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Modeling social interactions and their effects on individual decision making

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Abstract

In this thesis, we are interested in the influence of social environment on individual decision making. We develop models of social interactions and culture, with the aim to facilitate their integration into theories of individual decision making. In an interdisciplinary mindset, we adopt approaches derived from the study of physics to model and quantify aspects of individual decision making under risk and uncertainty, social relationships, population dynamics and cultural contexts. Each study adopts a different methodology, including the use of mathematical modeling, empirical data analysis, computer-based simulation, and qualitative literature review.

We motivate this work in the first chapter by highlighting the gap between theories of individual and social decision making. This introduction also summarizes subsequent chapters by providing simple examples illustrating their key ideas. We start by considering a theory of individual decision making and gradually extend our scope to social relationships, populations and societies.

In the second chapter of this thesis, we test a theory of decision making, quantum decision theory (QDT), on an empirical dataset. QDT is built on a mathematical formulation inspired by quantum mechanics with the assumption that decision making is inherently probabilistic. This theory offers a prediction for the frequency with which an option is chosen by one decision maker at different times, or by different decision makers in a population. We find that QDT predictions are in agreement with our results at the level of groups and could be refined at the individual level. The dataset shows gender differences in risk-taking behavior, a first hint of the role that social interactions may play in individual decision making.

To further investigate gender differences risk-taking behavior, we develop in the third chapter an agent-based model (ABM) of a population composed of females and males with interactions between genders. We quantify the effect of social and biological factors on population dynamics and gender-specific variance in reproductive success. This ABM allows us to investigate the degree of population heterogeneity and kind of mating system most likely to reproduce features of ancestry lines inferred by genetic analyses on humans. Our results support the hypothesis that we may be descended from men who were successful in a highly competitive context, while women were facing a smaller competition for reproductive success. Present generations inherited the genes and culture of these ancestors, which provides insights into gender-specific competitiveness and risk-taking behavior.

We then broaden the scope of our study by generalizing the analysis of social interactions. In the fourth chapter, we introduce a generic model of relationships between two persons or

groups. We propose that this model provides a coding for relational models theory (RMT), a theory of human social relationships (Fiske, 1991, 1992). RMT posits four "relational models" or templates for coordinated social action, to which two limiting cases are added, the asocial and null interactions. We offer a mathematical demonstration that the categories of social relationships arising from our model are exhaustive. Accordingly, we support the idea that the relational models form an exhaustive set of all types of relationships based on social coordination. Interacting people thus have a limited repertoire of structures of social relationships to choose from. The endless possible implementations and combinations of these basic forms account for the rich diversity of social life.

Social relationships are themselves influenced by the cultural setting they constitute. In the fifth chapter, we examine the forms that social relationships can take within different cultural contexts by combining two theories. We use again RMT to provide us with categories of social relationships. To describe cultural settings, we use plural rationality theory (PRT), also called cultural (grid-group) theory (Douglas, 1982; Thompson et al., 1990), which posits a typology of four social forms, called "ways of life" or "cultural biases." The latter are sets of values, beliefs, preferences and perceptions, including perceptions of risks. For each cultural bias, we find congruent implementations of all relational models in the literature of RMT and PRT. This study contributes to clarify the relation between RMT and PRT, and generally between social relationships and culture.

In conclusion, we come full circle with a richer understanding of social relationships and cultural contexts, as well as their influence on individual decision making.

Résumé

Dans cette thèse, nous nous intéressons à l'influence de l'environnement social sur la prise de décision individuelle. Nous développons des modèles d'interactions sociales et cultures, dans le but de faciliter leur intégration dans des théories de la prise de décision individuelle. Dans un état d'esprit interdisciplinaire, nous adoptons des approches dérivées de l'étude de la physique pour modéliser et évaluer de manière quantitative certains aspects de la prise de décision individuelle, des relations sociales, de la dynamique des populations et des contextes culturels. Chaque étude adopte une méthodologie différente, comprenant la modélisation mathématique, l'analyse de données empiriques, la simulation sur ordinateur, ainsi que la revue qualitative de littérature.

Nous motivons ce travail dans le premier chapitre en mettant en évidence le fossé entre les théories de la décision individuelle et sociale. Cette introduction résume aussi les chapitres suivants en offrant des examples simples illustrant leurs idées clés. Nous commençons par considérer la prise de décision individuelle et étendons graduellement notre champ d'intérêt aux relations sociales, populations et sociétés.

Dans le deuxième chapitre de cette thèse, nous testons une théorie de la décision, la théorie quantique de la décision (ou QDT, pour *quantum decision theory*), sur des données empiriques. La QDT est construite sur une formulation mathématique inspirée par la mécanique quantique en partant de l'hypothèse que la prise de décision est intrinsèquement probabiliste. Cette théorie offre une prédiction concernant la fréquence à laquelle une option est choisie par un individu, ou par différents individus au sein d'une population. Les résultats de notre analyse sont en accord avec les prédictions de la QDT au niveau des groupes. Ces prédictions pourraient être raffinées au niveau individuel. La base de données fait apparaître des différences entre les sexes dans le domaine du comportement face aux risques, une première indication de l'influence possible des interactions sociales sur la prise de décision individuelle.

Afin d'étudier plus en détails les différences de comportement des hommes et des femmes face aux risques, nous développons dans le troisième chapitre un modèle d'agents (ou ABM, pour *agent-based model*) représentant une population d'agents mâles et femelles en interaction. Nous quantifions l'effet de facteurs biologiques et sociaux sur la dynamique de la population et la variance du succès reproductif des hommes et des femmes. Cet ABM nous permet d'étudier le degré d'hétérogénéité de la population et le type de système de reproduction les plus susceptibles de reproduire des particularités de lignes d'ascendance déduites par des analyses génétiques sur des humains. Nos résultats soutiennent l'hypothèse que nous pourrions descendre d'hommes qui ont eu du succès dans un contexte très compétitif, alors que les femmes faisaient face à une plus

faible compétition liée au succès reproductif. Les générations présentes ont hérité les gènes et la culture de ces individus, ce qui contribue à éclairer les différences d'attitudes des hommes et des femmes face à la compétition et aux risques.

Nous étendons ensuite la portée de notre étude en généralisant l'analyse des interactions sociales. Dans le quatrième chapitre, nous introduisons un modèle générique de relations entre deux personnes ou groupes. Nous proposons que ce modèle fournit une représentation de la théorie des modèles relationnels (RMT, pour *relational models theory*), une théorie des relations humaines (Fiske, 1991, 1992). La RMT postule quatre "modèles relationnels" ou modèles d'interaction sociale coordonnée, auxquels deux cas limites sont ajoutés, les interactions asociales et nulles. Nous démontrons mathématiquement que les catégories de relations sociales dérivant de notre modèle sont exhaustives. En conséquence, nous soutenons l'idée que les modèles relationnels forment un ensemble exhaustif de tous les types de relations basées sur une coordination sociale. Les personnes en interaction ont donc un répertoire limité de structures de relations sociales parmi lesquelles choisir. Les inépuisables implémentations et combinaisons de ces formes de base sont responsables de la riche diversité de la vie sociale.

Les relations sociales sont elles-mêmes influencées par le contexte culturel qu'elles constituent. Dans le cinquième chapitre, nous examinons les formes que peuvent prendre les relations sociales dans différents contextes culturels, en combinant deux théories. Nous utilisons à nouveau la RMT pour nous fournir des catégories de relations sociales. Pour décrire les contextes culturels, nous utilisons la théorie de la rationalité plurielle (PRT, pour *plural rationality theory*), aussi appelée théorie culturelle (*cultural theory*: Douglas, 1982; Thompson et al., 1990), qui postule une typologie de quatre formes sociales, appelées "modes de vie" ou "biais culturels." Ces dernières sont des ensembles de valeurs, croyances, préférences et perceptions, y compris perceptions du risque. Pour chaque biais culturel, nous trouvons des implémentations de tous les modèles relationnels dans la littérature de la RMT et la PRT. Cette étude contribue à clarifier la relation entre la RMT et la PRT, et généralement entre relations sociales et culture.

En conclusion, nous terminons avec une plus riche compréhension des relations sociales et contextes culturels, ainsi que leur influence sur la prise de décision individuelle.

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Chapter 1

Introduction

1.1 Motivation: individual and social decision making

We all take decisions affecting inextricably our life and that of those around us every day. For their part, formal theories of decision making distinguish between individual and social decision making. Notably, there appears to be a partial disconnect between these two classes of theories. In non-social settings, individuals are assumed to maximize their benefits or follow universal heuristics or cognitive biases. In turn, these mechanisms are used as a basis in attempts to explain cooperative behavior in social settings. Individual decision theories thus inform social ones, at least to some extent, but social theories are not used to inform individual ones. It seems to be assumed that social decision making builds on individual decision making, with the relation between the two domains going only one way. As we argue below, this overlooks the observation that humans are inherently social, and that our individual and social cognition appear to be deeply intertwined. We may actually put into question whether there is any such thing as "individual" decision making, free of social influences.

In social decision making experiments, participants are invited to play two- or more person games, for example public good games or ultimatum games. In an ultimatum game, a participant (the proposer) receives an amount of money from the experimenter, and proposes to transfer a part of it to another participant (the responder). The responder may accept the offer, which is then implemented, or reject it, in which case neither player receives any money. This experiment puts in evidence social norms regarding what is seen as fair or acceptable. In a public good game, participants may contribute or not to a public good. The sum of the contributions is then multiplied (by a factor between 1 and the number of players), yielding a payoff that is evenly redistributed among all participants. This setting is thus vulnerable to the free-rider problem. This makes it an example of social dilemma, whereby each person receives a higher payoff for defecting than from cooperating, but all are better off if all cooperate than if all defect. Social decision making is mainly concerned with cooperation in social dilemmas.

Cultural factors are recognized to be critical determinants of outcomes in social decision making experiments. Henrich et al. (2010) point out that most studies of human psychology and behavior are performed on WEIRD ("western, educated, industrialized, rich and demo-

cratic") subjects, although cross-cultural studies show that economic and social environments shape individual behavior in social economic games (Henrich et al., 2001). Accordingly, central theoretical puzzles in this field are the evolution of cooperation, social norms and prosociality (e.g. Axelrod and Hamilton, 1981; Axelrod, 1984; Gintis et al., 2003; Henrich, 2006), and culture-gene coevolution (Bowles et al., 2003; Gintis, 2002; Jablonka and Lamb, 2007; Laland et al., 2000; Rogers and Ehrlich, 2008). In particular, social interactions such as altruistic punishment (whereby an individual punishes a free-rider at own cost) are believed to play a major role in maintaining cooperation and social norms (e.g. Fehr and Gächter, 2002; Hetzer and Sornette, 2013a, Hetzer and Sornette, 2013b, Hetzer, 2011 and references therein).

Let us now turn to individual decision making experiments. Here, participants have to make series of decisions affecting their individual payoff without interacting with others. For example, a subject may be asked to choose between (A) getting CHF 10 for sure, and (B) getting CHF 50 with a 25% chance, or nothing with a 75% chance. In more complex questions, both options may involve risk, probabilities may be unknown, or losses may occur. The social behaviors mentioned above (e.g. cooperation and altruistic punishment) do not apply to these situations, which may contribute to social factors being neglected altogether in analyses of individual decision making. Instead, the latter are primarily concerned with attitudes toward risk and uncertainty. Models of individual decision making include schemes describing how people interpret values and probabilities, as well as heuristics and cognitive biases. The leading theory in this domain is prospect theory (Kahneman and Tversky, 1979; Tversky and Kahneman, 1992), and is non-social by construction (Messick, 1999, 15).

There thus seems to be an implicit assumption that the label "individual" automatically makes individual decision making inherently non-social. However, insights from various fields (including anthropology, neuroscience, psychology, economics, social and political sciences) suggest that individual decision making may be largely influenced by social cognition and by the social environments experienced daily by subjects, even when they temporarily find themselves in non-social experimental settings.

Indeed, humans are considered to be inherently social. Twins show evidence of other-directed movements while still in the womb (Castiello et al., 2010): it appears that we are "wired to be social." Children are "insatiably social;" they wish to relate and learn their parents' culture (Fiske, 2000, 83). Moreover, from an evolutionary perspective, the large brain (relative to body size) of humans and other highly social animals may have been selected to accommodate the high computational capacities required to live in large, complex societies. This constitutes the social brain hypothesis (Dunbar, 1998).

These views are compatible with cognitive, behavioral, social, affective and cultural neuroscience, as they look into both individual and social decision making (e.g. Rilling and Sanfey, 2011). A key finding in these fields is that damage to the ventromedial prefrontal cortex impairs both social reasoning and individual decision making (Damasio, 2005; for reviews see Adolphs, 1999, 2003). The somatic marker hypothesis explains this by proposing that the ventromedial prefrontal cortex normally triggers an emotional response to stimuli playing a fundamental role

in guiding behavior in complex and uncertain situations (Damasio, 1994). Patients with damage to the ventromedial prefrontal cortex display flat emotions, impaired social behavior, and are unable to make advantageous decisions for themselves. Thus, individual and social cognition and behavior rely on the same neurological systems (Lieberman, 2007). In fact, Immordino-Yang and Damasio (2007, 6) argue that social and cultural functioning underlies our non-social decision making and reasoning.

Furthermore, the social science of risk suggests that risk perceptions are culture-dependent (Slovic, 2016). This idea is developed in particular by the cultural theory of risk (Douglas and Wildavsky, 1982; Rayner, 1992). According to this theory, social institutions determine which risks are attended to by individuals navigating these institutions. More generally, any choice we make, even apparently non-social, is influenced by the structure of our social circles (Douglas, 1996). Consequently, a participant in a non-social experiment may implicitly or explicitly draw a parallel between this situation and other situations presenting some degree of similarity or relevance and embedded in social life. Indeed, people make decisions at least partly by categorizing the decision situation based on analogies with specific cases, as expressed by Messick (1999) and Gilboa et al. (2015), for example. An individual decision maker is thus inextricably influenced by her social relations and culture, even when required to take decisions affecting her own payoff without consulting others.

There have been calls for the extension of individual decision making theories by integrating social components. Rilling and Sanfey (2011, 40) note that "Future research might fruitfully explore the degree to which social decision-making overlaps with the more fundamental mechanisms employed in individual decision-making, in order to generate a more complete model of how people choose and decide." Messick (1999, 15) suggests that "we may need to develop different types of theories for social contexts rather than try to fit new variants of instrumental, outcome-maximizing ideas onto them." Douglas and Wildavsky (1982, 79-80) argue that "it is time to incorporate some sociological dimensions into the description of simplifying procedures [i.e. heuristics, cognitive biases]. Humans are not isolated individuals. Their sociality should be included in the analysis of how their minds work." In a similar mindset applied to finance, Hirshleifer (2015, 133) states that "the time has come to move beyond behavioral finance to social finance, which studies the structure of social interactions, how financial ideas spread and evolve, and how social processes affect financial outcomes." Gigerenzer (2000, 199) designs a program for "social rationality," which seeks to explain "human judgment and decision making in terms of the structure of social environments." Verweij et al. (2015) combine social theories with the neuroscience of decision making, and propose to test empirically a theoretical mechanism through which social situations may be evaluated to achieve decision making.

Our view is that, in order to bridge the gap between individual decision making and social theories, one first needs to have a flexible model or framework of decision making on the one hand, and models of social relationships and culture on the other hand. In this thesis, we take this viewpoint as a road map and contribute to the development of such models (chapters 2 to 5). In the conclusion (chapter 6), we sketch an integration of social and cultural ingredients

into a particularly flexible theory of decision making. In the next sections of this chapter 1, we introduce chapters 2 to 5 separately and position each of them in the broader context of this thesis. We summarize these chapters and provide simple illustrative examples of their key ideas. We start with individual decision making and gradually extend our scope to social interactions and cultures.

1.2 Individual decision making

In chapter 2 (based on Favre et al., 2016), we examine biases in decision making manifested by "isolated" subjects invited into a scientific experiment. The participants are isolated in the sense that they make their decisions without consulting others, and these decisions affect their individual payoff only. We examine the choices made by individuals faced with a series of questions such as "Would you rather have a 20% chance to win CHF 50 (with an 80% chance to get nothing), or get CHF 10 for sure?" We work with a dataset of such binary lotteries in the domain of gains submitted to 27 participants asked 200 questions each.

We approach this dataset with an alternative approach to choices under risk and uncertainty, quantum decision theory (QDT: Yukalov and Sornette, 2008, 2009a,b,c, 2010a,b, 2011, 2013, 2014a,b,c, 2015). QDT is a theory of decision making based on the mathematics of Hilbert spaces, a framework known in physics for its application to quantum mechanics. It formalizes the concepts of uncertainty, entanglement and order effects that are particularly manifest in cognitive processes, which makes it well suited for the study of decision making.

QDT describes a decision maker's choice as a stochastic event occurring with a probability that is the sum of an objective utility factor and a subjective attraction factor. QDT offers a prediction for the average effect of subjectivity on decision makers, the quarter law. In chapter 2, we apply QDT and test the quarter law at three levels: (i) single individuals; (ii) individuals aggregated by gender; and (iii) the general population of participants.

We find that our results are in good agreement with the quarter law at the level of the general population and subgroups. Moreover, we observe gender differences in risk-taking behavior. We come back to and investigate this possibility in chapter 3. Finally, our results suggest that the quarter law could be refined in order to reflect individual characteristics. In particular, one may wonder (i) what are the variables hidden in the so-called attraction factor (the subjective term in the probability of choosing an option), i.e. what factors influence individual decisions; (ii) how isolated can a subject really be, even when asked to take individual decisions in a controlled experimental setting; and (iii) how to meaningfully aggregate individual results.

Answering these and similar questions is beyond the scope of chapter 2, whose main objective is to provide a guide of how to apply QDT in its present theoretical state to a dataset of simple gamble questions. However, these concerns set the stage for the rest of this thesis. Indeed, through a variety of approaches, we support the idea that social and cultural contexts are fundamental determinants of individual preferences and behavior. In QDT, this means that the attraction factor may be refined by including variables informed by, for example, gender,

social and cultural setting, and generally any aspect relating to individuals embedded in social surroundings.

In the experiment that generated the data analyzed in chapter 2, social relationships and culture are likely to influence individual decision making insofar as participants wonder, consciously or not: "What kind of situations is this? What does a person like me do in a situation like this?" (Messick, 1999, 13, 14) Or, "What do the experimenters expect from me? Can I trust them? What would my partner, friends, parents, or manager, advise or expect me to do? How will they react when I tell them about this situation and my choices?" Thus, when a person is asked to take individual decisions, even on her own, one may expect her perceptions and behavior to be influenced by her social relationships and cultural context. In line with this idea, the rest of this thesis is driven by an interest in modeling social relationships and culture with the aim to facilitate the understanding of their role as fundamental determinants of individual behavior, decision making and attitude toward risks.

1.3 A two-gender agent-based model

In chapter 3 (based on Favre and Sornette, 2012), we focus on the effect of interactions between genders on population dynamics and certain individual characteristics, namely reproductive success, competitiveness and risk-taking behavior. We introduce an agent-based model (ABM) of a population with interactions between female and male agents. This ABM takes as inputs a type of mating system, a degree of population heterogeneity and parameters defining biological lifecycle events. It provides as outputs a complete genealogical tree whose features can be exactly retrieved, including common ancestry lines and individual or gender-specific reproductive success. We find that the conditions most likely to produce outputs consistent with the results of genetic studies imply strong levels of competition between men.

Features of genealogical trees such as common ancestry lines are studied by population genetics (e.g. Hedrick, 2000). Looking back into lineages, every two person's genealogical trees start overlapping at some point. The most recent common ancestor (MRCA) of two or more people depends on which lineage one is looking at. One may not care along which ancestry lines the MRCA is found (e.g. female-male-male-female-etc.). This would amount to look for the MRCA in the most general sense. But one may also restrict the search to all-female ancestry lines, leading to the female MRCA, the most recent common great-great-...-great-grandmother of two or more individuals. Conversely, one may look for the male MRCA, the most recent common great-great-...-great-grandfather of two or more individuals. The time to the MRCA (TMRCA) can be inferred from the comparison of specific DNA samples.

The male and female MRCAs of present-day individuals were a priori not mates, and may have lived at different times. To illustrate, one may think of cousins whose mothers are sisters. The cousins thus share a common maternal grandmother (their female MRCA). It would however be a remarkable coincidence if they also shared a common paternal grandfather, i.e. a male MRCA in the same generation as their female MRCA. Indeed, this would mean that two sisters

married two brothers. Moreover, if the common maternal grandmother and paternal grandfather were partners, this would imply that the sisters married their own brothers.

In fact, a number of genetic studies (Wilder et al., 2004a,b; Tang et al., 2002; Ingman et al., 2000; Cann et al., 1987; Pritchard et al., 1999; Thomson et al., 2000; Hammer and Zegura, 2002) indicate that the current population has an approximately two-to-one female/male TMRCA ratio. That is, our female MRCA lived twice as long ago as our male MRCA. Wilder et al. (2004a,b) argue that this is due to gender-specific variances in reproductive success.[1] Namely, a higher male than female variance in reproductive success leads to a higher female than male TMRCA. We present an example illustrating this relation further below.

At this point, it is relevant to mention that the authors of another genetic study (Poznik et al., 2013) claim that the specific methodology they use yields a TMRCA ratio close to 1 in humans, unlike the aforementioned studies. In fact, our ABM manifests a high stochasticity. Namely, over hundreds of simulations starting with the same parameters, but with different random parameters regarding specific pairings, deaths, and so on, one gets a stretched distribution of TMRCA ratios with values between 0 (not comprised) and 10. However, different population characteristics and mating systems have a clear effect on rendering certain values more or less likely. Our approach consists in exposing which conditions in our model produce certain values of the TMRCA ratio, and with which likelihood. We focus on conditions producing a TMCRA ratio close to 2, but also present the full distribution of TMCA ratios under different conditions.

Surprisingly at first, population genetics models keep the genders entirely separate. Indeed, these models consider organisms that are either haploid (i.e. asexual, such as bacteria) or diploid, but hermaphrodites, such as snails (Wakeley, 2009, chap. 3.1). In such a population, the TMCRA can be derived mathematically on the basis of inputs such as variance in reproductive success, mutation rate, and so on. In particular, this yields a relation between variance in reproductive success and TMRCA in a population of hermaphrodites or haploid organisms. Population genetics models hypothesize that this relation also holds in a diploid, biparental population. This simplification is for mathematical tractability purposes: taking into account stochastic interactions between females and males is extremely costly (Iannelli et al., 2005).

This difficulty motivates us to develop an ABM including interactions between genders. Our ABM allows us to (i) explore exactly the genealogical tree of the population backward in time, (ii) study quantitatively the effect of population heterogeneity and mating system on female and male TMRCAs, and (iii) observe (as opposed to input) gender-specific variances in reproductive success under different conditions.

This research was initially motivated by an interpretation that Baumeister (2010) makes of genetic results indicating a two-to-one TMRCA ratio. In this book, Baumeister links the gender-biased TMRCA ratio with modern gender differences in risk-taking behavior. Baumeister suggests that we are descended from twice as many women as men, and that this explains men's higher average propensity to take risks. More precisely, he claims that "among the ancestors of

[1] However, as discussed in chapter 3, other geneticists (e.g. Seielstad et al., 1998) argue that the two-to-one TMRCA ratio is due to gender-biased migration.

today's human population, women outnumbered men about two to one." (p. 63)

One may wonder how it could be possible for the present population not to have the same number of male and female ancestors, since everybody has one biological parent of each gender. Note that we are talking about *ancestors* and not *common ancestors*. An ancestor is defined as an individual who has at least one descendant alive in the present generation (Baumeister, 2010, 61). Two children born from two different women and the same man have, as a population, two female and one male ancestors in the previous generation. If such a situation repeats over time (e.g. one man having children with different women), then the number of ancestors over a number of generations will be biased toward more female than male ancestors.

To understand the possible relation between TMRCA ratio, number of ancestors, reproductive success, competitiveness and risk-taking behavior, let us consider a population of constant size with two men and two women in each generation,[2] as in figure 1.1. In this example, the female MRCA of the present generation (depicted at the bottom of the figure) lived twice as long ago as the male MCRA. Within each generation, each woman has two children, whereas one man has four children and the other man has none. The female reproductive success is thus 2 ± 0, while male reproductive success is 2 ± 2. There is thus a gender difference in reproductive success, but it is not reflected by the average number of children, here 2 for both genders. This average is necessarily the same because for each woman who has a child, there is one man who also has a child, namely the father. Instead, the difference between genders is manifested by gender-specific *standard deviations (or variances)* in reproductive success.

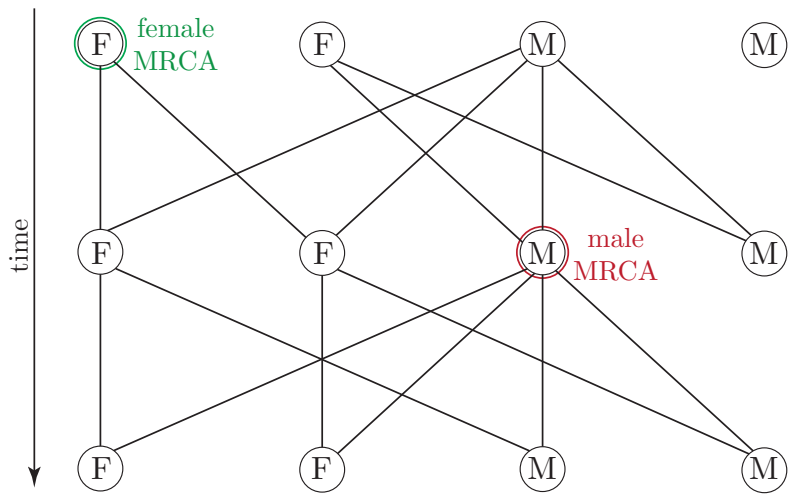

Figure 1.1: *Example of population with a two-to-one TMRCA ratio and gender-biased variances in reproductive success.*

Generally, if men have a higher variance in reproductive success, some men have many children, while others have none. The few men with many children may become common

[2]For simplicity, this particular example involves only four individuals. Chapter 3 generally considers a population of 150 individuals.

ancestors of a later generation relatively close in time. In our example, the man with four children immediately becomes the male MRCA of the next generation. On the other hand, if women have a low variance in reproductive success, all women have about the same number of children. Any woman has a relatively low probability of becoming common ancestor of a later generation, and this happening requires a relatively large number of generations. This is how the female TMRCA generally becomes greater than the male TMRCA when men show a greater variance in reproductive success than women.

Moreover, one can count in figure 1.1 the number of male and female ancestors of the present generation. We observe twice as many female than male ancestors both globally and in each generation.

Finally, this example also helps understand the idea that in a population with higher male than female variance in reproductive success, men might show greater competitiveness and risk-taking than women. Indeed, while women in our example have two children each, men might have either four or zero. Note that the goal pursued by individuals may be to mate, with reproduction being a consequence. Accordingly, the two men in this example find themselves in a competitive situation. The implication expressed by Baumeister (2010) is that we may be descended from men who were successful in a highly competitive context, while our female ancestors may not have had to face as high a competition for mating and reproduction.[3]

1.4 Generic modeling of social interactions

Chapter 4 (based on Favre and Sornette, 2015) broadens the scope of our study of social relationships by examining generically all types of interactions between any two persons or groups. A theoretical framework analyzing social relationships is indeed highly relevant to understand the possible mechanisms through which social environment may influence individual decision making.

We introduce a model of social interactions between a pair of agents A and B, each of whom can perform a social action X, Y or nothing, symbolized by $A \underset{X/Y/\varnothing}{\overset{X/Y/\varnothing}{\rightleftarrows}} B$. Our model is rooted in the observation that each party in an interaction can do either the same thing as the other party, a different thing or nothing at all. Namely, if they do the same thing, they both do X (or Y) ; if they perform different (non-null) actions, one does X and the other does Y. We demonstrate that the relationships generated by this model aggregate into six exhaustive and disjoint categories.

We establish the correspondence between this model and relational models theory (RMT), a theory of human relationships introduced by an anthropologist, Alan P. Fiske (1991, 1992). RMT posits four elementary models of relationships governing human interactions: communal sharing (CS), authority ranking (AR), equality matching (EM), and market pricing (MP). RMT claims that the four relational models are universal and exhaustive: all relationships in all societies

[3] In chapter 3, we also consider the effect of female competition, and argue that it leads to even higher male competition.

instantiate them, singly or in combination. To the relational models are added the limiting cases of asocial and null interactions, whereby people do not coordinate with reference to any shared principle.

We argue that the six categories emerging from our model offer suitable abstract representations of the social actions performed by dyads implementing the four relational models, the asocial and the null interactions. We infer that the four relational models form an exhaustive set of all types of coordinated social relationships. People thus have a limited repertoire of structures of relationships to choose from to construct their interactions. The diversity of social life is generated by the endless possible implementations and combinations of these basic forms.

In chapter 4, we use the term "dyadic" to emphasize that we focus on interactions between two agents (that can represent two persons, groups, institutions or nations), as opposed to settings involving more than two agents implementing multiple different relational models. However, our model also applies to homogeneous collective action, whereby all participants use the same relational model. In RMT, relational models are also used to characterize single groups of more than two individuals in which all members use the same relational model in the context of a social activity. For example, if members of a group are all implementing CS when sharing food, it can be called a "CS group" with respect to that activity (Fiske, 1991, 151). We argue below that in such situations of homogeneous collective action, our representation gives an accurate description of what happens between any two members and thus can be used to characterize the group as a whole.

Let us examine the example of a group composed of 3 individuals $\{A, B, C\}$ implementing EM in the context of a rotating credit association (Fiske, 1991, 153). The model we introduce in chapter 4 represents EM by $A \underset{X}{\overset{X}{\rightleftarrows}} B$, $A \underset{X}{\overset{X}{\rightleftarrows}} C$ and $B \underset{X}{\overset{X}{\rightleftarrows}} C$; individuals perform the same social action toward each other. Let us show that members in a rotating credit association indeed instantiate these social actions.

Say that it is first A's turn to receive a fixed amount of money from B and C. This is represented in figure 1.2 by B and C both performing the social action X toward A. It is then B's turn to receive the same amount of money from A and C. In other words, A and C both do X to B. In the last step, A and B do X to C. The cycle may then repeat. Over a cycle, each member receives once from others an amount of money that she may not have been able to accumulate on her own. At the same time, all contributions are equal, and members have paid out as much as they have received (Fiske, 1991, 153).

Cumulating the social actions fluxes (arrows) in figure 1.2, we observe EM fluxes between any two members. Thus, the representation we introduce applies between any two members of the group: an "EM group" can be entirely described by an ensemble of dyadic EM relationships of the type $A \underset{X}{\overset{X}{\rightleftarrows}} B$. The difference between the dyadic and the homogeneous group situation is the different periodicity. Indeed, instead of pairwise opposite fluxes at each time step, it is only over an entire cycle at the level of the group that the balance between all members is achieved.

Chapter 4 adopts a mathematical approach by defining an abstract model and rigorously demonstrating an exhaustiveness claim. Furthermore, our representation may be applied to

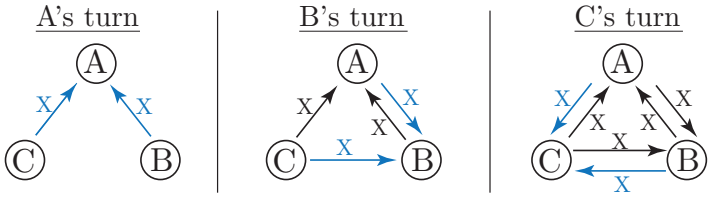

Figure 1.2: *Rotating credit association between three individuals* $\{A, B, C\}$*. Each member in turn gets a money amount* X *from others.*

computational modeling and analysis by providing ways to classify types of interactions in potentially large data sets of dyadic social interactions.

1.5 Social relationships embedded in culture

Building up on insights from previous chapters, chapter 5 (based on Favre and Sornette, 2016) broadens the scope of our study once more by examining the relation between cultural settings and the social relationships that people constitute within these settings. This research originates from an interest in understanding the relation between two social theories introduced by anthropologists.

