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24 August 2013

Online at <https://mpra.ub.uni-muenchen.de/53388/>  
MPRA Paper No. 53388, posted 31 Mar 2014 14:49 UTC

# Endowment as a Blessing\*

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February 3, 2014

## Abstract

We study the idea that seemingly unrelated behavioral biases can coevolve if they jointly compensate for the errors that any one of them would give rise to in isolation. We pay specific attention to barter trade of the kind that was common in prehistoric societies, and suggest that the “endowment effect” and the “winner’s curse” could have jointly survived natural selection together. We first study a barter game with a standard payoff monotonic selection dynamic, and show that in the long run the population consists of biased individuals with two opposed biases that perfectly offset each other. In this population, all individuals play the barter game as if they were rational. Next we develop a new family of “hybrid-replicator” dynamics. We show that under such dynamics, biases are stable in the long run even if they only partially compensate for each other and despite the fact that the rational type’s payoff is strictly larger than the payoffs of all other types.

**Keywords:** Endowment Effect, Winner’s Curse, Bounded Rationality, Evolution, Hybrid-Replicator Dynamics.

**JEL Classification:** C73, D82, D03

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\*We thank Eddie Dekel, John Duffy, Alan Grafen, Richard Katzwer, Shawn McCoy, Erik Mohlin, Luca Rigotti, Larry Samuelson, Lise Vesterlund, various seminar audiences for valuable discussions and suggestions, and to Sourav Bhattacharya for the query that initiated this project.

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# 1 Introduction

The growing field of Behavioral Economics has frequently identified differences between the canonical model of rational decision making and actual human behavior. These differences, usually referred to as “anomalies” or “biases,” have been identified through controlled experiments in the laboratory, as well as in field experiments (see, e.g., [Kagel & Roth, 1997](#); [Harrison & List, 2004](#)). Though some researchers have challenged the existence of some of these biases, others appear to be robust with a multitude of evidence on behavior that departs from payoff maximization. Such behavior is puzzling to economists, who are trained to think that competitive forces in our society and economy select optimal over suboptimal behavior.

In this paper, we explore a novel explanation for the existence of behavioral biases, arguing that sets of biases may persist because they jointly compensate for the errors that any one of them would give rise to in isolation. Thus, biases may coevolve as a “shortcut” solution that leads in specific important environments to behavior that is approximately optimal.<sup>1</sup> In circumstances that have less influence on the agents’ expected payoffs (e.g., circumstances of infrequent occurrence), agents may be subject to substantial behavioral “mistakes.” The vast majority of the existing literature studies behavioral biases separately (see related literature at the end of this section). The results in this paper suggest that we can gain a better understanding of different behavioral biases by analyzing their combined effects.

We specifically investigate a possible relation between the endowment effect and the winner’s curse, though our framework and insights are also relevant to the study of relations between other biases. The *endowment effect* ([Thaler, 1980](#)) refers to an individual’s tendency to place a higher value on a good once he owns it. In a seminal paper, [Kahneman et al. \(1990\)](#) distributed coffee mugs to half of the students in a classroom. When asked to assess the value of the mug, the mug-owners had on average a much higher valuation than the rest of the students.<sup>2</sup> The *winner’s curse* or *cursedness* ([Eyster & Rabin, 2005](#)) is the failure of an agent to account for the informational content of other players’ actions. The bias was first identified in common-value auctions in which the winners, who usually have the highest signal, tend to

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<sup>1</sup>[Cesarini et al., 2012](#) present experimental evidence suggesting that many common behavioral biases (and in particular, loss aversion, which is closely related to the endowment effect) are moderately heritable: genetic variation typically accounts for 20%–30% of the variance in the surveyed anomalies. Moreover, they conjecture that if the experimental methods were adapted to better filter out noise, then the genetic variation would account for about half of the variance (similar to the typical finding of the literature studying the heritability of the the “big five” personality traits, see, e.g., [Jang et al., 1996](#)). In Section 6.1 we discuss why our results also hold for partially heritable biases.

<sup>2</sup>See [Kahneman et al. \(1991\)](#) for a survey on the endowment effect, and see [Knetsch et al. \(2001\)](#); [Genesove & Mayer \(2001\)](#); [Bokhari & Geltner \(2011\)](#) for recent experimental support and field evidence.

overestimate the value of the object. A similar phenomenon was later observed in bilateral-trade interactions, of the kind discussed in this paper (Bazerman & Samuelson, 1983; Kagel & Levin, 1986; Kagel *et al.*, 1987; Lind & Plott, 1991).<sup>3</sup>

**Model and Results.** We demonstrate that these two seemingly unrelated biases compensate for each other in barter-trade interactions such as were common among prehistoric societies.<sup>4</sup> In our model, each of two traders owns a different kind of indivisible good and considers whether to participate in trade or not. The value of each good depends on an unobservable property that is known to the owner of the good but not to his trading partner. The potential gain of the traders also depends on additional conditions (initial stock, location, weather, etc.), which are known to both players before they engage in trading but can change from one instance of trade to another. Goods are exchanged if both traders agree.

Each agent in the population is endowed with a pair of biases. The level of these biases determines his type, and the agent with the minimal level of both biases (i.e., the unbiased one) is “rational.” The first bias is *cursedness*: the extent to which an agent underestimates the relation between the partner’s agreement to trade and the quality of this partner’s good. In the trade game, agents in general choose to trade goods that are not very valuable and keep valuable goods for themselves. A cursed trader does not pay enough attention to this fact and overestimates the value of his partner’s good conditional on trade (in the extreme case, a fully cursed agent simply expects to get a good of ex-ante value). As a result, a more cursed agent will agree to trade goods with a greater personal value. Thus, cursedness leads agents to trade too much, and higher cursedness results in more trade.

The second bias is a *perception bias*: a function ( $\psi$ ) that distorts an agent’s subjective valuation of his own good. If the good is worth  $x$ , an agent believes it to be worth  $\psi(x)$ . If  $\psi(x) > x$ , we say that the agent exhibits the endowment effect, but we allow agents to have also other perception biases as well. An agent with the endowment effect does not agree to trade goods with low values since he believes those goods to be more valuable than they actually are, and thus he loses profitable transactions.<sup>5</sup> Agents with the endowment effect

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<sup>3</sup>See Kagel & Levin (2002, Chapter 1) for a survey on the winner’s curse, and see Grosskopf *et al.* (2007); Massey & Thaler (2013) for recent experimental support and field evidence.

<sup>4</sup>Evidence from anthropology suggests that trade between groups, based on localization of natural resources and tribal specializations, was common in primitive societies (see Herskovits, 1952; Polanyi, 1957; Sahlins, 1972; Haviland *et al.*, 2007). Moreover, “[t]he literature on trade in nonliterate societies makes clear that barter is by far the most prevalent mode of exchange” (Herskovits, 1952, p. 188).

<sup>5</sup>The fact that traders may have an endowment effect seems at first sight at odds with experiments that have shown that professionals do not have an endowment effect for goods obtained solely for trade rather than personal consumption (e.g., Kahneman *et al.*, 1990 and List, 2003, 2004). For example, a shoemaker will not have an endowment effect for the shoes he makes. This may be related to the fact that either the shoemaker

trade too little, and traders with a higher level of endowment effect trade less.

We analyze the interaction among a large population of traders with different types (i.e., different levels of biases). Agents are randomly matched and play the barter game. We assume that agents do not observe the types of their partners and in each period they best-reply to an “average” trader. Their best reply, however, is distorted by their own biases. We show that there is a set  $\Gamma$  of types that exhibit both the winner’s curse and the endowment effect, such that the two biases compensate each other. The set  $\Gamma$  includes not only the rational unbiased type, but also types of all levels of cursedness, and types who are more cursed present a greater endowment effect.

Our first result (Proposition 1) shows that a distribution of types is a Nash equilibrium of the population game if and only if its support is a subset of  $\Gamma$ . Moreover, all agents in the population present the same “as-if-rational” behavior on the equilibrium path (their trading strategy is identical to that of a rational trader), and any type outside  $\Gamma$  achieves a strictly lower payoff if it invades the population. In a dynamic setting where the payoff of the barter game determine the agents’ fitness and the frequency of the types evolves according to a payoff-monotone selection (e.g., the replicator dynamic; see Taylor & Jonker, 1978), stable distributions of types are exactly those with a support in  $\Gamma$ .

We then extend our analysis to the case where fitness is determined not only by the outcome of barter trade, but is also a result of other activities. In such activities the biases typically do not compensate for each other, and an unbiased type has a strict advantage. We assume that while agents interact most of the time in barter trade, with some probability they play other games in which biases lead to strictly lower payoffs.<sup>6</sup> We show (Proposition 2) that in such a case the sole survivor of any payoff-monotone dynamics is the rational type.

We then show that under a wide collection of plausible selection dynamics, the above result is no longer true and types with both biases are stable. The replicator dynamic is based on two assumptions: (1) any newborn agent in a population replicates the type of an incumbent agent, and (2) the choice of which incumbent to replicate is proportional to the game payoffs of the incumbent types. We present the family of *hybrid-replicator dynamics* that relaxes the first assumption. Specifically, we assume that each new agent inherits with

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does not have much value for the goods unless he can sell them or does not see them as his “endowment” in the first place because they are made for sale. However, manufacturing goods solely for trade is a feature of the modern world. Though tribes did specialize in specific goods for trade, traded goods were also consumed by other tribe members (Herskovits, 1952). Thus, there is no contradiction between the assumption that tribe members developed the endowment effect for their goods in primitive times and the empirical evidence that professional traders exhibit less of an endowment effect for traded goods.

<sup>6</sup>In section 6.2 we discuss how to adapt our results to a setup in which players interact each time in slightly different barter trade interactions.

some probability each bias from a different incumbent, and with the remaining probability inherits both biases from a single incumbent. One plausible interpretation of hybrid-replicator dynamics is a biological evolutionary process where each offspring’s genotype is a mixture of his parents’ genes. Another interpretation is social learning in which some agents may learn different strategic aspects from different “mentors.”

The hybrid-replicator dynamic is not payoff-monotone because only a fraction of the agent’s offspring share his type, while the other offspring have “hybrid” types. Consider for example a population composed of a single type in  $\Gamma$ , that is, a type where the two biases compensate for each other. Now assume that this population is invaded by a small group of “mutant” rational agents. Such agents, by definition, have a higher fitness due to their advantage in non-barter activities. However, only a fraction of the rational agent’s offspring are rational and this “dilutes” their relative fitness advantage. The remaining hybrid offspring (which have only one bias) have low fitness, because their single bias is not compensated by the other bias in the barter interaction. As a result, the biased incumbent is stable against unbiased mutants.

We formalize this observation and obtain two key results. Proposition 3 shows a global convergence towards  $\Gamma$ ; that is, any type outside  $\Gamma$  can be eliminated by a mutant with the same cursedness level and a perception bias that is strictly closer to  $\Gamma$ .<sup>7</sup> The second result (Proposition 4) shows that each type in  $\Gamma$  is stable against each “mutant” type  $t'$  if the barter interaction is sufficiently frequent. We interpret these results as follows. First, the population converges relatively fast from any initial state towards a type close to  $\Gamma$ . The particular type depends on the initial state and it is generally a biased type. Once the population is near  $\Gamma$ , it remains for a long time in each state, and it slowly drifts between types near  $\Gamma$  such that each type is close to its precedent but has a slightly lower level of biases (giving it an advantage in non-barter activities). This drift is extremely slow, as only mutants that are “close” to the incumbent types can invade. We would therefore expect the population to be composed of agents with both cursedness and the endowment effect for a long period of time. Only in the “ultra-long” run will the population eventually reach the rational type. Previous studies have also discussed stability in shorter horizons than the “ultra-long” run, and suggest that biological populations can be found in locally optimal states that are not stable in the “ultra-long” run (see, e.g., [Hammerstein, 1996](#)).<sup>8</sup> This seems plausible also in

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<sup>7</sup>In Section 5.2 we justify the focus of our analysis on the stability of types rather than heterogeneous populations. We do it by sketching why, due to the concavity of the payoffs, heterogeneous populations are unstable.

<sup>8</sup>One famous example of this in the human population is Sickle cell disease. The disease occurs when a person has two mutated alleles and it severely reduces fitness. This genetic disease is relatively frequent,

processes of social learning (see, e.g., [Samuelson \(1998\)](#)).

