Economics Letters 170 (2018) 163–167

Contents lists available at ScienceDirect

Economics Letters

journal homepage: www.elsevier.com/locate/ecolet

Portfolio choice in personal equilibrium

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HIGHLIGHTS

- We study optimal portfolio choice where reference point arises endogenously in personal equilibria.
- In addition to CPE, UPE is also linked to the rank-dependent utility (RDU) in the context of portfolio choice.
- The equivalence between UPE and RDU only applies in the characterization of the *optimal* risky choice.
- The non-uniqueness of UPE is caused by non-convexities of the choice set.

ARTICLE INFO

Article history:
Received 13 December 2017
Received in revised form 18 June 2018
Accepted 19 June 2018
Available online 21 June 2018

JEL classification:
G21
G32

Keywords:
Loss aversion
Personal equilibrium
Portfolio choice
Rank-dependent utility

ABSTRACT

This paper finds that in portfolio choice where reference point arises endogenously in personal equilibria, investors behave as if they had a concave probability weighting function. This finding establishes a link between the reference-dependent utility and the rank-dependent utility theories.

1. Introduction

In a stimulating paper, Kőszegi and Rabin (2007) (KR, henceforth) explored how individuals with expectation-based reference-dependent preferences make a risky choice. In their model, individuals care about consumption utility as well as gain–loss utility (i.e., utility over deviations from the reference), and the reference is the full distribution of the payoff reflecting individuals' expectations. KR provide a solution framework for the formation of expectations-based reference, in which the individual knows exactly how he or she will behave in any future contingency and his or her reference point reflects this actual behavior. KR's framework has inspired numerous applications. Among others, Heidhues and Kőszegi (2008) use this framework to study the Salop price competition; Herweg et al. (2010) apply it to re-design the employee compensation contracts; Karle and Peitz (2014) employ it to study the firm competition with asymmetric information regarding consumer tastes. In financial markets, Pagel (2016) explores the asset-pricing implications of KR's solution in a Lucas-tree model with dynamic asset allocations, while Pagel (2018) uses KR's framework to solve a life-cycle portfolio choice problem in which the investor experiences loss-averse utility over news.

Despite the existing applications, the implications of KR's framework on optimal portfolio choice are not fully investigated. Pagel (2016, 2018) use KR's framework in intermediate steps to solve the portfolio choice problems. However, she obtained the unique solution only for power and log utility functions under lognormal distributions for risky assets. It is not clear whether the solution would be unique for all concave utility functions and all continuous distributions, and how to characterize the optimal portfolio weights in KR's framework in the more general setting. The purpose of our paper is to address these questions.

Specifically, we offer an explicit characterization of the solution to the portfolio choice problem in KR's framework under

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https://doi.org/10.1016/j.econlet.2018.06.018

a general setting. KR introduces two specific solution concepts. One is the "unacclimating personal equilibrium" (UPE, henceforth), defined for the case where the choice is made based upon the reference, and equilibrium is achieved when the optimal choice coincides exactly with the reference. The other one is the "choice-acclimating personal equilibrium" (CPE, henceforth), defined for the case where the individual first sets the choice as the reference, and then optimizes over the choices. As KR argued, UPE arises in a context where individuals expect a choice only if they are willing to follow it through, while CPE applies in a context where individuals commit to a choice before outcomes occur. We show that investors in both UPE and CPE behave as if they had a concave probability weighting function, as axiomatized by Yaari (1987). This characterization is interesting because it establishes an equivalence between nonstandard utility under correct beliefs and standard utility under distorted beliefs.

The equivalent concave probability weighting function implies that the choice in UPE is unique. Only with uniqueness, we are able to determine the UPE by virtue of the first-order condition and further translate this condition into a rank-dependent structure. This result is in contrast to the previous finding of multiple UPE choices under a discrete choice set, as shown in KR.[1] The change in the property of UPE is driven by the change in the structure of the choice set: when the choice set contains only discrete strategies, the adjustment of reference in the UPE is likely to get stuck on some choice that is not globally optimal, yielding multiple UPE. In contrast, when the choice set contains the continuum of all possible strategies (as in the context of portfolio choice), the sub-optimal equilibria are easily disturbed, and the UPE converges to a unique strategy. This result thus enriches our understanding on the implications of UPE.

