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On the Existence of Strategic Solutions for Games with Security- and Potential Level Players

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On the Existence of Strategic Solutions for Games with Security- and Potential Level Players[*]

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Abstract

This paper examines the existence of strategic solutions for finite normal form games under the assumption that strategy choices can be described as choices among lotteries where players have *security- and potential level preferences* over lotteries (e.g., Gilboa, 1988; Jaffray, 1988; Cohen, 1992). Since security- and potential level preferences require discontinuous utility representations, standard existence results for *Nash equilibria in mixed strategies* (Nash, 1950a,b) or for *equilibria in beliefs* (Crawford, 1990) do not apply. As a key insight this paper proves that non-existence of equilibria in beliefs, and therefore non-existence of Nash equilibria in mixed strategies, is possible in finite games with security- and potential level players. But, as this paper also shows, *rationalizable strategies* (Bernheim, 1984; Moulin, 1984; Pearce, 1984) exist for such games. Rationalizability rather than equilibrium in beliefs therefore appears to be a more favorable solution concept for games with security- and potential level players.

JEL Classification Numbers: C72, D81.

Keywords: Non-expected utility theories, Allais paradoxa, equilibrium in beliefs, Nash equilibrium, trembling hand perfect equilibrium, rationalizability

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1 Introduction

Nash (1950a,b) proves existence of mixed strategy equilibria in finite games. Following von Neumann and Morgenstern (1947) Nash presumes, first, that a player's best response can be described as a preference maximizing choice over a set of lotteries, and second, that these preferences are representable by an expected utility functional. Subsequently, several non-expected utility models of decision making have been developed either motivated by plausibility considerations (e.g., lexicographic expected utility theory in Hausner, 1954), or by observed violations of expected utility theory in experimental situations of decision making (e.g., Allais, 1953; Ellsberg, 1961; for an overview see, e.g., Karni and Schmeidler, 1991; Starmer, 2000; Schmidt, 2003).

This paper explores existence of equilibria and existence of rationalizable strategies (Bernheim, 1984; Moulin, 1984; Pearce, 1984), in finite games with mixed strategy sets under the assumption that players' best responses are described as preference maximizing choices of lotteries[1] such that players have so-called *security and potential level preferences* (Gilboa, 1988; Jaffray, 1988; Cohen, 1992; Essid, 1997; Schmidt and Zimper, 2003). Models of security and potential level preferences are generalizations of expected utility theory that explain Allais paradoxa by discontinuities in preferences arising from different security- or potential levels associated with lotteries. My investigation adopts Cohen's (1992) approach who defines a lottery's security level as worst and its potential level as best outcome in the lottery's support. According to this approach a *security effect* describes a discontinuous upward jump in a lottery's utility evaluation if the probability of a bad outcome drops to zero. Similarly, a *potential effect* describes a discontinuous downward jump in case the probability of a good outcome drops to zero.

Crawford (1990) also investigates existence of equilibria in finite games for players with non-expected utility preferences over lotteries. He shows that, although mixed strategy Nash equilibria may not exist in finite games, existence of so-called *equilibria in beliefs* can be established if players' preferences are representable by continuous utility functions. Key to Crawford's result is the observation that existence of Nash equilibria only fails for continuous utility functions if the best response correspondence is not convex-valued (which may be the case for randomization-averse players). Since an *equilibrium in beliefs* is defined as a fixed point of a convex-valued *beliefs over best-responses* correspondence, *equilibria in beliefs* exist for all continuously representable non-expected

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[1] Game theoretic models applying non-expected utility theories of choice under uncertainty, thereby reacting to paradoxa of the Ellsberg-type, assume either *non-additive beliefs*, i.e., *capacities*, (Dow and Werlang, 1994, Ghirardato and Le Breton, 1997 and 2000; Eichberger and Kelsey, 2000) based on Schmeidler (1989); or multi-prior models (Lo, 1995, Klibanoff, 1996) based on Gilboa and Schmeidler (1989).

utility preferences.

For players with security- and potential preferences, so-called SL,PL-players, the resulting discontinuous utility representation prevents an application of Crawford's existence results. Moreover, results of Dasgupta and Maskin (1989) establishing existence of Nash equilibria for discontinuous utility functions are not applicable either. This paper first proves the existence of rationalizable strategies - despite possible non-existence of best responses to some beliefs. Second, this paper shows that equilibria, even defined as *equilibria in beliefs*, may not exist for games with SL,PL-players. A third result states conditions implying existence of Nash equilibria in mixed strategies under the assumption that only potential but no security effects occur. This existence result is technically interesting because it guarantees existence of a fixed point under conditions preventing an application of Kakutani's fixed point theorem. Finally, existence of *trembling hand perfect equilibria* (Selten, 1975) and of *proper equilibria* (Myerson, 1978) is demonstrated. However, since these equilibria are not necessarily Nash equilibria, this existence result is, in my opinion, only of limited value.

The remainder of this paper is organized as follows. Section 2 motivates security- and potential level preferences. Section 3 recalls Cohen's (1992) utility representation of security- and potential level preferences, and section 4 lists relevant technical properties of security- and potential level preferences. Section 5 introduces SL,PL-players to finite games with mixed-strategy sets. Existence of rationalizable strategies in games with SL,PL-players is proved in section 6. Section 7 demonstrates possible non-existence of *equilibria in beliefs*. Furthermore, a restricted existence result for Nash equilibria in mixed-strategies is presented. Section 8 shows and interprets the existence of trembling hand perfect equilibria (Selten, 1975) and of proper equilibria (Myerson, 1978) in games with SL,PL-players regardless whether Nash equilibria exist or not. Section 9 concludes. Formal proofs are relegated to the appendix.

2 Security- and Potential Level Preferences: A Motivating Example

A well-known study on the psychology of decision making under risk by Lopes (1987) identifies three different factors a decision maker takes into account when evaluating lotteries: the expected utility of a lottery, the worst possible outcome of a lottery, i.e., the lottery's security level, and the best possible outcome of a lottery, i.e., the lottery's potential level. This conclusion motivated Cohen (1992) to develop a three-criteria decision model which generalizes expected utility by allowing for security level and potential level considerations.

Essid (1997) generalizes Cohen's model to non-finite outcome sets. Schmidt and Zimper (2003) introduce possible thresholds in the perception of security- and potential levels such that a small likelihood of a bad or of a good outcome does not necessarily influence the security, respectively potential, level of a lottery. Earlier models of Gilboa (1988) and Jaffray (1988) are very similar to Cohen's model but restrict attention to the security level alone. In contrast to alternative generalizations of expected utility theory, e.g., *models with the betweenness-property* (e.g., Chew, 1989; Gul, 1991), or *models of rank dependent utility* (e.g., Quiggin, 1982; Green and Julien, 1989; Segal, 1989 and 1993; Quiggin and Wakker, 1994), all security- and potential level models explain Allais paradoxa by discontinuities of preferences resulting from the different security- and potential levels of the lotteries involved.