**Related Literature and Contribution.** Our paper is related to the “indirect evolutionary approach” literature ([Güth & Yaari, 1992](#)), dealing with the evolution of preferences that deviate from payoff (or fitness) maximization. A main stylized result in this literature (see [Ok & Vega-Redondo, 2001](#); [Dekel \*et al.\*, 2007](#)) is that biases can be stable only if types are observable, so a player can condition his behavior on an opponent’s type.<sup>9</sup> We show, in contrast, that even with the “conventional” replicator dynamic, stable states may contain biased players who play as if they were rational on the equilibrium path (however, off the equilibrium path their “mistakes” can be observed). Moreover, when considering hybrid-replicator dynamics, players can also play suboptimally on the equilibrium path.<sup>10</sup>

Our paper is also related to the literature that explains how behavioral biases may evolve. A majority of these papers deal with a single bias.<sup>11</sup> Few papers have dealt with the possibility that evolution will create two biases that are significantly different and yet complementary. [Heifetz \*et al.\* \(2007\)](#) develop a general framework in which natural selection may lead to perception biases. In a non-evolutionary context, [Kahneman & Lovallo \(1993\)](#) suggest that two biases, excessive risk aversion and the tendency of individuals to consider decision problems one at a time, partially cancel each other out. Recently, [Ely \(2011\)](#) demonstrated that in evolutionary processes improvements tend to come in the form of “kludges,” that is, marginal adaptations that compensate for, but do not eliminate, fundamental design inefficiencies. Finally, [Herold & Netzer \(2011\)](#) show that, different biases that are postulated in prospect theory partially compensate for each other, and [Johnson & Fowler \(2011\)](#) show that overconfidence arise naturally in a setup where agents are not fitness-maximizing and use a non-Bayesian decision making heuristic.

Finally, our paper is related to the literature that studies the influence of sexual inheritance on stable properties of populations.<sup>12</sup> Various papers in the biological literature study

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especially in areas in which malaria is common, due to the heterozygote advantage: a person with a single mutated allele has a better resistance to malaria.

<sup>9</sup>A related example is [Huck \*et al.\* \(2005\)](#) and [Heifetz & Segev \(2004\)](#) who show that an endowment effect observed by others can evolve in populations that engage in bargaining, through its use as a “commitment” device. See also [Heller \(2013b\)](#) that shows a related result for limited foresight.

<sup>10</sup>The literature contains two other mechanisms that allow players not to maximize their material payoffs in stable states even without assuming observability of types: (1) finite population ([Schaffer, 1988](#)), and (2) assortative matching of players ([Alger & Weibull, 2013](#)).

<sup>11</sup>[Samuelson \(2004\)](#) and [Nöldeke & Samuelson \(2005\)](#) deal with relative consumption effects; [Robson & Samuelson \(2007, 2009\)](#) and [Dasgupta & Maskin \(2005\)](#) show how “present bias” (dynamic inconsistency) might have evolved; [Heller \(2013a\)](#) shows that overconfidence may emerge as a tool for risk diversification.

<sup>12</sup>Sexual inheritance induces a probability of “mixing” genes, known as the “recombination rate,” which is captured in the family of hybrid replicator dynamics by the probability of obtaining each trait from a different

the differences between the induced stable behavior in asexual populations (analogous to the standard replicator dynamic) and sexual populations (analogous to the hybrid-replicator dynamic), and the implications of these differences on the stability of sexual inheritance (see, e.g., [Maynard Smith, 1971](#); [Barton & Charlesworth, 1998](#)). The methodology of studying stable outcomes in sexual populations in which two traits co-evolve was developed in [Karlin \(1975\)](#) and extended, among others, in [Eshel & Feldman \(1984\)](#) and [Matessi & Di Pasquale \(1996\)](#). A few papers in the economic literature applied this methodology. [Waldman \(1994\)](#) shows that sexual inheritance can yield stable “second-best” adaptations in which agents have systematic errors, and demonstrates how this can induce overconfidence. [Bergstrom & Bergstrom \(1999\)](#) study the influence of sexual inheritance on parent-offspring conflicts in which the parent and the offspring do not agree about how resources should be allocated among family members. They show that, in contrast to the asexual case, offspring may successfully “blackmail” their parents into providing additional resources.

The main contribution of our paper with respect to this literature is threefold. First, we show how this approach can explain the joint stability of two widespread and established biases that are seemingly unrelated to each other. Second, we introduce the new family of “hybrid-replicator” dynamics that captures the important dynamical aspects of the co-evolution of several traits when each agent has more than one parent/mentor, while abstracting away the complex technicalities of the existing related models that analyze diploid sexual populations (in which each individual has two copies of each chromosome: see, e.g., [Eshel & Feldman, 1984](#)). We believe that this family of dynamics may be useful in future research of biological and cultural evolutionary processes. Third, we extend the related analysis of [Waldman \(1994\)](#), who deals only with local stability and an exogenously fixed finite set of feasible types, to analyze also global convergence and an unrestricted continuous set of feasible types.

The paper is organized as follows. Section 2 presents a model of a population of agents engaging in barter trade. A classic dynamic analysis is performed in Section 3 where we show that all types in  $\Gamma$  are stable. In Section 4 we introduce additional non-barter activities and show that only the unbiased type remains stable in the replicator dynamic. Section 5 presents the family of the hybrid-replicator dynamics and shows that under these dynamics the biased types in  $\Gamma$  are stable. We conclude with a discussion of additional issues related

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incumbent. The recombination rate is equal to 0.5 if each trait is influenced by a different chromosome (in which case each offspring has probability 0.5 of inheriting both traits from the same parent), and is strictly between 0.5 and 1 if both genes are located in the same chromosome; for an introductory analysis, see [Hartl et al. \(1997\)](#).

to the model in Section 6. All proofs appear in the Appendix.

## 2 Model

We present a model of barter trade, common and important in prehistoric societies, in which a population consists of a continuum of agents (or traders) that are randomly matched to engage in a trading interaction. Each agent in the population is endowed with a type that determines his biases. Agents do not observe the types of their trading partners. We describe below the different components of the interaction between each pair of traders in the population and then move on to describe the population game that is induced by these trade interactions.

### 2.1 Barter Interaction

A barter interaction is composed of two agents matched as trading partners. Each agent  $i \in \{1, 2\}$  in the pair owns a different kind of indivisible good, and obtains a private signal  $\mathbf{x}_i$  regarding the value of his own good. We assume  $\mathbf{x}_1, \mathbf{x}_2$  are continuous, independent, and identically distributed with full support over  $[L, H]$ , where  $0 < L < H$ . Let  $\mu \equiv E(\mathbf{x}_i)$  be the (ex-ante) expected value of  $\mathbf{x}_i$  and let  $\mu_{\leq y} \equiv E(\mathbf{x}_i | \mathbf{x}_i \leq y)$  be the expected value of  $\mathbf{x}_i$  given that its value is at most  $y$ .

Both traders receive a public signal  $\alpha \geq 1$ , which is a “surplus coefficient” of trade: the good owned by agent  $-i$  is worth  $\alpha \cdot \mathbf{x}_{-i}$  to agent  $i$ .<sup>13</sup> High  $\alpha$  represents better conditions for trade independently of the quality of the goods. For example, if both parties have a great need for the commodity they do not own, then  $\alpha$  will be high. Given that  $\alpha$  denotes trade conditions other than quality, which is represented by  $\mathbf{x}_1$  and  $\mathbf{x}_2$ , we assume that  $\alpha$ ,  $\mathbf{x}_1$ , and  $\mathbf{x}_2$  are all independent. The coefficient  $\alpha$  can have any continuous distribution with support  $[1, \frac{H}{L}]$ .<sup>14</sup> The agents interact by simultaneously declaring whether they are willing to trade. The goods are exchanged if and only if both agents agree to trade.

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<sup>13</sup>Our results remain qualitatively unchanged in the case where each agent  $i$  privately obtains an independent identically distributed surplus coefficient  $\alpha_i$ . The results would be similar if we had an interdependent values setup and not a common values setup, i.e., if the the good of agent  $-i$  were of worth  $\alpha x_{-i} + v_i$  to agent  $i$ , where  $v_i$  is some constant or random variable.

<sup>14</sup>Full support over  $[1, \frac{H}{L}]$  is needed for uniqueness. Specifically, it implies that for each fixed cursedness level, any two different perception biases induce different threshold strategies. Without this property our results would not change qualitatively: the equilibrium we define below would include more types, but the observed behavior of these types would be the same. Finally, the results are similar in the cases where we: (1) allow for smaller or greater  $\alpha$ 's, or (2) assume full support only over  $[1, \frac{H}{\mu}]$ ; however, this makes the notation cumbersome.

## 2.2 Biases / Types

Each agent has a pair of biases, and their specific level is denoted by its type,  $(\chi, \psi)$ . The first bias is *cursedness* à la [Eyster & Rabin \(2005\)](#). A trader of type  $\chi \in [0, 1]$  best-responds to a biased belief<sup>15</sup> that the expected value of his partner’s good is  $\alpha \cdot (\chi \cdot \mu + (1 - \chi) \cdot \mu_\alpha)$ , where  $\mu_\alpha$  is the expected value of his partner’s good when the partner agrees to trade and the trade coefficient is  $\alpha$ . Thus, a cursed trader only partially takes into account the informational content of the other trader’s action (a rational agent has  $\chi = 0$ ; a “fully cursed” trader with  $\chi = 1$  believes he always gets an “average” object). Notice that if  $\mu_\alpha < \mu$  (as we show below), then a  $\chi$ -cursed trader with  $\chi > 0$  overestimates the quality of his partner’s good.

The second component,  $\psi$ , is a trader’s *perception bias* regarding his own good. We assume that  $\psi \in \Psi$ , where  $\Psi$  is the set of continuous and strictly increasing functions from  $[L, H]$  to itself. A trader with perception bias  $\psi$  best-responds to a biased belief that his own good’s value is  $\psi(x)$  (rather than  $x$ ). If  $\psi(x) > x$  for all  $x \neq H$  we say that the trader exhibits an *endowment effect*. Given two perception biases,  $\psi_1$  and  $\psi_2$ , we say that  $\psi_1$  is *more biased* than  $\psi_2$ , denoted by  $\psi_1 \succeq \psi_2$ , if for all  $x \in [L, H]$  either  $\psi_1(x) \leq \psi_2(x) \leq x$  or  $\psi_1(x) \geq \psi_2(x) \geq x$ . We write  $\psi_1 \succ \psi_2$  if  $\psi_1 \succeq \psi_2$  and  $\psi_2 \not\succeq \psi_1$ . Letting  $I \in \Psi$  denote the identity function,  $I(x) \equiv x$ , type  $(0, I)$  is the unbiased, or the “rational” type. Denote  $T = [0, 1] \times \Psi$  the set of all types.

## 2.3 Strategies and Configurations

A general strategy for trader  $i$  is a function from  $\alpha$  to values of  $\mathbf{x}_i$  for which the trader agrees to trade. If an agent expects a positive surplus from trading an object of value  $x_i$ , then he expects a positive surplus also from trading objects with a value less than  $x_i$ . Thus, we can restrict our attention to threshold strategies. An agent’s *pure threshold strategy* (or simply, strategy) is a continuous function  $s : \left[1, \frac{H}{L}\right] \rightarrow \mathbb{R}^+$  that determines, for each  $\alpha$ , the maximal value of  $x$  for which the agent accepts trade.<sup>16</sup> That is, an agent who follows strategy  $s$  accepts trade if and only if  $x \leq s(\alpha)$ .<sup>17</sup> Note that  $\mathbf{x}_i$  is continuous and so there is always a unique best response (see eq. 1 below), hence the focus on pure strategies is without loss of generality. Since the actual value of the trader’s good belongs to the interval  $[L, H]$ , we

<sup>15</sup>The formal definition of best-responding to biased beliefs is formalized below.

<sup>16</sup>The mild assumption that the strategies are continuous with respect to  $\alpha$  is necessary to achieve uniqueness of equilibria in the population game (i.e., the support of any Nash equilibrium is a subset of  $\Gamma$ ). Without this continuity there may be a gap of values of  $x$  that does not influence agents’ decisions, and allow other  $\psi$ s that differ only over these  $x$ ’s to be part of an equilibrium.

<sup>17</sup>The results are unaffected if one assumes that traders reject trade if their signal is equal to their threshold.

interpret thresholds  $s(\alpha) < L$  and  $s(\alpha) > H$  as strategies where the trader never agrees to trade and always agrees to trade, respectively. Let  $S$  denote the set of strategies.

