Discussion Papers In Economics And Business

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Daijiro Kawanaka

Discussion Paper 23-02

February 2023

Graduate School of Economics
Osaka University, Toyonaka, Osaka 560-0043, JAPAN

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Daijiro Kawanaka†

Abstract

Köszegi and Rabin (2006, 2007) formulate loss-aversion models called Preferred Personal Equilibrium (PPE) and Choice-acclimating Personal Equilibrium (CPE) so successfully that many papers have been applied their models to a variety of economic fields in this decade. In this paper, without assuming any specific functional form, I show that these two loss-aversion models satisfy strong mixture aversion in the sense that a non-degenerate lottery is strictly preferred to any mixture between the lottery and its certainty equivalent. This property distinguishes these loss-aversion models from many other standard models such as the expected utility theory and disappointment aversion so that this result allows experimental economists to test a class of these models in a simple setting.

JEL Classification Numbers: D11, D81, D91

Keywords: Prospect theory, Loss aversion, Reference point, Mixture aversion, Betweenness

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* The author would like to thank Nobuyuki Hanaki, Taisuke Imai, Keigo Inukai, Takeshi Murooka, and Yosuke Yasuda. This research was supported by Grant-in-Aid for JSPS Fellows from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

† Graduate school of Osaka University. Email: kawanaka.daijiro@gmail.com

1 Introduction

Kahneman and Tversky (1979) proposed "prospect theory" to explain decisions under risk deviating from the expected utility theory of Neumann and Morgenstern (1944). In the prospect theory, it is often assumes that a decision maker has an *exogenous* reference point that causes loss aversion. Literature has often criticized that theorists can assume arbitrary reference points and explain any decisions. To overcome this problem, Köszegi and Rabin (KR) have developed models of *endogenous* reference-dependent utility, called Preferred Personal Equilibrium (PPE, Köszegi and Rabin 2006) and Choice-acclimating Personal Equilibrium (CPE, Köszegi and Rabin 2007). In their models, the reference point is assumed as a stochastic distribution, not a deterministic point.

In this decade, the KR loss aversion models have been applied to a variety of fields such as wage sheme (Herweg et al. 2010; Daido et al. 2013), pricing (Rosato 2016), financial decisions (Ai et al. 2018; Meng and Weng 2018), market design (Balzer and Rosato 2021; Meisner and Wangenheim 2022; Muramoto and Sogo 2022), and team incentives (Daido and Murooka 2016). Most applications of KR assume a linear utility function for simplicity. Few theoretical papers analyze the KR models due to their complexity. As one of the few theoretical papers, Masatlioglu and Raymond (2016) provide an axiomatic foundation of the linear case of CPE.

However, behavioral economists should pay more attention to the nonlinear model of KR. This is because the linear models of KR cannot solve Rabin's (2000) critique of the standard expected utility theory. On this issue, Masatlioglu and Raymond (2016) state in their final paragraph that "Linearity of CPE is crucial for the calibration result of Safra and Segal (2005). If the assumption that μ (the gain-loss function) is linear is relaxed, it is possible to generate plausible small- and large-stakes risk aversion. Köszegi and Rabin's (2007) Table 1 does exactly this. However, the most tractable form of Köszegi and Rabin's (2007) model, that with linear gain-loss utility, cannot avoid an extension of the Rabin critique. Thus, in order to model individuals who exhibit plausible behavior over both small- and large-stakes lotteries, we must turn to nonlinear gain-loss functionals."

In this paper, I analyze the both of PPE and CPE without assuming any specific functional form, and show that they satisfy *strong mixture aversion*: a decision maker *strictly* prefers a non-degenerate lottery p to any mixture $\theta p \oplus (1-\theta)\delta$ of p and its certainty equivalent δ. This is in contrast to many standard models as the expected utility theory, the betweenness literature

(Dekel 1986; Gul 1991), and the negative certainty independence models (Dillenberger 2010; Cerreia-Vioglio et al. 2015). That is, in these later models, a decision maker must be indifferent between the two options p and $\theta p \oplus (1-\theta)\delta$ for any mixture θ. Hence, these properties will allow experimental economists to differentiate KR from other models.

Masatlioglu and Raymond (2016) show that a class of CPE satisfies a weak version of mixture aversion but this paper generalize their results in the following senses: First, Masatlioglu and Raymond focus solely on CPE, whereas I study both CPE and PPE.[1] Second, Masatlioglu and Raymond assume specific functional forms such as lineality, whereas I assume only very mild conditions. Hence, my results suggest that the mixture aversion property can be applied to a wider range of real-world scenarios. Third, Masatlioglu and Raymond's results claim a *weak* mixture aversion that a decision maker *weakly* avoids a mixture alternative, while my results claim a strong one. This improves experimental testability of CPE and PPE.