In what follows a choice situation is described such that plausible preferences can be accommodated by security- and potential level models but not by any alternative generalization of expected utility theory I am aware of.

Consider a *pre-emptive strike* decision situation such that decision maker B may either *destroy* or *distribute* weapons of mass destruction in the nearer future while decision maker A can either keep *peace* or wage *war* in order to prevent *distribution* of WMD. Assume the following payoffs of A

		B will destroy	*B will distribute*
A	*peace*	2	0
	war	1	1

Suppose that A very strongly evaluates security such that *she does not take any chances*, that is, she strictly prefers *war* to *peace* whenever she believes there is a positive chance that B will *distribute*, i.e., for all $\beta > 0$

$$1 \cdot 1 \succ_A (1-\beta) \cdot 2 \oplus \beta \cdot 0 \tag{1}$$

where $\beta \in [0,1]$ denotes A's belief that B will *distribute*. These preferences are not representable by any continuous utility function. However, they can be represented by *lexicographic expected utility theory* (Hausner, 1954) as well as by security- and potential level models.

Now extend this *pre-emptive strike* decision situation by assuming that A somehow becomes aware of the possibility that B did *already distribute* WMD.

		B will destroy	*B will distribute*	*B did already distribute*
A	*peace*	2	0	0
	war	1	1	0

Suppose then A believes *with chance 0.1 B did already distribute WMD*, whereas the perceived chances that B *will distribute*, (respectively *destroy*), are 0.09, (respectively 0.81). Given these beliefs, A prefers *peace* if and only if

$$0.81 \cdot 2 \oplus 0.19 \cdot 0 \succeq_A 0.9 \cdot 1 \oplus 0.1 \cdot 0 \tag{2}$$

Under this situation, preferring *peace* while at the same time having preferences satisfying (1), an Allais paradox is committed by violation of the so-called independence axiom. To see this, substitute $\beta = 0.9$ in (1) and rewrite (2) to obtain

$$\begin{aligned} 1 \cdot 1 &\succ_A 0.9 \cdot 2 \oplus 0.1 \cdot 0 \\ 0.9 \cdot (0.9 \cdot 2 \oplus 0.1 \cdot 0) \oplus 0.1 \cdot 0 &\succeq_A 0.9 \cdot (1 \cdot 1) \oplus 0.1 \cdot 0 \end{aligned}$$

Allais paradoxa are very common deviations from expected utility theory in experimental situations of decision making under risk. In contrast to *lexicographic expected utility theory*, security- and potential level models may be able to accommodate Allais paradoxa because they do not have to satisfy the independence axiom.

To sum up, preferences satisfying (1) and (2) are neither representable by continuous non-expected utility theories nor by lexicographic expected utility theory. Are these preferences plausible? Yes, since they just presume decision makers *who do not take chances* and who commit Allais paradoxa. In the following section it is demonstrated how security- and potential level models can easily accommodate preferences satisfying (1) and (2) by a so-called *security effect*.

3 Utility Representation of Security- and Potential Level Preferences

Let $X = \{x_1, ..., x_n\}$ denote a finite set of totally ordered deterministic outcomes with $x_1 < ... < x_n$, and let $\triangle(X)$ denote the set of probability distributions, i.e., lotteries, over X. A lottery $\sigma \in \triangle(X)$ is also written as $(\sigma_1 \cdot x_1 \oplus ... \oplus \sigma_n \cdot x_n)$ where σ_k denotes the probability of the realization of outcome x_k. Throughout this paper *reduction of compound lotteries* is assumed, i.e., a compound lottery $(\mu \cdot \sigma \oplus (1 - \mu) \cdot \tau)$, with $\sigma, \tau \in$

$\triangle(X)$, is considered equivalent to the lottery

$$(\mu\sigma_1 + (1-\mu)\,\tau_1 \cdot x_1 \oplus ... \oplus \mu\sigma_n + (1-\mu)\,\tau_n \cdot x_n)$$

Let $\triangle(x,y)$ denote the subset of $\triangle(X)$ that contains all lotteries σ such that x is the worst and y is the best outcome in the support of σ, i.e., $\sigma \in \triangle(x,y)$ if and only if $x = \min \mathit{Support}(\sigma)$ and $y = \max \mathit{Support}(\sigma)$. Denote by $V : \triangle(X) \times X \times X \to \mathbb{R}_+$ a function such that, for all $\sigma \in \triangle(X)$ and all $x, y \in X$ with $x \leq y$,

$$V(\sigma, x, y) = b(x,y) + a(x,y) \sum_{k=1}^{n} \sigma(x_k)\, u(x_k) \tag{3}$$

where $a : X \times X \to \mathbb{R}_+$, $b : X \times X \to \mathbb{R}_+$, and $u : X \to \mathbb{R}_+$, $u(x_{k+1}) > u(x_k)$ for $k = 1, ..., n-1$. The following definition of an utility representation for security- and potential level preferences is equivalent to the utility representation derived in Cohen (1992) and it reduces to the utility representations of Gilboa (1988) and of Jaffray (1988) if, for all $x, y, \bar{y} \in X$ with $\bar{y} \geq y$, $b(x, \bar{y}) = b(x,y)$ and $a(x,\bar{y}) = a(x,y)$.[2]

Definition: *Consider a decision maker with preferences over* $\triangle(X)$ *that are representable by a utility function* $U : \triangle(X) \to \mathbb{R}_+$ *such that, for all* $\sigma \in \triangle(x,y)$ *and all* $x, y \in X$ *with* $x \leq y$,

$$U(\sigma) = V(\sigma, x, y) \tag{4}$$

for some function V *defined by (3). The decision maker has* security- and potential level preferences over $\triangle(X)$ *if, for all* $\sigma \in \triangle(x,y)$ *and all* $x, y, \bar{x}, \bar{y} \in X$ *with* $\bar{x} \geq x$ *and* $\bar{y} \geq y$,

$$U(\sigma) \leq V(\sigma, \bar{x}, \bar{y}) \tag{5}$$

Observe that $U(\sigma)$ results from adding $b(x,y)$ to the expected utility $\sum_{k=1}^{n} \sigma(x_k)\, u(x_k)$ of lottery σ multiplied by $a(x,y)$ where the numbers $a(x,y)$ and $b(x,y)$ depend on the security level x and the potential level y of lottery σ. Condition (5) assures that the evaluation of lotteries increases with increasing security- and potential levels and it is, e.g., satisfied if, for all $x, y, \bar{x}, \bar{y} \in X$ with $\bar{x} \geq x$ and $\bar{y} \geq y$, $b(x,y) \leq b(\bar{x}, \bar{y})$ and $a(x,y) \leq a(\bar{x}, \bar{y})$.