One of these two theories is relational models theory (RMT), the theory of social relationships that was the focus of the previous chapter (Fiske, 1991, 1992). Let us recall that RMT defines four structures of social relationships, the relational models, and argues that all societies at all times use diverse implementations of these four models and combinations thereof.

Plural rationality theory (PRT) is a political and social theory pioneered by anthropologist Mary Douglas (1982), developed by others (Thompson et al., 1990) and used mainly by political scientists. PRT posits that there are four ways of organizing social relationships, each of which is associated with a compatible set of individual norms, values, perceptions, beliefs and preferences, called cultural biases. In particular, an important branch of PRT has focused on risk perceptions, arguing that these are largely influenced by social and cultural contexts, and not only by the individual cognition of socially isolated persons (Douglas and Wildavsky, 1982; Wildavsky and Dake, 1990; Dake, 1991).

RMT and PRT share the idea that, in the domain of sociality, we have a limited number of options to choose from, while varied combinations and specific implementations of these options lead to cultural diversity (Fiske, 2000). A first intuition is that since RMT and PRT both describe social life using a "basis" of four elements, the two typologies may be related by a change of basis, as in linear algebra. This intuition leads to the hypothesis that each cultural setting is significantly associated with only some relational models, but not all. However, previous attempts to express or test such hypotheses have proved problematic (Realo et al., 2004; Verweij, 2007; Vodosek, 2009; Brito et al., 2011).

The idea we introduce is that RMT and PRT do not actually apply to the same level

of analysis. That is, they do not lie in the same "plane" or define bases of the same space that would be a transformation of each other. Instead, the typology of PRT seems to relate to structures of social networks, or patterns of social relationships between a number of actors forming a network. The relational models appear to provide templates for pairwise relationships, that is, for single ties between two actors generally embedded in a larger network.

With this idea in mind, we argue that all four relational models can be found in social contexts organized according to PRT's typology. However, the specific implementation of a relational model needs to be compatible with the cultural bias associated with its social setting. We support this thesis by extracting implementations of relational models compatible with cultural biases from the literature of RMT and PRT. We show that such examples can be found for all pairs of relational model and cultural bias. The approach used in this chapter is thus qualitative. At the same time, it suggests future research paths regarding the identification of cultural biases based on structures of social networks.

Chapter 5 provides a last upscaling step from individuals and their relationships to social contexts and cultures of entire societies. It allows us to close the loop in the conclusion by coming back to the "isolated" individuals considered in chapter 2 with a new set of tools to understand their cognitive biases, influenced by social relationships and culture.

Chapter 2

Individual decision making: Quantum decision theory in simple risky choices

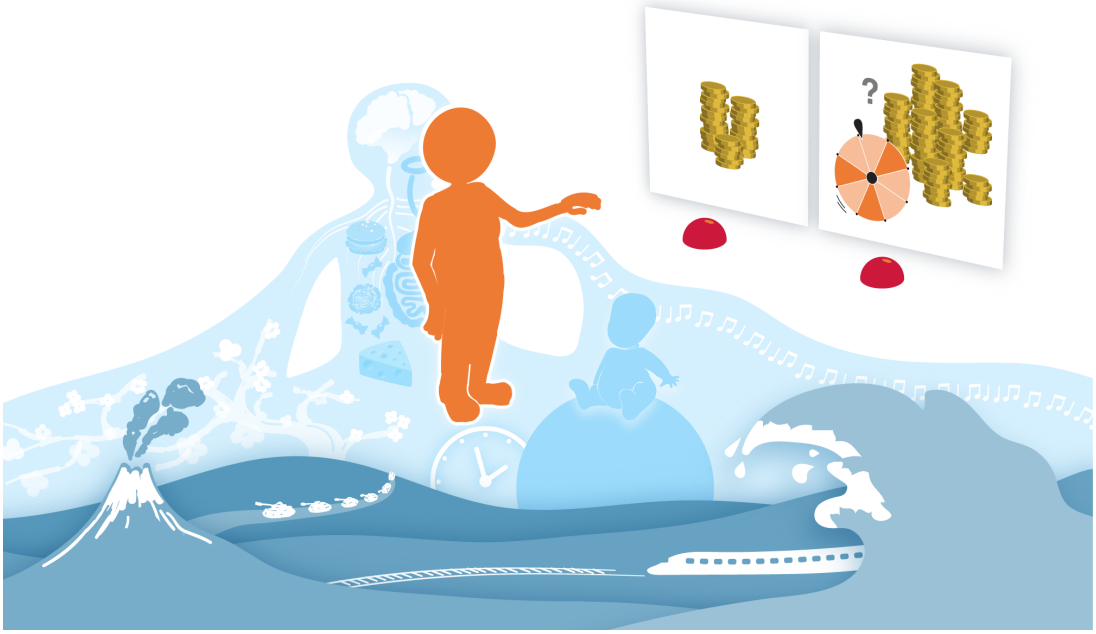

Figure 2.1: *This chapter is concerned with individual decision making under risk and uncertainty, as it is influenced by a combination of objective and subjective factors.*

2.1 Abstract

[1] Quantum decision theory (QDT) is a recently developed theory of decision making based on the mathematics of Hilbert spaces, a framework known in physics for its application to quantum mechanics. This framework formalizes the concept of uncertainty and other effects that are particularly manifest in cognitive processes, which makes it well suited for the study of decision making. QDT describes a decision maker's choice as a stochastic event occurring with a probability that is the sum of an objective utility factor and a subjective attraction factor. QDT offers a prediction for the average effect of subjectivity on decision makers, the quarter law. We examine individual and aggregated (group) data, and find that the results are in good agreement with the quarter law at the level of groups. At the individual level, it appears that the quarter law could be refined in order to reflect individual characteristics. We examine gender differences in our sample in order to illustrate how QDT can be used to differentiate between different groups. We find that women in our sample are on average more risk-averse than men, but stress that our sample is too small to generalize this result to the population outside our sample. This chapter offers a practical guide to researchers who are interested in applying QDT to a dataset of binary lotteries in the domain of gains.

Keywords: Decision making, quantum decision theory, risk, uncertainty, how-to guide

2.2 Introduction

In this chapter, we apply quantum decision theory (QDT) to a dataset of choices between a certain and a risky lottery, both in the domain of gains. Each decision task consists in a choice between (1) a risky option in which the decision maker can win a fixed amount, here $y = 50$ CHF with probability p, or nothing with probability $1 - p$, and (2) a certain option in which the decision maker gets an amount x with certainty, where $0 < x < y$. For example, a typical question could be to choose between the following options: "option 1: get CHF 50 with a 40% chance (or nothing with a 60% chance); option 2: get CHF 10 for sure." Our dataset includes the 200 decisions performed by each of 27 subjects with various values of p and x.

We use this dataset to illustrate how to apply QDT. This theory of decision making offers a quantitative prediction, the so-called quarter law, which concerns the average effect of subjectivity on people's decisions. In the present case, the quarter law allows us to predict the frequency with which either of two options will be chosen. We examine individual and aggregated (group) results, and find that our results are in good agreement with the quarter law at the level of groups. At the individual level, it appears that the quarter law could be refined in order to reflect individual characteristics. We also perform a gender analysis suggesting that men in our sample are more risk-taking than women, on average. However, the small sample size does not

[1] This chapter is based on Favre M., A. Wittwer, H.R. Heinimann, V.I. Yukalov, and D. Sornette, 2016: Quantum decision theory in simple risky choices. Submitted. URL: http://ssrn.com/abstract=2731774 and http://arxiv.org/abs/1602.04058.

allow to generalize this result to gender differences in general. We present these results in order to illustrate how QDT can be used to differentiate between groups of decision makers.

Let us stress that QDT does not suppose that the brain is a quantum object. The mathematical formalism of quantum mechanics, rigorously developed by von Neumann (1955), is that of complex separable Hilbert spaces. This formalism was already recognized by the founders of quantum mechanics to be well suited to describe the processes of human decision making (Bohr, 1929, 1933, 1936; von Neumann, 1955). Indeed, it naturally integrates the notion of uncertainty. QDT represents cognitive states and prospects as vectors in a Hilbert space. The idea that a system is in a superposition of states until it gets measured parallels the way our cognitive state is indefinite until we take a decision. Vectors in a Hilbert space can be entangled, as can be the options among which we choose. We may identify feelings, subconscious processes or contextual effects with so-called hidden (inaccessible) variables.[2] Finally, from the mathematics of Hilbert spaces naturally derive order effects and non-additive probabilities incorporating interference terms.

We thus use the same mathematical formalism as that of quantum mechanics, but do not claim that neurological processes are quantum in nature. For clarity, let us give a parallel example. Newton (1642-1726/7) was interested in planetary motion and developed calculus to establish the laws of movement and gravitation. That does not mean that there is anything fundamentally planetary to calculus. This formalism very generally allows the study of change. In the case of planetary motion, calculus describes the change of position and speed along physical trajectories in space and time. Meanwhile, calculus has been used in every scientific domain concerned with change. In the same way, the mathematical framework of Hilbert spaces is known in physics for its application to quantum mechanics, but it can be said to generally apply to the study of uncertainty, and this is what motivates us to make use of it for decision making processes.

Others have recently followed a similar path, most notably Busemeyer and collaborators (e.g. Busemeyer et al., 2006; Busemeyer and Trueblood, 2011; Busemeyer et al., 2015); see Ashtiani and Azgomi (2015) for a broad review of current so-called quantum-like models of cognition. QDT is constructed as a complete, general framework, may be applied to any problem in decision theory, and offers quantitative predictions (Ashtiani and Azgomi, 2015).

Let us now give a few elements of decision theory that help understand how QDT relates to classical theories of that field that are well known in the fields of psychology and behavioral economics. For this review, we consider how classical theories evaluate simple gambles. Simple gambles, as Kahneman (2011, 269) puts it, are to decision theorists what fruit flies are to geneticists. A simple gamble is a lottery that yields, for example, a 20% chance to win CHF 50 and a 80% chance to gain nothing. Throughout this paper, we call such gambles "prospects, "options" or "lotteries." A lottery (indexed by j) is characterized by a set of outcomes and their

[2]We do not, as of yet, attempt to answer whether QDT can actually be reproduced by a theory of hidden variables.

probability of occurrence, and is written as

$$L_j = \{x_n, p_j(x_n) : n = 1, 2, ..., N\}, \tag{2.1}$$

where p_j is a probability measure over the set of payoffs $\{x_n\}$ and thus belongs to the interval $[0, 1]$ and is normalized to one.

In experimental settings, it is common for decision makers to have to choose between two simple gambles or between a gamble and a sure thing, as in "would you rather have a 20% chance to win CHF 50 (with an 80% chance to get nothing), or get CHF 10 for sure?". We call this a "decision task" (alternatively, "choice problem", or "game"). We write the former example as

$$L_1 = \{50, 0.2|0, 0.8|10, 0\}, \tag{2.2}$$

$$L_2 = \{50, 0|0, 0|10, 1\}, \tag{2.3}$$

where the vertical line separates different outcomes, and all amounts present in the decision task appear in both lotteries.

In decision theory, such decision tasks serve as simple models for the more complex decisions we face in everyday life. In real situations, outcomes are often not expressed in monetary terms, and their probabilities are unknown. For instance, we are unable to assign a probability to the event that our happiness will increase if we get a new job and move, nor do we assign an exclusively quantitative value to that change of happiness. Nevertheless, it is the consensus of the field that simple choice problems such as the above elicit risk preferences, and we will focus on lotteries of that form.

A few risk elicitation methods are reviewed by Harrison and Rutström (2008). The method used to generate our dataset is called "random lottery pair design" in the former review. This method, made popular by Hey and Orme (1994), consists in offering the decision maker a series of random lottery pairs in sequence. Our dataset was produced as part of a PhD thesis (Wittwer, 2009, chap. 7) and the tool created for that purpose was called by its authors Randomized Lottery Task (RALT).

In accordance with probability theory, Pascal (1670) expressed the idea that it would be rational to choose the option with the highest "expected value," given by the weighted sum

$$U(L_j) = \sum_n x_n p_j(x_n). \tag{2.4}$$

Later on, Bernoulli (1738) examined the relationship between the psychological and the objective value of money. He introduced the idea of a "decreasing marginal value of wealth," which amounts to introducing a non-decreasing and concave "utility function" u transforming values in (2.4), giving an "expected utility":

$$\tilde{U}(L_j) = \sum_n u(x_n) p_j(x_n). \tag{2.5}$$

Bernoulli proposed that $u(x) = \ln(x)$, such as to reflect that we become more indifferent to changes of wealth as the initial amount of wealth increases. For example, an increase of wealth

from 1 million to 4 million has a higher psychological value than an increase from 4 million to 7 million.

The view that people should and will consistently choose the option with the highest expected utility given by (2.5) (with different forms of $u(x)$) remained dominant for a very long time. Von Neumann and Morgenstern (1953) expressed axioms of rational behavior according to which rationality consists in maximizing an expected utility. Expected utility theory was the foundation of the rational-agent model, whereby people are represented by rational and selfish agents exhibiting tastes that do not change over time. This forms the foundation of the standard economic approach to decisions under risk and uncertainty (Gollier, 2004).

Pioneered by Kahneman and Tversky (1979), prospect theory modifies expected utility theory in order to explain a collection of observations showing that people exhibit a variety of cognitive biases contradicting rationality, in particular the Allais paradox (Allais, 1953). In prospect theory, the utility $\hat{U}(L_j)$ is given by

$$\hat{U}(L_j) = \sum_{n=1}^{N} v(x_n) w(p(x_n)) \ , \tag{2.6}$$

where the value function $v(x)$ is constructed based on a reference point so that relative (and not absolute) wealth variations are considered in the expected utility $\hat{U}(L_j)$. Tversky and Kahneman (1992) proposed the following parametric functions (interpreted below):

$$v(x) = \begin{cases} x^{\alpha}, & x \geq 0; \\ -\lambda(-x)^{\beta}, & x < 0. \end{cases} \tag{2.7}$$

$$w^{+}(p) = \frac{p^{\gamma}}{(p^{\gamma} + (1-p)^{\gamma})^{1/\gamma}}, \quad w^{-}(p) = \frac{p^{\delta}}{(p^{\delta} + (1-p)^{\delta})^{1/\delta}} \ . \tag{2.8}$$

Note that these two expressions distinguish between gains (+) and losses (−).

Other functional specifications have been formulated in so-called non-expected utility theories (for a review, see Stott, 2006). The underlying ideas behind the value and the probability weighting functions is that people exhibit diminishing sensitivity to the evaluation of changes of wealth in the domain of gains (encapsulated in the concavity of $v(x)$ for $x \geq 0$), the reverse effect in the domain of losses (loss aversion), and a subjective probability weighting that overweights small probabilities and underweights large probabilities (and can be different for gains and losses). Also, evaluation is relative to a neutral reference point (here $x = 0$), below which changes of wealth are seen as losses. This contrasts with standard utility theory, in which only the final state of wealth contributes to the utility evaluation. Parameters (here $\alpha, \beta, \gamma, \delta$) are fitted to experimental data to reflect the choices of groups or individuals, assuming that people prefer the option with the highest utility.

Mosteller and Nogee (1951) observed that decision making can be inherently stochastic, that is, the same decision maker may take a different decision when faced with the same question at different times. Luce (1959) formalized this idea by offering a form for the probability of choosing one option over another. Several functions have since been proposed for this so-called stochastic

specification, stochastic error, or choice function; for reviews see Stott (2006) or Harrison and Rutström (2008). A probabilistic element can thus be integrated in prospect theory models, as is done for example by Hey and Orme (1994); Harless and Camerer (1994) and Murphy and ten Brincke (2014), providing in principle a limit for the explanation and prediction power of such models.

Prospect theory is a fertile field of research that currently dominates decision theory (Wakker, 2010). However, Safra and Segal (2008) and Al-Najjar and Weinstein (2009) point out that non-expected utility theories in general do not remove paradoxes, create inconsistencies and always necessitate an ambiguous fitting that cannot always be done. In this context, QDT proposes an alternative perspective that may provide novel insights into decision making.

The main features of QDT are the following. First, as mentioned above, QDT derives from a complete, coherent theoretical framework that explicitly formalizes the concepts of uncertainty, entanglement and order effects. In the framework of QDT, paradoxes of classical decision theory such as the disjunction effect, the conjunction fallacy, the Allais paradox, the Ellsberg paradox or the planning paradox (to name just a few) find quantitative explanations (Yukalov and Sornette, 2009b, 2010b, 2011). Within QDT, behavioral biases result from interference caused by the deliberations of decision makers making up their mind (Yukalov and Sornette, 2010a).

Second, QDT is inherently a probabilistic theory, in the sense that it focuses on the fraction of people who choose a given prospect, or on the frequency with which a single decision maker does so over a number of repetitions of the same question. In the theoretical part of this chapter, we derive the following expression for the probability $p(L_j)$ that a prospect L_j be chosen by one or several decision makers:

$$p(L_j) = \frac{U(L_j)}{\sum_i U(L_i)} + q(L_j), \tag{2.9}$$

where $U(L_j)$ is the same utility as in (2.4) and $q(L_j)$ is the aforementioned attraction factor; in that term are encompassed the "hidden variables" of decision theory, i.e. feelings, contextual factors, subconscious processes, and so on. Expression (2.9) can be derived from seeing prospects and cognitive states as vectors in a Hilbert space, as we show in section 2.3.1.

Last, QDT distinguishes itself from classical and other quantum-like decision theories by offering quantitative predictions. Specifically, the quarter law predicts that the average absolute value of $q(L_j)$ is $1/4$ under the null hypothesis of no prior information.

QDT has been developed in several ways. It provides expressions for discount functions, employed in the theory of time discounting (Frederick et al., 2002) and explains dynamical inconsistencies (Yukalov and Sornette, 2009a). QDT also describes the influence of information and a surrounding society on individual decision makers (Yukalov and Sornette, 2015, 2014b). While QDT has been developed to describe the behavior of human decision makers, it can also be used as a guide to creating artificial quantum intelligence (Yukalov and Sornette, 2009c). In the present chapter, we return to empirical analysis and offer an illustration of how to apply QDT to a dataset of binary lotteries.

This chapter is structured as follows. Section 2.3 presents the theoretical formulation of QDT in the formalism of Hilbert spaces. In particular, we recall the derivation of the quarter

law, which gives the average amplitude of the attraction factors. In section 2.4, we formulate how QDT applies to the dataset under study. Section 2.5 exposes our main results comparing QDT with experiments. Section 2.6 interprets our results and section 2.7 concludes.

2.3 Quantum decision theory

2.3.1 Hilbert space formalism

This section shows how expression (2.9) can be derived from seeing prospects and a decision maker's state of mind as vectors in a complex Hilbert space. This section thus requires some knowledge of the mathematics of Hilbert spaces and quantum mechanics. After equation (2.9) is derived, the rest of this chapter does not necessitate any such knowledge.

QDT publications (Yukalov and Sornette, 2008, 2009a,b,c, 2010b,a, 2011, 2013, 2014a,c, 2015, 2014b) stress that the theory is general and applies to any decision problem. Accordingly, these articles abstractly derive equation (2.9) from a general framework. Here, we choose to consider a simple, concrete decision problem and remain within its frame to obtain equation (2.9). We hope that this helps the reader understand the formalism in details.

2.3.1.1 Prospects

We consider the "fruit fly" of decision theory (Kahneman, 2011, 269), i.e. the situation where subjects can choose between two lotteries denoted by L_1 and L_2, expressed as

$$L_1 = \{x_n, p_1(x_n) : n = 1, 2, ..., N\}, \tag{2.10}$$

$$L_2 = \{x_n, p_2(x_n) : n = 1, 2, ..., N\}. \tag{2.11}$$

An example is given by expressions (2.2) and (2.3).

2.3.1.2 Observables and Hilbert spaces

Let us introduce two observables A and B, represented by operators $\hat{A}$ and $\hat{B}$ acting on Hilbert spaces $\mathcal{H}_A$ and $\mathcal{H}_B$, respectively. Each observable can take on two values,

$$A = \{A_1, A_2\} \quad \text{and} \quad B = \{B_1, B_2\}. \tag{2.12}$$

A_1 and A_2 represent the two options presented to the subjects of the experiment: when the lottery L_j is chosen, A takes the corresponding value A_j ($j = 1, 2$). B embodies an uncertainty (Yukalov and Sornette, 2014b, 1162). For instance, B_1 (resp., B_2) can represent the confidence (resp., the disbelief) of the decision maker that she correctly understands the empirical setup, that she is taking appropriate decisions, and that the lottery is going to be played out as announced by the experimenter. B thus encapsulates the idea that these choices involve an uncertainty for the decision maker, although it is not necessarily explicitly expressed in the

setup. The eigenstates of each operator form an orthonormal basis of the associated Hilbert space,

$$\mathcal{H}_A = \text{span}\{|A_1\rangle, |A_2\rangle\}, \quad \mathcal{H}_B = \text{span}\{|B_1\rangle, |B_2\rangle\}. \tag{2.13}$$

A decision maker's state is going to be defined in the tensor-product space

$$\mathcal{H}_{AB} = \mathcal{H}_A \otimes \mathcal{H}_B, \tag{2.14}$$

spanned by the tensor-product states $|A_i\rangle \otimes |B_j\rangle$ $(i, j \in \{1, 2\})$. For simplicity, we write $|A_iB_j\rangle$ without the tensor product sign:

$$\mathcal{H}_{AB} = \text{span}\{|A_1B_1\rangle, |A_1B_2\rangle, |A_2B_1\rangle, |A_2B_1\rangle\}. \tag{2.15}$$

2.3.1.3 States

A decision maker is assumed to be in a *decision-maker state* $|\psi\rangle \in \mathcal{H}_{\mathcal{AB}}$, which is a linear combination of the basis states:

$$|\psi\rangle = \alpha_{11}|A_1B_1\rangle + \alpha_{12}|A_1B_2\rangle + \alpha_{21}|A_2B_1\rangle + \alpha_{22}|A_2B_2\rangle, \tag{2.16}$$

with $\alpha_{mn} \equiv \alpha_{mn}(t) \in \mathbb{C}$ for $m, n \in \{1, 2\}$. Each decision maker is characterized by his or her own set of time-dependent, non-zero coefficients $\{\alpha_{mn}(t)\}$, $m, n \in \{1, 2\}$. This superposition state reflects our indecision until we make a choice. The time dependence implies that the same individual may take different decisions when asked the same question at different times. The time evolution can be seen as due to endogenous processes in the decision maker's body and mind (e.g. breathing, digestion, feelings, thoughts) as well as exogenous factors (interactions with the surroundings).

We assume that $|\psi\rangle$ is normalized, i.e.

$$\langle\psi|\psi\rangle = |\alpha_{11}|^2 + |\alpha_{12}|^2 + |\alpha_{21}|^2 + |\alpha_{22}|^2 = 1 \tag{2.17}$$

The *prospect states* are defined as product states $|\pi_j\rangle \in \mathcal{H}_{\mathcal{AB}}$,

$$\begin{aligned} |\pi_j\rangle &= |A_j\rangle \otimes \left\{\gamma^j_{j1}|B_1\rangle + \gamma^j_{j2}|B_2\rangle\right\} && (2.18)\\ &= \gamma^j_{j1}|A_jB_1\rangle + \gamma^j_{j2}|A_jB_2\rangle, \quad \gamma^j_{kl} = 0, \quad \forall j, k \neq j, l \in \{1, 2\}, && (2.19) \end{aligned}$$

where $\gamma^j_{kl} \in \mathbb{C}$, $j, k, l \in \{1, 2\}$. Concretely,

$$\begin{aligned} |\pi_1\rangle &= \gamma^1_{11}|A_1B_1\rangle + \gamma^1_{12}|A_1B_2\rangle, \quad \gamma^1_{21} = 0, \quad \gamma^1_{22} = 0 && (2.20)\\ |\pi_2\rangle &= \gamma^2_{21}|A_2B_1\rangle + \gamma^2_{22}|A_2B_2\rangle, \quad \gamma^2_{11} = 0, \quad \gamma^2_{12} = 0. && (2.21) \end{aligned}$$

The prospect states are superposition states, each corresponding to the decision maker ultimately choosing either lottery with indefinite mixed feelings about the setup and context. The use of three indices in γ^j_{kl} is useful to distinguish options that are available to the decision maker as opposed to options that are excluded, as illustrated in the next section 2.3.1.4.

2.3.1.4 Probability measure

QDT assumes that the following process takes place: the decision maker approaches any question in a state $|\psi\rangle$ of the form of (2.16). During her deliberations, she transits to either $|\pi_1\rangle$ or $|\pi_2\rangle$. If she transits to $|\pi_j\rangle$ $(j = 1, 2)$, she chooses the lottery L_j. The experimenter observes the choice of the lottery L_j, but does not know whether B took the value B_1 or B_2. The decision maker herself may remain undecided about B_1 or B_2. After the decision, the decision-maker state becomes $|\psi'\rangle$, a superposition state with the form of (2.16), but possibly with different coefficients than before, due to the time evolution. The same process is repeated when the next question is asked.

Hence, we identify the probability that the lottery L_j be chosen with the probability that $|\psi\rangle$ makes a transition to the superposition state $|\pi_j\rangle$ $(j = 1, 2)$:

$$p(L_j) \approx \text{proba}(\psi \to \pi_j) = |\langle\psi|\pi_j\rangle|^2 \quad (j = 1, 2) \ . \tag{2.22}$$

The approximation sign is because, a priori, one does not have $|\langle\psi|\pi_1\rangle|^2 + |\langle\psi|\pi_2\rangle|^2 = 1$. This is because, formally, there are additional states in $\mathcal{H}_{AB}$ than just $|\pi_1\rangle$ and $|\pi_2\rangle$ to which the system can make a transition; for instance, $|\pi_3\rangle = \gamma^3_{11}\,|A_1B_1\rangle + \gamma^3_{12}\,|A_1B_2\rangle + \gamma^3_{21}\,|A_2B_1\rangle$. However, $|\pi_3\rangle$ does not correspond to any decision that can be made in the experimental setting. In practice, decision makers have to choose between L_1 and L_2 (alternatively, if they fail to answer properly, their data is discarded). This amounts to constraining the system such that

$$\sum_{j=1}^{2} p(L_j) = 1, \tag{2.23}$$

which can be achieved by defining $p(L_j)$ as follows:

$$p(L_j) := \frac{|\langle\psi|\pi_j\rangle|^2}{|\langle\psi|\pi_1\rangle|^2 + |\langle\psi|\pi_2\rangle|^2}. \tag{2.24}$$

By defining the normalization quantity P, the former expression can also be written as

$$p(L_j) = \frac{1}{P}|\langle\psi|\pi_j\rangle|^2; \quad P = |\langle\psi|\pi_1\rangle|^2 + |\langle\psi|\pi_2\rangle|^2. \tag{2.25}$$

Expression (2.24) ensures that $\sum_{j=1}^{2} p(L_j) = 1$ and that $p(L_j) \in [0, 1]$ $(\forall j = 1, 2)$.

The probability $p(L_j)$ $(j = 1, 2)$ is to be understood as the theoretical frequency of the prospect L_j being chosen over a large number of times. Two types of setups can be put in place. The first setup involves a number of agents; in that case $p(L_j)$ gives the fraction of agents expected to choose L_j. In the second setup, a single decision maker is faced with a number of decision tasks, among which the same decision task appears several times. This setup is designed such that each repetition of the same decision task can be assumed to be independent of previous occurrences. That is, we assume negligible memory and influence of previous decisions. In this second setup, the option L_j is chosen a fraction $p(L_j)$ of the time by the same decision maker. QDT treats similarly these two setups.

2.3.1.5 Utility and attraction factors

Let us examine the quantity $|\langle\psi|\pi_j\rangle|^2$ in terms of the coefficients given in (2.16) and (2.18):

$$|\langle\psi|\pi_j\rangle|^2 = \langle\psi|\pi_j\rangle\langle\pi_j|\psi\rangle = (\alpha^*_{j1}\gamma^j_{j1} + \alpha^*_{j2}\gamma^j_{j2})(\alpha_{j1}\gamma^{j*}_{j1} + \alpha_{j2}\gamma^{j*}_{j2}) \tag{2.26}$$

$$= |\alpha_{j1}|^2|\gamma^j_{j1}|^2 + |\alpha_{j2}|^2|\gamma^j_{j2}|^2 + \alpha^*_{j1}\gamma^j_{j1}\alpha_{j2}\gamma^{j*}_{j2} + \alpha^*_{j2}\gamma^j_{j2}\alpha_{j1}\gamma^{j*}_{j1}. \tag{2.27}$$

In quantum mechanics, the last two terms in (2.27) correspond to an interference between different intermediate states as the system makes a transition from $|\psi\rangle$ to $|\pi_j\rangle$. In decision theory, this interference can be understood as originating from the decision maker's deliberations as she is in the process of weighting up options and making up her mind. These interference terms are encapsulated into what is called in QDT the *attraction factor*,

$$q(L_j) = \frac{1}{P}(\alpha^*_{j1}\gamma^j_{j1}\alpha_{j2}\gamma^{j*}_{j2} + \alpha^*_{j2}\gamma^j_{j2}\alpha_{j1}\gamma^{j*}_{j1}), \tag{2.28}$$

where P is the normalization quantity introduced in (2.25). The attraction factor is interpreted in QDT as a contextual object encompassing subjectivity, feelings, emotions, cognitive biases and framing effects.

The classical terms become the so-called *utility factor*,

$$f(L_j) = \frac{1}{P}(|\alpha_{j1}|^2|\gamma^j_{j1}|^2 + |\alpha_{j2}|^2|\gamma^j_{j2}|^2). \tag{2.29}$$

Equation (2.24) can then be rewritten as

$$p(L_j) = f(L_j) + q(L_j). \tag{2.30}$$

In the absence of interference effects, only the utility factor $f(L_j)$ remains in $p(L_j)$. When $q(L_j) = 0$, the standard classical correspondence principle (Bohr, 1920) leads one to let $p(L_j)$ connect to more classical decision theories such as those mentioned in the introduction. The utility factor $f(L_j)$ thus has to take the form of a probability function, satisfying

$$\sum_j f(L_j) = 1 \quad \text{and} \quad f(L_j) \in [0, 1]. \tag{2.31}$$

As the simplest non-parametric formulation connecting $f(L_j)$ to classical decision theories, the utility factor is equated with

$$f(L_j) = \frac{U(L_j)}{\sum_i U(L_i)}, \tag{2.32}$$

where $U(L_j)$ is an expected value or expected utility, as in (2.4), (2.5) or (2.6). In this chapter, we use the simple non-parametric form given by (2.4), $U(L_j) = \sum_{n=1}^{N} p(x_n)x_n$, making it an expected value.

A more general form for $f(L_j)$ has been proposed by Yukalov and Sornette (2014c), namely

$$f(L_j) = \frac{U(L_j)\exp\{\beta U(L_j)\}}{\sum_i U(L_i)\exp\{\beta U(L_i)\}}, \tag{2.33}$$

where $\beta \geq 0$ is called the "belief parameter." Previous applications of QDT to empirical data (e.g. Yukalov and Sornette, 2010b, 2011) use the case $\beta = 0$, which is also what we use in this chapter.

Let us examine what conditions (2.31) imply when the utility factors are written as in (2.29). Imposing that the utility factors sum to one means that

$$|\alpha_{11}|^2|\gamma_{11}^1|^2 + |\alpha_{12}|^2|\gamma_{12}^1|^2 + |\alpha_{21}|^2|\gamma_{21}^2|^2 + |\alpha_{22}|^2|\gamma_{22}^2|^2 = P. \tag{2.34}$$

Based on its definition in (2.25) and (2.27), the normalization coefficient P is explicited as

$$\begin{aligned} P &= |\alpha_{11}|^2|\gamma_{11}^1|^2 + |\alpha_{12}|^2|\gamma_{12}^1|^2 + |\alpha_{21}|^2|\gamma_{21}^2|^2 + |\alpha_{22}|^2|\gamma_{22}^2|^2 + & (2.35)\\ &+ \alpha_{11}^*\gamma_{11}^1\alpha_{j2}\gamma_{12}^{1*} + \alpha_{12}^*\gamma_{12}^1\alpha_{11}\gamma_{j1}^{1*} + \alpha_{21}^*\gamma_{21}^2\alpha_{22}\gamma_{22}^{2*} + \alpha_{22}^*\gamma_{22}^2\alpha_{21}\gamma_{21}^{2*}. & (2.36)\end{aligned}$$

From the definition of the attraction factors (2.28), and using (2.34), this can be rewritten as

$$P = P + P(q(L_1) + q(L_2)), \tag{2.37}$$

which yields

$$q(L_1) + q(L_2) = 0, \tag{2.38}$$

since the attraction factors are not zero by definition. The constraint that the utility factors sum to one thus imposes that the attraction factors sum to zero. This last condition is the focus of the next section.