This paper is not the first attempt to connect KR's reference-dependent utility theory to Yarri's dual theory, or more broadly, Quiggin (1982)'s rank-dependent utility theory. Masatlioglu and Raymond (2016) focus on CPE and show in their Proposition 4 (p. 2767) that for any risky choice, if investors set the distribution of the choice as the reference, then their evaluation of the choice with the reference is equivalent to an evaluation with a concave probability weighting function.[2] One novelty of our paper is that we also study UPE, for which the equivalent probability weighting function is more difficult to observe because it arises only for the optimal choice. Moreover, we show that the equivalent probability weighting function for UPE is less concave than that for CPE, which is consistent with the prediction in Proposition 8 of KR that investors in UPE are less risk averse than in CPE.

2. The concept of UPE and CPE

We model investors' reference-dependent utility in the manner of KR. Let the investor's risky wealth be $\tilde{w}$ and her reference be $\tilde{r}$. For any realized outcome $\tilde{w} = w$, the investor gets an intrinsic consumption utility $u(w)$, and a gain–loss utility

$$E[\mathscr{R}(u(w) - u(\tilde{r}))|\tilde{w} = w]. \tag{1}$$

The gain–loss utility describes the feeling of the investor when she compares the wealth outcome with the reference $\tilde{r}$. Denote the cumulative distribution functions (cdfs) of $\tilde{w}$ and $\tilde{r}$ by F and G respectively. In KR, $\tilde{w}$ and $\tilde{r}$ are assumed to be independent, and the gain–loss utility is calculated by comparing an outcome w to every possible outcome of $\tilde{r}$.[3] The investor's expected reference-dependent utility is given by

$$E[v(\tilde{w}; \tilde{r})] = \int\int u(w) + \mathscr{R}(u(w) - u(r))dF(w)G(r), \tag{2}$$

where u is a concave von Neumann–Morgenstern utility function and $\mathscr{R}$ is a universal gain–loss value function. In a portfolio problem, the investor's risky wealth is

$$\tilde{w}(\alpha) = w_0 + \alpha\tilde{x}, \tag{3}$$

where w_0 is her initial wealth, $\tilde{x}$ is the net return of the risky asset, and α (≥ 0) is the investor's risky allocation.

In the rest of the paper, UPE is defined for the case where the stochastic outcome generated by utility maximization conditional on a reference coincides with the reference. CPE is defined for the case where a decision is committed to before outcomes realize, and hence determines both the reference and the outcome distributions.

Definition 1. For a reference-dependent utility maximizer who needs to select the optimal risky investment, we say her choice α^U achieves a UPE, if and only if

$$\alpha^U = \arg\max_{\{\alpha\geq 0\}} E\left[v\left(\tilde{w}(\alpha);\, \tilde{w}\left(\alpha^U\right)\right)\right].$$

We say her choice α^C achieves a CPE, if and only if

$$\alpha^C = \arg\max_{\{\alpha\geq 0\}} E\left[v\left(\tilde{w}(\alpha);\, \tilde{w}(\alpha)\right)\right].$$

3. Portfolio choice in UPE and CPE

To gain tractability, we follow KR and Masatlioglu and Raymond (2016) to assume a linear gain–loss function: $\mathscr{R}(x) = \eta x$ for $x \geq 0$ and $\mathscr{R}(x) = \lambda\eta x$ for $x < 0$, where $\eta > 0$ and $\lambda > 1$. Under this assumption, an analytically amenable expression of (2) is available[4] :

$$\begin{aligned}
E[v(\tilde{w}; \tilde{r})] &= E[u(\tilde{w}) + \eta(u(\tilde{w} \vee \tilde{r}) - u(\tilde{r})) + \eta\lambda(u(\tilde{w} \wedge \tilde{r}) - u(\tilde{r}))] \\
&= \int u(s)dP(\tilde{w} \leq s) + \eta \int u(s)dP(\tilde{w} \vee \tilde{r} \leq s) \\
&\quad + \eta\lambda \int u(s)dP(\tilde{w} \wedge \tilde{r} \leq s) \\
&\quad - \eta(1+\lambda) \int u(s)dP(\tilde{r} \leq s) \\
&= \int u(s)dF(s) + \eta \int u(s)d[F(s)G(s)] \\
&\quad + \eta\lambda \int u(s)d[F(s) + G(s) - F(s)G(s)] \\
&\quad - \eta(1+\lambda) \int u(s)dG(s) \\
&= \int u(s)d[F(s)(1 + \eta\lambda - \eta(\lambda - 1)G(s))] \\
&\quad - \eta \int u(s)dG(s).
\end{aligned} \tag{4}$$

Especially, when $\tilde{r} =^d \tilde{w}$, $F(s) = G(s)$ and (4) turns out to be

$$E[v(\tilde{w}; \tilde{w})] = \int u(w)d\varphi(F(w)), \tag{5}$$

[1] KR (p. 1056) recognized that "There can be multiple UPE in a given situation – there can be multiple self-fulfilling expectations – and generically different UPE yield different expected utilities".