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[2] On the axiomatic level security- and potential level models assume that the expected utility axioms remain valid for lotteries with identical security- and potential levels whereas a violation of the independence axiom or of the continuity assumption may occur when lotteries with different security - or potential levels are involved; (for detailed axiomatic foundations see, e.g., Cohen, 1992; Schmidt and Zimper, 2003).

Except for the trivial case where security- and potential preferences reduce to expected utility preferences, i.e., for all $x, y, \bar{x}, \ \bar{y} \in X$ with $\bar{x} \geq x$ and $\bar{y} \geq y$,

$$b(\bar{x}, \bar{y}) = b(x, y) \text{ and } a(\bar{x}, \bar{y}) = a(x, y)$$

the utility representation U is discontinuous. These discontinuities can further be distinguished into *security-* and *potential effects.* A *security effect* occurs if there are security levels $\bar{x}$ and x, with $\bar{x} > x$, such that, for some $\sigma \in \triangle(x, y)$,

$$U(\sigma) < V(\sigma, \bar{x}, \ y)$$

That is, if every open neighborhood around a secure lottery $\bar{\sigma} \in \triangle(\bar{x}, y)$ contains insecure lotteries $\sigma \in \triangle(x, y)$ then there exists some neighborhood around $\bar{\sigma}$ such that $\bar{\sigma}$ is strictly preferred to all insecure lotteries in this neighborhood.

Accordingly, a *potential effect* occurs if there are potential levels $\bar{y}$ and y, with $\bar{y} > y$, such that, for some $\sigma \in \triangle(x, y)$,

$$U(\sigma) < V(\sigma, x, \ \bar{y})$$

i.e., a low potential lottery $\sigma \in \triangle(x, y)$ is inferior to all high potential lotteries $\bar{\sigma} \in \triangle(x, \bar{y})$ in some neighborhood of σ.

In the *pre-emptive strike* decision situation A wants to wage *war* as long as this strategy surely avoids the worst-case scenario *distribution of WMD.* However, once she comes to believe that the worst-case scenario has already become possible anyway - independent of her strategy choice - she goes for *peace.* These preferences are easily accommodated by assuming a sufficiently strong *security effect:* to satisfy condition (1) and (2) just let $u(x_k) = x_k$ for $x_k \in \{0, 1, 2\}$, and $b(x, y) = 0$, $a(2, y) = a(1, y) = 2$, $a(0, y) = 1$ for all $x, y \in X$ with $x \leq y$.

4 Properties of Security- and Potential Level Preferences

Specific technical properties of security- and potential level preferences are relevant for the existence of strategic solutions for games with SL,PL-players. Note that security- and potential level preferences satisfy *monotonicity with respect to first order stochastic dominance* (see, e.g., Cohen, 1992; Schmidt and Zimper, 2003). That is, for all $\sigma, \tau \in \triangle(X)$: $U(\sigma) \geq U(\tau)$ if $F[\sigma](x) \leq F[\tau](x)$ for all $x \in X$ where $F[\sigma]$ denotes the cumulative distribution function of σ.

Quasiconvex utility representations U, i.e., for all $\sigma, \tau \in \triangle(X)$

$$\begin{aligned} U(\sigma) &> U(\tau) \Rightarrow U(\sigma) > U(\lambda \cdot \sigma \oplus (1-\lambda) \cdot \tau) \text{ for } \lambda \in (0,1) \\ U(\sigma) &= U(\tau) \Rightarrow U(\sigma) \geq U(\lambda \cdot \sigma \oplus (1-\lambda) \cdot \tau) \text{ for } \lambda \in (0,1) \end{aligned}$$

characterize *randomization-averse* decision makers. In contrast, quasiconcave U, i.e., for all $\sigma, \tau \in \triangle(X)$

$$\begin{aligned} U(\sigma) &> U(\tau) \Rightarrow U(\lambda \cdot \sigma \oplus (1-\lambda) \cdot \tau) > U(\tau) \text{ for } \lambda \in (0,1) \\ U(\sigma) &= U(\tau) \Rightarrow U(\lambda \cdot \sigma \oplus (1-\lambda) \cdot \tau) \geq U(\tau) \text{ for } \lambda \in (0,1) \end{aligned}$$

describe *randomization-prone* decision makers. Recall that quasiconvex utility representations U may imply non-convex sets

$$\arg\max_{\triangle(Y)} U \text{ with } \triangle(Y) \subset \triangle(X) \tag{6}$$

of utility maximizing lotteries, which is not the case for quasiconcave U.

Further, recall that upper-semicontinuous U, i.e., for all sequences $\{\sigma_n\}_{n \in N} \subset \triangle(X)$ such that $\lim_{n \to \infty} \sigma_n = \sigma$

$$\limsup_{n \to \infty} U(\sigma_n) \leq U(\sigma)$$

imply non-empty sets (6) of utility maximizing lotteries for all compact $\triangle(Y) \subset \triangle(X)$, $\triangle(Y) \neq \emptyset$. In contrast, lower-semicontinuity of U, i.e., for all sequences $\{\sigma_n\}_{n \in N} \subset \triangle(X)$ such that $\lim_{n \to \infty} \sigma_n = \sigma$

$$\liminf_{n \to \infty} U(\sigma_n) \geq U(\sigma)$$

might induce empty sets (6) of utility maximizing lotteries for compact $\triangle(Y) \subset \triangle(X)$, $\triangle(Y) \neq \emptyset$.

The following properties of Cohen's (1992) utility representation for security- and potential level preferences are easily verified.

Observation 1.

If there do not occur any potential effects then U is quasiconvex and upper-semicontinuous. If there do not occur any security effects then U is quasiconcave and lower-semicontinuous.

For example, if some high potential lottery is inferior to some low potential lottery a sequence of high potential lotteries can be constructed which converges to a low potential lottery such that each lottery in this sequence is strictly preferred to all preceding lotteries. A *potential effect* then leads to a drop in the utility at the limit point of the sequence, implying that there does not exist a preference maximizing lottery for some non-empty, compact subset of $\triangle(X)$.