2.3.2 Quarter law: prediction of QDT on attraction factors

In this section, we recall the derivation of the so-called quarter law, which governs the typical amplitude of the attraction factors (e.g. Yukalov and Sornette, 2014b, 1159).

Since $p(L_j)$ and $f(L_j)$ both sum to one over the $L = 2$ prospects, it derives from (2.30) that the attraction factors $q(L_j)$ sum to zero. Also, since $p(L_j)$ and $f(L_j)$ are both comprised in the interval $[0, 1]$, $q(L_j)$ lies in the interval $[-1, 1]$. These two conditions are called in QDT the *alternation conditions*:

$$-1 \leq q(L_j) \leq 1, \quad \sum_{j=1}^{L} q(L_j) = 0. \tag{2.39}$$

Arising from interference effects between prospects in the mind of the decision maker, the attraction factor $q(L_j)$ can be seen as a random quantity varying across decision makers and over time for a single decision maker. One may thus introduce $\varphi(q)$, the normalized distribution of q, and write

$$\int_{-1}^{1} \varphi(q)dq = 1. \tag{2.40}$$

Because of the alternation conditions, the mean of q is zero:

$$\int_{-1}^{1} \varphi(q)qdq = 0. \tag{2.41}$$

Let us define the quantities

$$q_+ = \int_0^1 \varphi(q) q dq, \qquad q_- = \int_{-1}^0 \varphi(q) q dq. \tag{2.42}$$

From the alternation conditions (2.39) leading to (2.41), we have

$$q_+ + q_- = 0. \tag{2.43}$$

In the absence of any information, the variable q is equiprobable, i.e. the distribution $\varphi(q)$ is uniform. From (2.40), it derives that $\varphi(q) = \frac{1}{2}$. Put into (2.42), this yields

$$q_+ = \frac{1}{4}, \quad q_- = -\frac{1}{4}. \tag{2.44}$$

Applied to a binary lottery choice, this yields the prediction that, when L_1 is the most attractive prospect, we have

$$\bar{q}(L_1) = \frac{1}{4}, \quad \bar{q}(L_2) = -\frac{1}{4}, \tag{2.45}$$

where the signs are reversed if L_2 is the most attractive prospect. In QDT, this is called the *quarter law* and constitutes a quantitative prediction on the average value of the attraction factors in any given experiment, under the assumption of no additional prior information.

Importantly, several families of distributions $\varphi(q)$ yield the same average value of 1/4 for the attraction factor, which makes this result quite general, as pointed out by Yukalov and Sornette (2014b). For example, it is the case for the symmetric beta distribution,

$$\varphi(q) = \frac{\Gamma(2\alpha)}{2\Gamma^2(\alpha)} |q|^{\alpha-1} (1 - |q|)^{\alpha-1}, \tag{2.46}$$

defined on the interval $q \in [-1, 1]$, with $\alpha > 0$ and $\Gamma(\alpha)$ the gamma function. The beta distribution is employed in many applications, for example in Bayesian inference as a prior probability distribution. The quarter law also follows from several other distributions normalized on the interval $[-1, 1]$, such as the symmetric quadratic distribution,

$$\varphi(q) = 6 \left(|q| - \frac{1}{2} \right)^2, \tag{2.47}$$

and the symmetric triangular distribution,

$$\varphi(q) = \begin{cases} 2|q| & \text{if } 0 \leq |q| \leq \frac{1}{2}, \\ 2(1 - |q|) & \text{if } \frac{1}{2} < q \leq 1. \end{cases} \tag{2.48}$$

2.3.3 Sign of attraction factor in the case of close utility factors

Yukalov and Sornette (2014b, 1162) express a rule giving the sign of the attraction factor for a binary decision task with close utility factors.

This rule considers two lotteries

$$L_1 = \{x_i, p_1(x_i) : i = 1, 2, ...\}, \tag{2.49}$$

$$L_2 = \{y_j, p_2(y_j) : j = 1, 2, ...\}. \tag{2.50}$$

Note that not all of the same amounts appear in the two prospects.

The maximal and minimal gains are denoted as

$$x_{max} = \sup_i \{x_i\}, \qquad x_{min} = \inf_i \{x_i\}, \tag{2.51}$$

$$y_{max} = \sup_j \{y_j\}, \qquad y_{min} = \inf_j \{y_j\}. \tag{2.52}$$

The gain factor $g(L_1)$ of the first prospect, the risk factor $r(L_2)$ of choosing the second prospect, and the quantity $\alpha(L_1)$, are then defined as follows:

$$g(L_1) = \frac{x_{max}}{y_{max}} \tag{2.53}$$

$$r(L_2) = \begin{cases} \frac{p_2(y_{min})}{p_1(x_{min})}, & p_2(y_{min}) < 1 \\ 0, & p_2(y_{min}) = 1 \end{cases} \tag{2.54}$$

$$\alpha(L_1) = g(L_1)r(L_2) - 1. \tag{2.55}$$

Using these quantities, the sign of the first prospect attraction factor, $q(L_1)$, is defined by the rule

$$\text{sgn q}(L_1) = \begin{cases} +1, & \alpha(L_1) > 0 \\ -1, & \alpha(L_1) \leq 0. \end{cases} \tag{2.56}$$

2.4 Method

2.4.1 Prospects

In the dataset we are analyzing, subjects have to choose between one of two lotteries. One lotteries, L_1, is risky: subjects can win either CHF 50, with a probability p, or nothing, with a probability 1-p. In the other lottery L_2, subjects get the sure amount x in CHF (i.e., with probability 1). This can be seen as a "certain lottery." The condition $0 < x < 50$ is always ensured, otherwise there would be no point in choosing the risky lottery. The two lotteries are written

$$L_1 = \{0, 1-p|x, 0|y, p\}, \tag{2.57}$$

$$L_2 = \{0, 0|x, 1|y, 0\}, \tag{2.58}$$

with $0 < x < y$, and in the experiment, $y = 50$ CHF.

Note that the same amounts appear in both prospects. Writing L_1 as (2.57) means that one can get 0 with probability $1-p$, y with probability p and x with probability 0. Similarly, writing L_2 as (2.58) corresponds to gaining 0 with probability 0, y with probability 0 and x with probability 1. This way of expressing the two prospects captures the fact that the decision maker compares the two lotteries as she is making up her mind.

2.4.2 Decision tasks and participants

A decision task is characterized by the values of the two parameters p (the probability of winning the fixed amount CHF 50 in the risky lottery L_1) and x (the guaranteed payoff in the certain lottery L_2). In the experiment that generated the dataset, pairs of (p, x) values were randomly generated and the corresponding decision tasks (L_1, L_2) were submitted to subjects.

Each of 27 participants was given 200 randomly generated decision tasks, in 4 runs of 50 questions each. This amounts to 5,400 data points. Overall, the probability p was varied between 0.05 and 0.9 by steps of 0.05, and the sure amount x between 0 and 49 by steps of 1. At most 900 different (p, x) pairs could thus be generated.

Wittwer (2009, chap. 7), who performed the experiment with colleagues, gives the detailed method, including the description of conditions between which we do not differentiate in the present analysis.

The mean age of participants was 25.8 ± 3.6 years. Thirteen women (mean age 25 ± 3.3 years) and fourteen men (mean age 27 ± 3.7 years) were included in the study. The decisions were contextualized, in the sense that participants were asked to imagine a bank investment. Each decision was equally important, as participants were promised to receive, at the end of the experiment, the amount resulting from one randomly chosen decision task.

2.4.3 Application of QDT to the dataset

We now present how QDT specifically applies to the empirical dataset under study. The theoretical correspondence was carried out in section 2.3.1. Indeed, section 2.3.1 considers a decision problem whose structure corresponds to that of the decision tasks generating the dataset.

2.4.3.1 Utility factors

As stated in section 2.3.1.5, we equate prospect utilities with expected values given by (2.4), hence

$$U(L_1) = (1-p)0 + 0 \cdot x + p \cdot 50 = 50p, \tag{2.59}$$

$$U(L_2) = 0 \cdot 0 + 1 \cdot x + 0 \cdot 50 = x. \tag{2.60}$$

Then, according to (2.32), the utility factors are given by

$$f(L_1) = \frac{U(L_1)}{U(L_1) + U(L_2)} = \frac{50p}{50p + x}, \tag{2.61}$$

$$f(L_2) = \frac{U(L_2)}{U(L_1) + U(L_2)} = \frac{x}{50p + x}. \tag{2.62}$$

2.4.3.2 Aggregation of decision tasks

Since QDT is a probabilistic theory, a decision task must be offered several times in order to obtain an empirical choice frequency approximating $p(L_j)$. As is the case of other datasets available to researchers, the present dataset was not generated with QDT in mind. We discuss

in section 2.6.3 how to design decision tasks more suitable for testing QDT. There are several ways to aggregate the decision tasks, of which the following:

(i) Only aggregate decisions presenting the same (p,x) values, i.e. the same utilities $U(L_1)$, $U(L_2)$.

(ii) Aggregate decisions with close (p,x) values. For example, $(p = 0.1, x = 42)$ and $(p = 0.1, x = 45)$ present the same value of p and close values of x, and could be considered so similar as to represent the same decision task.

(iii) Aggregate decisions presenting the same utility factors $f(L_1)$, $f(L_2)$. For instance, the (p,x) pairs $A(p = 0.1, x = 42)$, $B(p = 0.1, x = 45)$ and $C(p = 0.05, x = 22)$ give respectively $f(L_1^A) = 0.106$, $f(L_1^B) = 0.1$ and $f(L_1^C) = 0.102$. Rounding these utility factors to the lowest 0.01, the three games A, B and C are aggregated as three realizations of the same decision task characterized by a utility factor $f(L_1) = 0.1$.

The issue with only aggregating identical (p,x) pairs (option (i)) is that the available empirical dataset does not always present a sufficient number of realizations of each (p,x) pair to perform a meaningful probabilistic analysis. For instance, in our dataset, 10.7% of all (p,x) pairs were offered only once; 11.5% were offered twice; 30.4% were offered three times or less. At most, one (p,x) pair was offered 126 times. Ignoring decision tasks with less than a minimum number of realizations is possible, but means giving up a substantial amount of data.

Aggregating by utility factor (option (iii)) partly resolves that issue. When rounding $f(L_1)$ to the lowest 0.01, no decision task characterized by its utility factor $f(L_1)$ was offered less than three times, and only 1.3% of all values of $f(L_1)$ were submitted exactly three times. At most, a given value of $f(L_1)$ was submitted 274 times. The number of decision tasks given per value of $f(L_1)$ is shown in figure 2.2. It indicates that some decision tasks were oversampled while others were undersampled. In section 2.6.3, we describe a sampling method that would be more adequate for our purposes.

In option (ii), one has to decide how close values of p and x from different (p,x) pairs have to be in order to aggregate the pairs. This option can bring an intermediate result between options (i) and (iii). In our analysis, we mostly use option (iii).

2.4.3.3 Probability

Empirically, we have access to the number of times N_j a prospect was chosen by one or several decision makers over the N times the same decision task was offered. Since the probabilities, utility factors and attraction factors for the two prospects ($j = 1, 2$) are related by equations (2.23), (2.31) and (2.38), the entire analysis can rest on the quantities associated with only one prospect. In what follows, we focus on the risky prospect, i.e. $j = 1$.

The empirical frequency is given by

$$p_{\text{exp}}(L_1) = \frac{N_1}{N}, \tag{2.63}$$

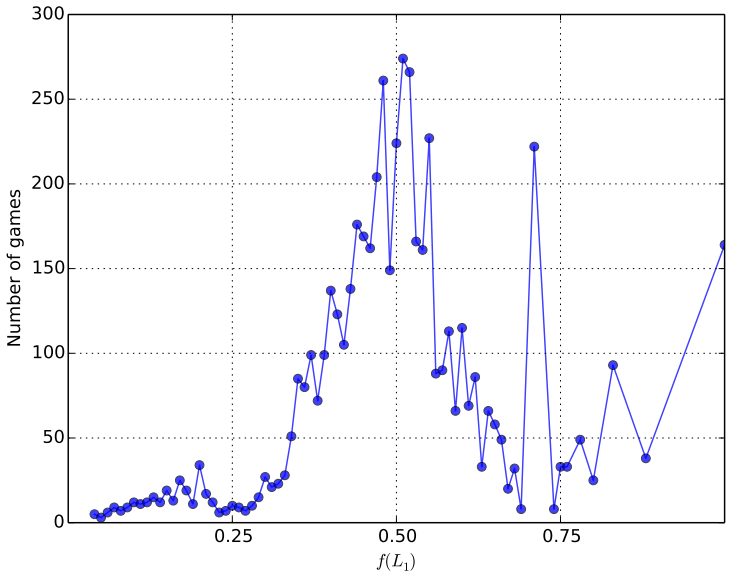

Figure 2.2: *Number of games offered in the dataset for each utility factor $f(L_1)$ rounded to the lowest 0.01.*

which approximates the probability $p(L_1)$. In what follows, we identify $p_{\text{exp}}(L_1)$ with $p(L_1)$.

Let us introduce a random variable X such that, at the k-th realization of a given decision task,

$$X_k = \begin{cases} 1, & \text{if the risky prospect is chosen,} \\ 0, & \text{if the certain prospect is chosen.} \end{cases} \tag{2.64}$$

The probability $p(L_1)$ is thus the Bernoulli distribution of X.

Let us additionally introduce the *retract* function, which retracts a variable z into an interval $[a, b]$:

$$\text{Ret}_{[a,b]}\{z\} = \begin{cases} a, & z \leq a \\ z, & a < z < b \\ b, & z \geq b \end{cases} \tag{2.65}$$

Empirically, based on (2.30), the following relationship holds between the probability $p(L_1)$, the utility factor $f(L_1)$ and the attraction factor $q(L_1)$:

$$p(L_1) = \text{Ret}_{[0,1]}\left\{f(L_1) + q(L_1)\right\}, \tag{2.66}$$

where the retract function ensures that $p(L_1)$ lies in $[0, 1]$ (see next section).

2.4.3.4 Attraction factors

The attraction factor can be deduced from experimental results as

$$q(L_1) = p(L_1) - f(L_1), \tag{2.67}$$

but only for $0 < p(L_1) < 1$, because of the retract function in (2.66). Indeed, for $p(L_1) = 0$ and $p(L_1) = 1$, $q(L_1)$ can have taken any value such that $f(L_1) + q(L_1) \leq 0$ or $f(L_1) + q(L_1) \geq 1$, respectively. Hence, the exact value of $q(L_1)$ that guided the decision maker(s) cannot be retrieved in these two cases; applying equation (2.67) may lead to over- or underestimate $q(L_1)$.

The dataset consists in decision tasks with various values of $f(L_1)$ in $[0, 1]$. In order to visualize to which extent empirical data conforms to the quarter law through equation (2.67), we plot empirical results as in figure 2.3, which shows $p(L_1)$ as a function of $f(L_1)$. Then $q(L_1)$ is given by the difference between $p(L_1)$ and the lower left to upper right diagonal of the graph ($p(L_1) = f(L_1)$), as long as $0 < p(L_1) < 1$. The absolute value of this distance is predicted by the quarter law to be equal to 0.25, on average. Table 2.1 and figure 2.3 illustrate this prediction. Figure 2.3 also offers a sketch of our empirical results, which we present in section 2.5.

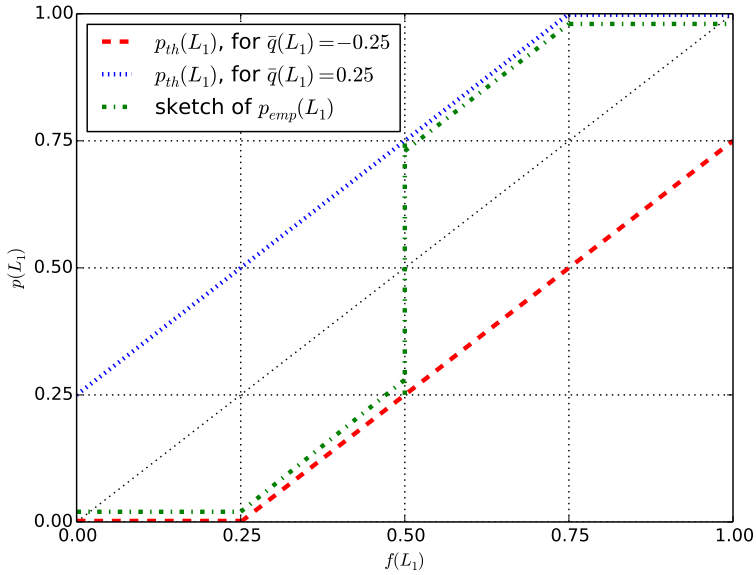

Figure 2.3: *Predicted (theoretical) appearance of the choice probability of the risky prospect, $p_{th}(L_1)$, for a positive (blue, dotted line) or negative (red, dashed line) attraction factor $\bar{q}(L_1)$ of absolute value equal, on average, to 0.25, and sketch of empirical probability, $p_{emp}(L_1)$ (green, dot-dash line).*

Region of $f(L_1)$	If $q(L_1) = -0.25$	If $q(L_1) = 0.25$
$0 \leq f(L_1) < 0.25$	$p(L_1) = 0$	$p(L_1) = f(L_1) + 0.25$
$0.25 \leq f(L_1) < 0.75$	$p(L_1) = f(L_1) - 0.25$	$p(L_1) = f(L_1) + 0.25$
$0.75 \leq f(L_1) \leq 0.1$	$p(L_1) = f(L_1) - 0.25$	1

Table 2.1: *Prediction on $p(L_1)$ by quarter law over different intervals of $f(L_1)$.*

2.4.3.5 Sign of attraction factors

The rule expressed in section 2.3.3 applies to the prospects written as

$$L_1 = \{50, p|0, 1-p\}, \tag{2.68}$$

$$L_2 = \{y, 1\}. \tag{2.69}$$

One gets $r(L_2) = 0$, $\alpha(L_1) = -1$ and sgn q$(L_1) = -1$. In other words, at and around $f(L_1) = f(L_2) = 0.5$, the risky prospect's attraction factor should be negative and the certain prospect should be preferred, in accordance with the principle of risk aversion.

2.4.3.6 Summary

For clarity, we summarize here the few steps necessary to obtain the attraction factors and test the quarter law in a dataset of choices between two simple lotteries in the domain of gains.

1. Choose a form for the utility factors satisfying $\sum_{j=1}^{2} f(L_j) = 1$ and $f(L_j) \in [0, 1]\ \forall j = 1, 2$.
2. Decide on an aggregation of decision tasks (e.g. per rounded value of utility factor).
3. For each aggregate, compute the frequency of a prospect L_j being chosen, $p(L_j)$.
4. For $p(L_j)$ in $]0, 1[$, compute for each aggregate the attraction factor $q(L_j) = p(L_j) - f(L_j)$.
5. Represent $p(L_j)$ as a function of $f(L_j)$.
6. Average the attraction factors $q(L_j)$ over intervals of interest.

2.5 Results

2.5.1 Individual results

The left panel of figure 2.4 represents the results of one individual, chosen for illustration purposes. We represent the frequency with which the individual chose the risky prospect, $p(L_1)$, as a function of the utility factor of that prospect, $f(L_1)$. Each point comprises the results of decision tasks presenting the same (p, x) values. The area of the markers is proportional to the number of decision tasks per point, which varies between 1 and 4. It is apparent in this panel that the majority of decision tasks were given only once, based on markers area as well as the fact that most points are situated at $p(L_1) = 0$ or $p(L_1) = 1$.

The left panel of figure 2.4 illustrates the fact that, faced with decision tasks presenting the same utility factor $f(L_1)$, the same individual may not consistently choose the same prospect, especially at intermediary values of $f(L_1)$. Yet, at low and high values of $f(L_1)$, decisions tend to be consistent, as may be expected.

We observe a preference switch from the certain to the risky prospect as the utility factor of the risky prospect increases. This switch is well known in the behavioral economics literature.

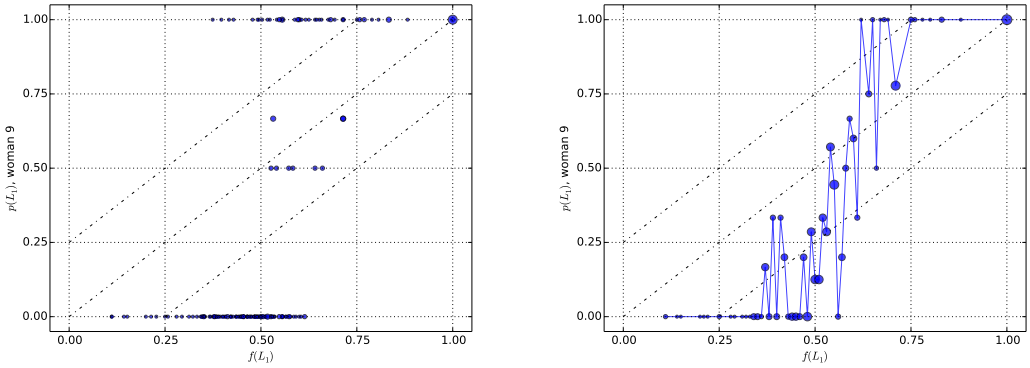

Figure 2.4: *For one individual, empirical probability $p(L_1)$ (choice frequency of the risky prospect) as a function of the utility factor $f(L_1)$. The area of the markers is proportional to the number of decision tasks per point (with a different proportionality factor in each panel). In the left panel, each point aggregates decision tasks that are exactly the same, i.e. presenting the same (p, x) values and thus the same utilities U_1, U_2. The number of decision tasks per point varies from 1 to 4. In the right panel, each point aggregates decision tasks presenting the same value of $f(L_1)$ rounded to the lowest 0.01. There are between 1 and 16 decision tasks per point.*

Its quantitative treatment usually consists in representing the frequency of a prospect being chosen (i.e. $p(L_1)$) as a function of a quantity depending on the question's parameters, which in our case is $f(L_1)$. To these data points is then typically fitted a logistic (S-shaped) function whose parameter can be interpreted as partly characterizing a decision maker's risk behavior (e.g. Mosteller and Nogee, 1951; Murphy and ten Brincke, 2014). The switch can be more or less sharp and is interpreted as decision makers being more or less discriminating and consistent.

The right panel of figure 2.4 also shows $p(L_1)$ as a function of $f(L_1)$ for the same individual, but here we aggregated (p, x) values yielding the same $f(L_1)$ value rounded to the lowest 0.01. As noted in section 2.4.3.2, there are thus more decision tasks per point. In contrast to aforementioned fitting approaches, we are interested in examining whether these data points follow the QDT prediction given by the quarter law (section 2.3.2). As a recall, the quarter law predicts that $p(L_1)$ is situated at $f(L_1) \pm 0.25$ on average.

It is instructive to take a closer look at individual results. Figure 2.5 shows the results of a sample of participants. Each panel corresponds to one participant. First, it is apparent that the quarter law would offer an unsatisfactory fit for these individuals, except perhaps for the one in the top right panel. To see this, one may recall figure 2.3 and compare it to these panels.

Second, it appears that different individuals behave quite differently. For example, the participant in the top left panel appears to have calculated the expected values of each prospect and consistently chosen the one with the highest expected value. By contrast, in the top right panel, the transition from the certain to the risky prospect is noisier and takes place along a longer interval of $f(L_1)$. The participant from the bottom left panel shows a strong preference for the certain prospect until high values of $f(L_1)$. In the bottom right panel, a relatively large

number of choices seem to be random, although there is overall a transition from the certain to the risky prospect.

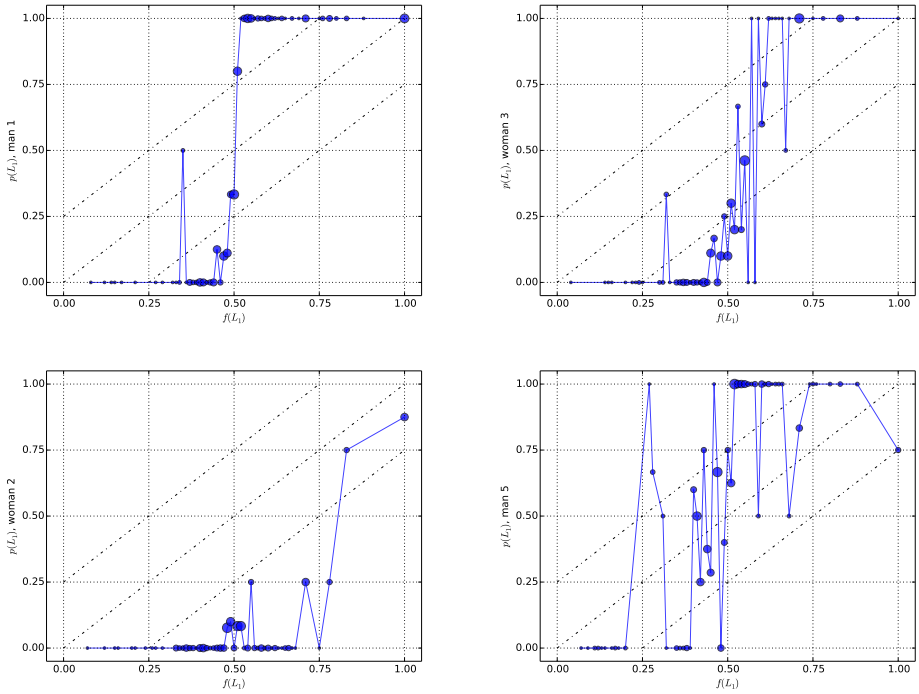

Figure 2.5: *For four participants separately, this shows the empirical probability $p(L_1)$ (choice frequency of the risky prospect) as a function of the utility factor $f(L_1)$. Each point aggregates decision tasks presenting the same value of $f(L_1)$ rounded to the lowest 0.01. In each panel, the area of the markers is proportional to the number of decision tasks per point, which ranges from 1 to 12 or 13 in these cases. The diagonal lines relate to the quarter law (see section 2.3.2).*

Figure 2.5 indicates the gender of participants (along the vertical axis of each panel), but let us stress that for each panel shown here, one may find an individual of the other gender whose choices follow a similar pattern.

In the next section, we carry out a first aggregation of individual results by gender and examine whether the quarter law holds at this level and whether gender differences can be observed in our sample.

2.5.2 Aggregation by gender

2.5.2.1 Female and male distributions of attraction factors

Figure 2.6 shows the frequency with which the risky prospect was chosen by women ($p_W(L_1)$) and men ($p_M(L_1)$) separately, as functions of the utility factor $f(L_1)$.

We perform a quantitative gender comparison using a Kolmogorov-Smirnov test on the two distributions of attraction factors $q_W(L_1)$ (for women) and $q_M(L_1)$ (for men). We use the SciPy

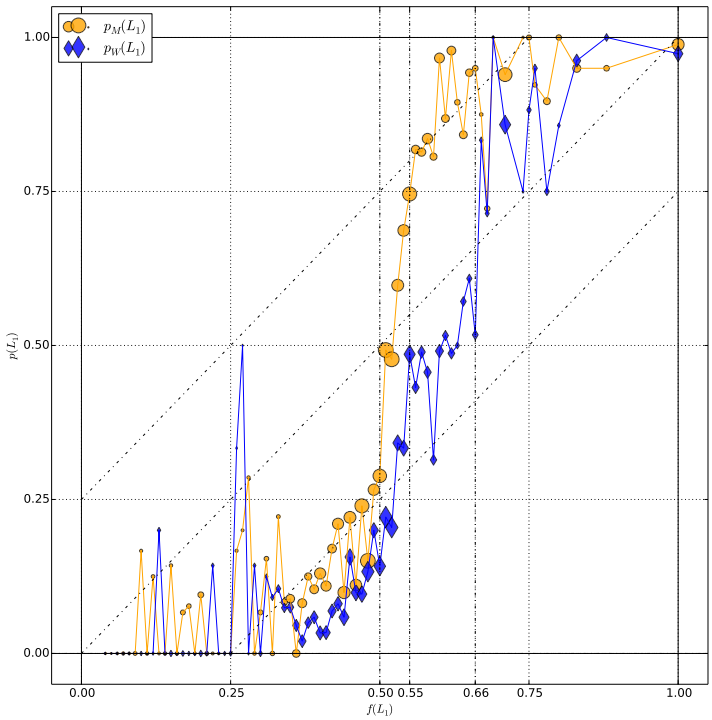

Figure 2.6: *For women (W) and men (M) separately, empirical probability $p(L_1)$ (choice frequency of the risky prospect) as a function of the utility factor $f(L_1)$. Each point aggregates decision tasks presenting the same value of $f(L_1)$ rounded to the lowest 0.01. The area of the markers is proportional to the number of decision tasks per point, which ranges from 1 to 140 for women and from 1 to 134 for men. The vertical dotted lines at $f(L_1) = 0.55$ and 0.66 relate to the transition, and the diagonal lines to the quarter law (see section 2.3.2).*

script `scipy.stats.ks_2samp`.[3] This test yields a p-value of 0.02. As a reminder, this means that, assuming the null hypothesis that the two samples $q_W(L_1)$ and $q_M(L_1)$ are drawn from the same distribution, there is a 2% chance to observe the obtained empirical data. In such a case, the consensus is to reject the null hypothesis and consider that the two samples, $q_W(L_1)$ and $q_M(L_1)$, are drawn from different distributions. The p-value we find thus mean that the distributions of attraction factors are significantly different for men and women in our sample.

2.5.2.2 Transition from the certain to the risky prospect

Figure 2.6 suggests that men's transition takes place along the interval $f(L_1) \in [0.5, 0.55]$, as compared to $f(L_1) \in [0.55, 0.66]$ for women. Namely,

- women (as a group) transition from the certain to the risky prospect at a higher value of

[3] Found at https://github.com/scipy/scipy/blob/v0.15.1/scipy/stats/stats.py, copyright Gary Strangman, last accessed 2016-03-04.

$f(L_1)$ than men, and

- women (as a group) transition over a longer interval of $f(L_1)$ than men.

The distance between the risk-neutral value $f(L_1) = 0.5$ and the preference transition to the risky prospect reflects the population's average risk aversion. The larger distance for women suggests that women in the sample show a stronger risk aversion than men, on average. However, let us stress that the sample size of thirteen women and fourteen men is too small to generalize these results to genders in general. We come back to this point in section 2.6.2.

The interval length, for its part, can have two different interpretations.

- First, if individual transitions all start and end at roughly the same values of $f(L_1)$ (homogeneous population), a longer interval reflects that decision makers showed little discrimination between different values of $f(L_1)$ along that interval, and were inconsistent in their choices, leading to intermediary values of $p(L_1)$.

- Alternatively, if individual transitions occur at different points or along intervals of different length (heterogeneous population), averaging over individuals will yield a broad transition at the level of the group. In that case, the transitional interval length at the group level reflects inter-individual variability.

The analysis performed in the next section 2.5.2.3 suggests that inter-individual variability is higher among women than men and is likely to contribute to the longer transition observed in figure 2.6 for women.

2.5.2.3 Intra- and inter-gender variability

We now compare the distributions of attraction factors in pairs of individuals, separating between same-gender and cross-gender pairs. We thus get three types of pairings, man-man, woman-woman and woman-man. For each pair, we perform a Kolmogorov-Smirnov test of the individual distributions of attraction factors $q(L_1)$. This yields one p-value per pair of individuals. Small p-values indicate that individuals in a pair make significantly different decisions.

Figure 2.7 shows the relative frequency of these p-values for the three types of pairings. About 13% of the man-man p-values are below 0.05, as compared to 28% of the man-woman p-values and 31% of the woman-woman p-values.