In what follows we assume that the number of types in the population is finite. Specifically, let  $\Delta(T)$  be the set of type distributions with finite support (we slightly abuse notation and denote by  $t$  degenerate distributions with a single type  $t$ ). A state of the population, or configuration, is formally defined as follows:

**Definition 1.** A *configuration* is a pair  $(\eta, b)$ , where  $\eta \in \Delta(T)$  is a distribution of types and  $b : \text{supp}(\eta) \rightarrow S$  is a *behavior* function assigning a strategy to each type.

Observe that the definition implies that an agent does not observe his opponent's type. He best-responds while taking into account the value of a random traded good, which is determined jointly by the distribution of types (biases) in the population and the strategy that each type uses in the game. Given a configuration  $(\eta, b)$ , let  $\mu_\alpha(\eta, b)$  be the mean value of a good of a random trader, conditional on the trader's agreement to trade when the trade coefficient is  $\alpha$  (formally defined in (5)). Notice that this mean value is determined jointly by the distribution of types (biases) in the population and the strategy each type employs in the game. Let  $s_t^*(\alpha)(\eta, b)$  denote the best-reply threshold of a trader of type  $t = (\chi, \psi)$  who is facing a surplus coefficient  $\alpha$  and configuration  $(\eta, b)$ . Formally,  $s_t^*(\alpha)(\eta, b)$  is the unique value in  $[L, H]$  that solves the equation

$$\psi(s_t^*(\alpha)(\eta, b)) = \alpha \cdot (\chi \cdot \mu + (1 - \chi) \cdot \mu_\alpha(\eta, b)). \quad (1)$$

The interpretation of (1) is as follows. The RHS describes the value of the good a trader expects to receive from a trade, given his cursedness level  $\chi$ . The LHS describes the value the trader attaches to a good of value  $s_t^*(\alpha)(\eta, b)$ , given his perception bias  $\psi$ . A trader strictly prefers to trade (respectively, not to trade) if his good's perceived value is less (respectively, greater) than the expected value of another trader's good, conditional on an agreement to trade. The unique threshold for which the trader is indifferent between trading and not trading is  $s_t^*(\alpha)(\eta, b)$ .

We conclude this section by explicitly mentioning the influence of biases on types' strategies (Equation 1):

*Remark 1* (Effect of biases on trading behavior).

1. A cursed trader ( $\chi > 0$ ) overestimates the good of his partner and therefore uses a threshold that is too *high* (note that since we deal with threshold strategies, goods

with the highest qualities are not traded, and  $\mu_\alpha \leq \mu$ ). That is, cursed traders trade too *much*.

2. A trader with an endowment effect ( $\psi(x) > x$ ) overestimates the quality of his own good and therefore uses a threshold that is too *low*. That is, traders with the endowment effect trade too *little*.

## 2.4 Equilibrium Configurations and the Population Game

A configuration is an equilibrium if each type best-responds in the manner presented above.

**Definition 2** (Equilibrium Configuration). A configuration  $(\eta, b)$  is an *equilibrium* if for each type  $t = (\chi, \psi) \in \text{supp}(\eta)$  and for every  $\alpha \in \left[1, \frac{H}{L}\right]$ ,  $b(t)(\alpha) = s_t^*(\alpha)(\eta, b)$ .

Our first result shows that for every distribution of types there exists an equilibrium configuration. Formally:

**Lemma 1** (Existence of Equilibrium Configurations). For every distribution of types  $\eta \in \Delta(T)$ , there exists a behavior  $b$  such that  $(\eta, b)$  is an equilibrium configuration.

There may be more than one equilibrium configuration with the same underlying distribution. In what follows, we assume that for any distribution, one specific equilibrium is always played. Formally, assume an arbitrary function  $b^*$  that assigns to each type distribution  $\eta \in \Delta(T)$  a behavior such that  $(\eta, b_\eta^*)$  is an equilibrium configuration. One example of  $b^*$  is a function that chooses the equilibrium with maximal trade, but any function will do. Since we assume that for each distribution  $\eta$  a specific equilibrium is played, in what follows we can focus solely on the distribution of types  $\eta$ .

The barter-trade interaction together with the equilibrium selection function  $b^*$  define a population game  $G_0 = (T, u)$ , where  $T$  is the set of types (as defined above), and  $u : T \times \Delta(T) \rightarrow [L, H]$  is the payoff function that describes the expected value of a good obtained by a type  $t$  agent that best-responds to a trade with a random partner from configuration  $(\eta, b_\eta^*)$ ; a formal definition of  $u(t, \eta)$  appears in Appendix A.2.<sup>18</sup>

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<sup>18</sup>Our notion of population game implicitly assumes a two-layer evolutionary process (as is common in the literature; see, e.g., Dekel *et al.*, 2007): a relatively slower process according to which the distribution of types evolves, and a faster process according to which agents learn to “subjectively” best-reply to the aggregate behavior in the population. We make this assumption for reasons of tractability and consistency with the existing literature. However, all our results can also be adapted to a setup in which the evolution of types is not much slower than the evolution of behavior (and agents subjectively best-reply to the aggregate behavior of the population in the recent past).

### 3 Compensation of Biases in Barter Trade

In this section we analyze the population game that arises when there are repeated interactions of the barter trade. We assume there is a large population of anonymous agents of various types. Agents are randomly matched each period and play the trade game. Agents' payoff from trade determines their fitness and therefore their frequency in the population in the next stage; that is, we assume that type's frequencies evolve through a payoff-monotone selection dynamic, such as the replicator dynamic (Taylor & Jonker, 1978). We restrict ourselves in this section to a static analysis of equilibria in such a game. Our main result is that the only stable populations are those where the endowment effect and winner's curse compensate each other and create an as-if rational behavior on the equilibrium path. Thus, behavioral biases survive natural selection together.

#### 3.1 Rational and As-If Rational Behavior

As a first step to characterizing the equilibrium of  $G_0$ , consider the case where the entire population is unbiased; that is, the threshold of each agent is determined by the indifference condition

$$x^*(\alpha) \equiv s_{(I,0)}^*(\alpha) = \alpha \cdot \mu_\alpha,$$

which is derived by substituting  $\psi(x) = x$  and  $\chi = 0$  into (1). It is easy to show that if all agents play homogeneously in such a way, then in a Nash equilibrium the "rational" threshold, denoted by  $x^*$ , must be a solution to the equation

$$x^*(\alpha) = \alpha \cdot \mu_{<x^*(\alpha)}.$$

Next, for each  $\chi \in [0, 1]$  associate the perception bias  $\psi_\chi^* \in \Psi$  defined by

$$\psi_\chi^*(x) \equiv \chi \cdot \frac{\mu}{\mu_{\leq x}} \cdot x + (1 - \chi) \cdot x. \quad (2)$$

Now, let  $\Gamma = \{(\chi, \psi_\chi^*) : \chi \in [0, 1]\} \subset T$  be the set of all such types. Observe that:

1.  $\psi_0^*(x) \equiv I$ . Thus the unbiased type  $(0, I)$  is in  $\Gamma$ .
2. All other types in  $\Gamma$  are cursed ( $\chi > 0$ ) and exhibit the endowment effect ( $\psi_\chi^*(x) > x$  for all  $x < H$ ).
3. Types in  $\Gamma$  who are more cursed also have a larger endowment effect:  $\chi_1 > \chi_2$  implies

that  $\psi_{\chi_1}^* \succ \psi_{\chi_2}^*$ .

A graphic representation of  $\Gamma$  appears in Figure 1. Assume again that the population behaves

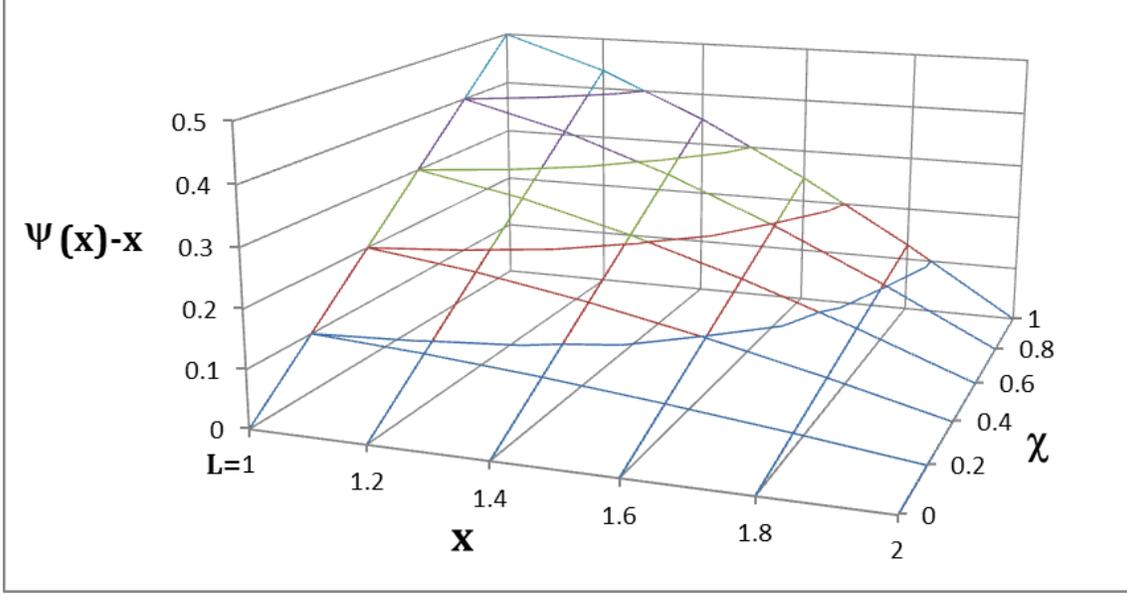


Figure 1: An example of  $\Gamma$ . For every level of cursedness  $\chi$  there is a perception bias function  $\psi_{\chi}^*(x)$ . The net bias  $\psi_{\chi}^*(x) - x$  is plotted as a line on the  $X$ - $Z$  plane. As can be seen, each bias function  $\psi_{\chi}^*$  presents the endowment effect, and therefore all values are positive. Moreover, high cursedness ( $\chi$  closer to one) is associated with a greater endowment effect (steeper slope for the function and higher values). This figure was calculated assuming  $L = 1$ ,  $H = 2$ , and a uniform distribution of values.

according to the “rational Nash equilibrium” described above, and therefore  $\mu_{\alpha} = \mu_{<x^*(\alpha)}$ . Then, the threshold chosen by each type in  $\Gamma$  is (equation (1))

$$\chi \cdot \frac{\mu}{\mu_{\leq s_t^*(\alpha)}} \cdot s_t^*(\alpha) + (1 - \chi) \cdot s_t^*(\alpha) = \alpha \cdot (\chi \cdot \mu + (1 - \chi) \cdot \mu_{\alpha}),$$

or

$$s_t^*(\alpha) = \alpha \cdot \mu_{<x^*(\alpha)} = x^*(\alpha).$$

That is, when all other agents in the population behave “rationally,” the behavior of types in  $\Gamma$  is indistinguishable from the rational type. The endowment effect and cursedness compensate for each other, and the  $(\chi, \psi_{\chi}^*)$  agent behaves (on the equilibrium path) as if he is unbiased.

### 3.2 Equilibrium and Stability

We now formalize the ideas that were presented informally above. First, let us define a Nash equilibrium of the population game. A distribution of types is a Nash equilibrium if it is a

best reply to itself. Formally:

**Definition 3** (Nash Equilibrium). Distribution  $\eta \in \Delta(T)$  is a *Nash equilibrium* in game  $G_0 = (T, u)$  if  $u(t, \eta) \geq u(t', \eta)$  for all  $t \in \text{supp}(\eta)$  and  $t' \in T$ . When the inequality is strict, we say that the distribution is a *strict equilibrium*.

The following definition assures that a set of types has two properties: (1) all types have the same payoff (internal-equivalence) and it is therefore internally stable; (2) the set is immune to an invasion of a small number of “mutant” types, since those types underperform types in the set (external strictness).

**Definition 4.** A set of types  $Y \subseteq T$  is *internally equivalent* and *externally strict* in game  $G_0 = (T, u)$  if  $u(t, \eta) = u(t', \eta) > u_p(\hat{t}, \eta)$  for all  $\eta \in \Delta(Y)$ ,  $t, t' \in Y$  and  $\hat{t} \in T \setminus Y$ .