5 Games with Security- and Potential Level Players

For a finite set of players $I = \{1, ..., m\}$ let S_i denote the finite, non-empty set of pure-strategies of player $i \in I$. If a pure-strategy profile $s \in S = \times_{i \in I} S_i$ is played each player $i \in I$ receives a deterministic payoff in $X = \{x_1, ..., x_n\}$ according to some outcome map $x^i : S \to X$. A mixed-strategy σ_i of player $i \in I$ is an additive probability measure over S_i, i.e., $\sigma_i \in \triangle(S_i)$, and the set of mixed-strategy profiles, i.e., $\times_{i \in I} \triangle(S_i)$, is abbreviated as $\triangle^{mix}(S)$. Throughout this paper it is assumed that every player $i \in I$ may play arbitrary non-degenerated mixed-strategies by means of some appropriate random device.

Suppose each player $i \in I$ resolves her uncertainty about her opponents' mixed-strategy choice by some additive *belief* β_i with finite support on her opponents' mixed strategy profiles, i.e., $\beta_i \in \triangle^{fin}\left(\triangle^{mix}(S_{-i})\right)$ where $\triangle^{fin}\left(\triangle^{mix}(S_{-i})\right)$ denotes the set of all additive probability measures with finite support on $\triangle^{mix}(S_{-i}) = \times_{j \neq i} \triangle(S_j)$. The following definition includes this paper's central assumption of how a decision maker's preferences over lotteries determine her preferences over mixed-strategy choices when she is a player in some strategic situation who has a belief about the mixed-strategy choices of her opponents.

Definition. *Let each player $i \in I$ have preferences over lotteries in $\triangle(X)$ representable by some utility function $U_i : \triangle(X) \to \mathbb{R}_+$. Then $G = (\triangle(S_i), U_i)_{i \in I}$ denotes a* finite game in normal form *where, for all $i \in I$ and all $(\sigma_i, \beta_i) \in \triangle(S_i) \times \triangle^{fin}\left(\triangle^{mix}(S_{-i})\right)$, the utility $U_i(\sigma_i, \beta_i)$ of choosing mixed-strategy σ_i - while believing β_i - is given as utility $U_i(\sigma)$ of choosing lottery*

$$\sigma = (\sigma(x_1) \cdot x_1 \oplus ... \oplus \sigma(x_n) \cdot x_n) \in \triangle(X)$$

such that, for all $x_k \in X$,

$$\sigma(x_k) = \sum_{\{(s_i, s_{-i}) \mid x^i(s_i, s_{-i}) = x_k\}} \sigma_i(s_i) \sum_{\sigma_{-i} \in Support(\beta_i)} \beta_i(\sigma_{-i}) \sigma_{-i}(s_{-i}) \tag{7}$$

Moreover, if all players $i \in I$ have security- and potential level preferences over $\triangle(X)$ then $G = (\triangle(S_i), U_i)_{i \in I}$ is called a game with SL,PL-players.

Condition (7) states that if player $i \in I$ chooses the mixed-strategy σ_i, while she believes β_i, she expects to receive outcome x_k with probability $\sigma(x_k)$ such that her perceived probabilities of all pure-strategy profiles (s_i, s_{-i}) giving outcome x_k are summed up. Furthermore, according to the reduction assumption for compound lotteries, player i calculates the probability that s_{-i} realizes by summing up her believed probabilities that mixed-strategies profiles σ_{-i} are played times the probability that s_{-i} realizes when σ_{-i} is played.

Given $G = (\triangle(S_i), U_i)_{i\in I}$ the *individual best response correspondence* in mixed-strategies of player $i \in I$ is defined as the map $f_i : \triangle^{fin}\left(\triangle^{mix}(S_{-i})\right) \rightarrow 2^{\triangle(S_i)}$ such that $f_i(\beta_i)$ collects player i's mixed-strategies that are best responses to her belief β_i, that is

$$f_i(\beta_i) = \arg\max_{\triangle(S_i)} U_i(\sigma_i, \beta_i)$$

For degenerated beliefs $\beta_i \in \triangle(S_{-i})$, assigning probability one to some mixed-strategy profile $\sigma_{-i} \in \times_{j\neq i}\triangle(S_j)$, the individual best response correspondence reduces to a map $f_i : \triangle^{mix}(S_{-i}) \rightarrow 2^{\triangle(S_i)}$ such that $f_i(\sigma_{-i})$ collects player i's mixed-strategies that are best responses to her opponents' mixed-strategy profile σ_{-i}.

For any game $G = (\triangle(S_i), U_i)_{i\in I}$ with SL,PL-players define the game

$$G^{EU} = (\triangle(S_i), V_i(\cdot, x_1, x_n))_{i\in I}$$

that is, each lottery is evaluated by players of G^{EU} as if it was evaluated by players of G at the lowest security and the highest potential level, i.e., for all $\sigma \in \triangle(S)$

$$V_i(\sigma, x_1, x_n) = b(x_1, x_n) + a(x_1, x_n)\sum_{k=1}^{n}\sigma(x_k)\, u(x_k) \tag{8}$$

By construction, players of G^{EU} are expected utility maximizers who have the same preferences over pure-strategy profiles as the SL,PL-players of G. A game G with SL,PL-players is therefore identical with the according game G^{EU} but for players' preferences over non-degenerated lotteries.

Recall the definition of a Nash equilibrium in mixed-strategies, σ^*, of a game $G = (\triangle(S_i), U_i)_{i\in I}$ as a fixed point of the best response correspondence $f = \times_{i\in I} f_i$, with $f_i : \triangle^{mix}(S_{-i}) \rightarrow 2^{\triangle(S_i)}$, i.e., $\sigma^* \in f(\sigma^*)$. Since security- and potential level preferences satisfy monotonicity with respect to first order stochastic dominance it immediately follows:

Observation 2. *The pure-strategy profile $s^* \in S$ is a Nash equilibrium of a game $G = (\triangle(S_i), U_i)_{i\in I}$ with SL,PL-players if and only if s^* is a Nash equilibrium of the game $G^{EU} = (\triangle(S_i), V_i(\cdot, x_1, x_n))_{i\in I}$ where $V_i(\cdot, x_1, x_n)$ is defined by (8).*

Observation 2 implies that only Nash equilibria in non-degenerated mixed-strategies might not exist when the assumption of expected utility maximizing players is generalized to the assumption of SL,PL-players.