We also compare these distributions of p-values, using again Kolmogorov-Smirnov tests, and find that the man-man distribution is very different from the man-woman distribution ($p = 0.025$) and from the woman-woman distribution ($p = 0.05$), but the woman-woman distribution is quite similar to the woman-man distribution ($p = 0.68$).

This means that women are more dissimilar from each other than men are; women are almost as different from each other as they are from men. In other words, there is a larger intra-group variability between women than men.

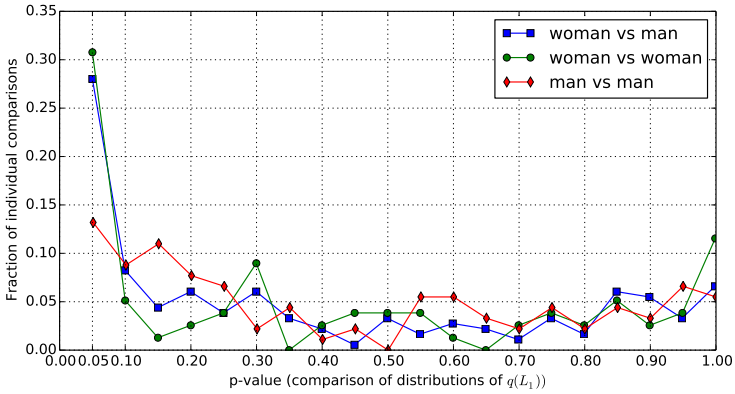

Figure 2.7: *Relative frequency of p-values (per intervals of 0.05) resulting from Kolmogorov-Smirnov tests of $q(L_1)$ distributions between pairs of decision makers. 30.1% of the woman-woman comparisons yield a p-value between 0 and 0.05 (i.e., their $q(L_1)$ distributions are clearly distinguishable), as compared to 28% of the woman-man comparisons and 13.1% of the man-man comparisons.*

2.5.2.4 Quarter law

We now test the validity of the quarter at the level of each gender. In order to calculate the attraction factor over intervals of $f(L_1)$, we need to account for the fact that we observe two regimes, one before and another after a transition occurring shortly after $f(L_1) = 0.5$. The attraction factor appears to jump from negative to positive values.

However, such a transition cannot be sharp in a finite sample with noisy data. Thus, data points that are part of the transition cannot be expected to satisfy the quarter law. This means that the transitional segment, $f(L_1) \in [0.5, 0.55]$ for men and $f(L_1) \in [0.55, 0.66]$ for women, has to be excluded from the estimation of the attraction factor. Hence, we compute the average of $q(L_1)$ separately over the two sides of the transitional segment. Moreover, as explained in section 2.4.3, one has to exclude from the analysis the decision tasks with $p(L_1) = 0$ or $p(L_1) = 1$.

We thus take for women $f(L_1) \in [0, 0.54]$ and $f(L_1) \in [0.67, 1]$ as the pre- and post-transition intervals. For men, we take the intervals $[0, 0.49]$ and $[0.56, 1]$. This yields the following attraction factors, for women (W) and men (M):

$$\bar{q}_{\text{W, pre}}(L_1) = -0.25 \pm 0.15 \tag{2.70}$$

$$\bar{q}_{\text{M, pre}}(L_1) = -0.18 \pm 0.12 \tag{2.71}$$

$$\bar{q}_{\text{W, post}}(L_1) = 0.06 \pm 0.10 \tag{2.72}$$

$$\bar{q}_{\text{M, post}}(L_1) = 0.21 \pm 0.10 \tag{2.73}$$

The pre-transition attraction factors do not show a significant discrepancy between genders, and are both compatible with the quarter law prediction of ± 0.25 on average. However, post-transition, women's attraction factor is much smaller than men's. This observation can be explained by the findings of sections 2.5.2.2 and 2.5.2.3. Namely, women prefer the risky prospect at higher values of $f(L_1)$ than men on average, and intra-gender variability is higher among women.

2.5.3 General population: quarter law

In this section, we aggregate all individual results together with the aim to test the quarter law at the global level. First, we check the prediction summarized in section 2.3.3 applying to the situation where the utility factors of the two competing prospects are very close. At $f(L_1) = 0.5$, we find the following attraction factor, based on 224 decision tasks:

$$\bar{q}_{\text{at}}(L_1) = -0.29 \ . \tag{2.74}$$

Within an experimental error of 14%, this result is in agreement with the quarter law and confirms the rule specifying the sign of the attraction factor close to $f(L_1) = 0.5$, expressed by Yukalov and Sornette (2014b, 1162) and recalled in section 2.3.3.

Figure 2.8 shows $p(L_1)$ as a function of $f(L_1)$ for the complete population. Based on this figure, we identify the interval of $f(L_1)$ along which the transition takes place as $f(L_1) \in [0.51, 0.54]$.

We compute the average of $q(L_1)$ separately on the two sides of the transitional segment, namely $f(L_1) \in [0, 0.5]$ and $f(L_1) \in [0.55, 1]$. As explained in section 2.4.3, one has to exclude from the analysis the decision tasks with $p(L_1) = 0$ or $p(L_1) = 1$.

We find the following averaged attraction factors for the risky prospect, respectively pre- and post-transition:

$$\bar{q}_{\text{pre}}(L_1) = -0.21 \pm 0.11 \tag{2.75}$$

$$\bar{q}_{\text{post}}(L_1) = 0.10 \pm 0.06 \tag{2.76}$$

The first of these results, $\bar{q}_{\text{pre}}(L_1)$, is in good agreement with the quarter law. The second estimation for $\bar{q}_{\text{post}}(L_1)$ is much lower, being located at 2.3 times its standard deviation from the predicted value of 0.25.

Informed by the gender analysis carried out in section 2.5.2, the low post-transitional attraction factor appears to be due to women in our sample showing, on average, a stronger risk aversion than men. More precisely, a number of decision tasks (characterized by a given value of $f(L_1)$) are associated with a positive attraction factor when presented to men, and a negative one when presented to women. This is particularly true of the decisions just after $f(L_1) = 0.5$ until all individuals have transitioned to preferring the risky prospect.

Finally, figure 2.9 shows the distribution of $q(L_1)$ values pre- and post-transition. As could already be seen in figure 2.8, apart from a few points, $q(L_1)$ consistently takes negative values pre-transition and positive ones post-transition. However, the irregularity of both distributions

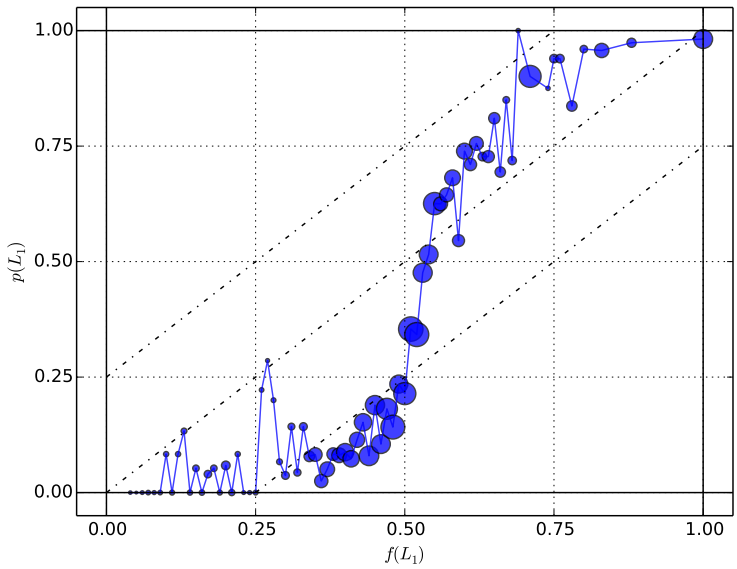

Figure 2.8: *Empirical probability $p(L_1)$ (choice frequency of the risky prospect) as a function of the utility factor $f(L_1)$. Each point aggregates decision tasks presenting the same value of $f(L_1)$ rounded to the lowest 0.01. The area of the markers is proportional to the number of decision tasks per point and varies between 3 and 274.*

(one could expect, for instance, bell-shaped, Gaussian distributions) suggests that there are not always enough decision tasks per value of $f(L_1)$ to ensure an adequate statistical sampling, as pointed out in section 2.4.3.2. This motivates to anticipate such analyses when setting up the experimental design, a point we come back to in section 2.6.3.

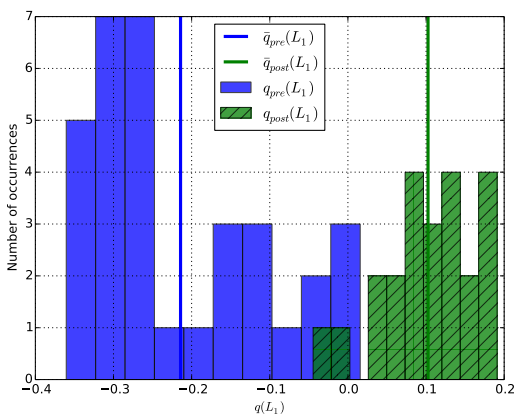

Figure 2.9: *Histogram of the values of the risky prospect attraction factor, pre- and post-transition ($q_{pre}(L_1)$ and $q_{post}(L_1)$, resp.), for an aggregation of decision tasks presenting the same $f(L_1)$ value rounded to the lowest 0.01.*

2.6 Discussion

2.6.1 Characterization of individual decision makers

Our analysis suggests that the quarter law holds at the group level and could be refined at the individual level to reflect characteristics of decision makers. As noted during the derivation of the quarter law in section 2.3.2, the value 1/4 is based on the condition that there is no prior or additional information other than the presentation of the competing prospects. Biological influences, psychological or cultural framing can be expected to break this hypothesis and give different predictions for the attraction factor, as shown in specific cases by Yukalov and Sornette (2014b, 2015).

Along the same lines, one may ask whether the attraction factor can be reliably used to characterize individuals. That is, one may attempt to calibrate the attraction factor on an empirical dataset for a given individual and make predictions for the same individual's decisions at a later time in a similar context. This is currently examined in prospect theory (Gonzalez and Wu, 1999; Fehr-Duda and Epper, 2012; Murphy and ten Brincke, 2014). Since QDT is a probabilistic theory, one would get a prediction for the frequency with which an individual chooses an prospect.

One shall thus examine specific forms for the distribution of attraction factors $q(L_j)$, and possibly refine the form of the utility factor $f(L_j)$ by replacing the expected values $U(L_j)$ (equations (2.59)-(2.60)) by expected utilities, as for example in prospect theory (Kahneman and Tversky, 1979; Tversky and Kahneman, 1992 ; see equation (2.6)). This may lead to an approximation for the form of $p(L_j)$ approaching a logistic function, as suggested by figure 2.8, which is done in classical approaches (e.g. Mosteller and Nogee, 1951; Murphy and ten Brincke, 2014). Such fitting is beyond the scope of the present work, whose main objective is to provide a guide of how to apply QDT in its present theoretical state to a dataset of simple gamble questions, but opens up an interesting path for future research.

2.6.2 Gender differences

Gender has a clear effect in our dataset. Namely, it supports the idea that men show on average less risk aversion than women. Another interesting result is that women show a larger intra-variability than men. Yet, the gender comparison we perform comes with a disclaimer about the small sample size. Thirteen women and fourteen men cannot be taken as representative of the genders. Our present purpose, rather than to draw general conclusions about gender differences in risk preferences, is to illustrate how to apply the QDT methodology at different levels, namely individuals and groups.

That being said, it is relevant to position these results in the context of the vast existing documentation on gender differences: reviews include Byrnes and Miller (1999); Eckel and Grossman (2008) and Croson and Gneezy (2009). Recently, more attention has been given to financial risk preferences (Powell and Ansic, 1997; Schubert et al., 1999; Fehr-Duda et al., 2006).

Understandably, this is a socially and politically loaded topic; see in particular the survey by Eagly (1995). In fact, it is next to impossible to find any research article that does not insist on being cautious in its conclusions (and we are no exception, as it happens). Reasons given are often the small sample size, possible biases from various demographic variables not controlled for, or artificial settings.

Despite some notable exceptions (Daruvala, 2007), the current state of affairs points toward the idea that there are indeed gender differences in risk-taking behavior, namely that women exhibit on average more risk aversion than men, with overlapping distributions. It has been suggested that gender differences in risk-taking behavior depend heavily on demographic factors: Hibbert et al. (2008) surveyed 1,382 finance and English professors and found that, when individuals have the same level of education, women are no more risk averse than their fellow male colleagues. Fehr-Duda et al. (2006) suggest that women and men have different probability weighting schemes that lead to a more risk averse behavior on the part of women. Gender differences in risk-taking behavior can be linked to the sociobiologists' hypothesis that men take more risks when they are trying to attract mates, while in parallel women tend to be more risk averse during their childbearing years (see Brinig, 1995, 17:n61 and Favre and Sornette, 2012).

2.6.3 Lotteries generation and sample size

One of the practical challenges we encountered was to choose an adequate aggregation of decision tasks in order to carry out a meaningful probabilistic analysis guided by QDT, given the empirical distribution of (p, x) decision tasks presented to subjects. In future experiments meant to be analyzed with QDT, we suggest the following lottery generation method. Let N be the number of decision tasks presented to each participant. Each decision task presenting a given value of the utility factor $f(L_j)$ should be planned to be offered at least three times to the same participant, and preferably more in the transition interval $f(L_j) \in [0.4, 0.7]$. A rounding of $f(L_j)$ should be chosen such as to allow this repetition over the N decision tasks and have the distribution of $f(L_j)$ cover the interval $[0, 1]$. The lotteries should be generated beforehand and the distribution of games should be controlled to reflect the desired distribution. The order in which (p, x) games are presented to subjects should be randomized so that participants are unlikely to answer very similar questions in a row.

Finally, 27 subjects do not constitute a large enough sample to generalize our results to a broader population, despite the large number of choice problems per subject (200). As a comparison, prospect theory founders Kahneman and Tversky typically ran experiments on 50 to 300 subjects (Kahneman and Tversky, 1979; Tversky and Kahneman, 1983; Shafir and Tversky, 1992). The tentative results presented in this chapter should be replicated in experiments with more participants in order to refine the QDT quantitative analysis of the observed phenomena.

2.7 Conclusion

We offer in this chapter an illustration of how to apply QDT to an empirical dataset of binary lotteries in which decision makers had to choose between a certain and a risky prospect. Through this, we hope to promote the empirical investigation of QDT, in order to test its current claims, but also challenge it and indicate new research directions. One such direction could be to calibrate the attraction factor and characterize individual decision makers or specific groups.

Acknowledgements

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Chapter 3

A two-gender agent-based model: Implications for competitiveness and risk taking

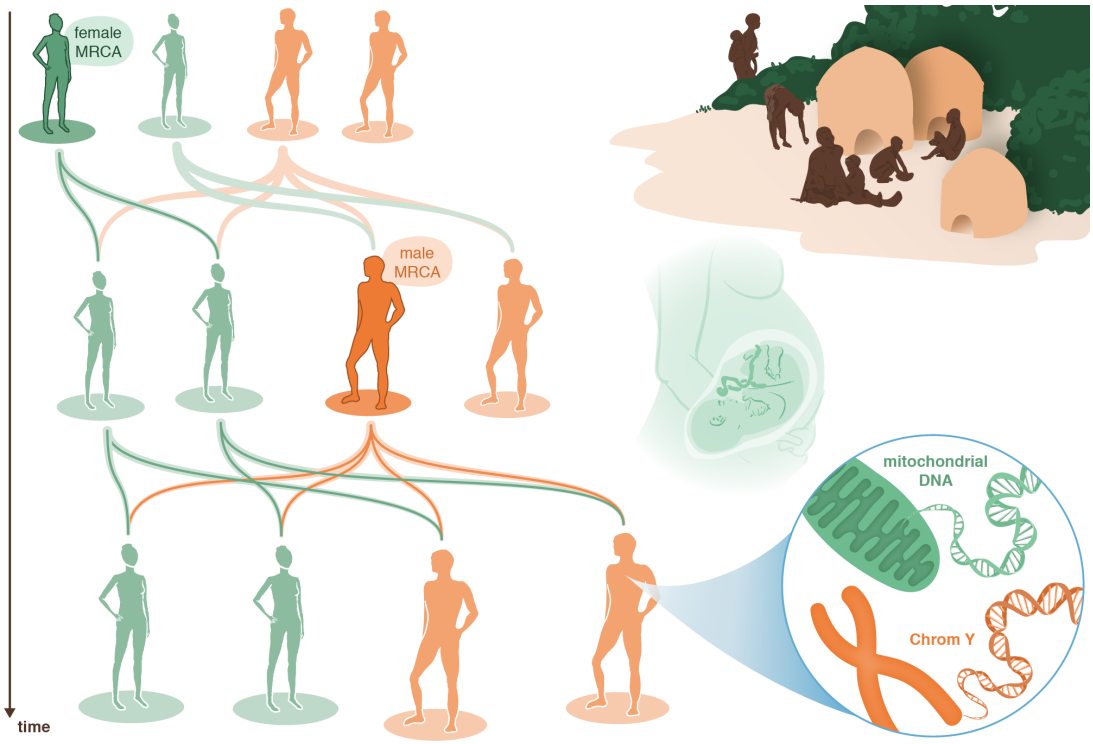

Figure 3.1: *This chapter investigates the influence of social and biological factors on features of genealogical trees inferred by genetic analyses. This has implications for gender differences in competitiveness and risk taking.*

3.1 Abstract

[1] The Time to the Most Recent Common Ancestor (TMRCA) based on human mitochondrial DNA (mtDNA) is estimated to be twice that based on the non-recombining part of the Y chromosome (NRY). These TMRCAs have special demographic implications because mtDNA is transmitted only from mother to child, while NRY is passed along from father to son. Therefore, the former locus reflects female history, and the latter, male history. To investigate what caused the two-to-one female-male TMRCA ratio $r_{F/M} = T_F/T_M$ in humans, we develop a forward-looking agent-based model (ABM) with overlapping generations. Our ABM simulates agents with individual life cycles, including events such as reaching maturity or menopause. We implement two main mating systems, polygynandry and polygyny, with different degrees in between. In each mating system, the male population can be either homogeneous or heterogeneous. In the latter case, some males are "alphas" and others are "betas," which reflects the extent to which they are favored by female mates. A heterogeneous male population implies a competition among males with the purpose of signaling as alpha males. The introduction of a heterogeneous male population is found to reduce by a factor 2 the probability of finding equal female and male TMRCAs and shifts the distribution of $r_{F/M}$ to higher values. In order to account for the empirical observation of the factor 2, a high level of heterogeneity in the male population is needed: less than half the males can be alphas and betas can have at most half the fitness of alphas for the TMRCA ratio to depart significantly from 1. In addition, we find that, in the modes that maximize the probability of having $1.5 < r_{F/M} < 2.5$, the present generation has 1.4 times as many female as male ancestors, if an ancestor is defined as an individual who has at least one descendant in the present generation. We also test the effect of gender-biased migration and gender-specific death rates and find that these are unlikely to explain alone the gender-biased TMRCA ratio observed in humans. Our results support the view that we are descended from men who were successful in a highly competitive context, while women were facing a smaller female-female competition.

Keywords: humans, male-male competition, agent-based model, mtDNA, NRY, risk taking

3.2 Introduction

3.2.1 Time to the most recent common ancestor

All humans alive today share common ancestors, which can be dated along specific ancestry lines using DNA samples. Human mitochondrial DNA (mtDNA) and the non-recombining part of the Y chromosome (NRY) have received particularly great attention in the context of modern human origin. Indeed, mtDNA is transmitted exclusively from mother to child (female or male),

[1] This chapter is based on Favre M. and D. Sornette, 2012: Strong gender differences in reproductive success variance, and the times to the most recent common ancestors. Journal of Theoretical Biology 310, 43-54. URL: http://dx.doi.org/10.1016/j.jtbi.2012.06.026.

while NRY is passed along only from father to son.

Unexpectedly, genetic studies have shown that the Time to the Most Recent Common Ancestor (TMRCA) along all-female ancestry lines (female TMRCA, or T_F) is about twice that along all-male lines (male TMRCA, or T_M): 170-240 thousand years for the female TMRCA (Tang et al., 2002; Ingman et al., 2000; Cann et al., 1987), compared with 46-110 thousand years for the male TMRCA (Tang et al., 2002; Pritchard et al., 1999; Thomson et al., 2000; Hammer and Zegura, 2002). This work seeks to interpret this finding.

3.2.2 Population genetics models and effective population size

In population genetics, the TMRCA is interpreted using the concept of effective population size. Geneticists use coalescent theory[2] to establish a correspondence between the genetic diversity of a population, its effective population size and its TMRCA. The two main population genetics models in coalescent theory are the Wright-Fisher model (Wright, 1931; Fisher, 1930) and the Moran model (Moran, 1958, 1962). Wakeley (2009) provides a review of these two models.

For example, the Wright-Fisher model assumes a haploid population (i.e. all-female or all-male), random mating, a Poisson distribution of reproductive success, non overlapping generations and a constant population size. The Wright-Fisher population size that would have yielded the same genetic diversity in the model as in reality is defined as the effective population size. In this model, the effective population is proportional to the TMRCA. A two-to-one TMRCA ratio thus means a two-to-one effective population size.

However, the concept of effective population size is merely a mathematical tool and does not correspond to any actual population size, such as census or breeding size, although approximations have been developed giving a connection between effective population size and breeding size (Hedrick, 2000).

Moreover, both models consider organisms that are either haploid (i.e. asexual, such as bacteria) or diploid, but hermaphrodites, such as snails (Wakeley, 2009, chap. 3.1). This implies that there are no genders and thus no interactions between genders. These models thus have to follow a top-down approach by assuming distributions of reproductive success from the start. The underlying hypothesis is that the relation found between inputs and TMRCA also holds in a diploid, biparental population. This simplification is for mathematical tractability purposes: taking into account stochastic interactions between females and males is extremely costly (Iannelli et al., 2005).

In this context, a better understanding of the correspondence between mating interactions (and underlying social structure) and TMRCA would provide insights into the origin of the ratio $r_{F/M} = T_F/T_M \simeq 2$. As we explain in section 3.2.6, one contribution of the ABM we develop is to give a concrete realization of the correspondence between mating system and TMRCA ratio through a representation as realistic as possible of a population in which genders interact with each other. This ABM allows us to (i) explore exactly the genealogical tree of the population backward in time, (ii) study quantitatively the effect of population heterogeneity and mating

[2]See Hedrick (2000) for an introduction to coalescent theory as a part of population genetics.

system on female and male TMRCAs, and (iii) observe (as opposed to input) gender-specific variances in reproductive success under different conditions.

3.2.3 Gender-biased variance in reproductive success and migration

Two classes of explanations have been proposed to explain the gender-biased genetic patterns that indicate unequal TMRCAs.

One class of explanations is based on effective polygyny, whereby males tend to father children with more females than females do with males (Wilder et al., 2004b). Effective polygyny implies that males exhibit a higher variance in reproductive success than females. Indeed, as soon as some males monopolize several females each, others leave no descendants, while the distribution of reproductive success among females remains fairly egalitarian.

In coalescent theory, a higher male than female variance in reproductive success is expected to result in a smaller male than female TMRCA. This is because less males than females contribute to the genetic diversity of the population, so that the male effective population size is smaller than the female one. The smaller male than female TMRCA arises because the males who have many more children than others are likely to become common ancestors of the whole population after potentially just a few generations. On the other hand, if all females have about the same number of children, it takes more time for a female to become a common ancestor (through what we could call pedigree drift in our model, by analogy with genetic drift).

The other class of explanations is based on female gender-biased geographic dispersal (Seielstad et al., 1998), whereby females disperse over larger spatial distances than males. This mechanism is often discussed as a possible explanation for observed patterns of genetic diversity in close non-human primates (Eriksson et al., 2006) and in humans. For example, Seielstad et al. (1998) argue in favor of female dispersal, while Wilder et al. (2004a) and Wilder et al. (2004b) dismiss it; Wilkins and Marlowe (2006) offer a review.

Migration of individuals results in a so-called gene flow, and coalescent theory including gene flow is called the structured coalescent (Wakeley, 2009; Hedrick, 2000). When females disperse, local mtDNA pools might include genes coming from a larger region, locally increasing genetic diversity. At the same time, if males do not migrate or migrate much less than females, NRY variation within populations should be quite small. Local DNA analyses then infer a larger female than male effective population size as more genetically different females than males contributed to each region, yielding a longer female than male TMRCA.

3.2.4 Number of female and male ancestors

The observed two-to-one TMRCA ratio has been interpreted by Baumeister (2010, 64) as meaning that we are descended from twice as many women as men, and that twice as many women as men reproduced. This interpretation needs clarification.

First, Baumeister uses the two concepts of breeding individuals and ancestors as if they were equivalent, which is not the case. Breeding individuals are individuals who reproduced, while

ancestors are determined by the presently living individuals. An ancestor is an individual who has at least one descendant alive in the present generation (Baumeister, 2010, 61). In general, an ancestor is not a common ancestor of the entire present generation. Importantly, an individual who reproduced is not necessarily an ancestor, while an ancestor necessarily reproduced. Baumeister assumes that a two-to-one ratio of ancestors implies a two-to-one ratio of breeding individuals and vice-versa. Indeed,

- regarding breeding individuals, Baumeister states that "Of all the people who ever reached adulthood, maybe 80% of the women but only 40% of the men reproduced. Or perhaps the numbers were 60% versus 30%;" (p.64)

- and regarding ancestors: "a woman's odds of having a line of descendants down to the present were *double* those of a man." (p.64)

As the TMRCA ratio reflects characteristics of ancestry lines, we retain the concept relating to the number of ancestors, and not breeding individuals. Indeed, the TMRCA ratio does not say anything about individuals who did reproduce but whose descendants did not, for example.

The second point to clarify is the correspondence between the two-to-one TMRCA ratio and a possible associated two-to-one ancestors ratio. In this context, it is unclear whether Baumeister counts our ancestors along all possible ancestry lines or only along all-female and all-male lines.

Since the TMRCA ratio informs us about all-female and all-male ancestry lines, let us examine what can be said of ancestors along all-female and all-male lines. Let us call such ancestors "mtDNA-ancestors" and "NRY-ancestors." Consider a man from a past generation who had no son but a daughter whose descendant line reaches someone from the present population (i.e. us). Then this man is not one of our NRY-ancestors, but he is an ancestor in the genealogical sense, and he potentially transmitted some of his DNA to some of us, although not including his NRY. This example illustrates the fact that the numbers of our mtDNA- and NRY-ancestors have little significance, if any, in terms of reproductive success and genetic transmission. This is because mtDNA and NRY are just two of a vast number of loci on the human genome. Thus, if Baumeister meant that we have twice as many mtDNA- as NRY-ancestors, no evolutionary behavioral conclusion based on reproductive success can be drawn for that assumption.

Hence, we are driven to consider the ratio of our male and female ancestors along all possible ancestry lines. If this ratio is significantly different from one, it would have behavioral implications. Indeed, the present generation is descended from ancestors along all possible ancestry lines, inherited the genes of these ancestors and learned from the culture they transmitted. However, the TMRCA ratio is not concerned with our ancestors along all possible ancestry lines. Thus, if Baumeister meant that we have twice as many female as male ancestors in the general sense, this quantitative claim actually cannot be justified by direct assimilation with the observed TMRCA ratio. In this context, an additional contribution of our ABM is to test Baumeister's interpretation concerning the relation between the number of our female and male ancestors and the TMRCA ratio.

3.2.5 Gender differences in risk-taking behavior

Gender-biased variances in reproductive success and a larger number of female than male ancestors mean that we are descended from men who were successful in a highly competitive context, while women were facing a smaller female-female competition for reproductive success. Baumeister (2010) argues that this helps explain many puzzling facts about male social behavior, including competitive behaviors and excessive risk taking in modern financial markets. Here, we put this interpretation into the context of the scientific literature on gender differences in risk-taking behavior.

Eagly (1995) provides a comprehensive review of the controversial science and politics of comparing genders. She examines the popular generalizations claiming that gender differences in empirical research are "small, unusually unstable across studies, very often artifactual, and inconsistent with gender stereotypes." (p. 155) She finds that these claims are not supported by quantitative research but generally support political agendas, in particular those of feminists. It appears that distributions of risk taking scores for men and women substantially overlap, but are still significantly different.

Croson and Gneezy (2009) review the literature on gender differences in economic experiments. They focus not only on risk preferences but also reaction to competition. They find that men are more risk-prone than are women (p. 2). In terms of competitive behavior, they find that, on average, men perform better and participate more than women in competitive environments (p. 17). These two themes of risk proneness and participation in competitive contexts may be connected to each other through the idea that "Males are more likely to see a risky situation as a challenge that calls for participation, while females interpret risky situations as threats that encourage avoidance." (p. 6)

Byrnes and Miller (1999) perform a meta-analysis of 150 studies addressing risk-taking tendencies of women and men, involving a total of over 100,000 participants. The range of areas tested is exceptionally broad and includes for example smoking, unprotected sex, driving, intellectual risk taking (e.g. raising one's hand in class) and physical risks. The studies reviewed include hypothetical choice, self-reported behavior and observed behavior (p. 370). Byrne et al. find that 60% of the results support the idea of greater risk taking on the part of men (p. 372). Notably, they stress that gender differences appear to vary across ages and contexts (p. 377).

The effect of age is tested by Brinig (1995, 16-7). Brinig finds that gender alone is not a significant predictor of choice, but that it is when combined with age. Men prefer risk more than women from about age 11 to 45, with a difference peak at about age 30. Brinig notes that this finding is "consistent with the sociobiologists' hypothesis that men are relatively more risk-loving during the period in which they are trying to attract mates; while women tend to be more risk-averse during their child-bearing years." (n61, p. 17)

The role of context is highlighted by Schubert et al. (1999), who do not find more risk taking on the part of men in the context of financial choices. They stress that "the comparative risk propensity of male and female subjects in financial choices strongly depends on the decision frame." (pp. 384-5)

Eckel and Grossman (2008) also stress the role of context in their review of experimental studies. They observe that "The findings from field studies conclude that women are more risk averse than men. The findings of laboratory experiments are, however, somewhat less conclusive." (p. 12) Importantly, they note that "both field and lab studies typically fail to control for knowledge, wealth, marital status and other demographic factors that might bias measures of male/female differences in risky choices." (p. 12)

Hibbert et al. (2008) address the above remark by surveying 1,382 Finance and English professors. They state that "when individuals have the same level of education irrespective of their knowledge of finance, women are no more risk averse than men." They also find that "the gender-risk aversion relation is a function of age, income, wealth, marital status, race/ethnicity and the number of children under 18 in the household." (p. 2) They conclude that "single women are no more risk-averse than single men when they are both highly educated." (p. 4)

The above considerations raise the question of the respective roles of nature versus nurture in gender differences (Croson and Gneezy, 2009, 20). A comparison of a patriarchal society (the Maasai in Tanzania) with a matrilineal society (the Khasi in India) suggests that "societal structure is crucially linked to the observed gender differences in competitiveness" (Gneezy et al., 2006, 12), stressing the role of nurture. Another study (Chen et al., 2013) uncovers the role of menstrual cycle and contraceptive pill usage on female competitiveness in bidding situations, putting in evidence the role of nature.

In this context, our model is consistent with a process of gene-culture coevolution. It includes both biological constraints (e.g. pregnancy and lactation times) and social components (mating system, population heterogeneity), and allows us to observe the cumulated effect of both classes of factors on the TMRCA ratio, variance in reproductive success and number of ancestors. Our results suggest that a high male-male competition for reproductive success may have been permeating the history of modern humans (200,000 years ago to recent times), which may have contributed to create cultural or biological gender differences in attitudes toward risk and competition.

3.2.6 Agent-based modeling

In this chapter, we investigate how social structure and biological constraints influence the resulting TMRCA, using an agent-based model (ABM, or individual-based model, as it is often called in biology). This ABM allows us to investigate which of several possible social organizations (including several mating systems and gender-biased migration) are most likely to result in longer female vs. male TMRCA. Our results focus on the TMRCA ratio $r_{F/M} = T_F/T_M$, which is about 2 according to genetic studies, as reviewed in section 3.2.1.