Using these definitions, we can explicitly formulate our first main result:

**Proposition 1** (Characterization of Equilibria in  $G_0$ ). *A distribution  $\eta \in \Delta(T)$  is a Nash equilibrium of  $G_0$  if and only if  $\text{supp}(\eta) \subseteq \Gamma$ . Moreover,  $\Gamma$  is an internally equivalent and externally strict set.*

Given Proposition 1, we can rely on well-known results to relate the static equilibria with dynamically stable distributions in payoff-monotone dynamics like the replicator dynamic (Taylor & Jonker, 1978). We show below that a distribution is dynamically stable if and only if it is a subset of  $\Gamma$ . That is, only types in  $\Gamma$  will survive in the long run. For brevity we omit the formal definitions which are well known (though we formally present in Section 5 the stability notions for single-type distributions).

A distribution of types  $\eta$  is Lyapunov stable if after any sufficiently small invasion of mutant types, the population composition remains close to  $\eta$  at all future generations. Nachbar (1990) shows that any Lyapunov stable distribution is a Nash equilibrium. A set of Lyapunov-stable distributions is asymptotically stable if after any small enough invasion of mutants to any of the distributions in the set, the population reverts back to the set in the long run. An asymptotically stable set is minimal if no strict subset is asymptotically stable. Thomas (1985) defines a notion of an evolutionarily stable set and shows that it implies asymptotic stability. It is immediate to see that if a set of types is internally equivalent and externally strict, then the set of distributions with a support over this set of types is evolutionarily stable. Using these definitions, we can write the following corollary of Proposition 1 which characterizes stable distributions in the replicator dynamics.

**Corollary 1.** *In game  $G_0$  with an underlying replicator dynamic, (1) type  $t$  is Lyapunov stable if and only if  $t \in \Gamma$ , and (2) the set of distributions with a support in  $\Gamma$  is a minimal asymptotically stable set.*

Proposition 1 and Corollary 1 entail that the only populations that can survive the replicator dynamics contain only types in  $\Gamma$ . All these populations have agents that behave as if they were rational on the equilibrium path, but in general these populations will have agents with both cursedness and the endowment effect.

## 4 Introducing Additional Activities

The main drawback of the analysis in the previous section is the assumption that fitness is a result of a single-barter interaction. Obviously, agents engage in many activities that determine their fitness, and it is reasonable to assume that in many of these activities only one of the behavioral biases is relevant, and that it therefore imposes limitations on the behavior of the biased agent. For example, if a non-rational agent also trades with goods of publicly observable quality or simply private value, then cursedness will not be relevant, and the endowment effect will result in an average loss. In what follows we allow agents to engage in additional activities, and assume that in such activities biases are harmful. In this section we show that in such a case the rational type has an advantage over all the other types, including those in  $\Gamma$ . In the next section we show that with some plausible assumptions on the dynamics, biased types can be stable.

We model additional activities as follows. With some probability  $p$  agents take part in other activities, in which biases are detrimental. Formally, for  $0 \leq p \leq 1$ , agents play a population game  $G_p = (T, u_p)$  with a payoff function  $u_p : T \times \Delta(T) \rightarrow [L, H]$  defined as

$$u_p(t, \eta) = (1 - p) \cdot u(t, \eta) + p \cdot v(t, \eta), \quad (3)$$

where  $v(t, \eta)$ , the payoff in other activities, is *bias-monotone*: larger biases yield lower payoffs. Formally, for every  $(\chi, \psi), (\chi', \psi') \in T$  and  $\eta \in \Delta(T)$ :

$$\chi < \chi' \text{ and } \psi \prec \psi' \Rightarrow v((\chi', \psi'), \eta) < v((\chi, \psi), \eta).$$

In addition, we assume that  $v(t, \eta)$  is *Lipschitz-continuous*.<sup>19</sup>

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<sup>19</sup>Formally, there exists  $K \in \mathbb{N}$  such that for every  $t, t' \in T$  and  $\eta \in \Delta(T)$ :  $v(t', \eta) - v(t, \eta) \leq K \cdot \|t' - t\|$ , where  $\|t' - t\| = \|(\chi', \psi') - (\chi, \psi)\| = |\chi' - \chi| + \|\psi' - \psi\|$  is the distance between types and  $\|\psi' - \psi\| =$

By definition, in any game  $G_p$  the rational type  $(I, 0)$  has maximal  $v$ . In the previous section we have shown that in  $G_0$  there are types that behave as if they were rational in some configurations, but clearly this cannot be the case when  $p > 0$ . In such a case, the rational type will always have an advantage. Therefore, extending Definition 3 to any population game, the only Nash equilibrium of  $G_p$  (for  $p > 0$ ) is a population of unbiased agents, and, moreover, it is a strict equilibrium.

**Proposition 2** (Unique Equilibrium in  $G_p$ ). *Type  $(0, I)$  is the unique Nash equilibrium for every  $p > 0$ . Moreover, it is a strict equilibrium.*

As in the previous section, we can use standard results from the literature to show that, if the population evolves according to the replicator dynamic, then eventually the rational type will be the only one that survives.

**Corollary 2.** *In  $G_p$  with  $p > 0$  and an underlying replicator dynamic, type  $(0, I)$  is asymptotically stable. Moreover, no other distribution of types is Lyapunov-stable.*

The above corollary shows that when one focuses on replicator dynamics, the results of Section 3 are not robust to the introduction of additional activities. As soon as additional activities are introduced, even when they are infrequent (i.e., with a low probability), only the rational type  $(0, I)$  is stable.

## 5 Preservation of Biases with Additional Activities

In this section we show that if one is willing to consider a broader family of evolutionary dynamics, then our results that biased types are stable continue to hold even when additional activities are present. In Section 5.1 we present and motivate a family of *hybrid-replicator dynamics*. This family extends the well-known replicator dynamic by allowing new agents to replicate each trait from a different incumbent. Then, in Section 5.2, we demonstrate why heterogeneous populations are unstable in our framework. This allows us to focus in Section 5.3 on the stability of homogeneous populations (i.e., types). We show that types in  $\Gamma$  are stable also when  $p > 0$  if the underlying dynamic belongs to this family (except in the extreme case of the replicator dynamic). Proposition 3 shows that the population converges to  $\Gamma$  from any initial state. Proposition 4 shows that the population will stay in this type for a relatively long time, since this type is stable against an invasion of mutants as long as

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$\int_{x=L}^H |\psi'(x) - \psi(x)| dx$  is the distance between perception biases.

they are not very close. Thus, although the population moves toward  $(I, 0)$ , it does so in a long series of mutations that have a low probability to occurrence.

## 5.1 Hybrid-Replicator Dynamics

We model the evolutionary selection process in discrete time with each time period  $\tau = 0, 1, 2, \dots$  representing a generation.<sup>20</sup> The dynamics are represented by a deterministic transition function  $g : \Delta(T) \rightarrow \Delta(T)$  describing the distribution of types in the next generation as a function of the distribution in the previous generation. The family of hybrid-replicator dynamics is characterized by a *recombination rate*  $r \in [0, 1]$  that describes the probability that each offspring is randomly assigned to two incumbent agents (“parents”) and copies a single trait from each one of them; under the complementary probability each offspring is assigned to a single incumbent and copies both of its traits. As in the case of replicator dynamics, all these random assignments are distributed according to the incumbents’ fitness. Below we provide a semiformal description of the transition function. The formal definitions appear in Appendix A.5.

As is common in the literature, we assume that the expected number of offspring of each agent is equal to his game payoff plus a positive constant that reflects background factors that are unrelated to the game. Let  $f_\eta(t) \in R^+$  be the relative fitness of type  $t$  in population  $\eta \in \Delta(T)$ , that is, this agent’s fitness divided by the average fitness in the population. Denote by  $\eta(\chi)$  and  $\eta(\psi)$  the total frequency of types in  $\eta$  with cursedness level  $\chi \in [0, 1]$  and perception bias  $\psi \in \Psi$ , respectively. Now, let  $f_\eta(\chi)$  and  $f_\eta(\psi)$  be the expected relative fitness of types in  $\eta$  with cursedness level  $\chi$  and perception bias  $\psi$ , respectively. The transition function is defined as follows:

$$g(\eta)((\chi, \psi)) = (1 - r) \cdot \eta((\chi, \psi)) \cdot f_\eta((\chi, \psi)) + r \cdot \eta(\chi) \cdot f_\eta(\chi) \cdot \eta(\psi) \cdot f_\eta(\psi). \quad (4)$$

The family of hybrid-replicator dynamics extends the standard replicator dynamics (Taylor & Jonker, 1978; reformulated in Weibull, 1997, Chapter 4.1) for which  $g(\eta)((\chi, \psi)) = \eta((\chi, \psi)) \cdot f_\eta((\chi, \psi))$ . Observe that a hybrid-replicator dynamic coincides with the replicator dynamic (and, thus, is payoff-monotone) if either  $r = 0$  or one of the biases has the same level in the entire population.<sup>21</sup>

<sup>20</sup>Similar results can also be obtained also with a selection process in continuous time.

<sup>21</sup>If all types have the same cursedness,  $\chi$ , then  $\eta(\chi) = 1$ ,  $\eta(\psi) = \eta((\chi, \psi))$ ,  $f_\eta(\chi) = 1$ , and  $f_\eta(\psi) = f_\eta((\chi, \psi))$ , which implies that this dynamic coincides with the replicator dynamic. The same happens when there is a single  $\psi$ .

One interpretation of the hybrid-replicator dynamics is biological heredity. If one assumes that each trait (cursedness and perception bias) is controlled by a different locus (position in the DNA sequence), then the probability that each child inherits each trait from a different parent is equal to the biological recombination rate between these loci. This parameter is equal to 0.5 if the two loci are on two different chromosomes, and it is strictly between 0 and 0.5 if the two loci are in different locations in the same chromosome. A hybrid-replicator dynamic is an exact description of a selection process in a haploid population in which each individual carries one copy of each chromosome, and it is a stylized description that captures the important relevant properties of a selection process in a diploid population, like the human population, in which each individual carries two copies of each chromosome (see, e.g., [Maynard Smith 1971](#) and [Nowak \*et al.\* 1997](#) for examples of using stylized models of haploid populations when analyzing biological evolutionary processes in humans). One can show that the hybrid-replicator dynamics have the same implications on asymptotic stability as a more detailed description of diploid populations.<sup>22</sup>

An additional interpretation is that of a social learning process. The parameter  $r$  determines the frequency of new agents that independently choose two “mentors” and imitate a single trait from each; each of the remaining new agents chooses a single “mentor” and imitates both his traits. In both cases, the probability of choosing a specific agent as a mentor is proportional to that agent’s fitness. The standard implicit assumption in models of social learning in the economic literature is that agents always imitate a single “mentor” (see, [Weibull, 1997](#), and the references there). However, if mentors are characterized by several separate observable traits that may be observed in different domains, it seems plausible that new agents may combine different traits from different mentors.

## 5.2 Instability of Heterogeneous Populations

In order to facilitate the formal analysis presented in Section 5.3, we focus on studying the stability of homogenous populations that include a single incumbent type against the invasion of a single mutant type, rather than studying the stability of heterogeneous distributions against an invasion of heterogeneous groups of mutant types. The restriction to a single mutant type reflects the assumption that mutants are rare; it can be relaxed without affecting the results (but it makes for more cumbersome notation and definitions). The restriction to a single incumbent type is explained in this section where we informally sketch why

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<sup>22</sup>In particular, assuming that each trait is influenced by a different chromosome and that the “mutant” type can be “dominant” in both loci yields  $r = 0.5$ . Other plausible assumptions yield a value strictly between 0 and 0.5.

heterogeneous populations are not stable in our setup.

We begin by demonstrating why a heterogeneous distribution that includes two types in  $\Gamma$  is unstable. Observe that the support of a fixed point of a hybrid-replicator dynamic (with  $r > 0$ ) must be a product set (i.e.,  $\mathcal{X}_\eta \times \Psi_\eta$ ). Let  $\eta$  be a distribution with a support that includes two types in  $\Gamma$  ( $t$  and  $t'$ ) and the two hybrid types that combine a trait from each of these types:

$$\{t = (\chi, \psi_\chi^*), t' = (\chi', \psi_{\chi'}^*), (\chi, \psi_{\chi'}^*), (\chi', \psi_\chi^*)\}.$$

For simplicity, assume that  $\eta$  is symmetric:  $\eta(t) = \eta(t')$ , and  $\eta((\chi, \psi_\chi^*)) = \eta((\chi', \psi_{\chi'}^*))$ , and denote  $\bar{\chi} = 0.5 \cdot (\chi + \chi')$ . Distribution  $\eta$  is not stable against an external mutant with type  $\bar{t} = (\bar{\chi}, \psi_{\bar{\chi}}^*)$  for low  $p$ 's because: (1) type  $\bar{t}$  has approximately the same fitness as types  $t$  and  $t'$ , and (2) the hybrid types that share one of the traits of the mutant type  $\bar{t}$ ,  $(\bar{\chi}, \psi_{\chi'}^*)$ ,  $(\bar{\chi}, \psi_\chi^*)$ ,  $(\chi, \psi_{\bar{\chi}}^*)$ , and  $(\chi', \psi_{\bar{\chi}}^*)$ , are substantially closer to  $\Gamma$  than are the hybrid incumbent types  $(\chi, \psi_\chi^*)$  and  $(\chi', \psi_{\chi'}^*)$ . Thus they achieve higher payoff in the barter trade. This implies that  $\bar{\chi}$  and  $\bar{\psi}$  have higher average fitness than the other biases (i.e.,  $f_\eta(\bar{\chi}) > f_\eta(\chi), f_\eta(\chi')$  and  $f_\eta(\bar{\psi}) > f_\eta(\psi), f_\eta(\psi')$ ). By (4), a hybrid-replicator dynamic implies that mutant  $\bar{t}$  succeeds in invading the population (his fitness is as high as that of the incumbents, and the fitness of each of his traits is strictly higher than that of the incumbents' traits).

