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Molecular neuroeconomics of crime and punishment:
implications for neurolaw.

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Summary:

Criminal behaviors have been associated with risk, time and social preferences in economics (Becker, 1968; Davis, 1988), criminology (Chamlin and Cochran, 1997), and neurolaw (Goodenough and Tucker, 2010). This study proposes a molecular neuroeconomic framework for the investigation into crime and punishment. Neuroeconomic parameters (e.g., risk-attitude, probability weighting, time discounting in intertemporal choice, loss aversion, and social discounting) are predicted to be related to criminal behavior. Neurobiological and neuroendocrinological substrates such as serotonin, dopamine, norepinephrine, cortisol (a stress hormone), sex hormones (e.g., testosterone), and oxytocin in brain regions such as the orbitofrontal cortex, the amygdala, and the cingulate may be related to the neuroeconomic parameters governing criminal behaviors. The present framework may help us develop “neurolaw” based on molecular neuroeconomics of criminal and antisocial decision-making processes.

Keywords: Crime, Neuroeconomics, Risk, Intertemporal choice, Neurolaw, Social discounting

1. Introduction:

Studies in economics and criminology have suggested that economic parameters such as risk attitude, time-discount rate, and altruism may determine the risk of criminal behavior. However, these theoretical considerations have been largely ignored in cognitive neuroscience of antisocial behavior. Past decades have witnessed that utilization of economic theory in other disciplines such as psychiatry, sociology, political science, behavioral ecology, and neuroscience is considerably useful. Therefore, introducing neuroeconomic frameworks is important for a better understanding of criminal behavior and criminals' sensitivity to punishment. Recent neurobiological studies on antisocial behavior demonstrated that several neurobiological substrates such as neurotransmitters (e.g., serotonin, dopamine, and norepinephrine) and hormones (e.g., cortisol and testosterone) in the brain regions such as the orbitofrontal cortex and the limbic structures modulate antisocial behavior. Therefore, combining neuroeconomic theory with these neurobiological finding is helpful for the establishment of molecular neurobiological theory of criminal behavior ("molecular neuroeconomics" of crime and punishment), which may finally contribute to neurolaw (Goodenough and Tucker, 2010).

This paper is organized in the following manner. In Section 2, I introduce neuroeconomic theory of risky, impulsive, and antisocial behavior. Also, implications from economics and criminology are introduced. In Section 3, findings in neurobiology regarding the molecular mechanisms of antisocial/criminal behavior are briefly reviewed. In Section 4, I proposed several predictions from molecular neuroeconomic theory of crime and punishment. Future study directions by utilizing the present molecular neuroeconomic theory of crime and punishment, and how to develop the emerging field of "molecular neurolaw" are also discussed.

2. Neuroeconomic theory of risky, impulsive and antisocial decision making

Economist Gary Becker proposed his economic theory of crime and punishment after his dissertation defense. In the morning of his dissertation defense, he had to weigh the cost and benefits of legally parking in an inconvenient garage versus illegally parking in a convenient place. After roughly calculating the probability of getting caught and potential punishment and being late for the dissertation defence, Becker rationally opted for the crime (i.e., illegal parking). As can be seen from this example, investigation into decision under risk (probably more irrational in most criminals than Becker's decision) is critical for developing molecular neuroeconomics of crime and punishment. In behavioral economics, in order to explain anomalies in human decision making under

risk (e.g., Allais paradox, 1953), the prospect theory has been proposed (Kahneman and Tversky, 1979) and introduced in recent studies in neuroeconomics, in addition to system dynamics (<http://www.systemdynamics.org/>). In Kahneman-Tversky's prospect theory (Kahneman and Tversky, 1979), a subjective value of an uncertain outcome x (x is either positive or negative, gain or loss), which is received at the probability of p , is $v(x) w(p)$, where $v(x)$ is a value function for either gain and loss, and $w(p)$ is a probability weighting function. Therefore, the prospect theory is a generalization of an expected utility theory in which $w(p)=p$ (von Neumann and Morgenstern, 1944). Furthermore, if the outcome is delayed, subjective value of the outcome is temporally-discounted. This temporal discounting is mathematically represented with a time-discount function $D(t)$. Then, the subjective value of the potentially uncertain and delayed outcome of the magnitude of x , which can be obtained at probability p and delay t , is $v(x) w(p) D(t)$. Moreover, if the outcome is received by another person at social distance N , the subjective value of the outcome (for a decision-maker herself) is socially-discounted, following the social discount function $S(N)$. Together, the subjective value of a potentially uncertain, delayed, and social outcome is $V(x, p, t, N) = v(x) w(p) D(t) S(N)$. The each functional component in $V(x, p, t, N)$ is explained below.