6 Rationalizable Strategies

Equilibrium concepts, on the one hand, and rationalizability concepts, on the other hand, represent two different approaches towards solution concepts for strategic games, i.e., of predicting how individuals will decide in a situation of strategic interdependency. The equilibrium approach claims that any solution has to be a Nash equilibrium such that each player of the game chooses a strategy that is a best response against the strategies chosen by her opponents. The rationalizability approach (Bernheim, 1984; Moulin, 1984; Pearce, 1984) starts out with the assumption that players only choose best responses to some belief. This assumption may effectively eliminate some - *unreasonable* - strategies and in a next step rationalizability requires the players to choose only best responses to beliefs over the remaining strategy choices of her opponents. Repeating this argument gives in the limit the set of correlated rationalizable strategies.

This process of *iterated elimination of strategies which are not best responses* can be understood as a formal description of a player's internal process of reasoning under the epistemic assumption that it is *common knowledge of the players that only best responses are chosen* (see Pearce 1984, Tan and Werlang 1988, Guesnerie 2002). Note that every Nash equilibrium is a correlated rationalizable strategy profile whereas the converse statement is not true.

Definition. *The set of correlated rationalizable mixed-strategy profiles of a game* $G = (\triangle(S_i), U_i)_{i\in I}$ *is given by* $R(G) = \bigcap_{k=0}^{\infty} \nu^k$ *such that* $\nu^k = \times_{i\in I}\nu_i^k$ *with*

$$\nu_i^k = \bigcup_{\beta_i \in \triangle^{fin}\left(\nu_{-i}^{k-1}\right)} f_i(\beta_i)$$

and $\nu_{-i}^0 = \triangle^{mix}(S_{-i})$.

Proposition 1. *For every game* $G = (\triangle(S_i), U_i)_{i\in I}$ *with SL,PL-players there exists a correlated rationalizable mixed-strategy profile.*

Remark. Existence of rationalizable strategies holds despite possible non-existence of best responses in mixed-strategies to some beliefs caused by lower-semicontinuous utility functions in the case of *potential effects*. The proof of proposition 1 exploits the fact that security- and potential level preferences satisfy monotonicity with respect to first order stochastic dominance by showing that there always exist pure-strategies among the best responses to degenerated probability-one beliefs, i.e., to pure-strategies. For this argument to work, it is crucial that pure-strategy profiles result in deterministic payoffs. The following example shows that existence of correlated rationalizable mixed-strategy profiles is not any longer guaranteed for games with SL,PL-players if pure strategy-profiles may result in stochastic payoffs.

Example: Suppose $X = \{0, 1, 2\}$ and let $\sigma = (0.5 \cdot 0 \oplus 0.5 \cdot 2) \in \triangle(X)$. Consider a game with two players, A and B, such that player A's payoffs are given as follows:

		B
		b
A	$a1$	σ
	$a2$	1

i.e., player A receives lottery $(0.5 \cdot 0 \oplus 0.5 \cdot 2)$ if pure-strategy profile $(a1, b)$ is played. Let player A have security- and potential level preferences such that $u(0) = 0$, $u(1) = 1.5$, $u(2) = 2$, $b(x, y) = 0$ for all $x \leq y$, and

$$\begin{aligned} a(2,2) &= a(1,2) = a(0,2) = 1.5 \\ a(0,0) &= a(0,1) = a(1,1) = 1 \end{aligned}$$

By a potential effect, there does not exist a mixed-strategy as A's best response to B's single strategy b since, for all $0 \leq \lambda < \mu < 1$,

$$U_A((1-\lambda) \cdot \sigma \oplus \lambda \cdot 1) < U_A((1-\mu) \cdot \sigma \oplus \mu \cdot 1)$$

whereas, for all $0 < \mu < 1$,

$$U_A(1) < U_A((1-\mu) \cdot \sigma \oplus \mu \cdot 1)$$

Thus, player A's utility strictly increases as the probability of pure strategy $a1$ increases in a non-degenerated mixed-strategy. However, if strategy $a1$ is played with probability one the utility sharply drops because the possibility of obtaining outcome 2 has vanished. Obviously, there does not exist a rationalizable mixed-strategy profile for this game.

7 Equilibria

7.1 Equilibria in Beliefs

For a finite game $G = (\triangle(S_i), U_i)_{i \in I}$ with utility functions U_i that are continuous on $\triangle^{mix}(S)$ and quasiconcave on $\triangle(S_i)$ for all $i \in I$, existence of Nash equilibria in mixed-strategies is guaranteed by Kakutani's fixed point theorem which establishes existence of a fixed point of a non-empty, convex-valued upper-hemicontinuous correspondence from a compact and convex subset of $\mathbb{R}^n$, as, e.g., $\triangle^{mix}(S)$, into its powerset. By Berge's maximum theorem (Berge, 1997) continuity of U_i, $i \in I$, implies upper-hemicontinuity and non-emptiness of the best-response correspondence f while quasiconcavity of U_i, $i \in I$, implies convex values of f (compare Theorem 1 in Dasgupta and Maskin, 1986).

Consequently, Nash equilibria in mixed-strategies exist in finite games $G = (\triangle(S_i), U_i)_{i \in I}$ if preferences over lotteries are continuously representable by quasiconcave utility functions. This existence result encompasses as special case Nash's existence result for expected utility maximizing players (Nash, 1950a,b) while it also applies to randomization-prone players who violate the independence axiom of expected utility theory but not the continuity assumption.

However, as Crawford (1990) observes, if not all players are randomization-prone then existence of Nash equilibria in mixed-strategies may fail in finite games. As a remedy, Crawford (1990) introduces the concept of *equilibria in beliefs* - for two-player games only. He proves that there always exist *equilibria in beliefs* for finite two-player games if players' preferences over lotteries are continuously representable. Crawford's existence result is quite powerful because, given a continuous utility representation, it holds for any kind of violation of the independence axiom. In what follows I define an *equilibrium in beliefs* for finite m-player games and I sketch the proof of existence.

Definition. *An* equilibrium in beliefs *of a game $G = (\triangle(S_i), U_i)_{i \in I}$ is an m-tupel $(\gamma_1, ..., \gamma_m)$ such that, for all $i \in \{1, ..., m\}$,*

(i) $\gamma_i \in \triangle^{fin}(\triangle(S_i))$ is the identical belief of all players $j \neq i$ about player i's mixed-strategy choice and

(ii) player i's mixed-strategies in the support of γ_i are best responses to her belief $\beta_i = \times_{j \neq i} \gamma_j$.

Define the map $g_i : \triangle^{fin}\left(\triangle^{mix}(S_{-i})\right) \rightarrow 2^{\triangle^{fin}(\triangle(S_i))}$ such that $g_i(\beta_i)$ collects all finite additive probability measures over player i's best responses to belief β_i, i.e.

$$g_i(\beta_i) = \triangle^{fin}\left\{\arg\max_{\sigma_i \in \triangle(S_i)} U_i(\sigma_i, \beta_i)\right\} \tag{9}$$

and call $g = \times_{i \in I} g_i$ the *beliefs over best-responses correspondence* of game $G = (\triangle(S_i), U_i)_{i \in I}$.

