faulty estimation of its consequences and the value of one's remaining life, it is a *disorder of prediction and choice*. We have discussed three hypotheses about mechanisms of suicidal behavior involving extreme or faulty predictions about the value of (i) time, (ii) options with risky or uncertain payoffs and (iii) social transactions. Increased delay discounting and disrupted value computations are broadly related to impulsivity, and constitute a theoretically and biologically grounded approach to investigating substrates of impulsive suicidal behavior in cortico-striato-thalamic networks subserving learning and decision-making. The notion of disproportionate Pavlovian influences on social decision-making relates to interpersonal vulnerability and escalation of social conflicts into a suicidal crisis.

These hypotheses refer to neural computations, utilizing environmental inputs (reward magnitude/delay, reinforcement history in the lab or experiences in real life) to generate choices. Our account of these computations can be descriptive as in delay discounting (i) or mechanistic as in reinforcement learning (ii, iii). Reductionist frameworks such as the Research Domain Criteria call for integration across different levels of analysis, from complex real-world behaviors (e.g. suicide) to moment-to-moment behavior in lab experiments to brain circuits etc. Computational models link these levels, explaining behavior in terms of operations that neural networks perform on inputs from the environment. This does not mean, however, that existing psychological theories of behavior

– including suicide – have been obviated. Rather, our challenge is to translate clinical theories of suicide into the formal language of computational models.

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Key points

- From a decision neuroscience perspective, suicide is a disorder of prediction and policy selection.
- Studies of attempted suicide have identified two key alterations in decision processes broadly related to impulsivity: (1) neglect of decision-relevant information paralleled by blunted value signals in the ventromedial prefrontal cortex and (2) increased delay discounting likely paralleled by basal ganglia alterations.
- We propose that aggressive and self-destructive responses to social stressors in people prone to suicide result from a predominance of automatic, Pavlovian processes over goal-directed computations.
- Computational modeling enables researchers to integrate across different levels of analysis, linking behavior and underlying neural computation to develop a reductionist account of disadvantageous decision-making in suicidal individuals.

Figure 1.

Discounting of future rewards and suicidal behavior in late-life depression

(A) Low-lethality suicide attempters and suicide ideators showed the strongest preference for immediate rewards, followed by the two non-suicidal comparison groups. In contrast, high-lethality suicide attempters were more willing to wait for larger rewards. (B)

Willingness to wait for larger rewards was associated with suicide attempts that were better planned.

Previously published, full cite: Dombrovski AY, Szanto K, Siegle GJ, et al: **Lethal forethought: delayed reward discounting differentiates high-and low-lethality suicide attempts in old age.** *Biological psychiatry* 2011, **70**: 138–144.

5-way Conjunction: [Positive > Negative] &
Decision & Receipt & Monetary & Primary

Figure 2.

Figure 2a. Architectonic parcellation of human and macaque ventromedial (top) and orbital (bottom) prefrontal surface.

The ventromedial prefrontal cortex includes agranular areas 25/24, 14c and dysgranular areas 32, 14r, with granular areas 14m, 11m also sometimes included. Areas 14c, 14r, and 11m encompass the medial orbitofrontal cortex (mOFC).

Previously published, full cite: Mackey S, Petrides M: **Quantitative demonstration of comparable architectonic areas within the ventromedial and lateral orbital frontal cortex in the human and the macaque monkey brains.** *European Journal of Neuroscience* 2010, **32**:1940–1950.

Figure 2b. Representations of subjective value in human fMRI studies. Conjunction analysis, designed to detect regions carrying a monotonic, modality-independent signal.

Subjective value signals are found most consistently in the ventromedial prefrontal cortex and ventral striatum. These signals specifically and monotonically track with increasing subjective value, unlike salience signals elsewhere in the brain, which increase with greater positive as well as greater negative outcomes.

Previously published, full cite: Oscar Bartra, Joseph T. McGuire, Joseph W. Kable: **The valuation system: A coordinate-based meta-analysis of BOLD fMRI experiments examining neural correlates of subjective value.** *NeuroImage* 2013, 76: 412–427

Figure 2c. Representations of learned value in the human vmPFC: meta-analysis of fMRI studies that employed reinforcement learning models.

This meta-analysis included human imaging studies that employed reinforcement learning models. Learned value signals were mapped to the ventromedial prefrontal cortex.

Previously published, full cite: Chase HW, Kumar P, Eickhoff SB, Dombrovski AY: **Reinforcement learning models and their neural correlates: An activation likelihood estimation meta-analysis.** *Cognitive Affective and Behavioral Neuroscience* 2015, doi: 10.3758/s13415-015-0338-7.

Figure 2d. Blunted value signals in the vmPFC of older depressed suicide attempters

A history of suicide attempts was related to a weaker response to expected reward in the pericallosal vmPFC (pregenual cingulate [BA 32, 24, and 25] on the posterior periphery of the reward-modulated vmPFC region of interest). $P < .05$, corrected, controlling for depression group status. The x and z values indicate Montreal Neurological Institute coordinates.

Previously published, full cite: Dombrovski AY, Szanto K, Clark L, Reynolds CF, Siegle GJ: **Reward Signals, Attempted Suicide, and Impulsivity in Late-Life Depression.** *JAMA Psychiatry* 2013, 70:1020–1030.

Table 1

Key terms

Subjective value
In economics, a measure of benefit associated with an option, the theoretical common currency used to compare disparate goods. Value is analogous to expected reward in animal learning.
Delay discounting
Formal descriptive account of preference for immediate over delayed rewards in humans and other animals. While economic agents typically discount future rewards exponentially as a function of time (c.f. compound interest), humans generally display hyperbolic discounting.
Pavlovian vs. instrumental learning
Formation of stimulus-outcome vs. action-outcome associations
Conditioned response (CR)
Innate, behaviorally inflexible response triggered by a conditioned stimulus
Neural computations
Computations performed by the brain that link environmental inputs to behavioral output. Marr's (1982) levels of analysis include (i) <i>computational</i> , formalizing the problem to be solved, (ii) <i>algorithmic</i> , specifying the mathematical procedure used to solve the problem, and (iii) <i>implementational</i> , describing how this solution is implemented by neurons.
Reinforcement learning
Formal, statistical account of animal learning, wherein the discrepancy between the actually received and expected reward (prediction error) represents the learning signal
Computational model-based fMRI
Task fMRI where a cognitive model representing putative neural computations is fit to experimental design (e.g. reinforcement history) and behavior. Model-predicted signals representing latent processes (e.g. prediction error) are then regressed against single-subject BOLD data.
Ventromedial prefrontal cortex (vmPFC; Fig. 2)
Phylogenetically ancient region of human prefrontal cortex including agranular areas 25/24, 14c and dysgranular areas 32, 14r, with newer granular areas 14m, 11m also sometimes included [2]. Areas 14c, 14r, and 11m encompass the medial orbitofrontal cortex (mOFC). Human imaging studies have mapped subjective value representations to the vmPFC.