[2] In their Proposition 4, Masatlioglu and Raymond (2016) translate the CPE into a convex distortion of decumulative distribution function. In our paper, we translate CPE into a concave distortion of cumulative distribution function. These two kinds of distortions are equivalent.

[3] The cross-state comparison basically builds on disappointment theory. De Giorgi and Post (2011) study the case where outcomes and stochastic reference are compared state by state.

[4] We use the notation $a \vee b = \max\{a, b\}$ and $a \wedge b = \min\{a, b\}$.

where $\varphi(q) = q[1 + \eta(\lambda - 1)(1 - q)]$. Expression (5) reproduces Proposition 4 of Masatlioglu and Raymond (2016), showing that for any risky prospect $\tilde{w}$, if investors set the distribution of $\tilde{w}$ as the reference, then their evaluation of $\tilde{w}$ with the reference is equivalent to an evaluation with a concave probability weighting function. Proposition 1 follows immediately from Eq. (5).

Proposition 1. *Let $\varphi(q) = q[1 + \eta(\lambda - 1)(1 - q)]$ and $\tilde{x}$ be continuously distributed with cdf F. The CPE of the portfolio choice problem is unique and satisfies*

$$\alpha^C = \arg\max_{\alpha \geq 0} \int u(w_0 + \alpha x) d\varphi(F(x)). \tag{6}$$

The equivalent probability weighting function for UPE, however, is less obvious. We summarize this result in Proposition 2.

Proposition 2. *Let $\psi(q) = q\left[1 + \frac{\eta(\lambda-1)}{2+\eta+\eta\lambda}(1 - q)\right]$ and $\tilde{x}$ be continuously distributed with cdf F. The UPE of the portfolio choice problem is unique and satisfies*

$$\alpha^U = \arg\max_{\alpha \geq 0} \int u(w_0 + \alpha x) d\psi(F(x)). \tag{7}$$

The right-hand sides of (6) and (7) are a special case of the rank-dependent utility model, which is first axiomatized by Quiggin (1982) and further developed by Yaari (1987). Since the weighting functions $\varphi, \psi : [0, 1] \to [0, 1]$ are onto, continuous and strictly concave, UPE and CPE display two dimensions of risk aversion: one is the diminishing marginal utility of wealth and the other is the dual risk aversion inherent in φ and ψ. Since φ' and ψ' are decreasing, the investor behaves pessimistically, as if bad outcomes were more likely than they really are and good outcomes were less likely than they really are. Notice that φ is concave, but not necessarily monotonically increasing (see Fig. 1 for an illustration). In particular, when $\eta(\lambda - 1) > 1$, which holds "whenever observed loss aversion is at least two-to-one—whenever overall sensitivity to losses, $1 + \eta\lambda$, is at least twice as high as overall sensitivity to gains, $1 + \eta$" (KR, footnote 20), φ is decreasing on the interval $\left(\frac{1+\eta(\lambda-1)}{2\eta(\lambda-1)}, 1\right)$. This property implies that the investor in CPE can even choose stochastically dominated options to reduce exposure to sensations of loss.

Propositions 1 and 2 demonstrate that UPE and CPE provide a mechanism to endogenize the concave probability weighting function, thereby can be linked to Yarri's dual theory. We complement Masatlioglu and Raymond (2016) by showing that in addition to CPE, UPE is also linked to the rank-dependent utility in the context of portfolio choice.

Importantly, we find that UPE is unique under our setting. This is of special interest because it suggests that the available choice set is critical in understanding investors' portfolio choices. When investors' choice set contains only finite allocation strategies, there can be multiple choices in UPE (KR, p. 1056). In contrast, when the investor has access to the continuum of all possible allocation strategies, she eventually obtains a unique optimal strategy after repeated updates of references in UPE.

To deal with the multiplicity in UPE, KR further defines the "preferred personal equilibrium" (PPE) as the UPE choice that maximizes the expected reference-dependent utility among all possible UPE choices (KR, p. 1056). Since a unique UPE implies that it must be the PPE, Proposition 2 implies that the PPE takes on the rank-dependent form as well.