Regarding the functional form of the value function $v(x)$, prospect theory's value function is assumed to be concave for gains, convex for losses, and steeper for losses than for gains. The most popular parametrization of the value function is a power function (Tversky and Kahneman, 1992):

$$v(x) = \begin{cases} x^\alpha & (x \geq 0) \\ -\lambda(-x)^\beta & (x < 0) \end{cases} \quad (1)$$

where $\alpha, \beta > 0$ measure the curvature of the value function for gains and losses, and λ is the coefficient of loss aversion (see Figure 1). A recent neuroeconomic study demonstrated that amygdala damage reduced loss aversion (De Martino et al., 2010). The probability weighting function has been parameterized as (Prelec, 1998; Takahashi, 2011):

$$w(p) = \exp[-(-\ln p)^s] \quad (2)$$

where s indicates a distortion in subjective probability (note that $s=1$ corresponds to linear probability weighting in the expected utility theory, see Figure 2), which has been shown to associate with the anterior cingulate activity (Paulus and Frank, 2006) and

psychophysical effect of waiting time in repeated gambles (Takahashi, 2011a). It is to be noted that subjects with a less concave value function for gain (i.e., larger α) and distorted probability weighting function (i.e., overweighting of small probabilities) are more risk-taking in uncertain gain.

In order to describe impulsivity and irrationality (time-inconsistency) in temporal discounting, the q -exponential time-discount model for delayed rewards has been studied (Cajueiro, 2006; Takahashi, 2007; et al., 2007a; Takahashi et al., 2008ab; Takahashi, 2009; Takahashi, 2011b):

$$D_{q^+}(t) = D_{q^+}(0) / \exp_{q^+}(k_{q^+}t) = D_{q^+}(0) / [1 + (1 - q^+)k_{q^+}t]^{1/(1 - q^+)} \quad (3)$$

where $D_{q^+}(t)$ is the discount factor for a reward obtained at delay t , q^+ is a parameter indicating irrationality in temporal discounting for gain (smaller $q^+ < 1$ values correspond to more irrational discounting for delayed gains), and k_{q^+} is a parameter of impulsivity regarding the reward at delay $t=0$ (i.e., q -exponential discount rate := $-D_{q^+}'(t)/D_{q^+}(t)$ at delay $t=0$). Note that when $q^+=0$, equation 3 is the same as a hyperbolic discount function, while $q^+ \rightarrow 1$, is the same as an exponential discount function (Cajueiro, 2006; Takahashi, 2009). The shape of the discount function is shown in Figure 3. It is to be noted that steeper temporal discounting indicates more impulsive decision over time. Kable and Glimcher (2007) reported that $v(x) D(t)$ is represented as neural activities in brain regions such as the orbitofrontal cortex and the striatum. Furthermore, it is known that delayed gains and losses are distinctly processed in the brain and loss is less steeply temporally-discounted than gains (“sign effect”, Xu et al., 2009) due to a difference in time perception in waiting gain and loss (Han and Takahashi, 2012). Therefore, we should prepare the q -exponential discount function for delayed loss:

$$D_{q^-}(t) = D_{q^-}(0) / \exp_{q^-}(k_{q^-}t) = D_{q^-}(0) / [1 + (1 - q^-)k_{q^-}t]^{1/(1 - q^-)} \quad (4)$$

where $D_{q^-}(t) > 0$ is the discount factor for a loss at delay t , q^- is a parameter indicating irrationality in temporal discounting for loss (smaller $q^- < 1$ values correspond to more irrational discounting for delayed losses), and k_{q^-} is a parameter of impulsivity regarding the loss (i.e., degree of procrastination) at delay $t=0$.

In order to describe antisocial (selfish) decision-making in social decisions on social gain, the following q -exponential social discount function has been proposed (Takahashi, 2010):

$$S_{q_+}(N) = S_{q_+}(0) / \exp_{q_{s_+}}(k_{q_{s_+}}N) = S_{q_+}(0) / [1 + (1 - q_{s_+})k_{q_{s_+}}N]^{1/(1 - q_{s_+})} \quad (5)$$

where $S_{q_+}(N)$ is a social discount factor for a social reward which another person at social distance N receives, $k_{q_{s_+}}$ is a social discount rate at social distance N , q_{s_+} indicates the deviation from exponential social discounting ($q_{s_+} = 0$, equation 5 is the same as a hyperbolic discount function, while $q_{s_+} \rightarrow 1$, is the same as an exponential discount function, see Takahashi, 2010). Because loss may be socially-discounted in a distinct manner from gain, we should prepare a social discount function for loss:

$$S_{q_-}(N) = S_{q_-}(0) / \exp_{q_{s_-}}(k_{q_{s_-}}N) = S_{q_-}(0) / [1 + (1 - q_{s_-})k_{q_{s_-}}N]^{1/(1 - q_{s_-})} \quad (6)$$

with similar notations to equation 5.

Taken together, it can be said that: (i) risky decision-making is parameterized by α , β , and s , (ii) aversion to loss is parameterized by λ , (iii) impulsive and time-inconsistent decision-making is parameterized by $k_{q_{\pm}}$ and q_{\pm} , and (iv) antisocial decision-making is parameterized by $k_{q_{s_{\pm}}}$ and $q_{s_{\pm}}$. Therefore, problematic behaviors, potentially associated with criminal behaviors, in both social and non-social domains can be captured by a relatively small number of these neuroeconomic parameters.