This argument can be extended to general heterogeneous distributions. Observe that the payoff of the barter trade is strictly concave in a trader's thresholds (see part 2 in the proof of Proposition 1, and assume trade occurs with positive probability). In addition, the thresholds of the traders are strictly increasing (decreasing) in the cursedness level (perception bias). These two observations imply that “intermediate” types use intermediate thresholds; that is, if each bias of type  $t$  is a mixed average of the respective biases of types  $t_1$  and  $t_2$ , then its threshold strategy is strictly between the threshold strategies of types  $t_1$  and  $t_2$ . If a heterogeneous population,  $\eta$ , is a fixed point of the dynamic, then different types must use different thresholds (because the support of the population is a product set, and two types that differ in only one of the traits must have different threshold strategies). Intuitively, due to these observations, there is a “mean” type  $\bar{t}$  with biases that are weighted averages of the incumbents' biases, such that it uses thresholds that are weighted averages of the incumbents' thresholds, and a similar property holds for his “hybrid” offspring. (The explicit expression of  $\bar{t}$  involves technical difficulties and this is why we only sketch an intuitive argument.) Finally, due to strict concavity, mutant agents with type  $\bar{t}$  and their “hybrid” offspring would achieve, on average, strictly higher payoffs in the barter trade relative to the incumbents. For a sufficiently low  $p$ , this implies that such mutants could successfully invade the population.

### 5.3 Stability of Types

In this section we analyze the stability of types given an underlying hybrid-replicator dynamic, which is perturbed by allowing at each generation a small probability that a small mass of “mutant” types invades the population.

Our first result shows global convergence to  $\Gamma$  from any initial type. Any type  $t = (\chi, \psi)$  outside  $\Gamma$ , provided that  $p$  is sufficiently low, will be eliminated by any mutant with the same cursedness level as  $t$  and a perception bias strictly closer to  $\Gamma$  but not too far from  $\psi$ . Formally, let  $g^\tau(\eta)$  be the induced distribution of type  $\tau$  generations after an initial distribution  $\eta$  (i.e.,  $g^2(\eta) = g(g(\eta))$ , etc.).

**Definition 5.** Type  $t' \in T$  eliminates  $t \in T$  if for any  $\epsilon \in (0, 1)$ :  $\lim_{\tau \rightarrow \infty} g^\tau(\epsilon \cdot t' + (1 - \epsilon) \cdot t) = t'$ .

**Proposition 3** (Convergence towards  $\Gamma$ ). *For every type  $t = (\chi, \psi) \in T \setminus \Gamma$  there exists  $\bar{p}, \bar{\beta} > 0$  such that for  $0 \leq p \leq \bar{p}$  and  $0 < \beta \leq \bar{\beta}$ , type  $t_\beta = (\chi, \beta \cdot \psi_\chi^* + (1 - \beta) \cdot \psi)$  eliminates type  $t$ .*

The sketch of the proof is as follows. For each surplus coefficient  $\alpha$ , the unique optimal threshold is  $\alpha \cdot \mu_\alpha$ . Due to Proposition 1, the fact that  $\psi \neq \psi_\chi^*$  implies that there is an interval of  $\alpha$ 's for which type  $t$  uses suboptimal thresholds. Moreover, one can show that for each  $\alpha$  for which type  $t$  uses a too low (high) threshold, type  $(\chi, \psi_\chi^*)$  uses a too high (low) threshold. Thus, for a sufficiently low  $\beta$ , the mixed perception bias  $\beta \cdot \psi_\chi^* + (1 - \beta) \cdot \psi$  induces thresholds that are strictly between type  $t$ 's thresholds and the optimal thresholds. This implies that type  $t_\beta$  achieves a strictly higher payoff against type  $t$ , and against any mixed population of these two types. Finally, since hybrid-replicator dynamics are payoff-monotone when all types share the same cursedness level, type  $t_\beta$  eliminates type  $t$ .

Given Proposition 3, we can expect that any population outside  $\Gamma$  will converge to  $\Gamma$  in several steps. Our second result shows that all types in  $\Gamma$  are stable in the following sense: for each incumbent type  $t \in \Gamma$  and mutant type  $t' \in T$ , if  $p$  is sufficiently small then after a small invasion of mutants the population never moves far away from its pre-entry state  $t$ , and it converges back to the pre-entry state in the long run. Formally:

**Definition 6.** Type  $t \in T$  is asymptotically stable against type  $t' \in T$  if for every  $\lambda \in (0, 1)$  there exists  $\epsilon$  such that for every  $\epsilon' \in (0, \epsilon)$ :

1. (Lyapunov stability)  $g^\tau(\epsilon' \cdot t' + (1 - \epsilon') \cdot t)(t) > 1 - \lambda$  for every  $\tau \in \mathbb{N}$ ; and
2.  $\lim_{\tau \rightarrow \infty} g^\tau(\epsilon' \cdot t' + (1 - \epsilon') \cdot t) = t$ .

Otherwise, we say that type  $t$  is asymptotically unstable against  $t'$ .

**Proposition 4** (Stability of  $\Gamma$ ). *Assume that  $r > 0$  and let  $t \in \Gamma$  and  $t' \in T$  where  $t \neq t'$ . Then, there exists  $\bar{p} > 0$  such that for every  $p \leq \bar{p}$ , type  $t$  is asymptotically stable against type  $t'$ .*

The sketch of the proof is as follows. First, we adapt a related result of [Waldman \(1994\)](#), and show that type  $t$  is asymptotically stable against type  $t'$  if the fitness of type  $t'$  is not more than  $\frac{1}{1-r}$  times the fitness of type  $t$ , and in addition the fitness of the hybrid types that share one trait of  $t$  and one trait of  $t'$  is lower than the fitness of  $t$ . The intuition for this is that as long as type  $t'$  and the hybrid types are rare, then at each generation the frequency of offspring of type  $t'$  is approximately  $(1-r)$  times its relative fitness, while its remaining offspring are hybrid (i.e., share one of its traits). Thus, if  $(1-r)$  times the fitness of  $t'$  and the fitness of each hybrid type is smaller than the fitness of  $t$ , then the frequency of all types other than type  $t$  converges to 0. Then we observe that [Proposition 1](#) implies that type  $t$  best-replies to itself, and that any type that shares one of the traits with  $t$  achieves a strictly smaller payoff against type  $t$ . Combining the lemma and the observation immediately completes the proof.

An important feature of hybrid-replicator dynamics (for  $r > 0$ ) is that in these dynamics the rational type  $(0, I)$  does *not* eliminate all other types when  $p > 0$ . A simple adaptation of the proof of [Proposition 4](#) yields the following:

**Corollary 3** (Rational Type Cannot Enter Population). *Any type that is sufficiently close to  $\Gamma$  and sufficiently far from  $(0, I)$  is asymptotically stable against  $(0, I)$  for a sufficiently small  $p > 0$ .*

The reason for this is that while type  $(0, I)$  strictly outperforms the incumbent type, its relative fitness is less than  $\frac{1}{1-r}$  (assuming the incumbent type is sufficiently close to  $\Gamma$  and  $p > 0$  is sufficiently small), and the hybrid types that have one unbiased trait are strictly outperformed by the incumbent type that has two biases that partially compensate for each other.

Note that parameter  $\bar{p}$  in [Proposition 4](#) depends on  $t$  and  $t'$ , and converges to 0 when  $t' \rightarrow t$ . When  $p$  is small but positive, type  $t \in \Gamma$  is asymptotically stable against all mutant types except those that are very close to  $t$  and have slightly smaller biases (such a close mutant,  $t'$ , can invade because it obtains almost the same payoff in the barter interaction and a strictly higher payoff in the non-barter activity). By continuity, a similar property holds for incumbent types that are very close to  $\Gamma$ . In other words, a type  $t$  that is close

to  $\Gamma$  may be invaded by some other type  $t'$  only if the latter type is close both to  $\Gamma$  and to  $t$ . Due to the Lipschitz continuity of  $v$ , one can show that each small neighborhood of  $\Gamma$  is an asymptotically stable set for a sufficiently small  $p > 0$ , and that each type in this neighborhood is asymptotically unstable only against other types that are very close.

Proposition 4 shows that a biased type close enough to  $\Gamma$  can survive as a unique incumbent type for a long time (that is, in the “long run”). Only the rational type, however, is asymptotically stable against all types, and therefore if we wait long enough the population will eventually be composed of that type (that is, the rational type is the only one stable in the “ultra-long run”). The latter implication is a result of the continuity of types: for each  $p > 0$  there exists a sufficiently close type that can invade the population. Restricting the set of feasible types to a large finite set (as in Waldman, 1994) would yield asymptotic stability of each type that is close enough to  $\Gamma$  (i.e., there exists  $\bar{p} > 0$  such that for every  $p < \bar{p}$ , each feasible type close enough to  $\Gamma$  is stable against all feasible types).

## 6 Discussion

### 6.1 Random Traits and Empirical Prediction

For simplicity, we have described agents with a particular type as having the same cursedness level and the same perception bias. However, as is standard in the evolutionary literature, the results remain qualitatively the same if the biases are only partially heritable; that is, if cursedness and perception bias that an agent of type  $(\chi, \psi)$  exhibits are  $\chi + \epsilon_\chi$  and  $\psi + \epsilon_\psi$ , respectively, where  $\epsilon_\chi$  and  $\epsilon_\psi$  are random “noise” factors unrelated to the agent’s type.

Combining this interpretation of our model with the instability of a heterogeneous distribution of types (Section 5.2) yields the following empirical prediction. In a specific society that shares the same evolutionary history, agents are expected to have on average a positive cursedness level and a positive endowment effect, and these traits should be uncorrelated (as society should be concentrated around a single type in  $\Gamma$ , and the heterogeneity reflects random type-unrelated “noise”). If one can compare different societies that have independent evolutionary histories, then these societies are expected to be at different states in  $\Gamma$ , and therefore one expects a strong positive correlation between the average cursedness and the average endowment effect across societies. We are unaware of any existing experimental evidence that can either validate or falsify this prediction.

## 6.2 Richer Environments

The model described in Section 4 (with slight modifications) can capture an environment in which agents randomly engage in one of *many* barter-trade interactions. Specifically, our stability results in Section 5 can be adapted to hold also when in each period players interact in a slightly different barter-trade interaction (rather than playing the same game with high probability while engaging in a completely different activity with some low probability, as in the model above).<sup>23</sup>

For concreteness, consider the following example. Assume that each period traders' private signals are drawn from a different distribution. The distribution is chosen i.i.d. each period according to a normal random variable  $\nu_\sigma \sim N(0, \sigma^2)$ . Given  $\nu_\sigma$ , the private value of each trader is distributed according to the CDF  $F_{\nu_\sigma}(x) = \left(\frac{x-L}{H-L}\right)^{\exp(\nu_\sigma)}$ . Both agents publicly observe the realization of  $\nu_\sigma$  before they decide whether or not to trade (the case in which  $\nu_\sigma$  is unobserved by the traders is equivalent to playing a fixed barter trade). This environment can be embedded in our model. Let the function  $u$  be defined as the payoff function in the barter trade with the distribution of private signals  $F_0(x)$ , and the function  $v(\sigma)$  be defined as the expected difference between the payoff in the game with distribution  $F_{\nu_\sigma}(x)$  and the payoff in the game  $F_0(x)$  (where the expectation is taken with respect to  $\nu_\sigma$ ). Now let  $u_\sigma = u + v(\sigma)$  be the expected payoff in such an environment. Note that the standard deviation  $\sigma$  replaces  $p$  as the magnitude of the perturbation in the model. Observe that: (1) the function  $u_\sigma(t, \eta)$  describes the expected payoff of type  $t$  in population  $\eta$  in this environment; (2)  $v(\sigma) \sim O(\sigma)$  for a sufficiently small  $\sigma$ ; and (3) function  $v(\sigma)(t, \eta)$  is Lipschitz continuous and bias-monotone. Due to these observations, all our stability results (Propositions 2-4) can be extended to this setup in a relatively straightforward way when  $\sigma$  is sufficiently small. This example can be generalized to any family of ex-ante distributions of private values, as long as the variance among these distributions is sufficiently small.