Based on the concave probability weighting function, we are able to provide unambiguous comparative statics for the portfolio choice in personal equilibria.

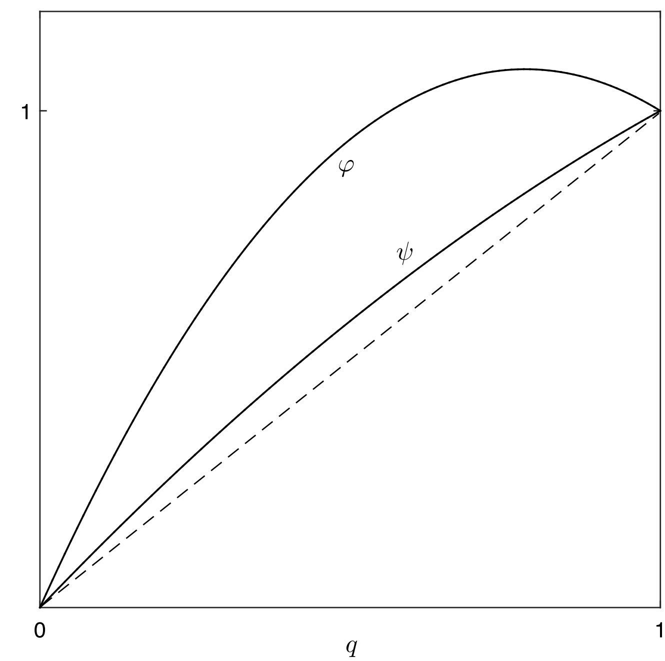

Fig. 1. A numerical illustration of φ and ψ [$\eta = 1, \lambda = 2.5$].

Corollary 1. *Other things being equal, the following comparative statics holds true:*
(i) $\alpha^C < \alpha^U$;
(ii) α^C *is decreasing in* λ *and* η;
(iii) α^U *is decreasing in* λ *and* η.

To understand (i), notice that φ is more concave than ψ in the sense that

$$-\frac{\varphi''}{\varphi'} > -\frac{\psi''}{\psi'} \quad \text{on } [0, 1]. \tag{8}$$

This amounts to saying that investors are more pessimistic in CPE than in UPE. Accordingly, given the same initial wealth and the same risky asset, an investor in CPE always invests less in the risky asset than the one in UPE. This result justifies the intuition that "people will be more risk averse when decisions are committed to well in advance than when people are uncommitted" (KR, p. 1060) in the context of portfolio choice. For (ii) and (iii), one can check that the concavity of the probability weighting function measured by $-\frac{\varphi''}{\varphi'}$ and $-\frac{\psi''}{\psi'}$ is increasing in λ and η, which indicates that the risk aversion inherent in the weighting function increases as loss aversion becomes more prominent.

4. Concluding remarks

With a piecewise linear gain–loss value function and a continuous choice set, we show that both UPE and CPE are unique, and an investor in both UPE and CPE behaves as if she had a concave probability weighting function. This finding suggests that personal equilibrium in combination with loss aversion provides a mechanism for the formation of a concave probability weighting function. In unreported results, we show that this result can be extended directly to a multi-period setting if personal equilibria are achieved in each step of the backward induction. An open question for future research is to seek a mechanism for the formation of non-concave or S-shaped probability weighting function in the context of personal equilibrium.

One reasonable conjecture to generalize the results is that the UPE is unique and has the rank-dependent utility form if the choice set is connected and convex. While this general analysis is beyond the scope of the current study, it seems to be a very valuable research avenue and can potentially shed light on certain new aspects in applications of KR as they may rely on some form of non-convexities.[5]

Empirically, UPE and CPE can be used to strengthen the explanatory power of loss aversion on the equity premium puzzle. Mehra and Prescott (1985) initiated this puzzle by arguing that the observed historical equity returns were too high, implying implausibly high risk-aversion coefficients employed in the asset allocation to achieve the observed 50–50 split between stocks and bonds. Benartzi and Thaler (1995) show that the observed equity premium is consistent with a moderate degree of loss aversion for an investment horizon of approximately 1 year. Their study assumes the reference point as the status quo, i.e., it uses zero capital gain as the reference level. Our estimates for personal equilibria show that α^U achieves 0.5 (50–50 split between stocks and bonds) with a horizon of approximate 5 months while α^C achieves 0.5 with a horizon slightly longer than 7 years. This result suggests that the observed asset allocation can be rationalized with personal equilibria for a wide range of investment horizons.[6] Further examination of the empirical relevance of the concave weighting function derived from personal equilibria presents a promising avenue for future research.