Regarding risky decision-making, in Becker's economic theory of crime and punishment (Becker, 1968) based on the expected utility theory (von Neumann and Morgenstern, 1944), it was hypothesized that criminals may be more risk-taking at least in the realm of punishment. Because recent studies in behavioral economics and neuroeconomics suggest that the prospect theory can capture several important anomalies in decision under risk, better than the expected utility theory, neuroeconomic studies of crime and punishment should employ equation 1 and 2, for analyzing problematic behavior by criminals in decision under risk. Pachur and colleagues (2010) demonstrated, by utilizing the prospect theory, that prisoners were more risk seeking than nonprisoners in lotteries involving losses, but prisoners were less risk seeking in lotteries involving high-probability gains, prisoners had stronger loss aversion than nonprisoners, and prisoners showed a diminished sensitivity to the probability of gains. This study further supports the advantage of the utilization of neuroeconomic theory of decision under risk.

Impulsive decision over time has also been associated with criminal behavior in economic theory. An economist Davis (1988) proposed an economic model of criminal behavior which incorporates temporal discounting. Davis' theory predicts that

agents with higher time-discount rates (k parameters in equation 3 and 4) will be likely to commit crime. However, by utilizing a simple hyperbolic time-discounting function (i.e., q_+ is fixed at 0 in equation 3), Wilson and Daly (2006) reported that young offenders were not significantly different from the control students in time-discount rates. Therefore, more sophisticated temporal discounting models (e.g., the q -exponential time-discount models, equations 3 and 4) should be adopted in future neuroeconomic studies on the effect of temporal discounting on criminal behavior. Concerning illegal substance use, Becker and Murphy's economic theory of addiction (Becker and Murphy, 1988) predicts a positive association between drug addiction and temporal discounting. Subsequently, behavioral and neuroeconomic studies confirmed this prediction (Bickel and Marsch, 2001; Ohmura et al., 2005; Takahashi et al., 2007c; Takahashi, 2009; Takahashi et al., 2009). Interestingly, rationality in addicts may be associated with nonlinearity of their future temporal cognition (Takahashi, 2011b). Therefore, neuroeconomic theory of intertemporal choice may also be useful in future studies on illegal drug use.

With respect to the relationship between crime and social preferences, criminologists Chamlin and Cochran (1997) reported that the cultural value of altruism is inversely related to property and violent crime rates. Neurocognitive studies also implied that psychopathy, which is characterized by a constellation of antisocial behavioral traits, may be associated with altered economic decision-making (Koenigs et al., 2010). However, to date, no study utilized the social discounting functions (equation 5 and 6) to examine the relationship between criminal behavior and social preferences. Therefore, future neuroeconomic studies on crime and punishment should investigate parameters in the social discounting functions in criminals.

3 Neurobiological substrates of risky, impulsive, and antisocial behavior

3.1 Brain regions related to criminal behavior

Abnormalities in brain regions such as the orbitofrontal cortex (Laakso et al., 2002; Anderson and Kiehl, 2012), the amygdala (Blair, 2005; Blair, 2010), the cingulate cortex (Kiehl et al., 2001) have been associated with antisocial behavior and psychopathy. For instance, Blair and colleagues demonstrated that amygdala-orbitofrontal cortex connectivity is reduced during moral judgment in psychopaths (Marsh et al., 2011), and psychopathic subjects have a reduction in amygdala and orbitofrontal cortex responses to emotionally provocative stimuli or during emotional learning (Blair 2010). These brain regions have also been associated with economic decision-making. For instance, the orbitofrontal cortex represents

subjective value of a delayed reward during intertemporal choice (Kable and Glimcher, 2007), the amygdala is related to loss aversion (De Martino et al., 2010), and the cingulate is associated with decision under uncertainty (Paulus and Frank, 2006; Goñi et al., 2010). Therefore, future neuroeconomic studies on crime and punishment should examine the roles of these brain regions by employing the neuroeconomic theory.

3.2 Neurotransmitters related to criminal behavior

Several neuroeconomic studies (Berns et al., 2007; Takahashi, 2008; Zhong et al., 2009) proposed that serotonin and dopamine affect the curvature of the value function in Kahneman-Tversky's prospect theory (equation 1); i.e., risk aversion and loss aversion. Furthermore, both serotonin and dopamine regulate temporal discounting (Takahashi, 2009). A reduction in serotonergic functioning was reportedly related to impulsive temporal and social decision-making (Crockett et al., 2010). Soderstrom et al. (2001) state that serotonin and dopamine distinctly contribute to psychopathy. A recent study found that norepinephrine (noradrenaline) is associated with aggression in prisoners (Chichinadze et al., 2010). We have reported that noradrenergic activity is related to temporal discounting (Takahashi et al., 2007b; Takahashi et al., 2010). Additionally, because risk and time preferences, and loss aversion are predicted to associate with criminal behavior (Becker, 1968; Davis, 1988; Pachur et al., 2010), involvement of serotonergic, noradrenergic, and dopaminergic systems in criminal behavior should more extensively be studied by employing neuroeconomic frameworks in future studies.