The rest part of this paper is organized as follows: Section 2 defines a model. Section 3 introduces Choice-acclimating Personal Equilibrium (CPE) proposed by Köszegi and Rabin (2007), and shows its behavioral implications. Section 4 introduces Preferred Personal Equilibrium (PPE) proposed by Köszegi and Rabin (2006), and shows its behavioral implications. Section 5 concludes.

2 Preliminaries

Let X be an arbitrary set of deterministic prizes. For any probability distribution p over X, denote $\mathrm{supp}(p) \coloneqq \{x \in X \mid p(x) > 0\}$. I refer a probability distribution p with a finite $\mathrm{supp}(p)$ to a *lottery* over X, and denote the set of all lotteries by Δ_X. I denote a degenerate lottery yielding a $z \in X$ by δ_z. I consider a binary relation $\succeq$ over Δ_X and a choice function over Δ_X. As usual, I define a lottery $\theta p \oplus (1-\theta)q$ for each $p, q \in \Delta_X$ and all $\theta \in (0,1)$. Given a lottery $p \in \Delta_X$, I will abbreviate $\sum_{x \in \mathrm{supp}(p)} p(x)$ as $\sum_x p(x)$ for short.

In this section, I introduce a general model of endogenous reference dependent utility, and show its property as a lemma. To do so, I introduce a *gain-loss function* denoted by $\mu : \mathbb{R} \to \mathbb{R}$. On the function, Bowman, Minehart, and Rabin (1999) postulate and Köszegi and Rabin (2006, 2007) employ the following assumptions (A1)-(A4) corresponding to Kahneman and

[1] As one of the few theoretical papers analyzing PPE, Freeman (2019) shows that PPE violations of the independence axiom and can also lead to violations of the weak axiom of revealed preference.

Tversky's (1979) explicit or implicit assumptions about their "value function:"

(A1) μ is strictly increasing in $x \in \mathbb{R}$.

(A2) $\mu(y) + \mu(-y) < \mu(x) + \mu(-x)$ for all x, y such that $y > x \geq 0$.

(A3) $f(x)$ is concave for all $x > 0$ and convex for all $x < 0$.

(A4) $\lim_{x \to 0} \mu'(-x)/\mu'(x) > 1$ if $x > 0$.

In words, these assumptions say that the graph of μ is an S-shaped curve as Kahneman and Tversky draw. In addition, Köszegi and Rabin (2006, 2007) assume on μ that $\mu(0) = 0$ as (A0) which says that the curve passes through the origin. However, this (A0) is not essential for the present analysis since $\mu(0)$ is just a constant term for total utility which we will define the below. I do not need (A1), (A3) and (A4) for the present analysis of this paper. This study needs (A2) and the following additional condition:

(A5) $\mu(\alpha) + \mu(-\alpha)$ is convex for $\alpha \in \mathbb{R}_+$.

Note that a "general CPE" called by Masatlioglu and Raymond (2016) satisfies (A2) and (A5). Thus, a functional of our analysis is more general than their called general CPE.

In this paper, I consider a functional $U_{KR} : \Delta_X \times \Delta_X \to \mathbb{R}$ given by

$$U_{KR}(p \mid q) := \sum_x u(x)p(x) - \sum_x \sum_r \mu(u(x) - u(r))p(x)q(r), \tag{1}$$

where $u : X \to \mathbb{R}$ is a Bernoulli function and $\mu : \mathbb{R} \to \mathbb{R}$ is gain-loss function. In (1), the first term represents a material utility and the second represents a psychological utility. In the later term, an r represents a reference point, and the definition of U_{KR} says that the r is distributed according to distribution q.

Let (u, μ) be given Bernoulli function and gain-loss function. For notational simplicity, I will denote the term of psychological loss by

$$\Lambda_{pq} := -\sum_x \sum_r \mu(u(x) - u(r))p(x)q(r) \tag{2}$$

for each $p, q \in \Delta_X$. Then, Λ_{pq} satisfies a triangle inequality as follows:

Lemma 1 (Triangle inequality)**.** Let a function $\Lambda : \Delta_X \times \Delta_X \to \mathbb{R}$ reduced from (u, μ) satisfy (A2) and (A5). Then,

$$\Lambda_{pq} + \Lambda_{qr} \geq \Lambda_{pr} \tag{3}$$

for each $p, q, r \in \Delta_X$. Moreover,

$$\Lambda_{pq} + \Lambda_{qr} = \Lambda_{pr} \tag{4}$$

binds only if $p = q = r$.