## 6.3 Different Ways to Capture the Biases

Our qualitative results are robust to the exact way in which the two biases are captured in the model. One can capture cursedness by following a different approach than [Eyster & Rabin \(2005\)](#) (e.g., by adopting the Analogy Based Expectation Equilibrium approach, as in [Jehiel & Koessler, 2008](#)). Since we allow a large set of perception bias functions,

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<sup>23</sup>The results can also be adapted to a setup in which both kinds of perturbations are present: players play with high probability a barter-trade game, but this game may be slightly-different each time, and with some small probability they engage in a completely different interaction.

we can still find a set of types for which the biases fully compensate each other also for that alternative representation of cursedness. One can claim that not every perception bias function is plausible, because biased individuals behave in a “simple” manner (for example, one can claim that  $\psi$ 's must be linear). However, even for a large class of restricted sets of perception bias function, where the two biases cannot fully compensate for each other, the results of Section 5 continue to hold. This is due to the fact that under the hybrid replicator dynamic biases survive in the long run even if they only approximately compensate for each other.

## 6.4 Different Barter-Trade Mechanisms

Our results remain qualitatively similar to other variants of barter with indivisible goods, such as having interdependent values instead of common values, or having a different surplus coefficient for each trader. One can also consider trade with divisible goods in which the relative price of exchange between the commodities is endogenously determined by haggling. Such trading mechanisms turn out to be analytically intractable (though numeric analysis suggests that similar results may hold in such a setup). The analysis can be rendered tractable by assuming that the price is determined by a noisy double auction: if the buyer's price is lower than the seller's price no trade occurs, while if it is higher then the probability of trade is increasing linearly in the difference between the two bids, and the price is the mean of the two bids. In this specific setup the results remain qualitatively similar.

# A Technical Appendix

## A.1 Proof of Lemma 1 (Existence of Equilibrium Configurations)

Denote by  $F$  the absolutely continuous cumulative distribution function of  $\mathbf{x}_i$ . The explicit formula for the expected value of the partner's good conditional on his agreement to trade,  $\mu_\alpha(\eta, b)$ , is

$$\mu_\alpha(\eta, b) = \frac{\sum_{t \in \text{supp}(\eta)} \eta(t) \cdot F(b(t)(\alpha)) \cdot \mu_{\leq b(t)(\alpha)}}{\sum_{t \in \text{supp}(\eta)} \eta(t) \cdot F(b(t)(\alpha))}, \quad (5)$$

and if the denominator equals 0 (i.e., no agent ever agrees to trade given coefficient  $\alpha$ ), let  $\mu_\alpha(\eta, \beta) = L$ .

Let  $\{t_i = (\chi_i, \psi_i)\}_{i \leq n}$  be the finite set of types in population  $\eta$  ( $n$  is the arbitrary number of types). Substituting (5) in (1), configuration  $(\eta, b)$  is an equilibrium if and only if for each

$\alpha \in \left[1, \frac{H}{L}\right]$  and for each type  $i \leq n$ :

$$\psi(b(t_i)(\alpha)) = \alpha \cdot \left( \chi_i \cdot \mu + (1 - \chi_i) \cdot \frac{\sum_{j \leq n} \eta_j(t_j) \cdot F(b(t_j)(\alpha)) \cdot \mu_{\leq b(t_j)(\alpha)}}{\sum_{j \leq n} \eta_j(t_j) \cdot F(b(t_j)(\alpha))} \right). \quad (6)$$

Fix any  $\alpha \in \left[1, \frac{H}{L}\right]$ . Let  $x_i = b(t_i)(\alpha)$  and  $\eta_i = \eta(t_i)$ . Then (6) is reduced to the following set of  $n$  equations:

$$\forall i \leq n \quad \psi(x_i) = \alpha \left( \chi_i \cdot \mu + (1 - \chi_i) \cdot \frac{\sum_{j \leq n} \eta_j \cdot F(x_j) \cdot \mu_{\leq x_j}}{\sum_{j \leq n} \eta_j \cdot F(x_j)} \right). \quad (7)$$

For each  $i \leq n$ , let  $g_{i,\alpha} : [L, \mu] \rightarrow [L, \alpha \cdot \mu]$  be a function that assigns, for any expected value of an object that is traded in the population  $v$ , the threshold of agent with type  $t_i$ . Formally:

$$g_{i,\alpha}(v) = \psi^{-1}(\alpha \cdot (\chi_i \cdot \mu + (1 - \chi_i) \cdot v)). \quad (8)$$

Notice that in equilibrium  $x_i = b(t_i)(\alpha) = g_{i,\alpha}(\mu_\alpha(\eta, b))$ . Now let  $h : [L, \alpha \cdot \mu]^n \rightarrow [L, \mu]$  be the function that assigns, to a profile of thresholds that are used in population  $\eta$ ,  $(x_1, \dots, x_n)$ , the expected value of an object that is traded in that population. Formally:

$$h_\eta(x_1, \dots, x_n) = \frac{\sum_{j \leq n} \eta_j \cdot F(x_j) \cdot \mu_{\leq x_j}}{\sum_{j \leq n} \eta_j \cdot F(x_j)}.$$

Notice that  $\mu_\alpha(\eta, b) = h_\eta[b(t_1)(\alpha), \dots, b(t_n)(\alpha)]$ . Finally, let  $f : [L, \mu] \rightarrow [L, \mu]$  be defined as follows:

$$f_\alpha(v) = h_\eta(g_{1,\alpha}(v), \dots, g_{n,\alpha}(v)).$$

Observe that any solution to the equation  $v = f_\alpha(v)$  induces thresholds that can be used as part of an equilibrium when the coefficient surplus is equal to  $\alpha$ ; that is,  $v = \mu_\alpha(\eta, b)$  and  $b(t_i)(\alpha) = g_{i,\alpha}(v)$ . We now show that there is at least one solution for  $v = f_\alpha(v)$ . First observe that since we assume that  $F$  and  $\psi$  are continuous functions then  $g$ ,  $h$ , and  $f$  are a continuous. Second, notice that for each  $\alpha \in \left[1, \frac{H}{L}\right]$   $f_\alpha(L) \geq L$  and  $f_\alpha(\mu) \leq \mu$ . Thus  $f_\alpha(v) = v$  at some  $v \in [L, \mu]$ .

Finally, we have to show that there exists a *continuous* function  $v^* : \left[1, \frac{H}{L}\right] \rightarrow [L, H]$  such that for each  $\alpha \in \left[1, \frac{H}{L}\right]$   $f_\alpha(v^*(\alpha)) = v^*(\alpha)$ .<sup>24</sup> Let  $v^*(\alpha)$  be the largest fixed point of  $f_\alpha$  (i.e., for each  $\alpha$   $v^*(\alpha) = \arg \max_{v \in [1, \frac{H}{L}]} f_\alpha(v) = v$ ). The fact that  $\psi^{-1}$  and  $h$  are continuous and increasing functions and the linear dependency in  $\alpha$  in (8) implies the continuity of  $v^*(\alpha)$

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<sup>24</sup>We have to show the continuity of  $v^*(\alpha)$  in order to have all types using a continuous threshold strategy as a function of surplus coefficient (as assumed in the definition of a strategy in Section 2.3).

with respect to  $\alpha$ .

Note that the above  $v^*(\alpha)$  is the function that selects the equilibria with maximal trade. All of our results remain the same if one chooses a different continuous function  $v^*(\alpha)$ , such as the one that selects the smallest fixed point of  $f_\alpha$  (and minimizes the probability of trade).

## A.2 Formal Definition of the Payoff Function of $G_0$

In this section we explicitly state the payoff of each type in the population game  $G_0$ . Let  $u(s_1, s_2 | \alpha, x_1, x_2)$  be trader's 1 payoff when his signal is  $x_1$  and he plays  $s_1$  while his partner, trader 2, has a signal  $x_2$  and plays  $s_2$ , and when the public signal is  $\alpha$ :

$$u_0(s_1, s_2 | \alpha, x_1, x_2) = \begin{cases} \alpha \cdot x_2 & x_1 \leq s_1(\alpha) \text{ and } x_2 \leq s_2(\alpha) \\ x_1 & \text{else.} \end{cases}$$

Now, let  $u(s_1, s_2)$  be the expected payoff of an agent with strategy  $s_1$  who faces a partner with strategy  $s_2$ , where the expectation is taken with respect to the values of of the signals  $\mathbf{x}_1, \mathbf{x}_2$  and  $\alpha$ .

$$u(s_1, s_2) = \int_{\alpha=1}^{H/\mu} \int_{x_1=L}^H \int_{x_2=L}^H u_0(s_1, s_2 | \alpha, x_1, x_2) dF_{\mathbf{x}_2} dF_{\mathbf{x}_1} dF_\alpha,$$

where  $F_j$  is the CDF of random variable  $i \in \{\alpha, \mathbf{x}_1, \mathbf{x}_2\}$ . Finally, given type  $t \in T$  and an equilibrium configuration  $(\eta, b^*(\eta))$ , define  $u(t, \eta)$  as the expected payoff of a type  $t \in T$  agent who faces an opponent randomly selected from population  $\eta$ :

$$u(t, \eta) = \sum_{t' \in \text{supp}(\eta)} \eta(t') \cdot u[s_t^*(\alpha)(\eta, b^*(\eta)), b^*(\eta)(t')].$$

## A.3 Proof of Proposition 1 (Characterization of Equilibria in $G_0$ )

*Proof.* The proof includes the following parts:

1. Definitions and notations:

- (a) *Probability of trade:* let  $q(\alpha | \eta)$  be the probability that a random partner from population  $\eta$  agrees to trade given  $\alpha$ . Note, that  $q(\alpha | \eta) > 0$  iff  $\exists t \in \text{supp}(\eta)$  with  $b_\eta^*(t)(\alpha) > L$ .

- (b) *Expected payoff of a threshold*: let  $u(x, \alpha|\eta)$  be the expected payoff of a player who uses threshold  $x \in [L, H]$ , and faces a distribution of types  $\eta$  (which plays according to  $b_\eta^*$ ) conditional on the coefficient being  $\alpha$ .
- (c) *Incumbents*: Given a distribution of types  $\eta$  we shall call the types in  $\text{supp}(\eta)$  the incumbents.
- (d) *Type's threshold strategy*: for each type  $t = (\chi, \psi)$  let strategy  $s_t^*(\alpha|\eta)$  be the threshold strategy of type  $t$  who faces population  $\eta$ ; that is, for each  $\alpha \in [1, \frac{H}{L}]$   $s_t^*(\alpha|\eta)$  is the unique solution to the equation:

$$\psi(s_t^*(\alpha|\eta)) = \alpha \cdot (\chi \cdot \mu + (1 - \chi) \cdot \mu_\alpha(\eta, b_\eta^*)).$$

- (e) *Mean threshold*: For each  $\alpha \in [1, \frac{H}{L}]$  and distribution of types  $\eta \in \Delta(T)$ , let  $\bar{x}(\alpha|\eta)$  be the unique solution to the equation:  $\mu_{\leq \bar{x}(\alpha|\eta)} = \mu_\alpha(\eta)$ ; that is, in an homogenous population in which everyone uses threshold  $\bar{x}(\alpha|\eta)$ , the mean value of a traded good is the same as in population  $\eta$  (given  $\alpha$ ).