3.3 Neuroendocrine modulation of criminal and antisocial behavior

Dysregulation of serotonin in the brain may contribute to the low cortisol (a stress hormone produced in response to the activation of hypothalamic-pituitary-adrenal (HPA) axis) levels (Sobczak et al., 2002; Cima et al., 2008) observed in psychopathy, resulting in a reduced sensitivity to punishment (van Honk et al., 2003). Our neuroeconomic studies demonstrated that stress hormones (cortisol and cortisone) modulate temporal discounting (Takahashi, 2004; Takahashi et al., 2010). Testosterone is a product of the hypothalamic-pituitary-gonadal (HPG) axis and is associated with approach-related behavior, reward sensitivity, and fear reduction (Boissy and Bouissou, 1994). Neuroeconomic studies revealed that testosterone is associated with risky decision-making (Goudriaan et al., 2010) and antisocial behavior (van Honk and Schutter, 2007). In males, testosterone is also nonlinearly associated with temporal discounting (Takahashi et al., 2006). Increased testosterone-to-cortisol ratio may be related to psychopathy (van Honk et al., 2006; Glenn et al., 2010). Chichinadze et al. (2010) reported that testosterone is related to aggression in prisoners. Therefore future studies should investigate how these steroid hormones collectively modulate

neuroeconomic parameters, resulting in an increased risk of criminal behavior and a decrease in sensitivity to punishment. With respect to social decision, oxytocin has been shown to increase generosity in economic games (Zak et al., 2007) but also increase antisocial emotions such as envy (Shamay-Tsoory et al., 2009). Therefore, how oxytocin modulates social discount functions should be examined in future studies.

4. Implications for neuroeconomics and neurolaw of crime and punishment

This is the first study to propose a possible unified framework for molecular neuroeconomic theory of crime and punishment. Neurobiological substrates such as serotonin, dopamine, norepinephrine, as well as neuroactive hormones may modulate neuroeconomic parameters determining risk, time, and social preferences, which conceivably control the risk of criminal behavior and sensitivity to punishment.

Regarding the extremely severe legal punishment (i.e., capital punishment), what we call “Becker’s paradox” is known (Persson et al., 2007): Although capital punishment is optimal in Becker’s economic theory of crime and punishment (1968), it is rarely observed in the real world, nor effective is capital punishment than thought from Becker’s theory of crime and punishment. Although Kahneman-Tversky’s prospect theory extends von Neumann-Morgenstern’s expected utility theory, the prospect theory cannot readily solve this paradox, because, in prospect theory, small probabilities are assumed to be overweighted. Therefore, criminals following the prospect theory may strongly be afraid of capital punishment even when the probability of the capital punishment is small. In order to solve this paradox, novel non-expected utility theories which further extend Kahneman-Tversky’s prospect theory may be necessary (Dhami and al-Nowaihi, 2012). Therefore, future neuroeconomic studies on crime and punishment should develop novel models of decision under risk.

Future studies in molecular neuroeconomics of crime and punishment should employ animal models such as transgenic mice, for a detailed analysis of molecular mechanisms determining the neuroeconomic parameters in the equations above. By utilizing the present neuroeconomic framework, future studies may help establish the discipline of “neurolaw” (Goodenough and Tucker, 2010) at the molecular and cellular levels (i.e., “molecular neurolaw”). This approach may lead us to better biomedical treatments for antisocial behavior and conduct disorders. In terms of medical treatment of criminals, structural nature of impairment in adult psychopaths’ brains make the disorder incurable after full development, the only time window for intervention is in childhood where reliable diagnostic tools for psychopathy traits are needed. The present theoretical frameworks may be useful for the development of the diagnostic tools.

References

Allais, M. (1953) Le comportement de l'homme rationnel devant le risque: critique des postulats et axiomes de l'école Américaine. *Econometrica* 21 (4): 503–546.

Anderson, N. E., and Kiehl, K. A. (2012) The psychopath magnetized: insights from brain imaging. *Trends Cogn Sci.* 16(1):52-56.

Becker, G. S. And Murphy K.M. (1988) A Theory of Rational Addiction. *J. Polit. Econ.* 96, 675–701.

Becker, G. S. (1968). Crime and punishment: An economic approach. *Journal of Political Economy*, 76, 169-217.

Berns GS, Capra CM, Noussair C. (2007) Receptor theory and biological constraints on value. *Ann N Y Acad Sci.* 1104, 301-309.

Bickel WK, Marsch LA. (2001) Toward a behavioral economic understanding of drug dependence: delay discounting processes. *Addiction.* 96, 73-86.