Acknowledgments

Lin Zhao acknowledges financial support from the National Center for Mathematics and Interdisciplinary Sciences, CAS, and National Science Foundation of China (Grant No. 71301161 and 71532013). Wei Zhu acknowledges financial support from the Humanity and Social Science Foundation of the Ministry of Education in China (No. 16YJA790072), Beijing Municipal Social Science Foundation (No. 17YJC039) and from the Fundamental Research Funds for the Central Universities in UIBE (CXTD8-03, 17YQ13).

Appendix

Proof of Proposition 2. Assume first that $\tilde{r} \equiv r$ is a constant. Then we have

$$\begin{aligned}
&E[v(w_0+\alpha\tilde{x};r)]\\
&=E[u(\tilde{w})+\eta(u(\tilde{w}\vee r)-u(r))+\eta\lambda(u(\tilde{w}\wedge r)-u(r))]\\
&=\int u(w_0+\alpha x)dF(x)+\eta\int_{\left[\frac{r-w_0}{\alpha},\infty\right)} u(w_0+\alpha x)dF(x)\\
&\quad+\eta u(r)F\left(\frac{r-w_0}{\alpha}\right)\\
&\quad+\eta\lambda\int_{\left(-\infty,\frac{r-w_0}{\alpha}\right]} u(w_0+\alpha x)dF(x)\\
&\quad+\eta\lambda u(r)\left(1-F\left(\frac{r-w_0}{\alpha}\right)\right)-\eta(1+\lambda)u(r).
\end{aligned}$$

For continuous $\tilde{x}$ with a density function f, simple calculus yields

$$\begin{cases}
\dfrac{d}{d\alpha}\displaystyle\int u(w_0+\alpha x)dF(x)=\int u'(w_0+\alpha x)xdF(x),\\
\dfrac{d}{d\alpha}\displaystyle\int_{\left[\frac{r-w_0}{\alpha},\infty\right)} u(w_0+\alpha x)dF(x)\\
\quad=\displaystyle\int_{\left[\frac{r-w_0}{\alpha},\infty\right)} u'(w_0+\alpha x)xdF(x)+u(r)\frac{r-w_0}{\alpha^2}f\left(\frac{r-w_0}{\alpha}\right),\\
\dfrac{d}{d\alpha}F\left(\dfrac{r-w_0}{\alpha}\right)=-\dfrac{r-w_0}{\alpha^2}f\left(\dfrac{r-w_0}{\alpha}\right),\\
\dfrac{d}{d\alpha}\displaystyle\int_{\left(-\infty,\frac{r-w_0}{\alpha}\right]} u(w_0+\alpha x)dF(x)\\
\quad=\displaystyle\int_{\left(-\infty,\frac{r-w_0}{\alpha}\right]} u'(w_0+\alpha x)xdF(x)-u(r)\frac{r-w_0}{\alpha^2}f\left(\frac{r-w_0}{\alpha}\right).
\end{cases}$$

Inserting the above into the first equation, we obtain

$$\begin{aligned}
&\frac{d}{d\alpha}E[v(w_0+\alpha\tilde{x};r)]\\
&\quad=\int u'(w_0+\alpha x)\left(1+\eta 1_{\{w_0+\alpha x\geq r\}}+\eta\lambda 1_{\{w_0+\alpha x\leq r\}}\right)xdF(x)\\
&\quad=\int u'(w_0+\alpha x)\left(1+\eta\lambda-\eta(\lambda-1)1_{\{w_0+\alpha x\geq r\}}\right)xdF(x).
\end{aligned}\tag{A.1}$$

When $\tilde{r}$ is random, with cdf given by G, we use (A.1) to deduce

$$\begin{aligned}
&\frac{d}{d\alpha}E[v(w_0+\alpha\tilde{x};\tilde{r})]=\frac{d}{d\alpha}\int E[v(w_0+\alpha\tilde{x};r)]dG(r)\\
&\quad=\int\int u'(w_0+\alpha x)\left(1+\eta\lambda-\eta(\lambda-1)1_{\{w_0+\alpha x\geq r\}}\right)xdF(x)dG(r)\\
&\quad=\int u'(w_0+\alpha x)\underbrace{[1+\eta\lambda-\eta(\lambda-1)G(w_0+\alpha x)]}_{\mathscr{D}(w_0+\alpha x;G)}xdF(x).
\end{aligned}\tag{A.2}$$