2. The expected payoff of a threshold is given by the following formula:

$$u(x, \alpha|\eta) = u(\alpha \cdot \mu_\alpha, \alpha|\eta) - q(\alpha|\eta) \cdot |F(x) - F(\alpha \cdot \mu_\alpha)| \cdot E(|y - \alpha \cdot \mu_\alpha| \mid y \in [\alpha \cdot \mu_\alpha, x]), \quad (9)$$

where, with slight abuse of notation,  $[\alpha \cdot \mu_\alpha, x] = [x, \alpha \cdot \mu_\alpha]$  if  $x < \alpha \cdot \mu_\alpha$ . The *optimal threshold*, which induces the maximal payoff, is  $x = \alpha \cdot \mu_\alpha$  because it results in trade iff the trader's good is worth less than the expected value of a trading partner. Using a different threshold  $x$  yields a wrong decision with probability  $q(\alpha|\eta) \cdot |F(x) - F(\alpha \cdot \mu_\alpha)|$ . Conditional on making a wrong decision and the partner's agreement to trade, the expected loss from trade is equal to  $E(|y - \alpha \cdot \mu_\alpha| \mid y \in [\alpha \cdot \mu_\alpha, x])$  (as this the expected difference between the value of the trader's good and the conditional expected value of his partner). Observe that  $u(x, \alpha|\eta)$  is concave w.r.t.  $x$ , and strictly concave if  $q(\alpha|\eta) > 0$ .

3. The previous step immediately implies that type  $(0, I)$  (Which always choose the optimal threshold of  $\alpha \cdot \mu_\alpha$ ) weakly outperforms any other type (i.e.,  $u((0, I), \eta) \geq u(t, \eta)$  for each  $t \in T$  and  $\eta \in \Delta(T)$ ), and strictly outperforms if there is any  $\alpha$  such that:  $q(\alpha|\eta) > 0$  and  $x \neq \alpha \cdot \mu_\alpha$ .
4. The "if" side. Let  $\eta \in \Delta(T)$  be a Nash equilibrium of  $G_0$ . We prove that  $\text{supp}(\eta) \in \Gamma$ .

- (a) In any Nash equilibrium all types use the optimal thresholds for all  $\alpha$ s; that is,  $\forall t \in \text{supp}(\eta)$  and  $\alpha \in \left[1, \frac{H}{L}\right]$   $b_\eta^*(t)(\alpha) = \alpha \cdot \mu_\alpha(\eta)$ .

Assume in contrast that there is at least one value of  $\alpha$  for which one of the incumbent types uses a non-optimal threshold. This set of  $\alpha$ 's is defined as

$$A_\alpha = \left\{ \alpha \mid \exists t_0 \in \text{supp}(\eta) \text{ s.t. } b_\eta^*(t_0)(\alpha) \neq \alpha \cdot \mu_\alpha(\eta) \right\}.$$

From 3 and the continuity of the threshold strategies an incumbent type in a Nash equilibrium distribution can use a non-optimal threshold in an  $\alpha$  only if  $q(\alpha|\eta) = 0$ .

Let  $\bar{\alpha}$  be the supremum of  $A_\alpha$ . Consider first the case where  $\bar{\alpha} = \frac{H}{L}$ . In such a case, the assumptions that each  $\psi$  is strictly increasing and  $\psi(H) \leq H$  implies that  $\psi(x) < H$  for each  $x < H$ , and therefore  $q(\alpha|\eta) > 0$  for  $\alpha$ 's sufficiently close to  $\frac{H}{L}$ , and  $u((0, I), \eta) > u(t, \eta)$  for some type  $t \in \text{supp}(\eta)$ .

Now consider the case where  $\bar{\alpha} < \frac{H}{L}$ . All types play the rational threshold for  $\alpha > \bar{\alpha}$ , and by continuity of  $b_\eta^*(t)(\alpha)$  all agents play the rational threshold at  $\bar{\alpha}$ . Observe, that the rational thresholds are always strictly larger than  $L$ , and this implies that  $q(\alpha|\eta) > 0$  for each  $\alpha \geq \bar{\alpha}$ . By continuity of  $b_\eta^*(t)(\alpha)$ , there exist an interval of  $\alpha$ s such that:  $\alpha < \bar{\alpha}$ ,  $q(\alpha|\eta) > 0$  and  $\alpha \in A_\alpha$ , and this implies that  $\eta$  cannot be a Nash equilibrium.

- (b) If there exists  $t_0 = (\chi_0, \psi_0) \in T \setminus \Gamma$  in  $\text{supp}(\eta)$  then there exists an  $\alpha$  such that type  $t_0$  does not use the optimal threshold: i.e.,  $\exists \alpha_0 \in \left[1, \frac{H}{L}\right]$   $b_\eta^*(t_0)(\alpha) \neq \alpha \cdot \mu_\alpha(\eta)$ . Assume to the contrary that for each  $\alpha \in \left[1, \frac{H}{L}\right]$ , all incumbents  $t \in \text{supp}(\eta)$  use the ‘‘optimal’’ threshold  $b_\eta^*(t)(\alpha) = x^*(\alpha) \equiv \alpha \cdot \mu_\alpha$ . This implies that  $\forall \alpha \in \left[1, \frac{H}{L}\right]$ :

$$\psi_0(\alpha \cdot \mu_\alpha) = \alpha \cdot (\chi_0 \cdot \mu + (1 - \chi_0) \cdot \mu_\alpha).$$

The fact that all players use the optimal thresholds implies that  $\mu_\alpha = \mu_{\leq x^*(\alpha)}$ , and therefore  $x^*(1) = L$  and  $x^*\left(\frac{H}{L}\right) = H$ . By continuity,  $x^*(\alpha)$  obtains all values in  $[L, H]$ . Given  $x^*(\alpha) \equiv \alpha \cdot \mu_\alpha$  we can rewrite the indifference condition above as follows:  $\forall x^* \in [L, H]$ ,

$$\psi_0(x^*) = \alpha \cdot \left( \chi_0 \cdot \mu + (1 - \chi) \cdot \frac{x^*}{\alpha} \right) = \chi_0 \cdot \frac{\mu}{\mu_{\leq x^*}} \cdot x^* + (1 - \chi) \cdot x^* = \psi_{\chi_0}^*(x^*),$$

which implies that  $\psi_0(x) = \psi_{\chi_0}^*(x)$  – a contradiction to the assumption that  $t_0 \in$

$T \setminus \Gamma$ .

5. The “only if” side and the “moreover” statement. Let  $\eta_0$  be a distribution with  $\text{supp}(\eta_0) \in \Gamma$ . We prove that  $\eta_0$  is a Nash equilibrium, that all incumbents use the same threshold strategy, and that each type  $t' \notin \Gamma$  is strictly out-performed (i.e.,  $u(t', \eta) < u(t_0, \eta)$  for each  $t_0 \in \text{supp}(\eta_0)$ ).

(a) In Section 3.1 we have shown that if all other agents use the “rational” threshold that is defined by  $x^*(\alpha) = \alpha \cdot \mu_{<x^*(\alpha)}$ , then a type  $t \in \Gamma$  also uses  $x^*(\alpha)$ . Thus,  $b^* = x^*(\alpha)$  is an equilibrium behavior induced by distribution  $\eta_0$ . In what follows we show that there are no other equilibrium behaviors induced by distribution  $\eta_0$ .

(b) Assume, in contrast, some other equilibrium behavior, that induces  $\bar{x}(\alpha|\eta_0) \neq x^*(\alpha)$

i. If  $\bar{x}(\alpha|\eta) > \alpha \cdot \mu_\alpha(\eta_0)$  then  $s_t^*(\alpha|\eta_0) < \bar{x}(\alpha|\eta_0)$  for each  $t = (\chi, \psi_\chi^*) \in \Gamma$ . To see why recall that  $\psi_\chi^*$  is strictly increasing, and observe that  $s_t^*(\alpha|\eta_0)$  is the unique solution to the following equation:

$$\begin{aligned} \psi_\chi^*(s_t^*(\alpha|\eta_0)) &= \alpha \cdot (\chi \cdot \mu + (1 - \chi) \cdot \mu_\alpha(\eta_0)) \\ &< \chi \cdot \frac{\mu}{\mu_{\leq \bar{x}(\alpha|\eta_0)}} \cdot \bar{x}(\alpha|\eta_0) + (1 - \chi) \cdot \bar{x}(\alpha|\eta_0) = \psi_\chi^*(\bar{x}(\alpha|\eta_0)), \end{aligned}$$

where the strict inequality is implied by  $\bar{x}(\alpha|\eta_0) > \alpha \cdot \mu_\alpha(\eta_0)$  and  $\mu_\alpha(\eta_0) = \mu_{\leq \bar{x}(\alpha|\eta_0)}$ . Since  $\bar{x}(\alpha|\eta)$  is the average threshold used in the population, we get a contradiction.

ii. By analogous argument, if  $\bar{x}(\alpha|\eta_0) < \alpha \cdot \mu_\alpha$  then  $s_t^*(\alpha|\eta_0) > \bar{x}(\alpha|\eta_0)$  for each  $t = (\chi, \psi_\chi^*) \in \Gamma$ , and we get again a contradiction.

iii. Therefore, it must be that  $\bar{x}(\alpha|\eta_0) = \alpha \cdot \mu_\alpha$ . In such a case, by an analogous argument,  $s_t^*(\alpha|\eta_0) = \bar{x}(\alpha|\eta_0) = x^*(\alpha)$  for each  $t = (\chi, \psi_\chi^*) \in \Gamma$ .

(c) The previous parts immediately imply that if  $\text{supp}(\eta_0) \in \Gamma$  then all incumbent types use threshold strategy  $x^*(\alpha)$  and are internally-equivalent. Moreover, this threshold strategy is the optimal one, and this implies that  $\eta_0$  is a Nash equilibrium.

(d) Finally, we can use a similar argument to 4b to show that for any  $\alpha$  there is a positive probability of trade, and therefore any type  $t' \notin \Gamma$ , that uses non-optimal threshold for some  $\alpha$ 's, has a strictly lower payoff compared to the incumbents

□

## A.4 Proof of Proposition 2 (Unique Equilibrium in $G_P$ )

*Proof.* Let  $t = (\chi, \psi) \in T$ ,  $t \neq (0, I)$ . We have to show that  $u_p((0, I), (0, I)) > u_p(t, (0, I))$  and  $u_p((0, I), t) > u_p(t, t)$ .

1. Case I:  $t \in \Gamma \setminus (0, I)$ . Observe this implies  $\chi > 0$  and  $\psi \succ I$ . Therefore  $v((0, I), \eta) > v(t, \eta)$  for each  $\eta \in \Delta(T)$ . By part (3) of the proof of Prop. 1  $u_0((0, I), \eta) \geq u_0(t, \eta)$ . Thus,  $u_p((0, I), \eta) > u_p(t, \eta)$  for each  $\eta \in \Delta(T)$ . In particular,  $u_p((0, I), (0, I)) > u_p(t, (0, I))$  and  $u_p((0, I), t) > u_p(t, t)$ .
2. Case II:  $t \notin \Gamma$ . By analogous arguments to part (4b) of the proof of Prop. 1  $u_0((0, I), t) > u_0(t, t)$  and  $u_0((0, I), (0, I)) > u_0(t, (0, I))$ . The bias-monotonicity assumption implies that  $v((0, I), (0, I)) \geq v(t, (0, I))$ . These inequalities imply that  $u_p((0, I), (0, I)) > u_p(t, (0, I))$  and  $u_p((0, I), t) > u_p(t, t)$ .