Our ABM is forward-looking in time and simulates a population with overlapping generations of female and male agents. Each simulation lasts hundreds of generations. Agents have life cycle events such as reaching reproductive maturity or menopause. Additionally, pregnancy and lactation time limit the fertility of female agents. Instead of being approximated based on mtDNA and NRY analyses, the female and male TMRCAs are exactly retrieved by exploring

the genealogical tree of the present male population backward in time. Our model thus includes no genetic evolution of individual traits.

In contrast to the population genetics models mentioned in section 3.2.2, we do not input distributions of reproductive success. Instead, we control the mating pattern at the population level and observe the resulting distributions of reproductive success for each gender. This is allowed by the unique features of our ABM, namely forward-looking and overlapping generations. This contrasts with coalescent models, which are backward-looking and assume non-overlapping generations. Existing forward-in-time models almost always assume non-overlapping generations, and because of this have to input distributions of reproductive success. To our knowledge, the only program that implements overlapping generations is BottleSim and it has been applied exclusively to the problem of bottlenecks (Kuo and Janzen, 2003).

The different social organizations implemented in our ABM correspond to polygynandry (or promiscuity), and polygyny, whereby a woman can be paired with only one man, but a man can be paired with several women. Each mode comes with at least two variants, whereby the male population is respectively homogeneous or heterogeneous. In the latter case, some male agents are "alphas" and others are "betas," which can be understood in our model as reflecting how easily they can mate based on female preferences. Input parameters are the proportion of alphas and how much more successful alphas are as compared to betas in attracting mates. A heterogeneous male population implies a competition among males as each of them strives to appear as an alpha. Effective polygyny (whose definition does not necessarily imply the existence of marriage in the form of a social contract) is or is not realized in our model, depending on the mode, variant and some agent life cycle characteristics. An additional variant in the polygyny mode allows to create a condition very close to lifelong monogamy.

Furthermore, gender-biased migration can take place within any of these mating systems. We implement this possibility by considering an island model of two subpopulations (or demes) exchanging agents.

3.2.7 Main results

The exploration of the parameter space of our ABM shows that a TMRCA ratio $r_{F/M}$ of 2 is realized with a significantly higher likelihood within a heterogeneous male population (consisting of alpha and beta males) than within a homogeneous male population, independently of the mating system (polygynandry or polygyny). Indeed, while about 60% of the simulations have $0.5 < r_{F/M} < 1.5$ in the homogeneous mode, a heterogeneous male population lowers by half this percentage and shifts the distribution of the TMRCA ratio to higher values. Moreover, the heterogeneity level needs to be high in order to observe this shift: less than half of the males can be alphas, while betas can have no more than half the fitness of alphas for the TMRCA ratio to depart from 1.

Our simulations suggest that gender-biased migration alone is very unlikely to contribute to the observed TMRCA ratio. We also discuss the possibility that unequal gender-specific death rates may have played an important role, but argue that it could hardly have taken place with

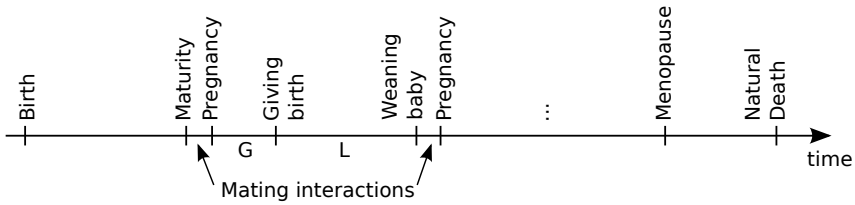

Figure 3.2: *Typical life cycle of a female (proportions are not respected). Males only have the events Birth, Maturity and Natural Death and participate to the mating interactions at every time step between Maturity and their death. When the carrying capacity is exceeded, any agent might die at any time between her birth and the age of natural death.*

the required intensity without the existence of significant male-male competition.

Additionally, the investigation of the genealogical tree produced by our ABM shows that, in the modes that maximize the probability of the TMRCA ratio to lie between 1.5 and 2.5, the present generation has approximately 1.4 times as many female as male ancestors. An ancestor is defined as an agent who has at least one descendant among the present generation, along any lineage. Counting the ancestors belonging to each gender provides a measure of the transmission success of females and males, in a genealogical, potentially genetic, and cultural sense.

Overall, our results support the interpretation of the observed TMRCA ratio made by Baumeister (2010) and the gender-specific behavioral consequences thereof. That is, our results indicate that we are descended from males who succeeded in a highly competitive context and from females who did not have to face the same competitive conditions.

The rest of this paper is organized as follows. We present our agent-based model in section 3.3. Detailed results are discussed in section 3.4. Our main results are summarized in section 3.5 and we discuss their implications in section 3.6.

3.3 Agent-based model

3.3.1 General set-up

Our agents have the following life cycles, as illustrated by figure 3.2.

- **Mating interactions** take place at every time step. Only mature males and mature premenopausal females participate. The different mating systems we implemented are described in section 3.3.3.

- **Pregnancies, births and lactation:** Pregnancy lasts G time steps. Pregnant females have the same probability of dying as any other agent. If this happens, the unborn baby is not counted as an agent in the simulation. Newborns have a 50% chance of being of either gender. A mother remains infertile after giving birth during a lactation time L.

- **Maturity and menopause:** When agents reach reproductive maturity, they start participating in the mating interactions. Depending on the variant, females stop or not when

they undergo menopause.

- **Deaths:** We give as inputs two carrying capacities K_F and K_M, respectively for females and males. At each time step, we ensure that the population size of either gender is at most equal to the respective carrying capacity. The population thus remains on average constant with $K_F + K_M$ members in total. Agents that reach the maximum allowed age die of natural death, independently of the population size. Specifically, if N_F is the number of females, the probability that a female survives at any time step, if she is younger than the maximum age, is equal to 1 if $N_F \leq K_F$ and to K_F/N_F otherwise. This is the same for males.

Considering that one time step represents one calendar day, we choose $G = 270$ (≈ 9 months) and $L = 1,200$ (≈ 3.5 years, which are typical of forager societies, e.g. see Konner, 1978). Agents reach reproductive maturity at 5,400 ($\approx$ 15 years old), females reach menopause at 18,000 ($\approx$ 50 years old) and natural death occurs at 25,000 ($\approx$ 70 years old). We checked that our results are not influenced by varying these parameters across realistic ranges, by having gender-specific ages of maturity or by letting menopausal females participate in the mating interactions (see section 3.4.5).

We also discuss gender-specific carrying capacities ($K_F \neq K_M$) in section 3.4.4. For most of our simulations, we set $K_F = K_M = 75$, corresponding in total to Dunbar's prediction for the typical size of social groups associated with the human cognitive power to manage social relationships (Dunbar, 1993). We tested several population sizes up to $K_F = K_M = 500$ and found that, as long as $K_F = K_M$, the population size does not influence our results. No change of our results are found when reducing all duration-related parameters by a proportional factor, i.e. by setting that one time step represents for instance one week (then $G = 38$, $L = 170$, etc.) or one month ($G = 9$, $L = 40$, etc.). Thus, within a broad range, the granularity of time steps has no influence on our results.

We simulate hundreds of synthetic worlds for each set of parameter values. For each simulation, we use the last generation of males as our sample and searched the genealogical tree for their female and male MRCAs. As generations are overlapping, the generation length has to be externally defined in order to select our sample. This definition influences only our sample choice. We usually choose the generation length l_{gen} equal to the maturity age and posit that agents born between iteration nl_{gen} and $(n+1)l_{gen}$ belong to generation $n+1$ ($n \in \mathbb{N}$).

The number of time steps per simulation is chosen such that a female and a male common ancestors could always be found for the sample. With the above parameters, this corresponds to approximately 2 million time steps. Then, for each gender, the TMRCA is computed as the last time step minus the MRCA's date of birth (counted in time steps from the start of the simulation). We observe that increasing the number of time steps does not increase TMRCAs but only shifts the MRCAs forward in time, as it should.

In summary, our parameters are as follows:

$$\begin{aligned}
&1 \text{ time step} \simeq 1 \text{ day};\\
&G = 270; L = 1,200; \text{Menopause} = 18,000;\\
&\text{Maximum Age} = 25,000;\\
&K_F = 75; K_M = 75; \text{Iterations} = 2 \times 10^6
\end{aligned} \tag{3.1}$$

3.3.2 Male population characteristics

Each newborn male is assigned a fitness $f \in [0, 1]$. It can represent a variety of traits that can be innate or acquired, such as physical characteristics, health, technical skills (such as hunting), resources, social status, sociability, intelligence, and so on, or a combination of these. Depending on the mating mode, this fitness acts as the probability that fertile females met by a male get pregnant from him, or as the probability that females choose a male to be their partner. f thus encapsulates the degree to which a male is favored by female choice based for example on his perceived qualities as a partner or father.

Alpha males have a fitness $f_\alpha = 1$ and beta males have a fitness f_β with $0 < f_\beta < 1$ (all beta males have the same fitness). Newborn males have a probability p_α of being alphas and $1 - p_\alpha$ of being betas, independently of their father's fitness.

If $p_\alpha = 1$ or $p_\alpha = 0$, the male population is homogeneous (all-alphas or all-betas). Otherwise, we refer to the situation as a heterogeneous mode characterized by p_α and f_β.

We discuss in section 3.6.1 the implications of additionally considering that females also constitute a heterogeneous population, implying that males choose mates among a preferred subset of females.

3.3.3 Mating interactions and gender-biased migration

We tested our model with two different mating systems, polygynandry and polygyny, as well as under a condition of gender-biased migration.

3.3.3.1 Polygynandry

At each time step in this mode, each mature male chooses a fertile female at random and attempts to mate. This results in a pregnancy with a probability equal to the male's fitness. The order in which males select females is randomized at each time step.

This mating pattern can be associated with polygynandry (or promiscuity), as pairings are not monitored in any way (i.e. partners may change at every time step). In a homogeneous male population, it is equivalent to fully random mate choice.

3.3.3.2 Polygyny

In the polygyny mode, a female agent who becomes mature chooses one of the mature male agents to be her husband, who will then father all of her children for as long as he lives. Females

select the male i with the largest "adjusted fitness" F_i, defined as

$$F_i = \frac{f_i}{w_i + 1}, \tag{3.2}$$

where f_i is the male's fitness and w_i counts how many wives he already has. If several males have the maximum adjusted fitness, females randomly choose one of them. This follows the concept of polygyny threshold (Verner and Willson, 1966; Orians, 1969), whereby a woman might gain from marrying a man who already has one or several wives, if the amount of resources he has to offer offsets the disadvantage of having to share with other wives, in comparison to choosing a single man with less resources.

This mode comes together with four possible variants, depending on two options. First, if one of a male's wives dies, she remains counted or not in F_i, decreasing the male's adjusted fitness. Still counting a deceased wife in F_i can be interpreted as taking into account that she most likely left her husband with at least one child to take care of, decreasing the amount of resources (encapsulated in f_i) he can offer to a new wife. This variant is abbreviated DWD (Deceased Wives Decrease adjusted fitness) versus DWnoD (Deceased Wives do not Decrease adjusted fitness).

Second, fertile females may remarry or not in the event that their husband dies, in which case female choice follows the same rule as above. We denote this option by WREM (Widows Remarry) or WnoREM (Widows do not Remarry). To simplify, menopausal females whose husband dies do not remarry, whatever the variant. Widows most likely already have children from their previous husband. WnoREM can thus be interpreted as integrating either a lack of male interest in females who already have children, or a lack of female interest in remarrying (because they already have children).

In contrast to the polygynandry mode, polygyny integrates explicit pair bonds, whereby one male can be paired with several females simultaneously and females are paired to a single male at a time. Actually, one of the polygyny variants turns out to be very close to lifelong monogamy, as shown in section 3.4.2. Anthropological studies indicate that the prevalent mating systems in humans are polygyny and monogamy, which account for approximatively 82% and 17% of human societies, respectively (Marlowe, 2000). Moreover, pair bonding and its counterpart, cooperative breeding, are essential features of humans (Burkart et al., 2009). Therefore, our polygyny mode simulating pair bonds seems more realistic than polygynandry. However, by its simplicity, the polygynandry mode constitutes a useful testing tool.

3.3.3.3 Gender-biased migration

We test a two-deme island model with gender-specific migration rates m_F for females and m_M for males. An agent can migrate only once in its lifetime, just before it reaches reproductive maturity. The probability that it migrates at this time is given by its gender's migration rate.

3.4 Results

With the parameter values given in section 3.3, the total number of agents born during a typical simulation is about 44,000. If a generation is set as the generation of the father plus 1 for a boy and as the generation of the mother plus 1 for a girl (the initial agents belonging to generation 0), 2 million time steps give about 200 generations with approximately 100 agents of each gender belonging to each generation. We measured inbreeding defined as the proportion of matings taking place between siblings or parent-child dyads. In all modes, it is found to be below 6%. All results are compiled in tables in section 3.5.

3.4.1 Polygynandry

3.4.1.1 Homogeneous male population

Among 1,000 simulations of a polygynandrous mating system in a homogeneous male population ($p_\alpha = 1$) and equal carrying capacities (so that death rates are equal for males and females), we find 58% of them with a TMRCA ratio $r_{F/M} = T_F/T_M$ between 0.5 and 1.5, compared with 20% between 1.5 and 2.5. This mode is thus approximately three times more likely to yield a TMRCA ratio close to 1 than to 2.

Figure 3.3 shows the distribution of the TMRCA ratio. This distribution has a mean of 1.2 and a median of 1, with a standard deviation of 0.8 reflecting the high stochasticity of the process.

We use the number of children born to an agent in its lifetime as a measure of its reproductive success. We consider only agents who reached maturity, as agents who died while still immature could not have any children by definition. Since the population is kept constant, the average number of children per agent of either gender is 2, but the average number of children per mature agent is approximately 4.

In the polygynandry mode with homogeneous male population (corresponding to random mating), males have a higher variance[3] in reproductive success than females. Indeed, the standard deviation in reproductive success is on average 4.2 for mature males, compared with 3 for mature females (the corresponding variances for males and for females are respectively 17.7 and 8.8).

Importantly, this gender difference takes place despite random mating because female reproductive rate is severely limited in time by biological constraints, namely pregnancy, lactation and menopause, while male reproductive rate is only limited by the number of mates a male can obtain in his lifetime. Given our parameters, the maximum number of children a female can have between maturity and menopause is 9. The most successful male of each simulation, in

[3]We use the term "variance" because of its common use in the context of measuring reproductive success. However, it should be kept in mind that the variance of a random variable is the square of its standard deviation, and it is the standard deviation that should be used as the measure of variability that can be compared meaningfully with the typical (or average) value of the random variable.

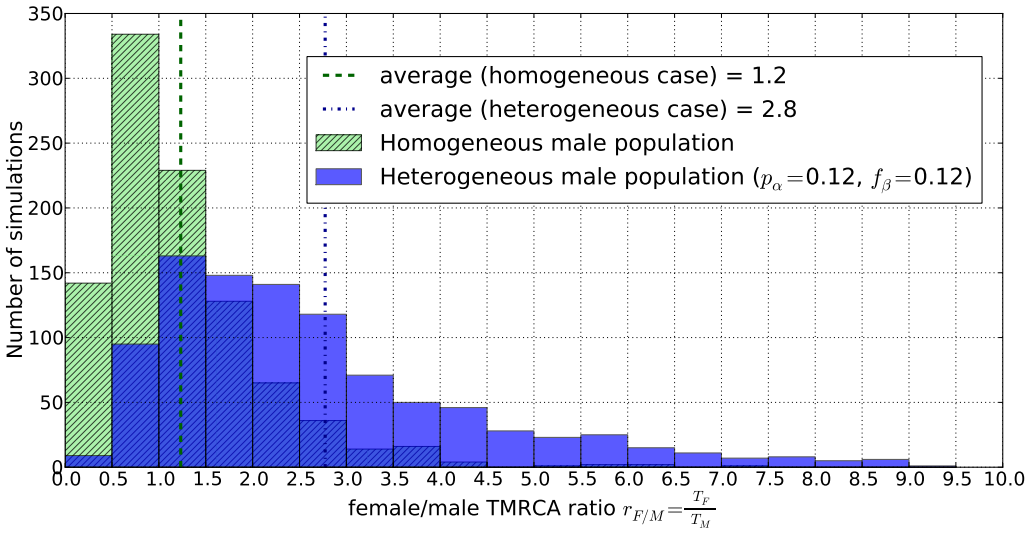

Figure 3.3: *Histogram of the TMRCA ratio $r_{F/M} = T_F/T_M$ for a polygynandry (random) mating system for a homogeneous male population (hatched area), and for a heterogeneous alpha-beta male population with a proportion of alphas given by $p_\alpha = 0.12$ and betas' fitness $f_\beta = 0.12$ (plain area). The average of each distribution is indicated by dotted lines. Each histogram is obtained over 1,000 simulations. Parameters are given in expression (3.1).*

contrast, typically has 26 children. This is illustrated by figure 3.4, which shows the distribution of number of children born to mature females and males in one specific simulation.

3.4.1.2 Heterogeneous male population

Polygynandry in a heterogeneous male population gives a very different distribution of TMRCA ratio compared to the previous case of homogeneous male population. Recall that male population heterogeneity is characterized by the two parameters p_α and f_β.

Figure 3.5 shows the fraction of simulations with a TMRCA ratio higher than 1.5 for values of p_α and f_β between 0.1 and 1. For the values $p_\alpha = 0.12$ and $f_\beta = 0.12$, it is possible to obtain more than 72% of the simulations with a TMRCA ratio higher than 1.5. Figure 3.6 refines the analysis by showing the fraction of simulations with a TMRCA ratio between 1.5 and 2.5 for $p_\alpha \in [0.075, 0.6]$ and $f_\beta \in [0.075, 0.3]$. The figure shows that in this region of the parameters space (p_α, f_β), it is possible to obtain up to 30% of the simulations with a TMRCA ratio between 1.5 and 2.5.

Let us now examine the male and female reproductive successes for $p_\alpha = 0.12$ and $f_\beta = 0.12$. In comparison to a homogeneous male population, the variance in reproductive success among mature males increases considerably. Indeed, the standard deviation is now equal to 8 (compared to 4.2) and the most successful males have on average 82 children (compared to 26), while the situation has not changed for females.

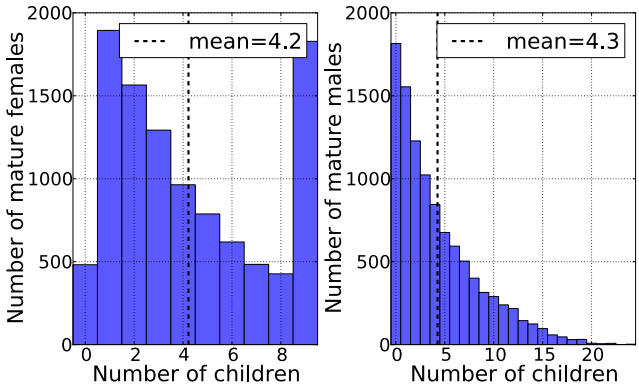

Figure 3.4: *Histogram of the number of children per mature female (left panel) and per mature male (right panel) in the polygynandry case with a homogeneous male population, for one specific simulation. As the population is kept constant, the average number of children per female and per male is 2, but here only the mature agents' numbers of children are shown, which is why the averages are around 4. The maximum number of children a female can have between maturity and menopause is 9, and all females who reach menopause have 9 children. 5% of mature females are childless because they (randomly) die before delivering their first child. In comparison, 18% of the mature males die without having had any children. Parameters are given in expression (3.1).*

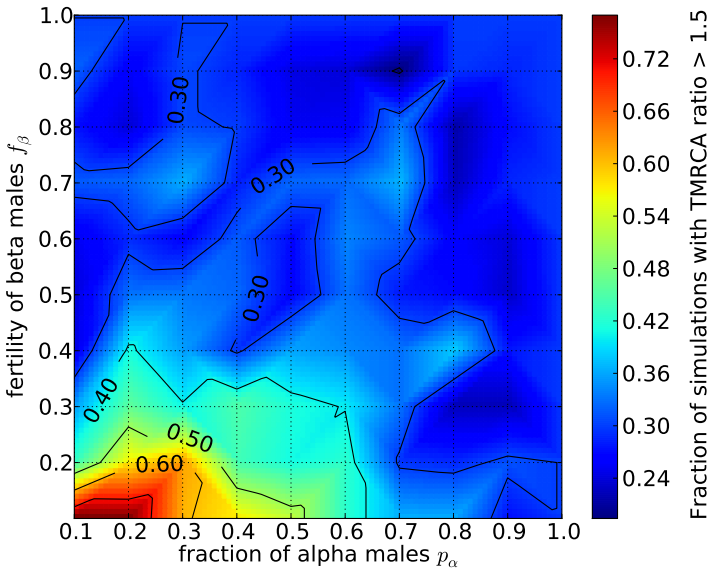

Figure 3.5: *Phase diagram in the case of polygynandry with heterogeneous male population, giving the fraction of simulations with a TMRCA ratio $r_{F/M} = T_F/T_M$ higher than 1.5 in the two-parameter space (fraction of alpha males p_α; fertility of beta males f_β). Each grid point is obtained over 200 simulations. Parameters are given in expression (3.1).*

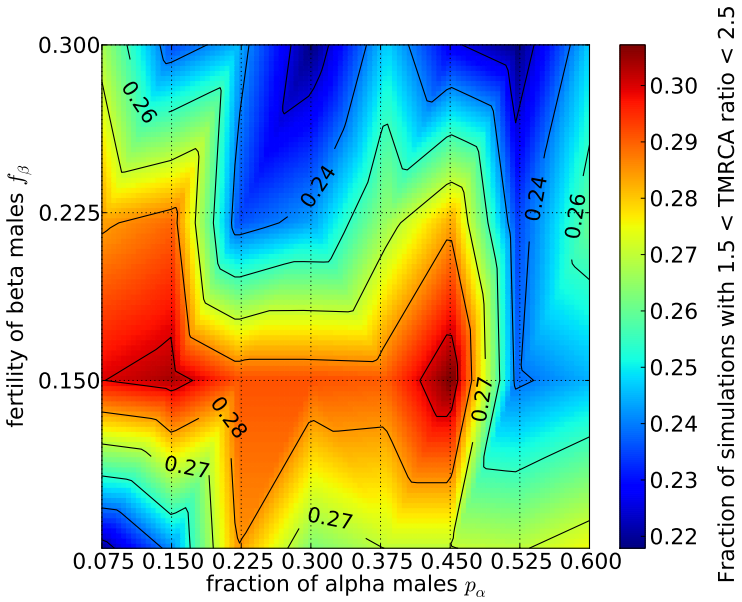

Figure 3.6: *Phase diagram in the case of polygynandry with heterogeneous male population, giving the fraction of simulations with a TMRCA ratio $r_{F/M} = T_F/T_M$ between 1.5 and 2.5 in a region of the two-parameter space (fraction of alpha males p_α; fertility of beta males f_β). Each grid point is obtained over 500 simulations. Parameters are given in expression (3.1).*

For $p_\alpha = 0.12$ and $f_\beta = 0.12$, the average TMRCA ratio is 2.8 (median 2.2). 26% of the simulations show a TMRCA ratio between 0.5 and 1.5 and 29% between 1.5 and 2.5, compared with respectively 58% and 20% in the homogeneous population. Figure 3.3 shows a superposition of the distribution of the TMRCA ratio in the homogeneous case and in the heterogeneous case with $p_\alpha = 0.12$ and $f_\beta = 0.12$.

3.4.2 Polygyny

Polygyny can be implemented in a homogeneous or heterogeneous male population and with four possible variants, DWD/WREM, DWD/WnoREM, DWnoD/WREM and DWnoD/WnoREM, defined in section 3.3.3.2.

3.4.2.1 Homogeneous male population

The variant in which deceased wives decrease a male's adjusted fitness and widows remarry (DWD/WREM) turns out to be equivalent to sequential polyandry together with mild polygyny. Indeed, because of random female choices and slightly fluctuating population sizes of mature females and males, some males have several wives at the same time and females have several husbands in their lifetime (but always one at a time). However, at some point a male might not be chosen as a husband anymore because he has too many deceased wives, while a fertile female will never be without a husband. This is illustrated by figure 3.7, which shows the distributions

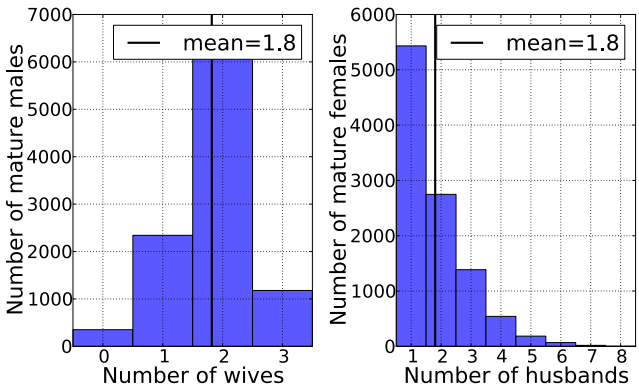

Figure 3.7: *Histogram of the number of spouses per agent (over its lifetime) in the polygyny mode with homogeneous male population, variant DWD/WREM (deceased wives decrease a male's adjusted fitness; widows remarry). Left panel: number of wives per mature male, right panel: number of husbands per mature female. Parameters are given in expression (3.1).*

of the number of spouses per agent over the agents' lifetime.

Of the four variants, this one give the highest average TMRCA ratio $\bar{r}_{F/M} = 1.5$, with a median of 1.2, 52% of the simulations with $0.5 < r_{F/M} < 1.5$ and 24% of the simulations with $1.5 < r_{F/M} < 2.5$.

If females do not remarry (DWD/WnoREM), polygyny is very weak and there is no polyandry at all. In effect, this variant becomes very close to lifelong monogamy. Males do not get many wives because, on the one hand, their fitness remains lower if their wife dies, and on the other hand, females do not seek remarriage if their husband dies. The only females looking for a husband are thus the newly mature ones, and since there are about as many mature females as males, this mode is very close to lifelong monogamy. Figure 3.8 shows that, in their majority, agents of either gender have one spouse in their lifetime.

If deceased wives do not influence males' adjusted fitness and if widows remarry (DWnoD/WREM), males can have more wives than in the first variant, so we can expect sequential polyandry and medium polygyny.

These two last variants have in common that they both make genders as equivalent as they can get in the polygyny mode, DWD/WnoREM being close to monogamy, and DWnoD/WREM allowing everyone to remarry without being influenced by past marriages. As a result, the average TMRCA ratio is close to 1 in both variants, with 55 to 59% of simulations with a TMRCA ratio between 0.5 and 1.5, and only 16 to 17% of simulations with a TMRCA ratio between 1.5 and 2.5.

Finally, in the DWnoD/WnoREM variant, females have only one opportunity to marry, while males not only can have several wives but are not penalized by their late wives to attract new ones. With this variant, a male may find it easier to become a common ancestor than in previous variants, which is reflected by the fact that the average TMRCA ratio $r_{F/M}$ is smaller

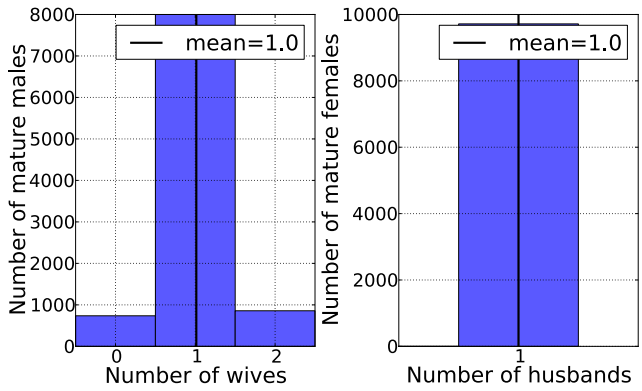

Figure 3.8: *Histogram of the number of spouses per agent (over its lifetime) in the polygyny mode with homogeneous male population, variant DWD/WnoREM (deceased wives decrease a male's adjusted fitness; no widows remarriage). Left panel: number of wives per mature male, right panel: number of husbands per mature female. Parameters are given in expression (3.1).*

than 1 (it is equal to 0.8), with only 7% of simulations with a TMRCA ratio between 1.5 and 2.5.

In summary, polygyny in a homogeneous male population, whatever the variant, gives an average TMRCA ratio smaller than those obtained with heterogeneous male populations in polygynandrous societies. As long as the male population is homogeneous, whether the mode is polygynandry or polygyny, the TMRCA ratio does not rise significantly above 1, although the variance in reproductive success of males is higher than that of females.

3.4.2.2 Heterogeneous male population

In order to investigate the impact of a heterogeneous male population in the polygyny mode, we choose the variant DWD/WREM because this is the one giving the highest average TMRCA ratio in a homogeneous population. This variant with heterogeneous male population is strongly polygynous, as alpha males attract many more wives than beta males. The TMRCA ratio falls between 1.5 and 2.5 in up to 30% of the simulations, as long as $p_\alpha \lessapprox 0.5$ and $f_\beta \lessapprox 0.5$. This is shown in figure 3.9.

Let us investigate further the results for fixed values of p_α and f_β. Informed by figure 3.9, we choose $p_\alpha = 0.4$ and $f_\beta = 0.2$. With these values, the distribution of the TMRCA ratio has an average of 2.9 and a median is 2.3. As in the polygynandry mode with heterogeneous male population, 26% of the simulations have a TMRCA ratio between 0.5 and 1.5 and 29% between 1.5 and 2.5.

Figure 3.10 shows the distributions of the number of spouses per female and male for $p_\alpha = 0.4$ and $f_\beta = 0.2$. Compared to the same variant DWD/WREM in a homogeneous male population (figure 3.7), the situation for females has not changed, while alpha males can now have up to 9 wives (compared to 3 in a homogeneous male population). There are many unmarried males

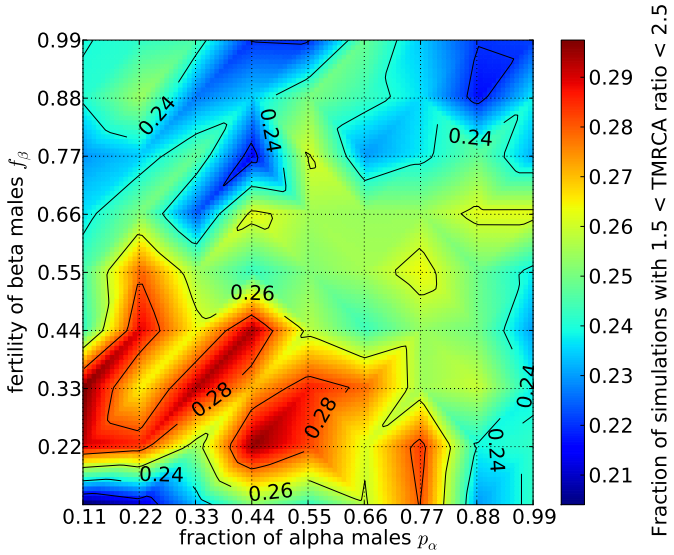

Figure 3.9: *Phase diagram in the case of polygyny with heterogeneous male population, deceased wives decreasing a male's adjusted fitness and widows remarriage (DWD/WREM), giving the fraction of simulations with a TMRCA ratio $r_{F/M} = T_F/T_M$ between 1.5 and 2.5 in the two-parameter space (fraction of alpha males p_α; fertility of beta males f_β). Each grid point is obtained over 1,000 simulations. Parameters are given in expression (3.1).*

because for each male who has n wives, there are $n-1$ males with no wife (if there are as many mature males as females). The bimodal distribution of the number of wives per male reveals the two populations of alpha and beta males.

3.4.3 Gender-biased migration

We test gender-biased migration in a two-deme island model of polygynandrous societies with homogeneous male populations. Female and male migration rates, comprised between 0 and 1, are denoted by m_F and m_M, respectively (section 3.3.3.3). Figure 3.11 shows the fraction of simulations with a TMRCA ratio between 1.5 and 2.5 in the two-parameter space (m_F; m_M). At most, approximately 30% of the simulations have a TMRCA ratio between 1.5 and 2.5, but this requires $m_M = 0$ and $m_F > 0.1$.