Recalling that $u''<0$ and $\mathscr{D}$ is nonincreasing, the term $u'(x)\mathscr{D}(x;G)$ in the right-hand side of (A.2) is nonincreasing, which justifies the second-order optimality condition. Therefore, given $\tilde{r}$, the optimal portfolio choice is determined by the first-order condition

$$\int u'(w_0+\alpha x)\mathscr{D}(w_0+\alpha x;G)xdF(x)=0.$$

Let α^R denote the reference allocation to the risky asset. Then, $\tilde{r}=w_0+\alpha^R\tilde{x}$, $G(x)=F\left((x-w_0)/\alpha^R\right)$ and

$$\mathscr{D}(w_0+\alpha x;G)=1+\eta\lambda-\eta(\lambda-1)F\left(\frac{\alpha}{\alpha^R}x\right).$$

The first-order optimality condition

$$\begin{aligned}
&\frac{d}{d\alpha}E[v(w_0+\alpha\tilde{x};w_0+\alpha^R\tilde{x})]\\
&=\int u'\left(w_0+\alpha x\right)\left(1+\eta\lambda-\eta(\lambda-1)F\left(\frac{\alpha}{\alpha^R}x\right)\right)xdF(x)=0
\end{aligned}\tag{A.3}$$

determines the optimal portfolio choice α^* as a function of α^R, i.e., $\alpha^*=\alpha^*(\alpha^R)$. By definition, UPE requires $\alpha_U^*=\alpha^*(\alpha^R)=\alpha^R$. Inserting this into (A.3), it follows that

$$\begin{aligned}
&\frac{d}{d\alpha}\Big|_{\alpha=\alpha_U^*}E[v(w_0+\alpha\tilde{x};w_0+\alpha_U^*\tilde{x})]\\
&=\int u'\left(w_0+\alpha_U^*x\right)(1+\eta\lambda-\eta(\lambda-1)F(x))xdF(x)\\
&=\frac{1}{2}(2+\eta+\eta\lambda)\int u'\left(w_0+\alpha_U^*x\right)xd\psi(F(x))=0.\qquad\square
\end{aligned}$$

[5] We thank an anonymous referee for pointing out this important question to us. In our analysis, we make use of two key properties of the portfolio choice problem to obtain the uniqueness of UPE and the rank-dependent form: (i) the choice set can be parameterized by a continuous parameter; (ii) the choice of the lottery can be determined by the first-order condition. Extending our findings to a general setting is possible if these two properties are still preserved in the new setting.

[6] We draw the historical data on monthly returns of the 10-year U.S. Treasury bond (Bonds) and the Standard and Poor's 500 stock market index (Stocks) from April 1953 to December 2011 (705 observations). We capture consumption utility with the logarithmic utility function $u(w)=\ln(1+w)$ and gain–loss utility with a piecewise linear function. The parameters used for our calibration are $\lambda=2.5$ and $\eta=1$.

Proof of Corollary 1. To prove this corollary, we first present a lemma.

Lemma A.1. *Let $\varphi : [0,1] \to [0,1]$ be a differentiable concave function with $\varphi(0) = 0$ and $\varphi(1) = 1$. For any cdf F, there is*

$$\int_{(-\infty,x]} td\varphi(F(t)) \leq \varphi'(F(0)) \int_{(-\infty,x]} tdF(t) \quad \text{for all } x.$$

In the terminology of Gollier (1995), the random variable with cdf F dominates the random variable with cdf $\varphi(F)$ in terms of central riskiness.

Observe that

$$\int_{(-\infty,x]} td\varphi(F(t)) - \varphi'(F(0)) \int_{(-\infty,x]} tdF(t)$$
$$= \int_{(-\infty,x]} t(\varphi'(F(t)) - \varphi'(F(0)))dF(t).$$

Lemma A.1 follows directly from the fact that $t(\varphi'(F(t)) - \varphi'(F(0))) \leq 0$ for all t.

To prove (i), in view of (8), there is a concave function $\zeta : [0,1] \to [0,1]$ such that $\varphi = \zeta(\psi)$, $\zeta(0) = 0$ and $\zeta(1) = 1$. By Lemma A.1 and Gollier (1995), we obtain $\alpha_C^* < \alpha_U^*$. The proofs for (ii) and (iii) are similar. □

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