□

## A.5 Formal Definition of the Hybrid-Replicator Dynamics

In this section we formalize the definition of the transition function  $g : \Delta(T) \rightarrow \Delta(T)$  of the distribution of types, which is described informally in Section 5.1. The relative fitness  $f_\eta(t)$  of type  $t$  in population  $\eta$  is

$$f_\eta(t) = \frac{\phi + u_p(t, \eta)}{\phi + E(u_p(t, \eta))} = \frac{\phi + u_p(t, \eta)}{\phi + \sum_{t' \in \text{supp}(\eta)} \eta(t') \cdot u_p(t', \eta)}, \quad (10)$$

where  $\phi \geq 0$  is the background expected number of offspring for an individual (unrelated to his payoff in the population game). Let  $\mathcal{X}_\eta$  and  $\Psi_\eta$  be the cursedness levels and the perception biases in population  $\eta$ :

$$\mathcal{X}_\eta = \{\chi \in [0, 1] \mid \exists \psi \in \Psi \text{ s.t. } (\chi, \psi) \in \text{supp}(\eta)\},$$

$$\Psi_\eta = \{\psi \in \Psi \mid \exists \chi \in [0, 1] \text{ s.t. } (\chi, \psi) \in \text{supp}(\eta)\}.$$

For each  $\chi \in \mathcal{X}_\eta$  ( $\psi \in \Psi_\eta$ ) define  $\eta(\chi)$  ( $\eta(\psi)$ ) as the total frequency of types with cursedness level  $\chi$  (perception bias  $\psi$ ):

$$\eta(\chi) = \sum_{\psi \in \Psi_\eta} \eta((\chi, \psi)) \quad \left( \eta(\psi) = \sum_{\chi \in \mathcal{X}_\eta} \eta((\chi, \psi)) \right),$$

and define  $f_\eta(\chi)$  ( $f_\eta(\psi)$ ) as the mean relative fitness of types with cursedness level  $\chi$  (perception bias  $\psi$ ):

$$f_\eta(\chi) = E(f_\eta((\chi, \psi)) | \psi \in \Psi_\eta) = \sum_{\psi \in \Psi_\eta} \frac{\eta((\chi, \psi))}{\eta(\chi)} \cdot f_\eta((\chi, \psi))$$

$$\left( f_\eta(\psi) = E(f_\eta((\chi, \psi)) | \chi \in \mathcal{X}_\eta) = \sum_{\chi \in \mathcal{X}_\eta} \frac{\eta((\chi, \psi))}{\eta(\psi)} \cdot f_\eta((\chi, \psi)) \right).$$

Lastly, the transition function is (for every  $(\chi, \psi) \in \mathcal{X}_\eta \times \Psi_\eta$ )

$$g(\eta)((\chi, \psi)) = (1 - r) \cdot \eta((\chi, \psi)) \cdot f_\eta((\chi, \psi)) + r \cdot \eta(\chi) \cdot f_\eta(\chi) \cdot \eta(\psi) \cdot f_\eta(\psi).$$

## A.6 Proof of Proposition 3 (Convergence Towards $\Gamma$ )

*Proof.* The proof uses definitions and notations that were introduced in the proof of Prop. 1. Assume an homogenous population  $\eta = t = (\chi, \psi)$  where  $t$  is an arbitrary type. Define  $t_\Gamma \equiv (\chi, \psi_\chi^*)$  as the type in  $\Gamma$  with the same cursedness as  $t$ .

1. By an analogous argument to part 4 of the proof of Prop. 1, there is an interval of  $\alpha$ 's such that: (1) type  $t$  induces trade with positive probability (i.e.,  $q(\alpha|t) > 0$ ); and (2) types  $t$  and  $t_\Gamma$  use different thresholds (i.e.,  $s_t^*(\alpha|\eta) \neq s_{t_\Gamma}^*(\alpha|\eta)$ ).
2. The optimal threshold is between the thresholds induced by types  $t$  and  $t_\Gamma$ : for each  $\alpha \in [1, \frac{H}{L}]$ , either  $s_{t_\Gamma}^*(\alpha|t) < \alpha \cdot \mu_\alpha < s_t^*(\alpha|t)$  or  $s_t^*(\alpha|t) < \alpha \cdot \mu_\alpha < s_{t_\Gamma}^*(\alpha|t)$ . Assume without loss of generality that  $s_t^*(\alpha|t) > \alpha \cdot \mu_\alpha$  (the proof is analogous in the opposite case). We have to show that type  $t_\Gamma$  does not want to trade if he has an object with value  $\alpha \cdot \mu_\alpha$ . Using (1), (2) and the monotonicity of  $\psi_\chi^*$  we write

$$\psi_\chi^*(\alpha \cdot \mu_\alpha) \stackrel{?}{>} \alpha \cdot (\chi \cdot \mu + (1 - \chi) \cdot \mu_\alpha) \Leftrightarrow$$

$$\chi \cdot \frac{\mu}{\mu_{\leq \alpha \cdot \mu_\alpha}} \cdot \alpha \cdot \mu_\alpha + (1 - \chi) \cdot \alpha \cdot \mu_\alpha \stackrel{?}{>} \alpha \cdot \chi \cdot \mu + \alpha \cdot (1 - \chi) \cdot \mu_\alpha \Leftrightarrow \mu_\alpha \stackrel{?}{>} \mu_{\leq \alpha \cdot \mu_\alpha},$$

and the last inequality is satisfied since  $\mu_\alpha = \mu_{\leq s_t^*(\alpha|t)}$  and  $s_t^*(\alpha|t) > \alpha \cdot \mu_\alpha$ .

3. By continuity, the previous step implies that there exists  $\bar{\beta} > 0$  such that type  $t_{\bar{\beta}} = (\chi, \beta \cdot \psi_\chi^* + (1 - \beta) \cdot \psi)$  induces threshold between  $t$ 's threshold and the optimal threshold. That is, for each  $\alpha \in [1, \frac{H}{L}]$  with  $x(t, \alpha|t) \neq \alpha \cdot \mu_\alpha$  either  $x(t, \alpha|t) < x(t_{\bar{\beta}}, \alpha|t) < \alpha \cdot \mu_\alpha$  or  $x(t, \alpha|t) > x(t_{\bar{\beta}}, \alpha|t) > \alpha \cdot \mu_\alpha$ . Note that  $u(t_{\bar{\beta}}, t) > u(t, t)$ .
4. By continuity, there exist  $\bar{p} > 0$  such that for each  $0 \leq p \leq \bar{p}$  and  $0 < \beta < \bar{\beta}$ , type  $t_\beta = (\chi, \beta \cdot \psi_\chi^* + (1 - \beta) \cdot \psi)$  satisfies  $u_p(t_\beta, t) > u_p(t, t)$ .
5. Observe, that all the above arguments work also in an heterogeneous population that includes a mixture of types  $t$  and  $t_\beta$ . That is, for each  $\gamma \in (0, 1)$ ,

$$u_p(t_\beta, \gamma \cdot t + (1 - \gamma) \cdot t_\beta) > u_p(t, \gamma \cdot t + (1 - \gamma) \cdot t_\beta).$$

As noted in Section 5.1, any hybrid-replicator dynamic coincides with the replicator dynamic when all types share the same cursedness. This implies that type  $t_\beta$  eliminates type  $t$  because it always achieves a strictly higher payoff.

□

## A.7 Stability in Hybrid-Replicator Dynamics and Prop. 4's Proof

In what follows, we first prove a lemma that characterizes stability in hybrid-replicator dynamics. The lemma shows that an incumbent type is asymptotically stable against a mutant type if: (1) the mutant's payoff is not substantially higher than incumbent's payoff (specifically, the mutant's fitness should be less than  $\frac{1}{1-r}$  times the incumbent's fitness); and (2) the hybrid types (who have one trait from type  $t$  and one trait from type  $t'$ ) yield lower payoffs than the incumbent. We then use this lemma to prove Proposition 4 that deals with stability of types in  $\Gamma$ . The lemma is a simple adaptation of Prop. 2 of Waldman (1994) that deals with sexual reproduction (see also the related analysis in Eshel & Feldman 1984; Matessi & Di Pasquale 1996).

**Lemma 2** (Characterization of Stability in the Hybrid-Replicator Dynamics). *Let  $t_1 = (\chi_1, \psi_1)$  and  $t_2 = (\chi_2, \psi_2)$  denote some arbitrary types. Assume a population game  $G_p$  with a hybrid-replicator dynamic with parameters  $\phi$  and  $r$ , and let  $u_p(t, \eta)$  and  $f_\eta(t)$  be the expected payoff and relative fitness of type  $t$  against population  $\eta$  as defined in (3) and (10).*

1. If  $(1 - r) \cdot f_{t_1}(t_2) > 1$ , then type  $t_1$  is asymptotically unstable against  $t_2$ .

2. If  $u_p((\chi_2, \psi_1), t_1) > u_p(t_1, t_1)$ , then type  $t_1$  is asymptotically unstable against  $(\chi_2, \psi_1)$ .
3. If  $u_p((\chi_1, \psi_2), t_1) > u_p(t_1, t_1)$ , then type  $t_1$  is asymptotically unstable against  $(\chi_1, \psi_2)$ .
4. If (a)  $(1-r) \cdot f_{t_1}(t_2) < f_{t_1}(t_1)$ , (b)  $u_p((\chi_2, \psi_1), t_1) < u_p(t_1, t_1)$ , and (c)  $u_p((\chi_1, \psi_2), t) < u_p(t_1, t_1)$ , then type  $t_1$  is asymptotically stable against  $t_2$ .

*Proof.* Let  $\epsilon > 0$  be sufficiently small, and let the initial distribution be:  $\eta_0 = (1-\epsilon) \cdot t_1 + \epsilon \cdot t_2$ .

Part (1). Assume that  $(1-r) \cdot f_{t_1}(t_2) = c > 1$ . By neglecting components that are  $O(\epsilon^2)$ , Eq. (4) implies that  $g^\tau(\eta_0)(t_2) \approx \epsilon \cdot ((1-r) \cdot f_{t_1}(t_2))^\tau = \epsilon \cdot c^\tau$  and this implies instability of  $t_1$  against  $t_2$ .

Parts (2)-(3) are immediately implied by well-known results for the replicator dynamic and the observation that when the population includes a single cursedness level (or a single perception bias), then the hybrid-replicator dynamic coincides with a replicator dynamic.

Part (4). Assume inequalities (a)-(c). Inequalities (b) and (c) imply  $f_{t_1}((\chi_2, \psi_1)) < 1$  and  $f_{t_1}((\chi_1, \psi_2)) < 1$ . Define a constant  $c$  such that

$$\max \{(1-r) \cdot f_{t_1}(t_2), f_{t_1}((\chi_2, \psi_1)), f_{t_1}((\chi_1, \psi_2))\} < c < 1.$$

Let  $\eta_\tau = g^\tau(\eta_0)$  be the distribution after  $\tau$  generations. By neglecting components that are  $O(\epsilon^2)$ , Eq. (4) implies that for every  $\tau$  in which  $\eta_\tau((\chi_1, \psi_2))$  and  $\eta_\tau((\chi_2, \psi_1))$  are  $O(\epsilon)$ :  $\eta_\tau(t_2) \approx \epsilon \cdot c^\tau$  which converges to 0 at an exponential rate. Assume to the contrary, that  $\eta_\tau((\chi_1, \psi_2))$  does not converge to zero at an exponential rate. Then, for a sufficiently large  $\tau$ ,  $\eta_\tau(t_2) \ll \eta_\tau((\chi_1, \psi_2))$ . In addition  $f_{\eta_\tau}(\psi_2) \approx f_{\eta_\tau}((\chi_1, \psi_2))$  where  $f_{\eta_\tau}(\psi_2)$  is the average relative fitness of all types with  $\psi = \psi_2$  (defined in Section A.5) –  $f_{\eta_\tau}(\psi_2)$  is a mixed average of  $f_{\eta_\tau}((\chi_1, \psi_2))$  and  $f_{\eta_\tau}(t_2)$ , and as the weight of the latter converges quickly to zero, the average converges to the former. Let  $\epsilon' = \eta_\tau((\chi_1, \psi_2))$ . By neglecting components that are  $O(\epsilon'^2)$ , Eq. (4) implies that:

$$\eta_{\tau+1}((\chi_1, \psi_2)) \approx (1-r) \cdot \epsilon' \cdot f_{\eta_\tau}((\chi_1, \psi_2)) + r \cdot \epsilon' \cdot f_{\eta_\tau}(\psi_2) \approx \epsilon' \cdot f_{\eta_\tau}((\chi_1, \psi_2)) < \epsilon' \cdot c$$

which implies that  $\eta_\tau((\chi_1, \psi_2))$  converges to zero at an exponential rate. An analogous argument works for  $(\chi_2, \psi_1)$ .

□

### A.7.1 Proof of Proposition 4 (Stability of Types in $\Gamma$ )

*Proof.* Let the incumbent type be  $t = (\chi, \psi_\chi^*) \in \Gamma$  and let the mutant type be  $t' = (\chi', \psi')$ . By Proposition 1, in  $G_0$  type  $t \in \Gamma$  plays optimally against itself and any type outside  $\Gamma$  achieves a strictly smaller payoff against type  $t$ . That is,  $u(t', t) \leq u(t, t)$  with strict inequality if  $t' \notin \Gamma$ . Observe that  $(\chi, \psi'), (\chi', \psi_\chi^*) \notin \Gamma$  because each pair of types in  $\Gamma$  differ in both traits. These observations imply that for each  $\delta > 0$  there exists  $\bar{p} > 0$  such that for each  $p \leq \bar{p}$ : (1)  $u_p(t', t) < u_p(t, t) + \delta$ , (2)  $u_p((\chi, \psi'), t) < u_p(t, t)$ , and (3)  $u_p((\chi', \psi), t) < u_p(t, t)$ . Notice that  $\delta$  can be chosen to be sufficiently small so that the first inequality will imply  $(1 - r) \cdot f_t(t') < 1$ . By Lemma 2, these inequalities imply that type  $t$  is asymptotically stable against  $t'$ .  $\square$

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