Blair, R.J. (2005) Applying a cognitive neuroscience perspective to the disorder of psychopathy. *Development and Psychopathology* 17, 865-891

Blair, R. J. (2010) Neuroimaging of psychopathy and antisocial behavior: a targeted review. *Curr Psychiatry Rep.* 12(1):76-82.

Boissy, A. and Bouissou, M.F. (1994) Effects of androgen treatment on behavioral and physiological responses to heifers to fear-eliciting situations. *Hormones and Behavior* 28, 66-83

Butterfield M. I., Stechuchak K. M., Connor K. M., Davidson J. R., Wang C., MacKuen C. L., Pearlstein A. M., Marx C. E. Neuroactive steroids and suicidality in posttraumatic stress disorder. *Am J Psychiatry.* 2005 162, 380-382.

Cajueiro D.O. A note on the relevance of the q-exponential function in the context of

intertemporal choices. *Physica A* 364 (2006) 385–388.

Chamlin, M. B., Cochran, J. K. (1997) Social altruism and crime. *Criminology*, 35, 203-228

Chichinadze KN, Domianidze TR, Matitaishvili TTs, Chichinadze NK, Lazarashvili AG (2010) Possible relation of plasma testosterone level to aggressive behavior of male prisoners. *Bull Exp Biol Med.* 149, 7-9.

Cima M, Smeets T, Jelicic M. (2008) Self-reported trauma, cortisol levels, and aggression in psychopathic and non-psychopathic prison inmates. *Biol Psychol.* 78, 75-86.

Crockett MJ, Clark L, Lieberman MD, Tabibnia G, Robbins TW. (2010) Impulsive choice and altruistic punishment are correlated and increase in tandem with serotonin depletion. *Emotion*, 10, 855-862.

Dhami, Sanjit, and Ali al-Nowaihi. "An extension of the Becker proposition to non-expected utility theory." *Mathematical Social Sciences* (2013). 65, 10–20

Davis M. L. (1988) Time and punishment-an intertemporal model of crime. *Journal of Political Economy*, 96, 383-390.

De Caro S, Kaplen MV. (2010) Current issues in neurolaw. *Psychiatr Clin North Am.* 33, 915-930.

De Martino B, Camerer CF, Adolphs R. (2010) Amygdala damage eliminates monetary loss aversion. *Proc Natl Acad Sci U S A.* 107, 3788-3792.

Glenn AL, Raine A, Schug RA, Gao Y, Granger DA. (2010) Increased testosterone-to-cortisol ratio in psychopathy. *J Abnorm Psychol.* (in press)

Goñi J, Aznárez-Sanado M, Arrondo G, Fernández-Seara M, Loayza FR, Heukamp FH, Pastor MA. (2011) The neural substrate and functional integration of uncertainty in decision making: an information theory approach. *PLoS One.* 6(3):e17408.

Goodenough O.R. and Tucker M. (2010) Law and cognitive neuroscience. *Annual Review of Law and Social Science*, 6, 61-92.

Goudriaan AE, Lapauw B, Ruige J, Feyen E, Kaufman JM, Brand M, Vingerhoets G. (2010) The influence of high-normal testosterone levels on risk-taking in healthy males in a 1-week letrozole administration study. *Psychoneuroendocrinology*. 35, 1416-1421.

Han, R. and Takahashi, T. (2012) Psychophysics of valuation and time perception in temporal discounting of gain and loss. *Physica A*, 391, 6568-6576.

Kable JW, Glimcher PW. (2007) The neural correlates of subjective value during intertemporal choice. *Nature Neuroscience*. 10, 1625-1633.

Kahneman, D, and Tversky A. (1979) "Prospect Theory: An Analysis of Decision under Risk", *Econometrica*, XLVII, 263-291.

Kiehl KA, Smith AM, Hare RD, Mendrek A, Forster BB, Brink J, Liddle PF. (2001) Limbic abnormalities in affective processing by criminal psychopaths as revealed by functional magnetic resonance imaging. *Biological Psychiatry* 50, 677-684

Koenigs M, Kruepke M, Newman JP (2010) Economic decision-making in psychopathy: A comparison with ventromedial prefrontal lesion patients. *Neuropsychologia* 48, 2198-2204.

Laakso MP, Gunning-Dixon F, Vaurio O, Repo-Tiihonen E, Soininen H, Tiihonen J (2002) Prefrontal volumes in habitually violent subjects with antisocial personality disorder and type 2 alcoholism. *Psychiatry Research*, 114, 95-102

Marsh, A. A., Finger, E. C., Fowler, K. A., Jurkowitz, I. T., Schechter, J. C., Yu, H. H., Pine, D. S., Blair, R. J. (2011) Reduced amygdala-orbitofrontal connectivity during moral judgments in youths with disruptive behavior disorders and psychopathic traits. *Psychiatry Res.* 194(3):279-286.