Proof of Lemma 1. See Appendix A.1. ■

This triangle inequality is important for my analysis, and to my knowledge no paper claim this property of psychological loss with stochastic reference points.

3 Choice acclimating personal equilibrium

In this section, I will show that a choice acclimating personal equilibrium (CPE) developed by Koszegi and Rabin (2007) satisfies a strong version of mixture aversion. Masatlioglu and Raymond (2016) have shown that a relation $\succeq$ with a CPE of a gain-loss function μ given by

$$\mu(\alpha) := \left\{ \begin{array}{ccc} \alpha & \text{if} & \alpha \geq 0 \\ \lambda\alpha & \text{if} & \alpha < 0 \end{array} \right\} \text{ where } 0 \leq \lambda \leq 1 \tag{5}$$

satisfies weak mixture aversion: if $p \sim q$, then $\theta p \succeq p \oplus (1-\theta) q$ for all $\theta \in (0, 1)$. This section will show that such a mixture aversion holds even when μ is more general, and moreover, it strictly holds when q is degenerate. (i.e., q is a certainty equivalent of p.)

By a function U_{KR} introduced in section 2, I define CPE as follows:

Definition 1. For a function U_{KR} reduced from given (u, μ), a binarly relation $\succeq$ has a *CPE model* if

$$p \succeq q \Leftrightarrow U_{KR}(p \mid p) \geq U_{KR}(q \mid q)$$

for each $p, q \in \Delta_X$. I will often abbreviate $U_{KR}(p \mid p)$ to $U_{KR}(p)$.

The result of this section is summarized as follows:

Theorem 2. Let $\succeq$ have a CPE model satisfying (A2) and (A5). For any $\theta \in (0, 1)$, any $p, q \in \Delta_X$ and $z \in X$ such that $p \sim q \sim \delta_z$ and $p \neq \delta_z \neq q$,

$$p \succeq \theta p \oplus (1-\theta) q \succ \theta p \oplus (1-\theta) \delta_z \tag{6}$$

holds.

Proof of Theorem 2. See Appendix A.2. ■

In words, the first $\succeq$ of (6) claims weak mixture aversion holds, and the second $\succ$ of (6) claims strong mixture aversion holds for the certainty equivalent. An example is as follows:

Example 1. Suppose a CPE with μ given by (5) and $u(z) \coloneqq z$. Consider a lottery $p \coloneqq (\$8, 50\%;\ \$0, 50\%)$. Then, $U_{KR}(p) = U_{KR}(\delta_3) = 3 > 4/11 = U_{KR}\left(\frac{1}{2}p \oplus \frac{1}{2}\delta_3\right)$. Hence, the strong mixture aversion holds.

I emphasize that Theorem 2 holds even if μ is neither linear in a sense of (5) nor of other symmetric property such as Masatlioglu and Raymond (2016) imposed in their section IV. Hence, according to Theorem 2, experimental economists can test CPE model by assuming very mild conditions (A2) and (A5).

4 Preferred personal equilibrium

A preferred personal equilibrium (PPE) developed by Koszegi and Rabin (2006) is also a famous model of endogenous reference-dependence loss aversion defined by functional U_{KR}. In this section, I will show that PPE also satisfies a strong version of mixture aversion for certainty equivalents.

To introduce PPE model, I define unacclimating personal equilibrium (UPE) model by a choice function:

Definition 2. For given U_{KR}, a choice function $C_{UPE} : 2^{\Delta_X} \to 2^{\Delta_X}$ has a *UPE model* whenever for all $D \subseteq \Delta_X$, $p \in C_{UPE}(D)$ if and only if $U_{KR}(p \mid p) \geq U_{KR}(q \mid p)$ for all $q \in D$.

Definition 3. For given U_{KR}, a choice function $C_{PPE} : 2^{\Delta_X} \to 2^{\Delta_X}$ has a *PPE model* whenever for all $D \subseteq \Delta_X$, $p \in C_{PPE}(D)$ if and only if $p \in C_{UPE}(D)$ and $U_{KR}(p \mid p) \geq U_{KR}(q \mid q)$ for all $q \in C_{UPE}(D)$.