Observation 3: $\gamma^* \in \times_{i \in I} \triangle^{fin}(\triangle(S_i))$ *is an* equilibrium in beliefs *of game $G = (\triangle(S_i), U_i)_{i \in I}$ if and only if γ^* is a fixed point of the beliefs over best-responses correspondence, i.e., $\gamma^* \in g(\gamma^*)$.*

By the reduction assumption for compound lotteries, i.e., $\triangle^{fin}(\triangle(S_i)) = \triangle(S_i)$, the *beliefs over best-responses correspondence* $g : \times_{i\in I} \triangle^{fin}(\triangle(S_i)) \to 2^{\times_{i\in I}\triangle^{fin}(\triangle(S_i))}$ has a fixed point if and only if $g : \triangle^{mix}(S) \to 2^{\triangle^{mix}(S)}$ has a fixed point. Since, by definition (9), for all $\sigma_{-i} \in \triangle^{mix}(S_{-i})$ and all $i \in I$, the sets $g_i(\sigma_{-i})$ are convex closures of the sets $f_i(\sigma_{-i})$ the beliefs over best-responses correspondence g is convex-valued even if the best response correspondence f is not. Thus, by Kakutani's fixed point theorem, existence of *equilibria in beliefs* in finite games is, guaranteed for continuous utility representations regardless whether these utility functions are quasiconcave or not.

Finally note, that existence of a Nash equilibrium in mixed-strategies implies existence of an *equilibrium in beliefs* whereas the converse statement is not necessarily true unless the utility representations are quasiconcave.

7.2 A Non-Existence Result

For continuous utility representations the concept of *equilibria in beliefs* re-establishes existence of equilibria by a convexicifation of the best response correspondence. Unfortunately, this is not any longer the case for the discontinuous utility representations of security- and potential level preferences.

Proposition 2. *For a game $G = (\triangle(S_i), U_i)_{i\in I}$ with SL,PL-players existence of an equilibrium in beliefs may fail if there occur security- or potential effects.*

The validness of this non-existence result is demonstrated by two examples of games with SL,PL-players.

Example 1: Non-existence due to a security effect. Consider the following payoff matrix of a *pre-emptive strike game.*

B

		de	di
A	p	2,0	0,1
	w	1,1	1,0

Specify for player A: $x_k \in X$, $u(x_k) = x_k$ for all $x_k \in X$, $b(x, y) = 0$ for all $x, y \in X$, and $a(2, y) = a(1, y) = 2$, $a(0, y) = 1$ for all $y \in X$. Then, the best responses of A to beliefs $\lambda \cdot de \oplus (1-\lambda) \cdot di$ with $\lambda \in [0,1]$ are given as:

$$\begin{aligned} \{w\} \text{ for } 0 &\leq \lambda < 1 \\ \{p\} \text{ for } \lambda &= 1 \end{aligned}$$

An equilibrium in beliefs can here only exist if B is indifferent between her pure-strategies, that is, B must believe A to play her pure-strategies with equal chance. However, by the *security effect*, A is never indifferent between her pure-strategies nor would she strictly prefer to randomize since U_A is quasiconvex (observation 1).

Example 2: Non-existence due to a potential effect. Consider a game with two players, A and B, and the following payoff matrix:

B

A

	d_1	d_2	d_3
c_1	$0,1$	$4,0$	$0,0$
c_2	$3,0$	$3,1$	$0,0$
c_3	$-10,0$	$5,0$	$-10,1$

Specify for A: $u(x_k) = x_k$ for all $x_k \in X$, $a(x,5) = 2$ and $a(x,y) = 1$ for $y \neq 5$, and $b(x,y) = 0$ for all x, y with $x \leq y$. Observe at first that there does not exist a Nash equilibrium in pure-strategies. Since U_A is quasiconcave (observation 1) it suffices to show non-existence of a Nash equilibrium in mixed-strategies in order to demonstrate non-existence of an equilibrium in beliefs. If there exists a Nash equilibrium in mixed-strategies player B has to be indifferent between at least two of her pure-strategies[3] which leaves the following four cases of possible equilibrium strategies for A

i. $\sigma(c_1) = \sigma(c_2) = 0.5$ implying that B *is indifferent between* d_1 *and* d_2

ii. $\sigma(c_1) = \sigma(c_3) = 0.5$ implying that B *is indifferent between* d_1 *and* d_3

iii. $\sigma(c_2) = \sigma(c_3) = 0.5$ implying that B *is indifferent between* d_2 *and* d_3

iv. $\sigma(c_1) = \sigma(c_2) = \sigma(c_3) = \frac{1}{3}$ implying that B *is indifferent between* d_1*,* d_2*, and* d_3

Observe that none of these strategies is a best response to any of B's best responses to these strategies:

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[3] In general a SL,PL-player has not to be indifferent between pure-strategies when she prefers to randomize over them. However, with only two outcomes, 0 and 1, security– and potential level preferences reduce to expected utility preferences for player B.

Case (i). If $\sigma(c_1) = \sigma(c_2) = 0.5$ is a best response of A she must be indifferent between c_1 and c_2 since there is no potential effect involved with these strategies. Thus, in equilibrium B must play $\sigma(d_2) = 3 * \sigma(d_1)$ whereby we can obviously can exclude $\sigma(d_2) = \sigma(d_1) = 0$ since d_3 is not a best response of B in case (i). But then there does not exist a best response of A, satisfying the conditions of case (i), to any of B's strategies: Consider the family of mixed-strategies

$$\mu \cdot (0.5 \cdot c_1 \oplus 0.5 \cdot c_2) \oplus (1 - \mu) \cdot c_3$$

for $0 < \mu \leq 1$. For $\sigma(d_2) = 3* \sigma(d_1) > 0$ the utility of A is strictly increasing in μ as it approaches one; but at $\mu = 1$, i.e., at $\sigma(c_1) = \sigma(c_2) = 0.5$, A's utility drops by the *potential effect*. An analogous argument applies to case (iv).

Case (ii). If B mixed between d_1 and d_3 then A strictly prefers the pure-strategy c_2; contrary to the assumption of case (ii).

Case (iii). If B mixed between d_2 and d_3 then A would choose c_1 over c_2 in the support of any best response; contrary to the assumption of case (iii).

This establishes non-existence of an equilibrium in beliefs.