Ohmura Y, Takahashi T, Kitamura N. (2005) Discounting delayed and probabilistic monetary gains and losses by smokers of cigarettes. *Psychopharmacology (Berl)*. 182(4):508-515.

Pachur T, Hanoch Y, Gummerum M. (2010) Prospects behind bars: analyzing decisions under risk in a prison population. *Psychon Bull Rev.* 17, 630-636.

Paulus MP, Frank LR (2006) Anterior cingulate activity modulates nonlinear decision weight function of uncertain prospects. *Neuroimage.* 30, 668-677.

Persson, M. and Siven, C.-H. (2007), THE Becker paradox and type I versus type II errors in the economics of crime. *International Economic Review*, 48: 211–233.

Prelec D. (1998). The probability weighting function. *Econometrica* 60, 497-528.

Shamay-Tsoory SG, Fischer M, Dvash J, Harari H, Perach-Bloom N, Levkovitz Y. (2009) Intranasal administration of oxytocin increases envy and schadenfreude (gloating). *Biol Psychiatry.* 66, 864-870.

Sobczak S, Honig A, Nicolson NA, Riedel WJ. (2002) Effects of acute tryptophan depletion on mood and cortisol release in first-degree relatives of type 1 and type 2 bipolar patients and healthy matched controls. *Neuropsychopharmacology* 27, 834-842

Soderstrom H, Blennow K, Manhem A, Forsman A. (2001) CSF studies in violent offenders. I. 5-HIAA as a negative and HVA as a positive predictor of psychopathy. *J Neural Transm.* 108, 869-878.

Takahashi T, (2004) Cortisol levels and time-discounting of monetary gain in humans. *Neuroreport.* 15, 2145-2147.

Takahashi T, Sakaguchi K, Oki M, Homma S, Hasegawa T. (2006) Testosterone levels and discounting delayed monetary gains and losses in male humans. *NeuroEndocrinol Lett.* 27, 439-444.

Takahashi, T. (2007) A comparison of intertemporal choices for oneself versus someone else based on Tsallis' statistics, *Physica A* 385, 637-644

Takahashi T. (2008) Biophysics of risk aversion based on neurotransmitter receptor theory. *Neuro Endocrinol Lett.* 29, 399-404.

Takahashi, T (2009) Theoretical frameworks for neuroeconomics of intertemporal choice. *Journal of Neuroscience, Psychology, and Economics*. 2(2), 75-90.

Takahashi, T. (2010) A social discounting model based on Tsallis' statistics. *Physica A: Statistical Mechanics and its Applications*, 389, 3600-3603.

Takahashi, T (2011a) Psychophysics of the probability weighting function. *Physica A: Statistical Mechanics and its Applications* 390, 902-905.

Takahashi, T (2011b) A neuroeconomic theory of rational addiction and nonlinear time-perception. *Neuro Endocrinology Letters*, 32, 221–225

Takahashi T, Ono H, Radford MHB (2007a) Empirical estimation of consistency parameter in intertemporal choice based on Tsallis' statistics *Physica A* 381, 338-342

Takahashi T, Ikeda K, Fukushima H, Hasegawa T. (2007b) Salivary alpha-amylase levels and hyperbolic discounting in male humans. *NeuroEndocrinol Lett.* 28, 17-20.

Takahashi T, Furukawa A, Miyakawa T, Maesato H, Higuchi S. (2007c) Two-month stability of hyperbolic discount rates for delayed monetary gains in abstinent inpatient alcoholics. *NeuroEndocrinol Lett.* 28, 131-136.

Takahashi, T., Oono, H., Radford, M.H.B. (2008a) Psychophysics of time perception and intertemporal choice models. *Physica A: Statistical Mechanics and its Applications* 387, 2066-2074

Takahashi T, Oono H, Inoue T, et al. (2008b) Depressive patients are more impulsive and inconsistent in intertemporal choice behavior for monetary gain and loss than healthy subjects - An analysis based on Tsallis' statistics, *NeuroEndocrinology Letters*, 29, 351-358

Takahashi T, Ohmura Y, Oono H, Radford M. (2009) Alcohol use and discounting of delayed and probabilistic gain and loss. *NeuroEndocrinol Lett.* 30, 749-752.

Takahashi T, Shinada M, Inukai K, Tanida S, Takahashi C, Mifune N, Takagishi H,

Horita Y, Hashimoto H, Yokota K, Kameda T, Yamagishi T. (2010) Stress hormones predict hyperbolic time-discount rates six months later in adults. *NeuroEndocrinology Letters*, 31, 616-621.

Tversky, A and Kahneman D (1992). "Advances in prospect theory: Cumulative representation of uncertainty". *Journal of Risk and Uncertainty* 5: 297–323.

van Honk, J. and Schutter, D.J.L.G. (2006) Unmasking feigned sanity: A neurobiological model of emotion processing in primary psychopathy. *Cognitive Neuropsychiatry* 11, 285-306

van Honk J, Schutter DJ. (2007) Testosterone reduces conscious detection of signals serving social correction: implications for antisocial behavior. *Psychol Sci.* 18, 663-667.

van Honk J, Schutter DJ, Hermans EJ, Putman P. (2003) Low cortisol levels and the balance between punishment sensitivity and reward dependency. *Neuroreport.* 14, 1993-1996.