A non-zero female migration rate together with a zero male migration rate means that "as soon as" (backward in time) one branch of the backward all-female ancestry lines exits deme A to enter deme B, we can find a female common ancestor for deme A only if either this branch comes back into A, or all-female ancestry lines from A all enter B and coalesce there. This is why female dispersal in the absence of male dispersal requires more time (backwards) to find a female common ancestor, resulting in a TMRCA ratio higher than 1.

Let us examine the distribution of the TMRCA ratio for one of the two demes when males never migrate and 10% of the females do. The average TMRCA ratio is 2.1 with a median of

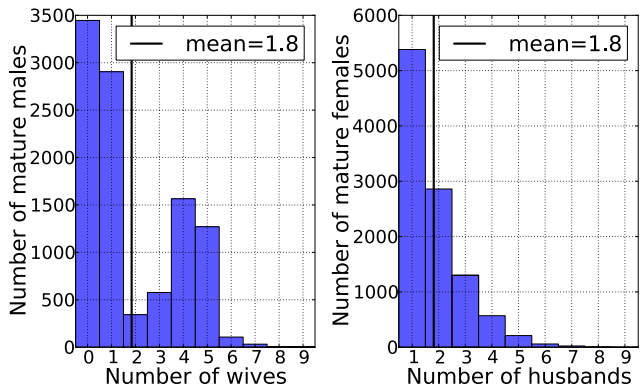

Figure 3.10: *Histogram of the number of spouses per agent in the polygyny mode with heterogeneous male population ($p_\alpha = 0.4$, $f_\beta = 0.2$), variant DWD/WREM (deceased wives decrease a male's adjusted fitness; with widows remarriage). Left panel: number of wives per mature male, right panel: number of husbands per mature female. Parameters are given in expression (3.1).*

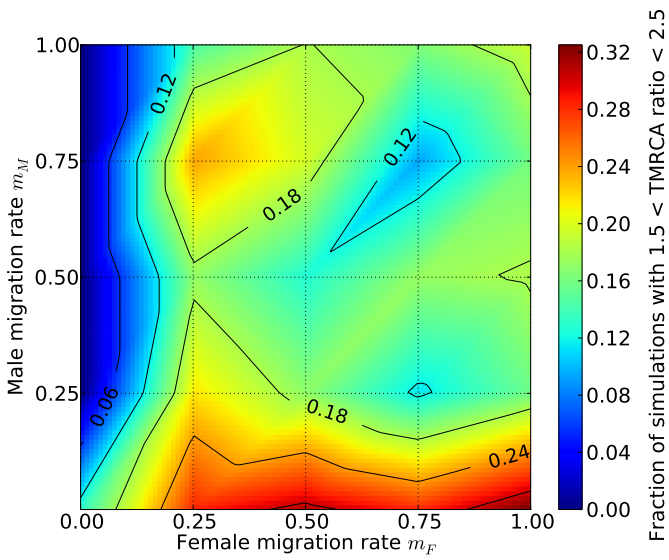

Figure 3.11: *Phase diagram in the case of polygynandry with homogeneous male population and migration, giving (for one deme) the fraction of simulations with a TMRCA ratio $r_{F/M} = T_F/T_M$ between 1.5 and 2.5 in the two-parameter space (female migration rate m_F; male migration rate m_M). Each grid point is obtained over 200 simulations. Parameters are given in expression (3.1). In the left region where $m_F = 0$ and $m_M > 0$, the TMRCA ratio is not really zero but in fact does not exist because no MRCA female could ever be found for our sample (the last generation of males). Indeed, if any male from the sample of one of the demes (say A) was born in the other deme (B) and migrated later to A, his mother necessarily belonged to deme B. Since the female migration rate is zero, this female's all-female ancestry line is entirely in B and will never coalesce with the all-female ancestry lines of the other males from the sample in A, which are entirely in A.*

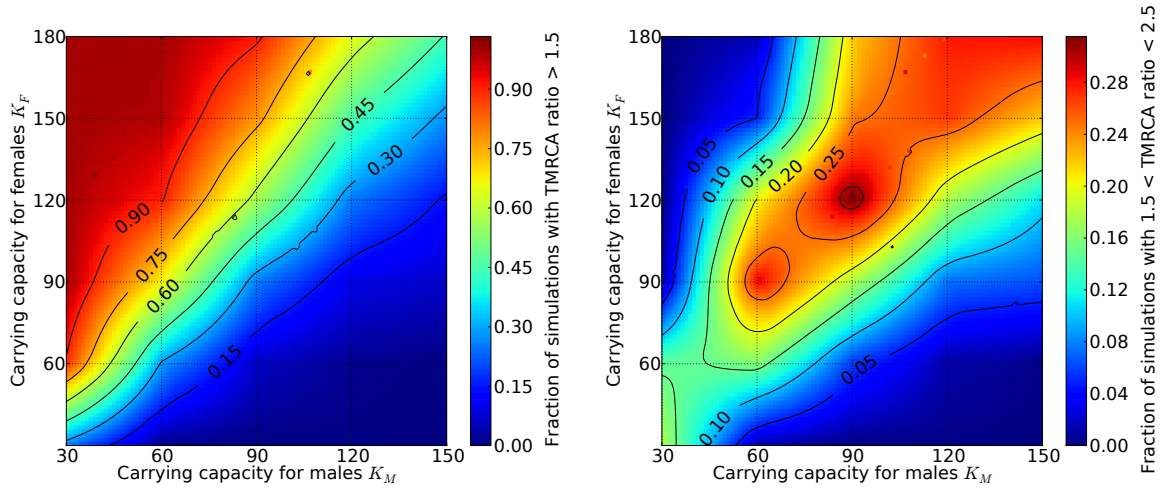

Figure 3.12: *Phase diagram in the case of polygynandry with homogeneous male population and gender-specific carrying capacities, giving the fraction of simulations with a TMRCA ratio $r_{F/M} = T_F/T_M$ higher than 1.5 (left panel) and between 1.5 and 2.5 (right panel) in the two-parameter space (carrying capacity for males K_M; carrying capacity for females K_F). Each grid point is obtained over 500 simulations. Parameters are given in expression (3.1), except for K_M and K_F which vary as indicated on the axes.*

1.7. At first sight, gender-biased migration thus succeeds to increase the average TMRCA ratio to a value close to 2. However, there are still slightly more simulations with ratios between 0.5 and 1.5 than between 1.5 and 2.5 (37% vs. 32%). In addition, the condition $m_M = 0$ is quite unrealistic, as discussed in section 3.6.3.

3.4.4 Gender-specific death rates and gender-biased bottleneck

There is another way than gender-biased migration to shift the distribution of the TMRCA ratio $r_{F/M} = T_F/T_M$ to values higher than 1 in a homogeneous male population (with any mating system). This is to set a smaller male (K_M) than female (K_F) carrying capacity, so that there is a higher male than female death rate (the gender of newborns being randomly chosen with equal probability).

The left panel of figure 3.12 shows that manipulating gender-specific carrying capacities allows to obtain cases where nearly all simulations have a TMRCA ratio above 1.5. However, for small K_M and comparatively large K_F, the TMRCA ratio becomes higher than 2 on average. The right panel of figure 3.12 specifically shows the fraction of simulations with a TMRCA ratio between 1.5 and 2.5 for different pairs of values (K_M;K_F). This panel shows that about 30% of the simulations have a TMRCA ratio between 1.5 and 2.5 when $K_F \approx 1.5 \cdot K_M$. For example, with $K_F = 120$ and $K_M = 75$, we get 23% of the simulations with $0.5 < r_{F/M} < 1.5$, 30% with $1.5 < r_{F/M} < 2.5$ and 45% of the simulations above 2.5.

As suggested by Hammer et al. (2008), another mechanism that could be responsible for the

two-to-one female-male TMRCA ratio in humans is a gender-biased bottleneck at some time in the past, during which more males than females died. It is possible to get a TMRCA ratio higher than 1 by introducing a gender-biased bottleneck in our ABM as follows: we start a simulation with the usual carrying capacities $K_F = K_M = 75$ and impose for instance $K_M = 2$ during 300 time steps near the end of the simulation (e.g. at time step 1.7×10^6 within a simulation of total duration 2×10^6 time steps), and then restore $K_F = K_M = 75$ for the remaining time steps (results not shown).

An interesting constraint is that the duration of the bottleneck has to be longer than the pregnancy length ($G = 270$). Otherwise, many unrelated males are born shortly after the bottleneck from females who were pregnant before the bottleneck started, which considerably lowers its effect on paternal ancestry lines. We discuss theses results in section 3.6.2.

3.4.5 Other mechanisms

We tested the effect of gender-specific maturity ages, namely females reaching reproductive maturity before males, so as to reflect findings of anthropological studies showing that the age at first reproduction (AFR) tends to be younger for females than for males (Helgason et al., 2003; Tremblay and Vezina, 2000). As explained by Tang et al. (2002), increasing the male generation length in a genetic model would decrease the per-year NRY mutation rate, so that the genetic distance would be greater for mtDNA than for NRY and coalescent models would infer a longer female than male TMRCA (counted in years). However, in our non-genetic model, increasing the male AFR actually slightly reduces the number of children a male can have in his lifetime, so the male variance in reproductive success is reduced as well. The average TMRCA ratio remains close to 1 under this condition in all mating systems with a homogeneous male population (results not shown).

We also tested the effect of letting menopausal females continue to participate in the mating interactions, thus mating without getting pregnant. In the polygynandry mode, this uniformly affects all males by making them susceptible to lose opportunities to reproduce by selecting menopausal females. It thus slightly reduces the male variance in reproductive success, so the average TMRCA ratio remains close to 1. In the polygyny mode, having a menopausal wife decreases a male's adjusted fitness F_i without bringing him the benefit of having additional children from her. Again, this affects all males uniformly and does not make the average TMRCA ratio rise above 1 (results not shown).

3.4.6 Number of female and male ancestors

In this section, we examine the relation between TMRCA ratio and ancestors ratio. As explained in section 3.2.4, we verify whether, in our simulations, a TMRCA ratio higher than 1 is associated with more female than male ancestors along all ancestry lines.

To that aim, we count the number of agents whose descendant line along any genealogical path reaches at least one agent of the present generation. We call these agents "ancestors" and

categorize them according to their gender. Let us stress that the lines of descent can follow any path (e.g. female-male-male-female-etc.), not only all-female and all-male lines, and the gender of an ancestor's descendant(s) belonging to the present generation does not play any role. This means that from the viewpoint of the present generation, non-ancestors are found along branches that are genealogical dead ends. The numbers of female and male ancestors give a fair measure of the transmission success of each gender, in a genealogical and potentially genetic sense.

Over 500 simulations, the average ratio of the number of female ancestors over the number of male ancestors, $\bar{r}_A$, is approximately 1.4 in the modes that maximize the probability that the TMRCA ratio lies between 1.5 and 2.5, namely the heterogeneous male population modes. The average ancestors ratio $\bar{r}_A$ remains close to 1 in homogeneous male population modes. The standard deviation of r_A is very small ($\sigma(r_A) = 0.01$).

In heterogeneous male population modes, the ratio $\bar{r}_A \simeq 1.4$ translates into approximately 20% of the males becoming ancestors (42% of the mature males), compared to 27% of the females (59% of the mature females). In other words, 20% of all males born during a simulation have a descent line that reaches the present generation, as compared to 27% of all females. These values also hold within each generation, on average. For instance, approximately 20% of the males within each generation (except for the generations that are closest to the present generation) became ancestors in the sense of having at least one descendant alive in the present generation. These results are shown in table 3.1.

In summary, Baumeister's guess of a female-male ancestors ratio of 2 is of the right order, although it is probably overestimated by approximately 30% according to our simulations. Yet, this does not prove that the observed TMRCA ratio $r_{F/M} = T_F/T_M \simeq 2$ could not be found for quite different female-male ancestors ratios under different simulation conditions. Since, as stressed in section 3.2.4, there is no direct logical link between the female-to-male ancestors ratio and the TMRCA ratio, the factor of two for the later does not translate into a prediction for the former. We can state that, under the conditions in our ABM that make the TMRCA ratio most likely to be between 1.5 and 2.5, the present generation has 1.4 times as many female as male ancestors. This supports qualitatively the thesis defended by Baumeister (2010) concerning gender-biased behaviors in risk taking and competitiveness.

3.5 Summary of results

The ABM that we have introduced allows us to determine exactly the female and male TMRCAs under several different conditions: two fundamentally different mating systems (polygynandry and polygyny), with several variants each, and in the presence or absence of gender-biased migration. In our ABM, each male has a fitness $f \in [0, 1]$. Depending on the mating mode, this fitness acts as the probability of either mating with a random partner or getting a life-long partner. It may be understood as reflecting males' estimated qualities as partners or fathers in females' judgement. In a heterogeneous male population, alpha males have a fitness $f_\alpha = 1$ and beta males have a fitness f_β with $0 < f_\beta < 1$ (all beta males have the same fitness). If all males

Condition	$\bar{r}_0$	$\bar{r}_A$	$\sigma(r_A)$	$\bar{r}_A^F$	$\bar{r}_A^M$	$\bar{r}_A^{F,mat}$	$\bar{r}_A^{M,mat}$
Polygynandry HMP	1.0	1.13	0.01	30%	26%	64%	57%
Polygyny HMP, WREM, DWD	1.0	1.05	0.01	31%	30%	67%	64%
Polygynandry $p_\alpha = 0.12$, $f_\beta = 0.12$	1.0	1.38	0.02	27%	20%	59%	43%
Polygyny WREM, DWD $p_\alpha = 0.4$, $f_\beta = 0.2$	1.0	1.42	0.01	27%	19%	58%	41%

Table 3.1: *Characteristics of the numbers of female and male ancestors of the present generations in four modes. Averages are denoted by bars over the variables.* r_0 *is the ratio of the number of females over the number of males who were born during a simulation. It is shown as a control and should always be very close to 1.* r_A *is the ratio of the number of female ancestors over the number of male ancestors;* $\sigma(r_A)$ *is the standard deviation of this ratio. The standard deviations of all values shown in this table are very small, so only that of* r_A *is shown.* r_A^F *is the ratio of the number of female ancestors over the number of females born during a simulation. In other words, it is the fraction of females who became ancestors.* r_A^M *is the fraction of males who became ancestors.* $r_A^{F,mat}$ *and* $r_A^{M,mat}$ *are, resp., the fractions of mature females and mature males who became ancestors. HMP stands for Homogeneous Male Population. The following abbreviations are explained in section 3.3.3.2: WREM = Widows Remarry; DWD = Deceased Wives Decrease males' adjusted fitness.* p_α *is the proportion of alpha males;* f_β *is the fitness of beta males. Parameters are given in expression (3.1). Averages are obtained over 500 simulations with approximately 44,000 agents each.*

have the same fitness (all-alphas or all-betas), the male population is homogeneous.

We find that the mating system (polygynandry or polygyny) has little influence on the TMRCA ratio $r_{F/M} = T_F/T_M$. The variant that has the highest impact on the TMRCA ratio is the introduction of a heterogeneous male population, whereby some males are alphas and others are betas. Indeed, homogenous and heterogeneous male populations lead to two very different regimes, the latter being more likely than the former to be responsible for the observed TMRCA ratio of 2 found by genetic studies (mtDNA-based TMRCA: Tang et al., 2002; Ingman et al., 2000; Cann et al., 1987, NRY-based TMRCA: Tang et al., 2002; Pritchard et al., 1999; Thomson et al., 2000; Hammer and Zegura, 2002).

More precisely, across all modes, the maximum fraction of simulations giving a TMRCA ratio between 1.5 and 2.5 is approximately 30%. The modes yielding 30% of simulations with $1.5 < r_{F/M} < 2.5$ are those with a heterogeneous male population. In these modes, the likelihood of obtaining the empirical value $r_{F/M} \simeq 2$ is maximized if less than half of the males are alphas, and if betas have at most half the fitness of alphas (figures 3.6 and 3.9). Such a strongly heterogeneous male population implies an important level of competition among males in order to be recognized as an alpha or appear like one.

It shall be noted that the forward-looking population dynamics exhibits a large stochasticity. Moreover, males always have a higher variance in reproductive success than females. This is because of the life cycle parameters input into our ABM concerning pregnancy and lactation times. These two facts contribute to produce a stretched $r_{F/M}$ distribution with values higher than 1 even with a homogeneous male population, a phenomenon discussed in section 3.6.1.

For example, in the polygyny variant (DWD/WREM) with homogeneous male population, we obtain an average $\bar{r}_{F/M} = 1.5$, a median of 1.2, 9% of the simulations with $r_{F/M} < 0.5$, 52% with $0.5 < r_{F/M} > 1.5$, 24% with $1.5 < r_{F/M} < 2.5$ and the remaining 15% with $r_{F/M} > 2.5$ (over a total of 1,000 simulations). These values indicate that it is possible for a homogeneous male population to produce a TMRCA ratio between 1.5 and 2.5, yet the probability of this happening is twice as small as the probability of producing a TMRCA ratio between 0.5 and 1.5.

By contrast, in the same polygyny variant, but this time with a heterogeneous male population made of 40% alphas males with betas' fitness five times smaller than alphas', we obtain $\bar{r}_{F/M} = 2.9$, a median of 2.3, 1% of the simulations with $r_{F/M} < 0.5$, 26% with $0.5 < r_{F/M} < 1.5$, 29% with $1.5 < r_{F/M} < 2.5$ and 43% with $r_{F/M} > 2.5$ (over 1,000 simulations). Hence, in this example, the probability of finding a TMRCA ratio between 0.5 and 1.5 is reduced about twofold by a heterogeneous male population as compared to a homogeneous population.

Gender-biased migration in our two-deme island model is also able to increase the TMRCA ratio significantly, but only under the quite unrealistic condition of strictly zero male dispersal. Another mechanism that can yield an average TMRCA ratio above 1 is a higher male than female death rate over either the whole simulation duration or a given number of time steps, corresponding to a gender-biased bottleneck. These two mechanisms and our implementation thereof are discussed in section 3.6.3.

The empirical data to which we compare our model simulations refers to a unique human evolutionary history, which corresponds to a single realization of a complex stochastic process. The comparison between our simulations and empirical data is thus not straightforward. Our simulations give the likelihood of the TMRCA ratio being close to the empirical value of 2 given a model with fixed parameters. Yet, this does not directly say to which extent the model is accurate or representative of reality. This would be given by the likelihood of the model given the empirical TMRCA ratio close to 2. The two likelihoods are proportional to each other, as they are related through Bayes' rule, but we do not have all necessary information to evaluate quantitatively the likelihood of the model. We discuss this further in section 3.6.

Another finding of the present study concerns the hypothesis made by Baumeister (2010) that the observed TMRCA ratio $r_{F/M} \simeq 2$ means that we have twice as many female as male ancestors. We define an "ancestor" as an individual whose descendant line along any genealogical path reaches at least one individual in the present generation. We find that in the modes maximizing the probability of the TMRCA ratio to take a value between 1.5 and 2.5, the present generation has approximately 1.4 times as many female as male ancestors. Therefore, our results support Baumeister's interpretation to a certain degree, and at the same time the important behavioral consequences he develops regarding higher male than female competitiveness and risk taking.

Tables 3.2 and 3.3 compile the characteristics of the distribution of the TMRCA ratio and of the distribution of reproductive success under all conditions.

Condition	$\bar{r}_{F/M}$	$\sigma(r_{F/M})$	$\mu_{1/2}(r_{F/M})$	$0.5 < r_{F/M} < 1.5$	$1.5 < r_{F/M} < 2.5$
Polygynandry HMP	1.2	0.8	1.0	58%	20%
Polygyny HMP, WnoREM, DWnoD	0.8	0.6	0.6	54%	7%
Polygyny HMP, WnoREM, DWD	1.1	0.9	0.9	59%	16%
Polygyny HMP, WREM, DWnoD	1.2	0.9	0.9	55%	17%
Polygyny HMP, WREM, DWD	1.5	1.1	1.2	52%	24%
Polygynandry $p_\alpha = 0.12$, $f_\beta = 0.12$	2.8	2	2.2	26%	29%
Polygyny WREM, DWD $p_\alpha = 0.4$, $f_\beta = 0.2$	2.9	2.2	2.3	26%	29%
Gender-biased migration Polygynandry, HMP $m_F = 0.1$, $m_M = 0$	2.1	1.4	1.7	37%	32%
Unequal death rates Polygynandry, HMP $K_F = 120$, $K_M = 75$	2.9	2.1	2.3	23%	30%

Table 3.2: *Characteristics of the distribution of the TMRCA ratio $r_{F/M} = T_F/T_M$ in all modes. σ and $\mu_{1/2}$ denote respectively the standard deviation and the median. Averages are denoted by bars over the variables. $a < r_{F/M} < b$ gives the proportion of the simulations with a TMRCA ratio comprised between a and b. HMP stands for Homogeneous Male Population. The following abbreviations are explained in section 3.3.3.2: WREM = Widows Remarry, WnoREM = Widows do not Remarry, DWD = Deceased Wives Decrease males' adjusted fitness, DWnoD = Deceased Wives do not Decrease males' adjusted fitness. p_α is the proportion of alpha males; f_β is the fitness of beta males; m_F and m_M are the female and male migration rates; K_F and K_M are the female and male carrying capacities. Parameters are given in expression (3.1), except for K_F, K_M and the number of iterations (3 million) in the unequal death rates mode, and the number of iterations (2.5 million) in the migration mode. Averages are obtained over 1,000 simulations.*

Condition	$\bar{k}_F$	$\bar{k}_M$	$\overline{\sigma}(k_F)$	$\overline{\sigma}(k_M)$	$\overline{\max(k_F)}$	$\overline{\max(k_M)}$	$\overline{w}_F$	$\overline{w}_M$
1. Polygynandry HMP	4.3	4.3	3	4.2	9	26	5%	17%
Polygyny HMP, WnoREM, DWnoD	3.4	3.4	2.6	3.4	9	16	2%	29%
Polygyny HMP, WnoREM, DWD	3.5	3.5	2.5	3	9	19	2%	10%
Polygyny HMP, WREM, DWnoD	4.3	4.3	2.9	3.9	9	22	3%	11%
Polygyny HMP, WREM, DWD	4.3	4.3	2.9	3.6	9	24	3%	7%
Polygynandry $p_\alpha = 0.12$, $f_\beta = 0.12$	4.3	4.3	3	8	9	82	4%	25%
Polygyny WREM, DWD $p_\alpha = 0.4$, $f_\beta = 0.2$	4.3	4.3	2.9	7.8	9	47	3%	58%
Gender-biased migration Polygynandry, HMP $m_F = 0.1$, $m_M = 0$	4.3	4.3	3	4.2	9	26	4%	17%
Unequal death rates Polygynandry, HMP $K_F = 120$, $K_M = 75$	4.3	7	3	7.2	9	51	4%	12%

Table 3.3: *Characteristics of the distributions of male and female reproductive success for mature agents in all modes. The number of children per mature female and male are denoted by k_F and k_M, resp. Averages are denoted by bars over the variables. σ denotes the standard deviation. w_F and w_M are the proportions of childless mature females and males. HMP stands for Homogeneous Male Population. The following abbreviations are explained in section 3.3.3.2: WREM = Widows Remarry, WnoREM = Widows do not Remarry, DWD = Deceased Wives Decrease males' adjusted fitness, DWnoD = Deceased Wives do not Decrease males' adjusted fitness. p_α is the proportion of alpha males; f_β is the fitness of beta males; m_F and m_M are the female and male migration rates; K_F and K_M are the female and male carrying capacities. Parameters are given in expression (3.1), except for K_F, K_M and the number of iterations (3 million) in the unequal death rates mode, and the number of iterations (2.5 million) in the gender-biased migration mode. Averages are obtained over 1,000 simulations with approximately 44,000 agents each, except for the unequal death rates and the gender-biased migration modes that simulate approximately 106,000 and 55,000 agents per simulation, respectively.*

3.6 Discussion

3.6.1 Biological differences, social factors and overall mechanism

An important result is the observation of gender-biased variances in reproductive success and higher female than male TMCRAs even in the polygynandry (i.e. random mating) mode with homogeneous male population. This is due to gender-specific biological constraints. Pregnancy, postnatal infertility and menopause represent periods of time during which females in our model cannot have any additional child. For their part, males can reproduce during their entire mature lifetime. Due to this availability asymmetry, fertile females may always find a mate, whereas fertile males may not. Females of the same age thus all have the same number of children in our model. Some males, on the other hand, randomly select unavailable females more often than other males and thus have less children. This causes a higher male than female variance in reproductive success even with a random mating system. The occurrence of this phenomenon caused by asymmetrical so-called "mating times" in a context of random mating has notably been observed by Sutherland (1985) in fruit fly data produced by Bateman (1948).

Constantly higher male than female variance in reproductive success, together with the high stochasticity of the entire process, results in a TMRCA ratio distribution extending to values higher than 1 even with a homogeneous male population, although the average remains close to 1. A two-to-one TMRCA ratio may thus be obtained despite a presumably low male-male competition. However, the fraction of simulations yielding a TMRCA ratio close to 1 is reduced about twofold by the introduction of a heterogeneous male population.

Our model and results are compatible with unequal biological costs of reproduction interacting with social settings to favor unequal TMRCAs. At a biological level, females make a larger investment into their offspring than males by bearing them. This cost asymmetry may cause female choosy selection (Baumeister, 2010). Female choice causes male-male competition and male's honest signaling to appear as an "alpha," which takes the form of risk-taking behavior (Zahavi, 1975; Diamond, 2002). This further contributes to higher male than female death rates through risky signaling and results in a smaller male than female breeding population, both because females select a subset of males for reproduction and because of higher male death rate. Mild polygyny appears as a by-product of this chain mechanism, favored by female selection and higher male than female death rate.

Let us note that we are not dismissing female-female competition, although we have not included it in our ABM. Male choice, resulting in female-female competition, can be expected in humans because of high paternal investment (Geary, 2000). However, competition between women usually does not take the same form or lead to such severe life-threatening consequences as male-male competition (Campbell, 2002). In our ABM, the introduction of male choice would reduce the female breeding population through the selection by males of a subset of females. This would result in a shorter female TMRCA than without female competition. Therefore, taking male choice into account in our ABM would have required even higher levels of male population heterogeneity in order to reproduce a two-to-one female-male TMRCA ratio with

the same likelihood.

3.6.2 Gender-specific death rates and gender-biases bottleneck

A mechanism that can yield an average TMRCA ratio above 1 is a higher male than female death rate over either the whole simulation duration or a given number of time steps, the latter corresponding to a gender-biased bottleneck. However, unequal death rates sustained over the time necessary to induce unequal TMRCAs would unlikely be caused by chance alone. They would need to rest on an existing gender discrepancy in the susceptibility to the main cause of death.

Death causes reported in studies of hunter-gatherer societies are usually categorized into four classes: diseases (illness or parasites), degenerative or congenital diseases (including childbirth and old age), accidents, and violence (Hill et al., 2007; Hill and Hurtado, 1996). The main gender difference observed in a mortality study among the Hiwi hunter-gatherers of Venezuela (Hill et al., 2007) is mainly due to violence (19 deaths per 1,000 years at risk for males vs. 3 for females) and is observed in people older than 40 years old. In another large study among the Ache people of Paraguay (Hill and Hurtado, 1996), accidents and external warfare account together for 37% of male deaths vs. 18% of female deaths.

However, if a higher male than female death rate is mainly due to violence, it cannot be the ultimate explanation for a TMRCA ratio higher than 1, as higher levels of lethal violence among males pinpoints gender-specific behaviors that require in turn an explanation. High levels of violence and accidents among males would mean that there is an underlying male-male competitive drive to be more skilled, less exposed to hazards, perceived as either stronger or socially integrated, and so on.

As for other causes of death, although modern medical studies show that men are generally more susceptible than women to diseases (Hon and Nelson, 2006), we are unaware of any disease occurring in hunter-gatherer societies that would affect males more than females at the level necessary to induce a significantly gender-biased distribution of TMRCA ratio. According to our results, such a disease would have to spare at least 1.5 times more women than men.

A gender-biased bottleneck would necessitate that men and women facing the same hostile conditions have very different survival rates in a consistent way over several months or years. Warfare with indigenous tribes, being attacked by or hunting unknown animals, toxic food ingestions or simply accidents during a long-distance migration through unknown territories could be explanations for a one-off (or repeated) gender-biased bottleneck. Yet again, such a gender-biased exposure to death causes would in turn require an explanation likely to point to male-male competition.

3.6.3 Migration

Gender-biased migration in our two-deme island model is able to increase the TMRCA ratio significantly, but only under the quite unrealistic condition of strictly zero male dispersal. When

both female and male migration rates are nonzero in our model, it becomes difficult for both genders to become a common ancestor and does not significantly bias the TMRCA ratio distribution toward values higher than 1. This difficulty of becoming a common ancestor is due to agents being able to migrate only once per lifetime. If both genders could migrate repetitively, with females migrating more than males, one may observe a higher fraction of simulations with a TMCRA ratio close to 2. However, a gender-biased migration pattern would also require an explanation, which is likely to point to reproductive matters and male-male competition again.

Moreover, modern foragers actually show a fluid multilocal pattern of residence, whereby couples alternate living with the wife's and the husband's kin (Marlowe, 2004). From an ethnological point of view, male and female migration rates are thus supposed to have been similar among modern humans before the transition to agriculture (Wilkins and Marlowe, 2006).

Finally, a genetic study suggested that global NRY and mtDNA patterns are not shaped by female gender-biased dispersal (Wilder et al., 2004a), although human migration in general plays a complex and important role in shaping patterns of genetic variation (Hammer et al., 2008; Cox and Hammer, 2010).

Overall, our model, together with ethnological and genetic studies, suggest that migration alone is unlikely to explain alone the gender-biased TMCRA ratio observed in humans.

3.6.4 Cooperation

Let us stress that, by highlighting male-male competition, we are not dismissing the essential role of cooperation (among males, females and between genders) in the past and present history of humans. In fact, our two closest primate relatives, the chimpanzee and the bonobo, show high levels of cooperation, although the former is highly competitive (de Waal, 1997, 2007).

The observed genetical patterns at the origin of the two-to-one TMRCA ratio reflect pre-agricultural lifestyles (Wilkins and Marlowe, 2006). Our model thus aims at modeling the life conditions of hunter-gatherers of the past 200,000 years. Based on studies of modern human foragers (Lee, 1968; Boehm, 1999), these hunter-gatherers are assumed to have been mostly egalitarian. For our present purposes, we may neglect the fact that human social structures changed drastically with the apparition of states and empires, made possible by the introduction of agriculture about 12,000 years ago (Diamond, 2005).

It is important to stress that the alpha-beta male structure introduced here does not stand in contradiction with political equality. Indeed, even in a society of foragers showing an egalitarian political organization, men may compete for women. A heterogeneous male population does not imply the presence of a social structure based on status differences extending from reproductive success to other domains of social life such as decision making or access to resources. Instead, the male fertility f only encapsulates the degree to which a male is favored by female choice based on his perceived qualities as a partner or father. The alpha-beta structure considered here can thus be compatible with strong social cooperation and political equality.

We thus support the idea that cooperation and competition are not exclusive. For example, cooperative hunting and sharing offer opportunities for (competitive) reputation building, which

can be positively correlated with mating success (Gurven and Hill, 2009). Communal male hunting can thus integrate an element of competition for being the best hunter, while the outcome of such a competition need not be reflected by hierarchical social statuses. Furthermore, within-group cooperation might be maintained or enhanced by between-groups competition, although this is debated; Bowles (2006) argues in this sense but is contradicted by Langergraber et al. (2011). Finally, Hetzer and Sornette (2013a) implemented an ABM of a public good game with altruistic punishment and found that cooperation can thrive among selfish disadvantageous inequity averse agents, a conclusion also supported by game theoretical calculations (Darcet and Sornette, 2008; Hetzer and Sornette, 2013b). This suggests that competitive agents may still find it advantageous to cooperate in order to achieve their goals.

3.7 Conclusion

In the ABM we developed, we have modeled the interplay of biological together with social mechanisms susceptible to cause gender differences in variance in reproductive success, competitiveness and risk-taking behavior. A domain of modern activity where differences in gender attitudes may be prominent is the financial area. The idea is now emerging that financial bubbles and crashes originate on trading floors that appear to promote male-male competition (Coates et al., 2010). These considerations raise the question of how to adjust our cultures or design society rules in the presence of traits that we may have inherited from gene-culture coevolution.