Remark. Dasgupta and Maskin (1986) present results (Theorem 2 and corollary in Dasgupta and Maskin, 1986) which establish existence of Nash equilibria for games with strategy sets that are compact and convex subsets of $\mathbb{R}^n$ under the assumption that players have discontinuous utility functions. Their strategy is to look for conditions guaranteeing upper-hemicontinuous best response correspondences in order to apply Kakutani's fixed point theorem even if Berge's maximum theorem (Berge, 1997) is not at hand for deriving upper-hemicontinuous best response correspondences from continuous utility functions.

Since the mixed-strategy space, $\times_{i \in I} \triangle(S_i)$, of a finite game is a compact and convex subset of $\mathbb{R}^n$ the findings of Dasgupta and Maskin would immediately establish existence of Nash equilibria in mixed-strategies for finite games with SL,PL-players if the discontinuous utility representations for SL,PL-players satisfied the according assumptions. Besides graph-continuity (see definition 3 in Dasgupta and Maskin,1986), Dasgupta and Maskin's existence results presume upper-semicontinuous utility functions that are quasiconcave in a player's strategy choice. However, by observation 1, upper-semicontinuity and quasiconcavity of the utility functions can not be simultaneously satisfied when there occur potential- or security effects.

7.3 A Limited Existence Result

For the special case that there do not occur security effects, a limited existence result for Nash equilibria in mixed-strategies of games $G = (\triangle(S_i), U_i)_{i \in I}$ with SL,PL-players can be established. The key assumption for this existence result refers to the occurrence of so-called *high-potential* pure-strategies in an equilibrium mixed-strategy profile of game $G^{EU} = (\triangle(S_i), V_i(\cdot, x_1, x_n))_{i \in I}$. More specifically, consider a pure-strategy $t_i \in S_i$ which appears in the support of mixed strategy σ_i^{mix} such that the mixed-strategy profile $\left(\sigma_i^{mix}, \sigma_{-i}^{mix}\right)$ is a Nash equilibrium of $G^{EU} = (\triangle(S_i), V_i(\cdot, x_1, x_n))_{i \in I}$. Call t_i a *high-potential pure-strategy* if there do not occur discontinuous downward jumps in the utility representation when some sequence of high potential level lotteries approaches lottery $\left(t_i, \sigma_{-i}^{mix}\right) \in \triangle(x, y)$, i.e., for all $\bar{y} \geq y$,

$$b(x, \bar{y}) = b(x, y) \text{ and } a(x, \bar{y}) = a(x, y)$$

Proposition 3. *Given a game $G = (\triangle(S_i), U_i)_{i \in I}$ with SL,PL-players such that no security effects occur. If there exists a Nash equilibrium σ^{mix} of $G^{EU} = (\triangle(S_i), V_i(\cdot, x_1, x_n))_{i \in I}$, where $V_i(\cdot, x_1, x_n)$ is defined by (8), such that, for all players $i \in I$, a* high-potential pure-strategy *$t_i \in S_i$ appears in the support of σ_i^{mix} then σ^{mix} is also a Nash equilibrium of G.*

Proposition 3 establishes existence of Nash equilibria for strategic situations where Kakutani's fixed point theorem is not applicable since *potential effects* entail non-existence of some best responses. Example 1 of the preceding subsection demonstrates that there does not exist an analogous result for security effects. Moreover, example 2 shows that the assumptions of proposition 3 can not be generalized to mixed-strategy Nash equilibria of G^{EU} such that these equilibria have no high-potential pure-strategy in their support: key to the non-existence result for game G of example 2 is the fact that A's (high potential) strategy $c3$ does not belong to the support of any equilibrium strategy of game G^{EU}.

As an immediate consequence of proposition 3, a Nash equilibrium exists for a game G with SL,PL-players if there do not occur security effects and if all pure-strategy profiles appear in the support of a mixed-strategy Nash equilibrium of game G^{EU}. Finally note, that proposition 3 and observation 2 imply existence of Nash equilibria in 2 × 2-player games with SL,PL-players if there do not occur security effects.

8 Trembling Hand Perfect Equilibria and Proper Equilibria

Proposition 2 implies possible non-existence of Nash equilibria for games with SL,PL-players. However, as this section demonstrates, for games with SL,PL-players there always exist *trembling hand perfect equilibria* (Selten, 1975) and *proper equilibria* (Myerson, 1978). Denote by $\triangle^{\varepsilon}(S_i) \subset \triangle(S_i)$ a set of mixed-strategies such that each $s_i \in S_i$ appears in the support of $\sigma_i \in \triangle^{\varepsilon}(S_i)$ with probability $\sigma_i(s_i) \geq \varepsilon(s_i) > 0$, and call $G(\varepsilon) = (\triangle^{\varepsilon}(S_i), U_i)_{i \in I}$ a *perturbed game.*

Definition (Selten, 1975): *The mixed-strategy profile* $\sigma^* = \times_{i \in I} \sigma_i^*$ *is a* trembling hand perfect equilibrium *of* G *if there is a sequence* $\{\varepsilon^k\}_{k \in \mathbb{N}}$, $\lim_{k \to \infty} \varepsilon^k(s_i) = 0$ *for all* $s_i \in S_i$ *and all* $i \in I$, *such that* $\sigma^* = \lim_{k \to \infty} \sigma^*(\varepsilon^k)$ *where* $\sigma^*(\varepsilon^k)$ *is a Nash equilibrium of the perturbed game* $G(\varepsilon^k)$*.*

Proposition 4. *There exists for every game* $G = (\triangle(S_i), U_i)_{i \in I}$ *with SL,PL-players a trembling hand perfect equilibrium. Moreover,* σ^* *is a trembling hand perfect equilibrium of* G *if and only if* σ^* *is a trembling hand perfect equilibrium of* $G^{EU} = (\triangle(S_i), V_i(\cdot, x_1, x_n))_{i \in I}$ *where* $V_i(\cdot, x_1, x_n)$ *is defined by (8).*

Proposition 4 is easily derived. For every perturbed game $G(\varepsilon)$ SL,PL-players behave like expected utility maximizers: since every outcome realizes with positive probability all relevant mixed-strategy profiles have the worst security level x_1 and the best potential level x_n. As a consequence, there exists a Nash equilibrium in mixed-strategies for every perturbed game $G(\varepsilon^k)$, and the result obtains because any limit point of Nash equilibria for some sequence of perturbed games is, by definition, a trembling hand perfect equilibrium of G^{EU}.