Von Neumann, J, and Morgenstern, O, Theory of Games and Economic Behavior, Princeton, NJ, Princeton University Press, 1944, second ed. 1947, third ed. 1953.

Wilson M, Daly M. (2006) Are juvenile offenders extreme future discounters? *Psychol Sci.* 17, 989-994.

Xu L, Liang ZY, Wang K, Li S, Jiang T. Neural mechanism of intertemporal choice: from discounting future gains to future losses. *Brain Res.* 2009 1261:65-74.

Zak PJ, Stanton AA, Ahmadi S. (2007) Oxytocin increases generosity in humans. *PLoS One.* 2(11):e1128.

Zhong S, Israel S, Xue H, Sham PC, Ebstein RP, Chew SH. (2009) A neurochemical approach to valuation sensitivity over gains and losses. *Proc Biol Sci.* 276, 4181-4188.

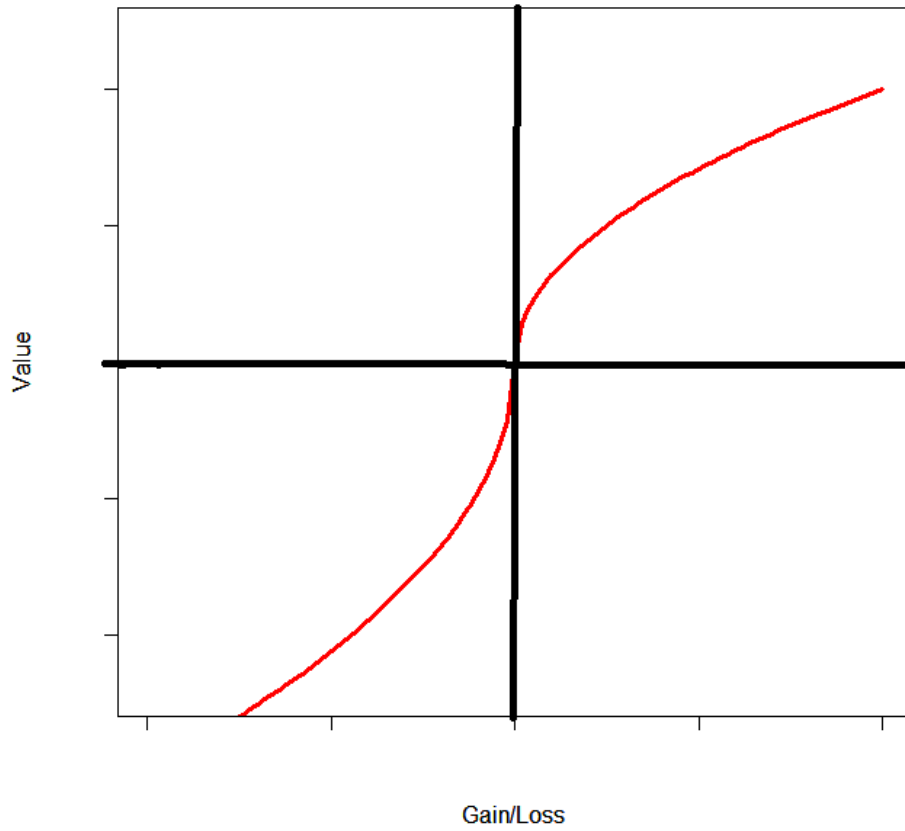


Figure 1.

Value function of Prospect theory. Value function is concave (risk aversion) in gain and convex (risk preference) in loss. Also, value function is more steep in loss.