Definition 4. For given choice function C, $z \in X$ is a *certainty equivalent* of given lottery $p \in \Delta_X$ if $C(\{p, \delta_z\}) = \{p, \delta_z\}$.

Now, I can extend the first part of Theorem 2 of CPE to PPE:

Theorem 3. Let C_{PPE} be reduced from U_{KR} satisfying (A2) and (A5). Take any $p, q \in \Delta_X$, any $D \subseteq \Delta_X$ and any $\theta \in (0, 1)$. Then, $p, q \in C_{PPE}(D \cup \{\theta p \oplus (1-\theta)q\})$ if $p, q \in C_{PPE}(D)$.

Proof of Theorem 3. See Appendix A.3. ■

Theorem 3 claims that a decision maker weakly prefers p ($\sim q$) to $\theta p \oplus (1-\theta)q$ in the perspective of PPE. That is, PPE model also exhibits the weak mixture aversion.

From Lemma 1 and Theorem 3, I can also obtain the following claim:

Collolary 4. Take any $p \in \Delta_X$, any $D \subseteq \Delta_X$ and any $\theta \in (0,1)$. Then, $\theta p \oplus (1-\theta)\delta_z \notin C_{PPE}(D \cup \{\theta p \oplus (1-\theta)\delta_z\})$ if $p, \delta_z \in C_{PPE}(D)$.

This collolary corresponds to the second part of Theorem 2: a decision maker strictly prefers p ($\sim \delta_z$) to $\theta p \oplus (1-\theta)\delta_z$ in the perspective of PPE. That is, PPE model also exhibits the strong mixture aversion for certainty equivalents.

5 Conclusion

This paper shows that both CPE (Köszegi and Rabin 2007) and PPE (Köszegi and Rabin 2006) both exhibit weak mixture aversion under milder conditions than known in the literature. Moreover, the both models exhibit strong mixture aversion for certainty equivalents. This behavioral implication identifies these models of loss aversion from other decision models such as disappointment aversion (Gul 1991). This insight will encourage both of theoretical and experimental research applying Köszegi-Rabin type loss aversion.

A Proofs

A.1 Proof of Lemma 1

Given a gain-loss function $\mu : \mathbb{R} \to \mathbb{R}$, I define $\nu(\alpha) := -\mu(\alpha) - \mu(-\alpha)$ for each $\alpha \in \mathbb{R}$. By construction,

$$\Lambda_{pq} + \Lambda_{qp} = \sum_x \sum_y \nu(x-y)p(x)q(y) \tag{7}$$

holds for any $p, q \in \Delta_X$.

Take arbitrary $a, b, c \in X$. From (A2), $\nu(\alpha)$ is strictly increasing in $\alpha \in \mathbb{R}_+$. Thus, by the geometric triangle inequality, I have

$$\nu(|a-b| + |b-c|) \geq \nu(|a-c|). \tag{8}$$

From (A5), $\nu(|\alpha|)$ is concave. Thus, I have

$$\nu(|a-b|)+\nu(|b-c|) \geq \nu(|a-b|+|b-c|). \tag{9}$$

From (8) and (9), I have

$$\nu(|a-b|)+\nu(|b-c|) \geq \nu(|a-c|). \tag{10}$$

Because $\nu(\alpha)=\nu(-\alpha)$, I obtain from (10) that

$$\nu(a-b)+\nu(b-a)+\nu(b-c)+\nu(c-b) \geq \nu(a-c)+\nu(c-a). \tag{11}$$

Take arbitrary $p, q, r \in \Delta_X$. Multiplying the both hand sides of (11) by $p(a)q(b)r(c)$ and taking summation of them for each $(a,b,c) \in \mathrm{supp}(p) \times \mathrm{supp}(q) \times \mathrm{supp}(r)$, I have

$$2\Lambda_{pq}+2\Lambda_{qr} \geq 2\Lambda_{pr}. \tag{12}$$

Hence, I obtain (3). Moreover, inequalities (8), and thus (12), bind only if $p=q=r$. Hence, now I obtain (4). ■

A.2 Proof of Theorem 2

To show Theorem 2, I show the following Lemma 5:

Lemma 5. Let $\succeq$ have a CPE model. Take any $p, q \in \Delta_X, z \in X$ and $\theta \in (0,1)$ such that $p \sim q \sim \delta_z$. Then, $p \succ \theta p \oplus (1-\theta)q$ if and only if

$$\Lambda_{pq}+\Lambda_{qp} > \Lambda_{pp}+\Lambda_{qq}. \tag{13}$$

Especially, $p \succ \theta p \oplus (1-\theta)\delta_z$ if and only if

$$\Lambda_{p\delta_z}+\Lambda_{\delta_z p} > \Lambda_{pp}. \tag{14}$$

Proof of Lemma 5. Suppose $p \sim q$, i.e.,

$$\sum_x u(x)p(x)-\Lambda_{pp}=\sum_x u(x)q(x)-\Lambda_{qq}. \tag{15}$$

Take an arbitrary $\theta \in (0,1)$. Then, $U_{KR}(\theta p \oplus (1-\theta)q)$ is calculated as

$$\theta \sum_x u(x)p(x)+(1-\theta)\sum_x u(x)q(x)-\theta^2\Lambda_{pp}-(1-\theta)\theta(\Lambda_{pq}+\Lambda_{qp})-(1-\theta)^2\Lambda_{qq}. \tag{16}$$

Hence, $U_{KR}(p) - U_{KR}(\theta p \oplus (1-\theta)q)$ is calculated as

$$(1-\theta)\left(\sum_x u(x)p(x) - \Lambda_{pp} - \sum_x u(x)q(x) + \Lambda_{qq}\right) + (1-\theta)\theta(\Lambda_{pq} + \Lambda_{qp} - \Lambda_{pp} - \Lambda_{qq}), \quad (17)$$

which is larger than zero if and only if $p \succ \theta p \oplus (1-\theta)q$. From (15) and (17), I can say that $p \succ \theta p \oplus (1-\theta)q$ if and only if (13) holds. Because

$$\Lambda_{\delta_z \delta_z} = 0 \quad (18)$$

by construction of (2), I obtain (14) by asigning $q = \delta_z$ to (13). ■

From Lemmas 1 and 5, Theorem 2 is shown. ■

A.3 Proof of Theorem 3

To show Theorem 3, I show the following Lemmas 6 and 7

Lemma 6. Take an arbitrary $D \subseteq \Delta_X$. If $p, q \in C_{UPE}(D)$, then $\Lambda_{pq} + \Lambda_{qp} \geq \Lambda_{pp} + \Lambda_{qq}$.

Proof of Lemma 6. Suppose $p, q \in C_{UPE}(\{p, q\})$. Then, $U_{KR}(p \mid p) \geq U_{KR}(q \mid p)$ and $U_{KR}(q \mid q) \geq U_{KR}(p \mid q)$ hold. That is,

$$\sum_x u(x)p(x) - \Lambda_{pp} \geq \sum_x u(x)q(x) - \Lambda_{qp}, \quad (19)$$

and

$$\sum_x u(x)q(x) - \Lambda_{qq} \geq \sum_x u(x)p(x) - \Lambda_{pq}. \quad (20)$$

From (19) and (20), I have $\Lambda_{pq} + \Lambda_{qp} \geq \Lambda_{pp} + \Lambda_{qq}$. ■

Lemma 7. Take any $p, q \in \Delta_X$ and any $D \subseteq \Delta_X$. Let $m := \theta p \oplus (1-\theta)q$ for given $\theta \in (0,1)$. Then, $p, q \in C_{UPE}(D \cup \{m\})$ if $p, q \in C_{PPE}(D)$.

Proof of Lemma 7. Suppose $p, q \in C_{PPE}(D)$. Then, I have $U_{KR}(p \mid p) = U_{KR}(q \mid q)$, i.e., $\sum_x u(x)p(x) - \Lambda_{pp} = \sum_x u(x)q(x) - \Lambda_{qq}$. Therefore, I obtain from (19) and (20) that

$$\Lambda_{qp} \geq \Lambda_{qq}, \quad (21)$$

and

$$\Lambda_{pq} \geq \Lambda_{pp} \quad (22)$$

respectively. Note that $U_{KR}(p \mid p) = U_{KR}(q \mid q) = \theta U_{KR}(p \mid p) + (1-\theta)U_{KR}(q \mid q)$ by Definition 4. Therefore, I obtain that

$$U_{KR}(q \mid q) \geq U_{KR}(m \mid q) \tag{23}$$

from (21). Similarly, $U_{KR}(p \mid p) \geq U_{KR}(m \mid p)$ holds from (22). Hence, I have

$$p, q \in C_{UPE}(D \cup \{m\}). \tag{24}$$

From Theorem 2 and (24), I have $p, q \in C_{PPE}(D \cup \{m\})$. ■

From Lemmas 6 and 7, Theorem 3 is shown. ■

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