Our model could be further improved in future work by adding genetics. In particular, agents could be endowed with genetic sequences that are inherited, undergo mutations, determine agents' fitness and are thus under selection pressure. More realistic migration patterns could also be implemented, for example by introducing the concepts of isolation by distance or population split. Finally, after integrating genetics, it would be highly interesting to see whether existing softwares that infer TMRCAs using DNA samples are able to find the TMRCAs realized by our ABM with a reasonable accuracy under different mating systems and life cycle characteristics, when given only a sample of genetic sequences.

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3.8 Appendix

Algorithm 1: Algorithm following the maternal ancestry lines from a sample of males, and identifying the female ancestors along these lines. Following paternal ancestry lines works the same way.

```
Input: A sample of males (vector Males)
Output: Female ancestry lines of the males (vector FemalesAncestors). Each
        ancestor has a counter descendants which is the number of descendants she
        or he has among the sample of males.
function Follow(agent)
    if agent has no mother then      // happens when agent belongs to initial
    population
        return
    end
    let ancestor = agent's mother
    if ancestor is not in FemalesAncestors then
        FemalesAncestors.Insert(ancestor)
    end
    add 1 to ancestor's counter 'descendants'
    Follow(ancestor's mother)
end
foreach male of Males do                                          // main loop
    Follow(male)
end
```

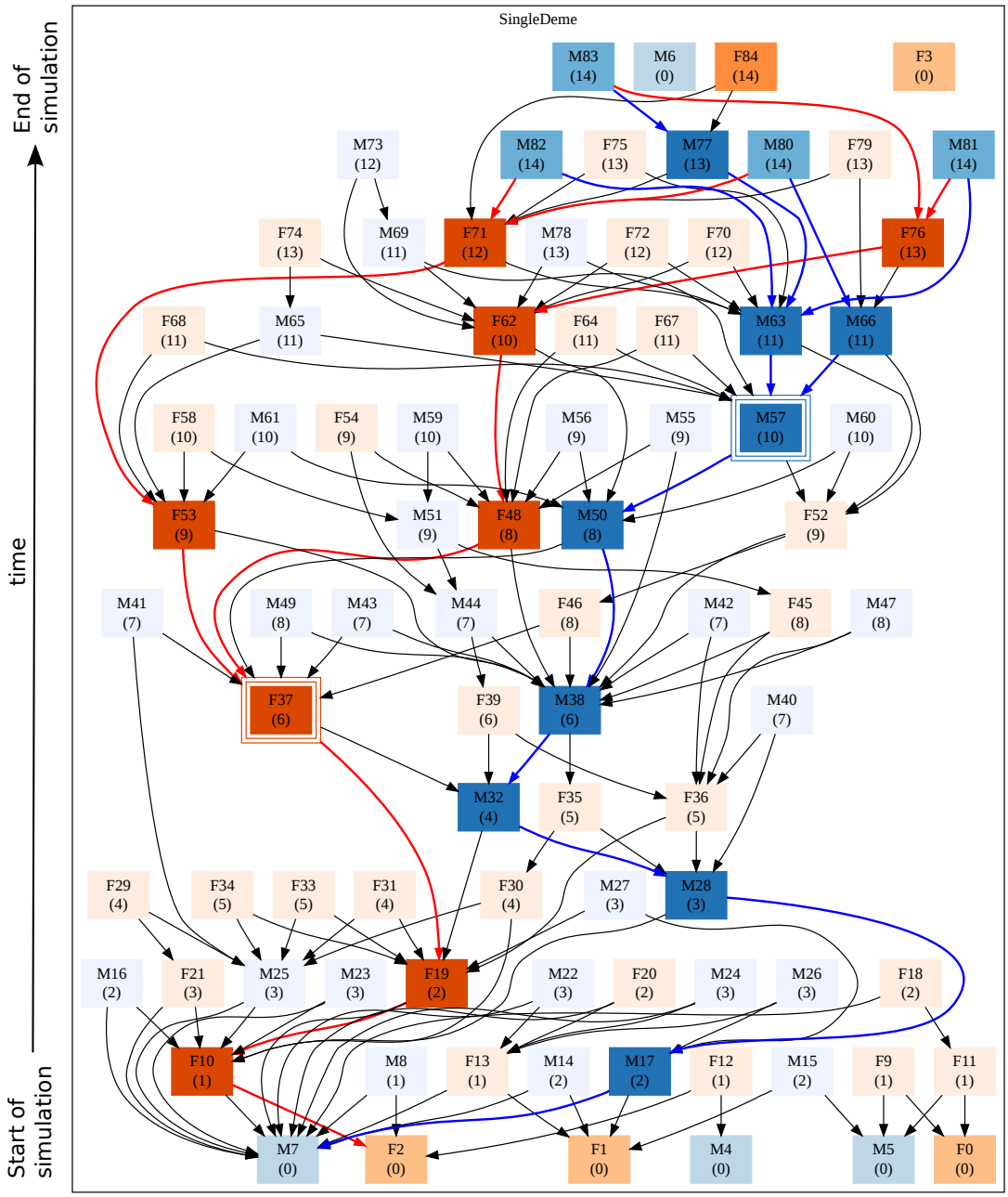

Figure 3.13: *Genealogical tree of a population of 8 agents with equal carrying capacities for females and males ($K_F = K_M = 4$), over 100,000 iterations, for a specific simulation. Time flows from bottom to top. Each box represents an agent. Arrows point from child to parent. Agents are identified by an F for females and an M for males and have a unique identification number (e.g. M83). The number in brackets below an agent's ID is its generation, which relates to its birthdate. Males from generation 14 (M80, M81, M82, M83) constitute the sample of males whose female and male MRCAs are retrieved. These males' all-female and all-male ancestry lines are highlighted with resp. red and blue arrows, and the boxes of the agents along these ancestry lines have a darker color. The female and male MRCAs' boxes are double framed and are F37 and M57. The positions of the agents in the tree are managed by the software graphviz (http://www.graphviz.org).*

Algorithm 2: Algorithm finding the female Most Recent Common Ancestor (MRCA) of a sample of males, given their female ancestors along maternal ancestry lines. Finding the male MRCA works the same way, given the male ancestors along paternal ancestry lines. Dates of birth are given as the number of time steps since the beginning of the simulation.

```
Input: A sample of males (vector Males), the vector FemalesAncestors, an MRCA
       (initially empty)
Output: The female MRCA

foreach ancestor of FemalesAncestors do
    if ancestor.descendants == Size(Males) then
        if MRCA does not exist yet then MRCA ← ancestor
        else
            if ancestor's date of birth > MRCA's date of birth then MRCA ← ancestor
        end
    end
end
```

Chapter 4

A generic model of dyadic social relationships

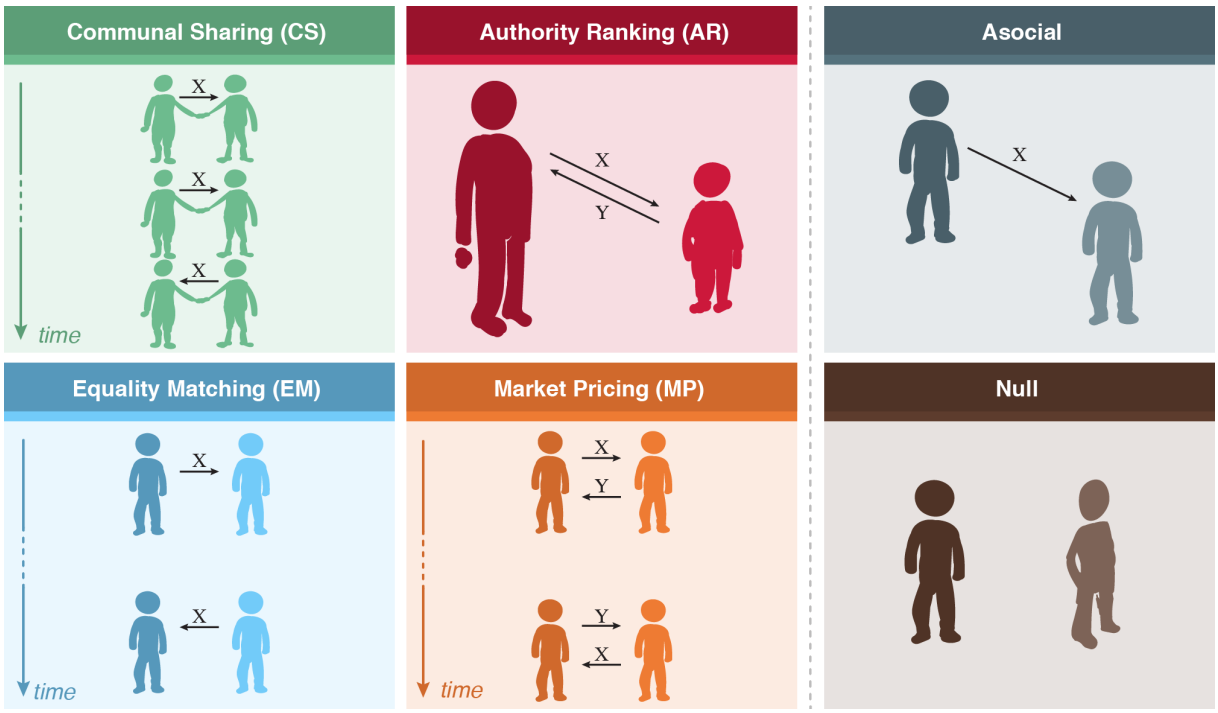

Figure 4.1: *This chapter categorizes dyadic social relationships based on a model in which two agents A and B can each perform a social action X, Y, or do nothing:* $A \underset{X/Y/\varnothing}{\overset{X/Y/\varnothing}{\rightleftarrows}} B$. *This model is put in correspondence with relational models theory (Fiske, 1991, 1992).*

4.1 Abstract

[1] We introduce a model of dyadic social interactions between two agents (that can represent two persons, groups, institutions or nations) and establish its correspondence with relational models theory (RMT), a theory of human social relationships (Fiske, 1991, 1992). We use the term "dyadic" to emphasize that we focus on interactions between two agents, as opposed to settings involving more than two agents implementing multiple different relationships. RMT posits four elementary models of relationships governing human interactions, singly or in combination: communal sharing, authority ranking, equality matching, and market pricing. To these are added the limiting cases of asocial and null interactions, whereby people do not coordinate with reference to any shared principle. Our model is rooted in the observation that each agent in a dyadic interaction can do either the same thing as the other agent, a different thing or nothing at all. To represent these three possibilities, we consider two agents who can each act in one out of three ways toward the other: perform a social action X or Y, or alternatively do nothing. We demonstrate that the relationships generated by this model aggregate into six exhaustive and disjoint categories. We argue that four of these categories match the four relational models, while the remaining two correspond to the asocial and null interactions defined in RMT. We generalize our results to the presence of N social actions. We infer that the four relational models form an exhaustive set of all types of social relationships based on social coordination. Hence, we contribute to RMT by offering an answer to the question of why there exist just four relational models. In addition, we discuss how to use our representation to analyze data sets of dyadic social interactions, and how social actions may be valued and matched by agents.

Keywords: relational models theory, social actions fluxes, exhaustiveness, data set analysis

4.2 Introduction

In this chapter, we are interested in the basic building blocks of social interactions, namely dyadic relationships. We use the term "dyadic" to emphasize that we focus on interactions between two agents (that can represent two persons, groups, institutions or nations), as opposed to entire sets or "compounds" of more than two agents implementing multiple and diverse interaction modes. However, as we argue later, our representation also extends to homogeneous collectives, whereby all actors use the same interaction mode.

Our contribution is to introduce a representation of dyadic relationships which realistically matches an existing theory of human social relationships, relational models theory (RMT) and can be used for theoretical purposes. Moreover, we discuss how to apply our model to computational modeling and analysis.

[1] This chapter is based on Favre M. and D. Sornette, 2015: A generic model of dyadic social relationships. PLoS ONE 10(3): e0120882. URL: http://dx.doi.org/10.1371/journal.pone.0120882.

Our model is built on the basic assumption that, in any dyadic interaction, each agent can do either the same thing as the other agent, a different thing, or nothing at all. To represent these three possibilities, it is sufficient to consider that each agent can do X, Y or nothing ($\varnothing$) to the other agent. Namely, if both agents do the same thing, they both do X (or Y); if they perform different (non-null) actions, one does X and the other does Y. X and Y are two different "social actions," in the sense that they intentionally affect their target. Social actions can have positive or negative effects on the receiver's welfare. For example, an agent A could transfer a useful commodity to an agent B, or A could hit and harm B. In what follows, we generally assume that an agent is a person, but it can also represent a social group (e.g. a company, team, nation and so on) that acts as a single entity in specific interactions with other actors.

This setting is represented by $A \underset{X/Y/\varnothing}{\overset{X/Y/\varnothing}{\rightleftarrows}} B$. For instance, an interaction in which A does X and B does Y is represented by $A \underset{Y}{\overset{X}{\rightleftarrows}} B$. We call the arrows in these symbols "action fluxes." This model generates a number of possible relationships between the two agents A and B.

We find that these relationships aggregate into exactly six disjoint categories of action fluxes. These six categories describe all possible relationships arising from our model, singly or in combination. We propose a mapping between these categories and the four basic social relationships, or relational models (RMs), defined by RMT. Namely, four of the six categories map to the RMs, while the remaining two correspond to asocial and null interactions. We argue that this categorization and mapping show that the RMs constitute an exhaustive set of coordinated dyadic social relationships. To take into account that real social interactions involve an infinite variety of social actions, we generalize our model to the presence of any number N of social actions and show that this leads to the same six categories of action fluxes.

Relational models theory was introduced by Alan P. Fiske (1991, 1992) in the field of anthropology to study how people construct their social relationships. RMT posits that people use four elementary models to organize most aspects of most social interactions between people or groups in all societies. These models are communal sharing, authority ranking, equality matching, and market pricing.

- In the communal sharing (CS) model, people perceive in-group members as equivalent and undifferentiated. CS relationships are based on principles of unity, identity, conformity and undifferentiated sharing of resources. Decision making is achieved through consensus. CS is typically manifested in close family or friendship bonds, teams, nationalities, ethnicities or between soldiers exposed to stressful conditions.

- In authority ranking (AR) relationships, people are asymmetrically ranked in a linear hierarchy. Subordinates are expected to defer, respect and obey high-rankers, who take precedence. Conversely, superiors protect and lead low-rankers. Subordinates are thus not exploited and also benefit from the relationship. Resources are distributed according to ranks and decision making follows a top-down chain of command.

- Equality matching (EM) relationships are based on a principle of equal balance and one-

to-one reciprocity. Salient EM manifestations are turn-taking, democratic voting (one person, one vote), in-kind reciprocity, coin flipping, distribution of equal shares, and tit-for-tat retaliation.

- The market pricing (MP) model is based on a principle of proportionality. Relationships are organized with reference to socially meaningful ratios and rates, such as prices, cost-benefit analyses or time optimization. Rewards and punishment are proportional to merit. Abstract symbols, typically money, are used to represent relative values. MP relationships are not necessarily individualistic; for instance, utilitarian judgments seeking the greatest good for the greatest number are manifestations of MP.

The four relational models have in common that they suppose a coordination between individuals with reference to a shared model. To these, Fiske adds two limiting cases that do not involve any other-regarding abilities or coordination (Fiske, 1991, 19-20):

- In asocial interactions, a person exploits others and treats them as animate objects or means to an end (as in psychopathy, armed robbery, pillage);
- In null "interactions," people do not interact at all (they do not actively ignore each other, which still requires a coordination), as can be the case of two inhabitants of the same building who never cross each other's way or fail to notice each other's existence, and thus do not adapt their actions to each other.

RMT has motivated a considerable amount of research that supports, develops or applies the theory, not only in its original field of social cognition (Fiske, 1995; Fiske et al., 1991; Fiske, 1993; Fiske and Haslam, 1997), but also in diverse disciplines such as neuroscience (Iacoboni et al., 2004), psychopathology (Haslam et al., 2002), ethnography (Whitehead, 2002), experimental psychology (Brodbeck et al., 2013), evolutionary social psychology (Haslam, 1997), and perceptions of justice (Goodnow, 1998), to name a few. For an overview of this research, see Haslam (2004) or Fiske and Haslam (2005).

In order to better understand RMT, it is helpful to locate it in the landscape of other social, political and economical theories. RMT can be identified as a theory of constrained relativism (Verweij, 2007, Lockhart and Franzwa, 1994, 176), together with other theories such as plural rationality (or cultural) theory initiated by Douglas (1978, 1982) and developed further by colleagues (Thompson et al., 1990), and moral foundations theory (Haidt, 2007), among others. Theories of constrained relativism are based on the idea that there are a limited number of elementary ways of organizing social relations that serve as building blocks for the infinitely varied aspects of social and political life.

RMT, and constrained relativism in general, lie between the two extremes of rational choice analysis and post-structuralism (Senior et al., 2013). Rational choice theory holds that people behave as if they were fully rational, followed their self-interest and instantly processed all available information. Universal analytical models are thus expected to predict the behavior of these rational agents. At the other extreme, post-structuralism posits that every person,

society and epoch, is fundamentally unique. According to that view, no generalization can be made; only descriptions are possible and relevant, without offering any possibility of scientific prediction.

Theories belonging to rational choice theory and post-structuralism have dominated political science, sociology and economy for several decades, while constrained relativism has had less influence and is not as widely known (Senior et al., 2013). However, Verweij et al. (2015) argue that rational choice theory, post-structuralism, and additionally behavioral economics, are inconsistent with the way our brain appears to function. By contrast, they propose that theories of constrained relativism, including RMT, are compatible with the findings of affective and social neuroscience.

A common point of previous approaches of RMT is that they define the RMs as cognitive models. Correspondingly, their implementation has been described in terms of how people mentally represent their relationships, using concepts like group belonging (CS), asymmetrical hierarchies (AR), peer equality (EM) and cost-benefit calculations (MP). Formally, the RMs were compared to the four measuring scales defined by Stevens (1946): nominal (CS), ordinal (AR), interval (EM) and ratio (MP) (Fiske, 1991, 210-23). This made any attempt to understand why and how people from widely different cultures manage to coordinate using these same psychological concepts a very ambitious undertaking, and naturally led to consider the evolution and functioning of the human brain, as did Bolender (2010) and Iacoboni et al. (2004), for instance.

Nettle et al. (2011) recently opened the way to model what is being transferred from one individual to another. These authors defined three strategies to allocate a resource between two individuals. They presented one of the strategies as typifying CS. Their result was to determine the domain of parameters making each strategy evolutionarily stable. In an analogous modeling spirit, our approach offers an abstract representation of the patterns of social actions performed by dyads in all four relational models, as well as the asocial and null interactions.

The rest of this chapter is organized as follows. In section 4.3, we present our model of action fluxes. In section 4.4, we demonstrate the exhaustiveness of the six categories arising from this representation, and match the categories to the four relational models and the asocial and null interactions. We then generalize the finding of these six categories to the situation involving any number N of social actions. In section 4.5, we discuss a method to analyze and interpret data sets of dyadic social interactions. We also express a hypothesis about how social actions are valued and matched by the agents. We conclude in section 4.6.

4.3 Method

We consider a model of two agents interacting through social actions. A social action corresponds to any action intentionally targeting the receiver and affecting her welfare positively or negatively. It can consist in the transfer of commodities (e.g. objects, food, water, etc.) or services, but can also be a comforting act, or talking, harm, violence, and so on.

Let A and B be two distinct agents, and X and Y different social actions. In general, we assume that A and B are two people. However, an agent can also represent a group that acts as a social unit toward a person or another group (e.g. a nation, in the context of its diplomatic relation with another nation). We posit that each agent can act in one out of three ways toward the other agent: do X, Y or nothing ($\varnothing$). The idea at the root of our model is that, in general, each individual in a dyadic interaction can do either the same thing as the other individual, a different thing, or nothing at all. Hence the three possibilities X, Y and $\varnothing$ are sufficient to abstractly describe what can happen in any given interaction between two individuals. Namely, if they do the same thing, they both do X (or Y); if they perform different (non-null) actions, one does X and the other does Y. Our setting is represented by $A \underset{X/Y/\varnothing}{\overset{X/Y/\varnothing}{\rightleftarrows}} B$. We call "action fluxes" the arrows in that symbol.

The setting $A \underset{X/Y/\varnothing}{\overset{X/Y/\varnothing}{\rightleftarrows}} B$ generates nine cases shown in table 4.1 that we call "elementary interactions" or just "interactions." The bottom right case of that table corresponds to the null interaction. For example, the elementary interaction $A \underset{Y}{\overset{X}{\rightleftarrows}} B$ means that agent A does X to B, and agent B does Y to A. The elementary interaction $A \underset{\varnothing}{\overset{X}{\rightleftarrows}} B$ means that agent A does X to B, without any linked flux going reciprocally from B to A. For convenience of notations, we reduce this symbol to $A \overset{X}{\rightarrow} B$. Table 4.2 uses this simplified notation for the interactions with one empty flux (i.e. one null action, $\varnothing$).

$A \underset{X}{\overset{X}{\rightleftarrows}} B$	$A \underset{Y}{\overset{X}{\rightleftarrows}} B$	$A \underset{\varnothing}{\overset{X}{\rightleftarrows}} B$
$A \underset{X}{\overset{Y}{\rightleftarrows}} B$	$A \underset{Y}{\overset{Y}{\rightleftarrows}} B$	$A \underset{\varnothing}{\overset{Y}{\rightleftarrows}} B$
$A \underset{X}{\overset{\varnothing}{\rightleftarrows}} B$	$A \underset{Y}{\overset{\varnothing}{\rightleftarrows}} B$	$A \underset{\varnothing}{\overset{\varnothing}{\rightleftarrows}} B$

Table 4.1: *In our model, each agent (A and B) can do X, Y or $\varnothing$ (nothing) to the other agent. This generates the nine elementary interactions shown in this table. The bottom right case corresponds to the null interaction.*

$A \underset{X}{\overset{X}{\rightleftarrows}} B$	$A \underset{Y}{\overset{X}{\rightleftarrows}} B$	$A \overset{X}{\rightarrow} B$
$A \underset{X}{\overset{Y}{\rightleftarrows}} B$	$A \underset{Y}{\overset{Y}{\rightleftarrows}} B$	$A \overset{Y}{\rightarrow} B$
$A \overset{X}{\leftarrow} B$	$A \overset{Y}{\leftarrow} B$	$A \underset{\varnothing}{\overset{\varnothing}{\rightleftarrows}} B$

Table 4.2: *Same as table 4.1, with simplified notations for the interactions involving one empty flux.*

We call "relationship" a realization of one or several elementary interactions between two

individuals. A "composite relationship" is a combination of different elementary interactions, for example $[A \overset{X}{\rightarrow} B$ and $A \overset{Y}{\leftarrow} B]$. We put between brackets the elementary interactions belonging to a composite relationship, in order to distinguish a composite relationship from a mere enumeration of elementary interactions. A "simple relationship" corresponds to the occurrence of only one type of elementary interaction, for instance $A \underset{Y}{\overset{X}{\rightleftarrows}} B$.

In both relationships above, A does X and B does Y. We differentiate between these two relationships according to the following rule. We posit that, over time, the (simple) relationship $A \underset{Y}{\overset{X}{\rightleftarrows}} B$ entails m fluxes $A \overset{X}{\rightarrow} B$ and also m fluxes $A \overset{Y}{\leftarrow} B$ in alternation, i.e. each flux $A \overset{X}{\rightarrow} B$ is followed by a flux $A \overset{Y}{\leftarrow} B$. Every time A does X, B does Y. Correspondingly, if the relationship started with B doing Y, then every time B does Y, A does X. The number m may be equal to 1 (if the interaction occurs just once) or may be larger (if the interaction is repeated). This does not imply that the "amounts" of X and Y inside the fluxes match, or even that such quantities can be measured. We come back to that possibility in the discussion. Here we are only talking about the number of fluxes, not the weight of their content. For simplicity, we do not specify the number m when we talk about $A \underset{Y}{\overset{X}{\rightleftarrows}} B$.

In contrast, we posit that, in the composite relationship $[A \overset{X}{\rightarrow} B$ and $A \overset{Y}{\leftarrow} B]$, fluxes are not alternated, such that there are generally m fluxes $A \overset{X}{\rightarrow} B$ and n fluxes $A \overset{Y}{\leftarrow} B$, with $m \neq n$ and $m, n \geq 1$. As time goes by, A does X on m occasions, while B does Y on n occasions, without any pattern of alternation. Again, the quantities of X and Y within the fluxes are not specified. Also, for simplicity, we do not write how many times (m and n) each action flux occurs within the relationship.

For clarity, it is useful to examine how many relationships can be defined in our setting. Each of the nine elementary interactions can be present or not in a relationship. There are thus $2^9 = 512$ possible relationships. However, by definition, the null interaction $A \underset{\varnothing}{\overset{\varnothing}{\rightleftarrows}} B$ cannot coexist with any non-null elementary interaction within the same relationship. Therefore, we really only have eight elementary interactions that can combine to form relationships, giving $2^8 = 256$ relationships, plus the null relationship that we keep separated. But one of the 256 relationships corresponds to the eight non-null elementary interactions being absent. We identify this relationship with the null relationship. Hence, since we want to count the null relationship only once, our model results in 256 relationships in total. Of these relationships, nine are simple. These are the nine elementary interactions. The other relationships are composite and include between two and eight elementary interactions each. These 256 relationships constitute the "relationship space" of our model with two social actions.

Our goal is to determine the smallest complete categorization of relationships able to span the relationships space. That is, we want to find "representative relationships" such that all relationships arising from our model can be expressed in terms of representative relationships, singly or in combination.

Let us give the example of two individuals in a relationship $[A \underset{X}{\overset{X}{\rightleftarrows}} B$ and $A \underset{Y}{\overset{Y}{\rightleftarrows}} B]$. They are

implementing the same interaction with respect to actions X and Y, respectively. If we posit that $A \underset{X}{\overset{X}{\rightleftarrows}} B$ is a representative relationship, we can fully describe A and B's relationship by saying that they are in this representative relationship for both X and Y.

In what follows, we present the reasoning that leads us to define six representative relationships and demonstrate that these six correspond to an exhaustive categorization of the relationships space.

4.4 Results

4.4.1 Building six representative relationships

We categorize the relationships arising from our model by exhausting the distinctions that can be done in that setting:

- actions can be null ($\varnothing$) or not (X or Y);
- agents can perform identical or different actions;
- in the case of different actions, individuals can be able to exchange roles or not within their relationship. For example, say that A pays B to provide her with goods. This is represented by $A \underset{Y}{\overset{X}{\rightleftarrows}} B$, an elementary interaction involving different actions: X for "giving money" and Y for "giving goods." Say that A also has the possibility to sell or return goods to B, and this occasionally occurs ($A \underset{X}{\overset{Y}{\rightleftarrows}} B$). Overall, this is a relationship written $[A \underset{Y}{\overset{X}{\rightleftarrows}} B$ and $A \underset{X}{\overset{Y}{\rightleftarrows}} B]$ and involving exchangeable roles. Now, say that A pays B so that B protects A ($A \underset{Y}{\overset{X}{\rightleftarrows}} B$, with Y representing this time "protecting"). For her part, A is unable to offer any protection to B, so that this never happens nor is expected to happen. This is a relationship consisting of only $A \underset{Y}{\overset{X}{\rightleftarrows}} B$ and involving non-exchangeable roles.

This leads to six different representative relationships, or six categories of action fluxes, that are summarized in table 4.3 and explained below. The correspondence between these categories and the RMs is presented later.

1. Non-null identical actions result in a simple relationship symbolized by $A \underset{X}{\overset{X}{\rightleftarrows}} B$, or $A \underset{Y}{\overset{Y}{\rightleftarrows}} B$. It does not matter whether the social action is denoted by X or Y. We choose $A \underset{X}{\overset{X}{\rightleftarrows}} B$ as the representative relationship in that situation.

2. Two agents identically doing nothing toward each other are in a null relationship written $A \underset{\varnothing}{\overset{\varnothing}{\rightleftarrows}} B$.

Category	Fluxes characteristics	Representative relationship	Alternative notations	RMT
	Identical actions			
1	Non-null actions	$A \underset{X}{\overset{X}{\rightleftarrows}} B$	$A \underset{Y}{\overset{Y}{\rightleftarrows}} B$	EM
2	Null actions	$A \underset{\varnothing}{\overset{\varnothing}{\rightleftarrows}} B$		Null
	Different actions			
3	Non-null actions, exchangeable roles	$[A \underset{Y}{\overset{X}{\rightleftarrows}} B$ and $A \underset{X}{\overset{Y}{\rightleftarrows}} B]$		MP
4	Non-null actions, non-exchangeable roles	$A \underset{Y}{\overset{X}{\rightleftarrows}} B$	$A \underset{X}{\overset{Y}{\rightleftarrows}} B$	AR
5	One null action, exchangeable roles	$[A \overset{X}{\rightarrow} B$ and $A \overset{X}{\leftarrow} B]$	$[A \overset{Y}{\rightarrow} B$ and $A \overset{Y}{\leftarrow} B]$	CS
6	One null action, non-exchangeable roles	$A \overset{X}{\rightarrow} B$	$A \overset{Y}{\rightarrow} B$, or $A \overset{X}{\leftarrow} B$, or $A \overset{Y}{\leftarrow} B$	Asocial

Table 4.3: *Exhaustive categorization of relationships in the model of two agents A and B who can each do X, Y or nothing ($\varnothing$). In elementary interactions, agents can do the same thing or not (i.e. actions can be identical or different) and actions can be null ($\varnothing$) or not (X or Y). Within a relationship, agents can be able to exchange roles or not.*

3. Agents performing different non-null actions and able to exchange roles are in a composite representative relationship $[A \underset{Y}{\overset{X}{\rightleftarrows}} B$ and $A \underset{X}{\overset{Y}{\rightleftarrows}} B]$.

4. Agents performing different non-null actions and unable to exchange roles are in a simple relationship consisting in just $A \underset{Y}{\overset{X}{\rightleftarrows}} B$ (or just $A \underset{X}{\overset{Y}{\rightleftarrows}} B$: again, the notation used for the actions does not matter).

5. When one individual does nothing and the other performs a non-null action in an elementary interaction, and roles are exchangeable in the relationship, it is symbolized by $[A \overset{X}{\rightarrow} B$ and $A \overset{X}{\leftarrow} B]$ (or the same interactions with the notation Y instead of X).

6. When one individual does nothing and the other performs a non-null action in an elementary interaction, and roles cannot be exchanged in the relationship, it consists in only $A \overset{X}{\rightarrow} B$ (or the same with Y instead of X, or with the action flux going from B to A).

4.4.2 Proof of exhaustiveness

Our first result is to prove the proposition that the six categories of action fluxes given in table 4.3 are exhaustive.

Proposition 1 : To describe all relationships arising from the model $A \underset{X/Y/\varnothing}{\overset{X/Y/\varnothing}{\rightleftarrows}} B$, one needs exactly the six categories of action fluxes defined in table 4.3.

Proof: On the one hand, the six categories are mutually disjoint. Indeed, the fluxes characteristics defining the categories do not overlap. Two actions cannot be identical and different at the same time, an action cannot be null and non-null at the same time; and roles cannot be both exchangeable and non-exchangeable. This shows that no less than these six categories could suffice to characterize relationships arising from the setting $A \underset{X/Y/\varnothing}{\overset{X/Y/\varnothing}{\rightleftarrows}} B$.

On the other hand, we noted during the building of the six categories that in some cases, the notation X or Y does not matter, giving rise to alternative notations for some categories, shown in table 4.3. Taking into account these arbitrary choices of notation, the six categories of table 4.3 cover the nine elementary interactions of table 4.2, as is seen by comparing these two tables. Hence, any relationship built on these nine elementary interactions can be expressed in terms of the six categories, singly or in combination. This shows that no more than these six categories are necessary to characterize relationships arising from the setting $A \underset{X/Y/\varnothing}{\overset{X/Y/\varnothing}{\rightleftarrows}} B$. This concludes the proof.