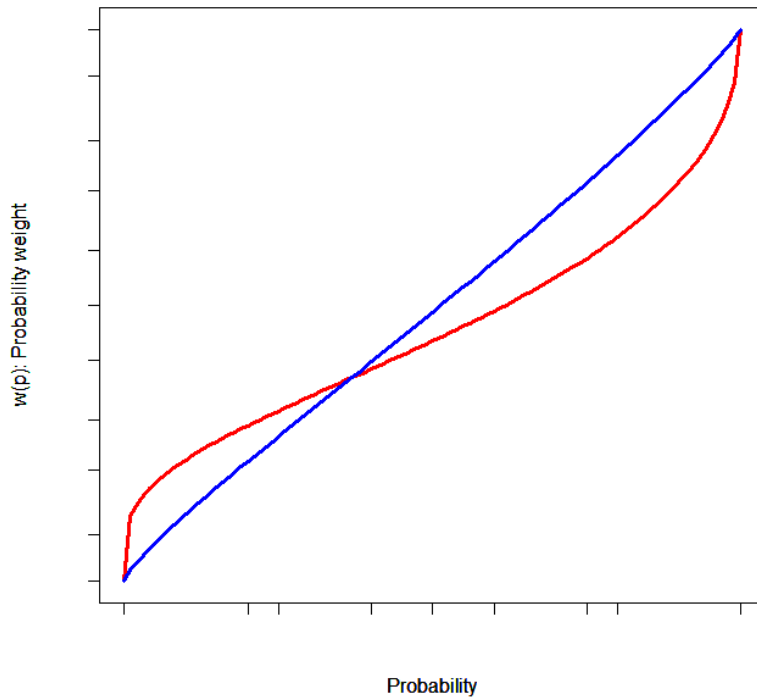


Figure 2

Probability weighting function. The horizontal axis indicates (objective) probability of winning the outcome. The vertical axis indicates probability weight (subjective probability). The red curve indicates more exaggerated tendency of overweighing small probability and underweighing large probability in decision under risk than the blue curve.

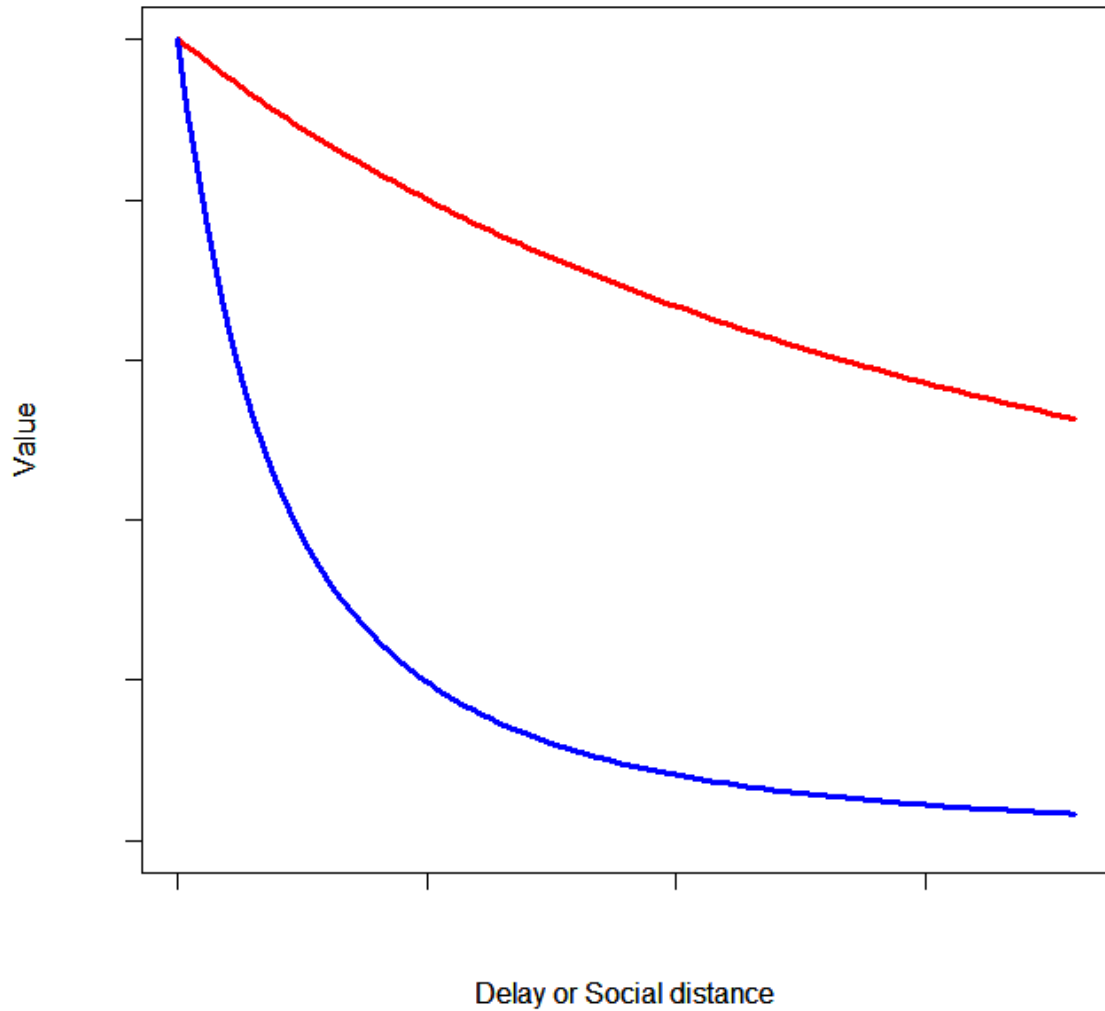


Figure 3 Delay of Social discount functions (q-exponential functions).
The horizontal axis indicates delay until receipt or social distance of receiver from donor. The vertical axis indicates subjective value. Note that the blue curve indicates more impulsive (selfish) discounting than the red curve.