Obviously, the same argumentation applies to the proper equilibrium of Myerson (1978) who imposes particular restrictions on the probability weights $\varepsilon(s_i)$ by which pure strategies s_i may be played in a so-called ε-proper equilibrium $\sigma'(\varepsilon)$ of G. In particular, it is required for an ε-proper equilibrium $\sigma'(\varepsilon)$ of G that $0 < \varepsilon(t_i) = \sigma_i'(t_i) \leq \varepsilon(s_i) * \varepsilon(s_i)$ if $U_i(t_i, \sigma_{-i}'(\varepsilon)) < U_i(s_i, \sigma_{-i}'(\varepsilon))$. A proper equilibrium of G is then defined as a limit point $\sigma' = \lim_{k \to \infty} \sigma'(\varepsilon^k)$ where each $\sigma'(\varepsilon^k)$ is an ε-proper equilibrium of G and $\lim_{k \to \infty} \varepsilon_k(s_i) = 0$ for all $s_i \in S_i$ and all $i \in I$. Analogously, a proper equilibrium of G is given by any proper equilibrium of G^{EU}; which actually exists (Myerson, 1978; van Damme, 1991).

Note that the concepts of trembling hand perfect equilibria or of proper equilibria are not any longer selection - *perfectness* - criteria for Nash equilibria in games with SL,PL-players. For example, the unique trembling hand perfect equilibrium σ^* in the *pre-emptive strike* game of example 1 is given by $\sigma_A^*(p) = \frac{1}{2}$ and $\sigma_B^*(de) = \frac{1}{2}$. But, as example 1 shows, this mixed-strategy profile is not a Nash equilibrium. In my opinion, trembling hand perfect equilibria or proper equilibria that are not Nash equilibria are meaningless as strategic solutions except players actually play a slightly perturbed game $G(\varepsilon)$ such that the analyst does not know the exact value of ε. This analyst could then regard a trembling hand perfect equilibrium of G as a good approximation for the unknown Nash equilibrium of the actually played game $G(\varepsilon)$.

Remark. Cohen's model of security- and potential level preferences only deviates from expected utility theory if the probability of a bad or a good outcome drops to zero whereas Selten's assumption of *trembles* prevents exactly this to happen. Both approaches stand for conflicting ideas of how a decision maker perceives her influence on the possibility of outcomes. While Selten presumes a decision maker who believes that, independently of her own choice, anything may happen anyway, it is crucial for Cohen's decision maker that she may either exclude or include by her own choice the possibility of particular outcomes.

Finally note, that trembling hand perfect equilibria do not necessarily exist for *security- and potential level preferences with thresholds* as introduced in Schmidt and Zimper (2003). Discontinuities due to security- or potential effects may there already occur for small probabilities of bad or good outcomes such that the above limit point argument, establishing existence of trembling hand perfect equilibria, is not at hand.

9 Concluding Remarks

From an applicational point of view, rationalizability concepts have the practical disadvantage of being weaker solution concepts than equilibrium concepts, that is, any Nash equilibrium is rationalizable whereas the converse statement is not true. The results of this paper contribute to the comparison of different strategic solution concepts for strategic games by demonstrating that this seeming disadvantage of rationalizability may become an advantage for games with players who have security- and potential level preferences: On the one hand, there are strategic situations such that not all security- and potential level players can choose best responses and simultaneously have correct beliefs about their opponents' strategy choices. On the other hand, there always exist rationalizable strategies such that a security- and potential level player may choose her strategy via strategically sophisticated reasoning despite non-existence of equilibria.

10 Appendix: Proofs

Proof of proposition 1: Fix some point-belief $\beta_i(s_{-i}) = 1$ and pick a pure strategy s_i that is preference-maximizing over S_i, i.e., $s_i \in \arg\max_{t_i \in S_i} U_i(t_i, \beta_i)$, whereby finiteness of S_i guarantees the existence of s_i. Suppose now there exists some mixed-strategy $\sigma_i \in \triangle(S_i)$ such that $U_i(\sigma_i, \beta_i) > U_i(s_i, \beta_i)$. But this is impossible:

Since $\bar{x} = x^i(s_i, s_{-i})$ is the maximal element in the support of any lottery (σ_i, β_i) with $\beta_i(s_{-i}) = 1$, for all $\sigma_i \in \triangle(S_i)$, the lotteries (σ_i, β_i) belong to some subset $\triangle(x, y)$ such that $x \leq \bar{x}$ and $y \leq \bar{x}$. Implying for security- and potential level preferences

$$\begin{aligned} U_i(s_i, \beta_i) &= V_i(1 \cdot \bar{x}, \bar{x}, \bar{x}) \\ &\geq V_i(\sigma_i, \beta_i, \bar{x}, \bar{x}) \geq V_i(\sigma_i, \beta_i, x, y) = U_i(\sigma_i, \beta_i) \end{aligned}$$

for all $\sigma_i \in \triangle(S_i)$. Thus, s_i is a best response on $\triangle(S_i)$ to the point-belief $\beta_i(s_{-i}) = 1$.

As a consequence the set of so-called point-rationalizable strategies is non-empty which implies non-emptiness of $R(G)$.□

Proof of proposition 3: If $\left(\sigma_i^{mix}, \sigma_{-i}^{mix}\right)$ is a Nash equilibrium of G^{EU} then, for any pure-strategy $s_i \in S_i$ belonging to the support of σ_i^{mix},

$$V_i(s_i, \sigma_{-i}, x_1, x_n) = V_i\left(\sigma_i^{mix}, \sigma_{-i}, x_1, x_n\right) \tag{10}$$

implying, for all $x, y \in X$,

$$V_i(s_i, \sigma_{-i}, x, y) = V_i\left(\sigma_i^{mix}, \sigma_{-i}, x, y\right) \tag{11}$$

Let t_i be a *high-potential pure-strategy* belonging to the support of σ_i^{mix}. Since, by assumption, only potential effects may occur equality (10) implies, for all $\sigma_i \in \triangle(S_i)$,

$$U_i\left(t_i, \sigma_{-i}^{mix}\right) \geq U_i\left(\sigma_i, \sigma_{-i}^{mix}\right)$$

Thus, σ_i^{mix} is a best response to σ_{-i}^{mix} of player i in game G if and only if

$$U_i\left(t_i, \sigma_{-i}^{mix}\right) \leq U_i\left(\sigma_i^{mix}, \sigma_{-i}^{mix}\right)$$

This is satisfied by equation (11) because lottery $\left(\sigma_i^{mix}, \sigma_{-i}^{mix}\right)$ has at least the potential level of lottery $\left(t_i, \sigma_{-i}^{mix}\right)$ since t_i appears in the support of σ_i^{mix}.□

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