4.4.3 Mapping between the categories of action fluxes and the relational models

Our second result is to propose a mapping between the six categories of action fluxes defined in table 4.3 and the four relational models, the asocial and null interactions defined in RMT. The mapping is indicated in the last column of table 4.3 and put in words as follows (in the same order as in the table).

1. In EM relationships, actions or items of the same nature are exchanged, usually with a time delay making the exchange relevant. Dinner invitations is a typical example. It is essential in EM that each social action is reciprocated. This is what category 1 captures with the representative relationship $A \underset{X}{\overset{X}{\rightleftarrows}} B$. Note that when people contribute equally to a collective action, for example by sharing equally the cost of gas on a trip (Fiske, 1992, 711), the action X does not represent the contribution itself, here an amount of money. Instead, by paying a certain share of the total cost to the gas station, the action X that travelers perform toward their partners consists in freeing the latter from paying this share themselves.

2. In the null interaction, people do not interact; this corresponds to empty fluxes in both directions, as in category 2 ($A \underset{\varnothing}{\overset{\varnothing}{\rightleftarrows}} B$).

3. In MP relationships, one thing is exchanged for another; typically, money or another medium of exchange for a good or service. Agents thus perform different actions in elementary interactions. A defining feature of MP is that a buyer can become a seller and

vice-versa toward anybody in a fluid manner, provided that agents possess the right resource or skill. Hence, roles can be exchanged, as in category 3, represented by [$A \underset{Y}{\overset{X}{\rightleftarrows}} B$ and $A \underset{X}{\overset{Y}{\rightleftarrows}} B$].

4. As in MP, AR relationships involve the exchange of one social action against another. However, AR is not as flexible as MP. To start with, actions are fixed: one of them is typically protection, leadership or management, while the other is obedience, respect, subordination, possibly the payment of a tax under one form or another, and so on. In a well-established relationship, roles are fixed as well: superiors and subordinates may never exchange roles. In social hierarchies mediated by AR, such reversals typically occur infrequently and at the price of spectacular power struggles that cause a period of social and political instability and result in new sets of relationships. These considerations lead us to think of AR as a relationship involving different social actions and non-exchangeable roles, as in category 4, represented by $A \underset{Y}{\overset{X}{\rightleftarrows}} B$. We note that the impossibility for agents to exchange roles in category 4 implies that at least one individual does something that the other cannot replicate. It thus has to be something hard to learn or based on innate characteristics (e.g. adult body size), or both; this evokes leadership, dominance, protectiveness, wisdom, experience or popularity. In RMT, these are the typical fundamental determinants of any AR relationship; the non-exchangeability in category 4 connects with the notion of asymmetry present in the RMT description of AR.

5. In CS relationships, people give without counting or expecting a reciprocation, which in our representation translates into the property that each flux going one way does not necessarily entail a reciprocating flux. However, overall, each party contributes to the relationship, such that it is not entirely one-sided. This is represented by category 5 with the relationship [$A \overset{X}{\rightarrow} B$ and $A \overset{X}{\leftarrow} B$].

6. In the asocial interaction described by RMT, a person uses others as means, exploits them, or takes from them, possibly by force, whatever can be useful to her. Roles are not exchanged, as there is no social coordination. This corresponds to category 6 where only agent A acts toward B ($A \overset{X}{\rightarrow} B$). The asocial interaction of RMT specifically corresponds to the case in which A acts in a harmful, exploitative and abusive way that makes it impossible for B to react in a socially coordinated way toward A. However, our model generally involves social actions that can be beneficial or harmful to their target. From that point of view, category 6 is more general than the asocial interaction of RMT, and perhaps may best be called "unilateral," with RMT's asocial interaction being a particular case of that category.

Based on the above mapping, we infer that the categories of action fluxes arising from our model offer suitable abstract representations of the exchange of social actions performed by dyads implementing the RMs. Moreover, given the exhaustiveness of our categorization, we

propose that the four RMs constitute an exhaustive description of coordinated dyadic social relationships.

Let us now highlight properties of our model and resulting categorization that match important aspects of RMT.

We mentioned at the beginning of this chapter that we use the term "dyadic" to stress that our model describes relationships between two agents, as opposed to sets or "compounds" of more than two agents instantiating different relational models. However, Fiske (1991) also uses RMs to characterize groups of more than two individuals in which all members use the same relational model in the context of a social activity. For example, if members of a group are all implementing CS when sharing food, it can be called a "CS group" with respect to that activity (Fiske, 1991, 151). Rotating credit associations (Fiske, 1991, 153) or equal distribution of any common resource are typical examples of EM within a group of more than two people. As we illustrate below, our model also describes such situations of homogeneous collective action, whereby all participants use the same relational model.

Let us consider three agents $\{A, B, C\}$ taking turns at performing a social action X that affects equally and simultaneously other agents, for example taking a turn playing a board game. First, A does X (i.e. takes her turn), which affects B and C. Then, B does X to A and C. Finally, C does X to A and B. Over an entire cycle, the action fluxes between the agents are $A \underset{X}{\overset{X}{\rightleftarrows}} B$, $A \underset{X}{\overset{X}{\rightleftarrows}} C$ and $B \underset{X}{\overset{X}{\rightleftarrows}} C$, corresponding to EM in each dyad. In other words, in this situation of homogeneous collective action, our representation gives an accurate description of what happens between any two members. It can thus be used to characterize the group as a whole. That is, an EM group can be described as an ensemble of dyadic EM relationships.

A set or "compound" of N agents implementing different RMs may be represented by a combination of these RMs, for example $A \underset{X}{\overset{X}{\rightleftarrows}} B \underset{Y}{\overset{X}{\rightleftarrows}} C$, but the group itself (here $\{A, B, C\}$) cannot be characterized by only one RM or one category in our model. Instead, a combination of different RMs between more than two actors may be identified as what is called in RMT a "metarelational model" (Fiske, 2011), which is beyond the scope of this chapter and model.

The six classes of action fluxes that we define are mutually disjoint categories. This is in line with the proposition made by Haslam (1994a) that the relational models are indeed categories, as opposed to "dimensions" (whereby there would be no well-defined boundaries between the RMs) or "prototypes" (whereby theoretical, ideal RMs would never be realized by real social interactions; RMs would only be approximated along continuous dimensions).

Moreover, the disjointness of the categories reflects the view of RMT that any specific aspect of any social interaction corresponds to one, and only one RM (or alternatively, the asocial or the null interaction). This applies to two levels: the way people think of their dyadic relationships with particular persons (Haslam, 1994a,b), and the way people categorize each aspect (e.g. decision making, allocation of resources, organization of work) of the coordination of a particular dyad (Fiske, 2004b).

At the same time, RMT points out that any relationship between two actors generally consist in a composite of RMs (Fiske, 1991, 155-68). Using table 4.3, any composite relationship arising

from our model can now be interpreted in terms of the RMs. For example, the relationship $[A \underset{X}{\overset{X}{\rightleftarrows}} B$ and $A \underset{Y}{\overset{Y}{\rightleftarrows}} B]$ is interpreted as EM for both X and Y. The relationship $[A \underset{X}{\overset{X}{\rightleftarrows}} B$, $A \overset{Y}{\rightarrow} B$ and $A \overset{Y}{\leftarrow} B]$ is an instance of EM for X and CS for Y. The relationships space also includes cases that are less obvious. For instance, $[A \underset{X}{\overset{X}{\rightleftarrows}} B$, $A \underset{Y}{\overset{X}{\rightleftarrows}} B$ and $A \underset{X}{\overset{Y}{\rightleftarrows}} B]$ is interpreted in our categorization as EM for X and MP for X and Y. Yet it is rather odd to imagine two people taking turns at doing X and in parallel trading X for Y. This may correspond to a relationship evolving with time from one RM to the other. The generalization of our model to N social actions, presented in the next section, helps represent any familiar composite relationship.

4.4.4 Generalization to N social actions

In real social relationships, the number of occurring social actions is expected to be larger than two, which motivates the generalization of our results to any number N of social actions. This is our third result.

For the generalization that follows, we let X and Y be elements of a larger set $\mathbb{S}$ of N social actions S_i: $\mathbb{S} = \{S_i | i = 1, ..., N\}$, such that $X, Y \in \mathbb{S}$, for instance $S_1 \equiv X$ and $S_2 \equiv Y$.

Proposition 2 : In the general case of N non-null social actions ($S_1, S_2, ..., S_N \in \mathbb{S}$, $N \geq 2$), one still needs exactly the six categories of table 4.3 to describe all possible relationships arising from the setting $A \underset{S_1/S_2/.../S_N/\varnothing}{\overset{S_1/S_2/.../S_N/\varnothing}{\rightleftarrows}} B$.

Idea of the proof: We show that the proof of exhaustiveness of the six categories of table 4.3 carried out for $N = 2$ holds for any $N \geq 2$. Namely, the same process allows to build the same six mutually disjoint categories of action fluxes, and these categories span the relationship space for any $N \geq 2$.

Proof: In the general case of $N \geq 2$ non-null social actions, there are 2^{N+1} elementary interactions and $2^{(N+1)^2-1}$ relationships.

Cases such as $A \underset{S_3}{\overset{S_1+S_2}{\rightleftarrows}} B$ (where A performs several actions simultaneously) can be written $A \underset{S_3}{\overset{S_4}{\rightleftarrows}} B$ (where S_4 is a bundle of actions). More generally, any number of actions can be bundled as in that example. Starting from a set of N social actions, the set $\mathbb{S}$ can be redefined to include all subsets of that set. (The cardinality of $\mathbb{S}$ is then 2^N.) Hence, any union of two or more subsets (such as S_1 and S_2 to give S_4) gives another subset that is an element of $\mathbb{S}$.

Then, because there are still two agents and thus at most two different social actions (which can be bundles) per elementary interaction, the elementary interactions take the same forms as for $N = 2$, just with additional notations for the social actions.

As an illustration, table 4.4 shows the sixteen elementary interactions that result from the case $N = 3$, i.e. the model $A \underset{X/Y/Z/\varnothing}{\overset{X/Y/Z/\varnothing}{\rightleftarrows}} B$.

Let us now consider an elementary interaction between two individuals for any $N \geq 2$.

$A \underset{X}{\overset{X}{\rightleftarrows}} B$	$A \underset{Y}{\overset{X}{\rightleftarrows}} B$	$A \underset{Z}{\overset{X}{\rightleftarrows}} B$	$A \overset{X}{\rightarrow} B$
$A \underset{X}{\overset{Y}{\rightleftarrows}} B$	$A \underset{Y}{\overset{Y}{\rightleftarrows}} B$	$A \underset{Z}{\overset{Y}{\rightleftarrows}} B$	$A \overset{Y}{\rightarrow} B$
$A \underset{X}{\overset{Z}{\rightleftarrows}} B$	$A \underset{Y}{\overset{Z}{\rightleftarrows}} B$	$A \underset{Z}{\overset{Z}{\rightleftarrows}} B$	$A \overset{Z}{\rightarrow} B$
$A \overset{X}{\leftarrow} B$	$A \overset{Y}{\leftarrow} B$	$A \overset{Z}{\leftarrow} B$	$A \underset{\varnothing}{\overset{\varnothing}{\rightleftarrows}} B$

Table 4.4: *This table shows the sixteen elementary interactions arising from our model with $N = 3$ non-null social actions X, Y, Z between two agents A and B, that is, $A \underset{X/Y/Z/\varnothing}{\overset{X/Y/Z/\varnothing}{\rightleftarrows}} B$. We use simplified notations for the interactions involving one empty flux.*

One can still only differentiate between (i) identical or different actions, (ii) interchangeable or non-interchangeable roles, (iii) null or non-null actions. Hence, with more than two actions, this differentiation process leads to the same six disjoint categories, yet with more alternative notations than in table 4.3.

For example, for $N = 3$, category 1 (EM) gets one more alternative notation than for $N = 2$, namely $A \underset{Z}{\overset{Z}{\rightleftarrows}} B$. Category 3 (MP) gets two alternative notations: [$A \underset{Z}{\overset{X}{\rightleftarrows}} B$ and $A \underset{X}{\overset{Z}{\rightleftarrows}} B$], and [$A \underset{Z}{\overset{Y}{\rightleftarrows}} B$ and $A \underset{Y}{\overset{Z}{\rightleftarrows}} B$]. Category 4 (AR) gets four more alternative notations: $A \underset{Z}{\overset{X}{\rightleftarrows}} B$, $A \underset{X}{\overset{Z}{\rightleftarrows}} B$, $A \underset{Z}{\overset{Y}{\rightleftarrows}} B$, and $A \underset{Y}{\overset{Z}{\rightleftarrows}} B$. Category 5 (CS) gets one more alternative notation, [$A \overset{Z}{\rightarrow} B$ and $A \overset{Z}{\leftarrow} B$]. Finally, category 6 (asocial) gets two more alternative notations, $A \overset{Z}{\rightarrow} B$ and $A \overset{Z}{\leftarrow} B$.

For any $N \geq 2$, all of the 2^{N+1} elementary interactions are included in the representative relationships of the six categories and their alternative notations. This derives from the building process of the six categories, with the differentiations covering all possible cases.

In the example of $N = 3$, the above statement is illustrated by the comparison of the sixteen elementary interactions of table 4.4 with the six categories and their alternative notations for $N = 2$ (table 4.3), completed by the alternative notations for $N = 3$ listed above.

This concludes the proof of exhaustiveness of the six categories of table 4.3 for any number $N \geq 2$ of non-null social actions.

With N social actions at hand, richer composite relationships can be represented. Let us translate into our action fluxes representation an example of composite relationship given by Fiske (1992, 711): "roommates may share tapes and records freely with each other (CS), work on a task at which one is an expert and imperiously directs the other (AR), divide equally the cost of gas on a trip (EM), and transfer a bicycle from one to the other for a price determined by its utility or exchange value (MP)." This gives [$A \overset{S_1}{\rightarrow} B$, $A \overset{S_1}{\leftarrow} B$, $A \underset{S_3}{\overset{S_2}{\rightleftarrows}} B$, $A \underset{S_4}{\overset{S_4}{\rightleftarrows}} B$, $A \underset{S_6}{\overset{S_5}{\rightleftarrows}} B$, $A \underset{S_5}{\overset{S_6}{\rightleftarrows}} B$]. Here the relationship was known and we wrote it in terms of action fluxes. The next step is to find out how to identify a relationship as a combination of relational models when the

action fluxes are given. We touch on how to achieve this in the discussion.

4.5 Discussion

4.5.1 Analyzing data sets

Our representation in action fluxes provides a tool to identify types of dyadic relationships occurring within potentially large data sets of social interactions. Both collective and dyadic interactions may occur in real social contexts, but our approach applies specifically to the latter.

The obtention of such data sets is not straightforward. Large data sets can result from any type of online social network or massively multiplayer online role-playing games (MMORPG), for instance. MMORPGs bring hundreds of thousands of players together to cooperate and compete by forming alliances, trading, fighting, and so on, all the while recording every single action and communication of the players. They are used in quantitative social science, for example by Thurner et al. (2012); Szell et al. (2010); Fuchs et al. (2014) in the context of a game called Pardus. Moreover, ethnological and anthropological studies can provide rich reports of social interactions occurring in non-artificial settings that could be coded and interpreted with the aid of our categorization. Finally, data sets of dyadic interactions can be generated by computer simulations such as agent-based models (ABMs) to test specific questions.

We offer the sketch of a method to analyze a potentially large data set of dyadic social interactions expressed as action fluxes ("A does X to B," etc.). Given a data set involving a number of individuals, one needs to consider separately each pair of individuals. For each pair, one shall examine each social action and test into which category of action fluxes it falls, possibly jointly with another social action (in the case of MP and AR). In its second column, table 4.5 specifies the patterns of fluxes expected to be observed in each category.

Let us stress the following points:

- The patterns of observed fluxes given in table 4.5 are not meant as definitions of the categories. Instead, they correspond to properties of the fluxes in each category.

- Linked to the previous point, we stress that the patterns given in that table are not mutually disjoint. They should thus be tested in a certain order. MP should be tested before AR and CS, and category 6 (asocial) should be tested after all other categories. Let us illustrate this point with an example: if A and B are in an MP relationship, one observes alternated fluxes $A \xrightarrow{X} B$ and $A \xleftarrow{Y} B$, as well as alternated fluxes $A \xrightarrow{Y} B$ and $A \xleftarrow{X} B$, re-written as $[A \underset{Y}{\overset{X}{\rightleftarrows}} B$ and $A \underset{X}{\overset{Y}{\rightleftarrows}} B]$. Yet, A and B's relationship will also respond positively to a CS test, because non-alternated fluxes $A \xrightarrow{X} B$ and $A \xleftarrow{X} B$ are present overall in the relationship (indicative of CS for X), as well as non-alternated fluxes $A \xrightarrow{Y} B$ and $A \xleftarrow{Y} B$ (CS for Y). In such a case, the alternation characterizing an MP relationship should prevail in the observer's interpretation because it is unlikely to happen by chance alone.

Category	Pattern of observed fluxes	Representative relationship	RMT
1	Alternated fluxes $A \xrightarrow{X} B$ and $A \xleftarrow{X} B$	$A \underset{X}{\overset{X}{\rightleftarrows}} B$	EM
2	No fluxes between A and B	$A \underset{\varnothing}{\overset{\varnothing}{\rightleftarrows}} B$	Null
3	Alternated fluxes $A \xrightarrow{X} B$ and $A \xleftarrow{Y} B$, and separately, alternated fluxes $A \xrightarrow{Y} B$ and $A \xleftarrow{X} B$	$[A \underset{Y}{\overset{X}{\rightleftarrows}} B$ and $A \underset{X}{\overset{Y}{\rightleftarrows}} B]$	MP
4	Alternated fluxes $A \xrightarrow{X} B$ and $A \xleftarrow{Y} B$	$A \underset{Y}{\overset{X}{\rightleftarrows}} B$	AR
5	Fluxes $A \xrightarrow{X} B$ and $A \xleftarrow{X} B$, not systematically alternated	$[A \xrightarrow{X} B$ and $A \xleftarrow{X} B]$	CS
6	Fluxes $A \xrightarrow{X} B$	$A \xrightarrow{X} B$	Asocial

Table 4.5: *Patterns of action fluxes expected to be observed in each category. X and Y are social actions belonging to a set $\mathbb{S}$ of size N. A and B are agents.*

- A tolerance level should be defined for the alternation of fluxes (in EM, MP and AR). For example, the alternation of fluxes in an EM relationship does not need to be strict. In real conditions, people can be flexible and take several turns in a row before the other party reciprocates. Inexact record keeping or occasional cheating may also occur within an otherwise stable relationship. Hence, a low tolerance could lead to false negatives, whereby the observer would miss instances of EM, MP and AR. On the other hand, high tolerance levels might lead to wrong interpretations: fluxes could be falsely interpreted as manifestations of EM, MP or AR. The adequate tolerance level may vary per data set or relationship and may be checked against the individuals' communications, if available.

- Relationships may change over time. Individuals may initiate a certain relationship that transforms over time into another, linked to increased trust (or mistrust), availability of resources in the environment, and so on. To detect such changes, analyses can be carried out over different time windows.

- In any real data set, individuals may belong to larger social units interacting with each other. If blindly applied to all pairs of individuals, our model may miss these higher-level effects. For instance, say that agent A from group G_1 attacked B from group G_2. Agent C from G_2, feeling very close to B (perhaps in a CS way), decides to punish A and attacks her in an eye-for-an-eye, tooth-for-a-tooth fashion (EM). If one knows nothing of the groups, one analyzes separately the pairs (A, B) and (A, C). From the observations $A \xrightarrow{X} B$ and $A \xleftarrow{X} C$, one concludes to the presence of an asocial interaction (category 6) between A and B, as well as between A and C. If however one knows of the groups and applies our

model to the higher-level agents G_1 and G_2, one observes $G_1 \underset{X}{\overset{X}{\rightleftarrows}} G_2$ and interprets it as an EM relationship between the two groups. This example motivates to identify the relevant social units in the data set under study. One possible way to achieve this would be to measure the number and duration of interactions between all pairs of individuals and thus creating a weighted graph. By choosing a threshold for the weight of the links, one may be able to isolate social units. Our model would then apply to pairs of members of the same social unit, as well as to pairs of social units.

4.5.2 Valuing the action fluxes

Our fluxes representation reflects only the presence or absence of fluxes, without saying anything about the quantities involved. The amount carried by an action flux can be readily measured when the action consists in the transfer of a physical item for which a unit of measure can easily be agreed upon. Valuing an action in general is not straightforward. The average time or physical effort necessary to perform the action can be measured (or intuitively approximated), but it is much harder to agree on a possible emotional or intellectual quantitative value. We propose that a value function does not need to be identical for each agent, and each agent does not need to possess a fixed, deterministic value function. For our present needs, it is sufficient for each agent to have personal or cultural notions of the value of social actions performed by herself and others. These individual scales may be probabilistic, in the sense that the value they return may follow probability distributions. Correspondingly, decisions may be probabilistic, as suggested by quantum decision theory (Yukalov and Sornette, 2010b, 2011). Alternatively, a value function could be a von Neumann-Morgenstern utility (von Neumann and Morgenstern, 1953), a subjective cumulative prospect utility (Kahneman and Tversky, 1979), or any other value function capturing different forms of happiness or contentment, as in the theory of utilitarianism (Mill, 1906).

We hypothesize that, in a population of interacting agents evolving under selective pressure, the action fluxes of our model converge toward equilibria characterized by an equality in value between opposite fluxes. This proposition rests on the idea that unequal fluxes disadvantage at least one party. They are thus likely to jeopardize the relationship in the short term (in case of inequity aversion), and negatively affect the survival or reproductive success of the disadvantaged party in the long run. Hence, both individual optimization and selection pressure from external forces in the environment should drive interactions toward stable equilibria characterized by value equalities. We expect these equilibria to depend upon initial conditions and previous states. In other words, different societies would estimate that different things or actions have equal values.

Let us now examine this suggestion in relation to RMT. MP requires a formal matching agreement stating the respective values of what is exchanged, whether actions (such as work), commodities or symbolic items (e.g. money). In EM, the things exchanged are not only of the same nature, but also of the same value. Thus, the idea of value equalities is already embedded

into the definitions of these two RMs. RMT keeps CS and AR apart by stating that these RMs are not supposed to necessitate any kind of counting. It may be the case that CS relationships are established only between individuals so close that individual optimization does not occur, such that these relationships may not need to rest on equal contributions overall.

For its part, the RMT definition of AR is based on the presence of a linear hierarchy and states that superiors generally get more and better things, but have the obligation to act generously according to the principle "noblesse oblige" (Fiske, 1991, 42-3). There is a deep principle of asymmetry and inequality, expressed for instance by Goldman (1993, 343-4): "When people transfer things from person to person in an AR mode, higher-ranking people get more and better things, and get them sooner, than their subordinates. Higher-ranking people may preempt rare or valuable items, so that inferior people get none at all." In this quote, only one side of the relationship is looked at, namely what the higher-ranking people get from subordinates. Yet AR relationships entail an exchange of protection (or management, etc.) in return for obedience, loyalty, tax payments, and so on. In our representation, the equality would be between the protection offered by the leader and the obedience of the subordinates, whereby the leader may well get "more and better things," but matching in value the safety she offers to her subjects. Nevertheless, it may be that respective contributions match only in idealized AR relationships, because in practice it is difficult for subordinates to monitor and enforce equality in an essentially asymmetrical relationship.

Another point concerning AR is that, according to Fiske (1991, 209), the distance between ranks is not socially meaningful; only the linear ordering of ranks is (i.e. which rank is higher, without specifying how much higher). Yet, a value function would allow to measure the distance between ranks. We point out that just because a value function is introduced does not mean that the use of AR requires any computation from the agents. Similarly to the way we adapt our every move to the law of gravity without solving mentally at each instant the corresponding equations, or as dogs catch frisbees using simple heuristics (Shaffer et al., 2004; Gigerenzer et al., 1999), it is conceivable that we are able to recognize and interact with individuals of different ranks without using or having defined any measure of ranks differences or action values. In the case of humans, these heuristics are facilitated by evolved language and culture, which permit the existence of predefined roles (for instance "chief" or "servitor") offering an idea of what is expected from each party.

An agent-based model would be a convenient approach to observe and test the evolution of a system toward value equalities. Naturally, it would also be of high interest to examine real social relationships in the making. This, however, raises practical difficulties such as the fact that even new relationships develop within a cultural context that largely predefines how RMs should be implemented, making transient forms unlikely to occur or last long enough to be observed.

4.6 Conclusion

We have introduced a model of social interactions between a pair of individuals A and B, each of whom can perform a social action X, Y or nothing, symbolized by $A \underset{X/Y/\varnothing}{\overset{X/Y/\varnothing}{\rightleftarrows}} B$. We demonstrated that from this setting arise six exhaustive and disjoint categories of relationships, four of which match the relational models of RMT, while the remaining two are identified as the asocial and the null interactions. We generalized this categorization to the case of any number N of social actions. We argued that the categories of action fluxes offer suitable abstract representations of the social actions performed by dyads implementing the relational models. Hence, simulated or real dyads may exhibit various patterns of interactions that can be matched to the six categories of action fluxes, singly or in combination. In that spirit, we discussed a method to identify relational models, expressed as categories of action fluxes, in data sets of dyadic interactions. Finally, we expressed a hypothesis about how social actions are valued and matched by the agents. Our representation can be used to interpret social relationships in terms of RMT and test hypotheses on dyadic social interactions occurring in potentially large data sets.

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Chapter 5

Forms of social relationships in distinct cultural settings

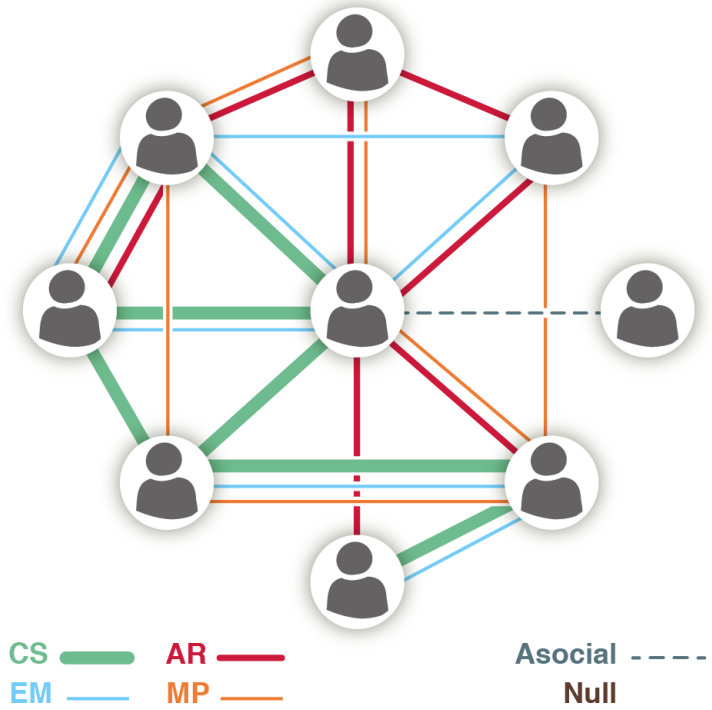

Figure 5.1: *This chapter describes social relationships embedded in congruent cultural settings. CS stands for communal sharing, AR for authority ranking, EM for equality matching and MP for market pricing (Fiske, 1991, 1992).*

5.1 Abstract

[1] We contribute to the understanding of social relationships within cultural contexts by proposing a connection between a social theory, relational models theory (RMT: Fiske, 1991, 1992) and a social and political one, cultural or plural rationality theory (PRT: Douglas, 1978, 1982; Thompson et al., 1990). Drawing examples from the literature of both theories, we argue that each relational model of RMT may be implemented in ways compatible with each cultural bias of PRT. A cultural bias restrains the range of congruent implementations of relational models, but does not preclude any relational model altogether. This stands in contrast to earlier reconciliation attempts between PRT and RMT. Based on hypothetical one-to-one mappings, these attempts expect each cultural setting to be significantly associated with some, but not all, relational models. The framework we develop helps explain the findings of these previous attempts and provides insights into empirical research by clarifying which associations to expect between relationships and cultural contexts. We discuss the theoretical basis of our framework, including the idea that RMT and PRT apply to different levels of analysis: RMT's relational models are tied to relationships between two actors and PRT's cultural biases to structures of social networks.

Keywords: social relationships, culture, social networks, relational models theory, plural rationality theory, cultural grid-group theory

5.2 Introduction

5.2.1 Motivation

We propose a connection between relational models theory (RMT: Fiske, 1991, 1992) and plural rationality theory (PRT: Douglas, 1978, 1982; Thompson et al., 1990). These two theories connect to the works of social and political theorists and anthropologists such as Durkheim, Weber, Piaget, Marx, Polanyi, Sahlins, Evans-Pritchard, Lévi-Strauss, and a number of others, and can be called theories of *constrained relativism*[2] (Verweij, 2007, Lockhart and Franzwa, 1994, 176).

The idea behind constrained relativism is that the variety of social life emerges from just a small number of fundamental options, and that the particular choice of an option may be largely influenced by the cultural context. This contrasts with the post-structuralist view, which holds

[1] This chapter is based on Favre M. and D. Sornette, 2016: Forms of dyadic relationships in distinct cultural settings. Submitted. URL: http://ssrn.com/abstract=2772520.

[2] The tradition of constrained relativism goes back to Maine, Tonnies, Durkheim, and Weber. Other theories that can be said to belong to constrained relativism are, for example, Jonathan Haidt's moral foundations theory (Haidt, 2007), Hofstede's cultural dimensions (Hofstede, 1984), Triandis' culture orientation scales (Triandis, 1995), Richard Shweder's tripartite theory of morality (Schweder et al., 1997) and Pierre Bourdieu's theory of practice (Bourdieu, 1977). Except for Triandis' constructs, to which we come back in section 5.5, the description of these theories is beyond the scope of the present work.

that social life derives from an infinite diversity of options, such that each person is unique and only individual descriptions make sense. Constrained relativism also departs from rational choice theory, insofar as the latter posits that people behave as if they had access to and processed all information instantly, and used this ability to form preferences obeying well-defined axioms.

Recently, Verweij et al. (2015) argued that rational choice theory, post-structuralism, and additionally behavioral economics, are inconsistent with the way our brain functions according to processes described by affective and social neuroscience. These authors propose that PRT and generally theories of constrained relativism are compatible with the findings of neuroscience. By reconciling two theories of constrained relativism, our hope is to contribute to strengthening it.

When one is confronted with the PRT and RMT typologies (to which an introduction is given in sections 5.2.2 and 5.2.3), it immediately appears that they should be related. One may intuitively imagine one to be a simple transformation of the other. Indeed, RMT and PRT seem to describe the same fundamental ingredients of social life. PRT posits that there are four ways of organizing social relationships, each of which is associated with a compatible set of individual norms, values, perceptions, beliefs and preferences (called *cultural biases*). RMT postulates four models of relationships, the *relational models*, and recently examined their combinatorics (Fiske, 2011) as well as the moral norms and values associated with them (Rai and Fiske, 2011; Fiske and Rai, 2014). Moreover, each theory claims its fourfold typology to be exhaustive and universal: in each and every social domain, people are supposed to attend to the types defined by the theory, singly or in combination.

As a result of the similarities between these two important theories, several researchers have previously attempted to unite them, or one of them and concepts present in the other. These efforts, which we review in section 5.5, face related issues. Vodosek (2009) and Realo et al. (2004) seek associations between RMT's typology and the typology introduced by Triandis (1995, 1996), which can be argued to closely parallel the PRT typology (Verweij et al., 2014, 87-9). Vodosek (2009) tests hypotheses expressed by Triandis (1995, 50-1) connecting relational models with Triandis' constructs, but Vodosek's empirical results only partly confirm these hypotheses. Realo et al. (2004), for their part, conclude that there is no one-to-one mapping between the typology of RMT and social contexts in general, but do not propose any other model. Verweij (2007) undertakes a reconciliation attempt of PRT and RMT at a theoretical level, which brings out several apparent inconsistencies. Finally, Brito et al. (2011) empirically test for a subset of associations between relational models and social contexts, but without constructing a complete theoretical explanation for their results.

Our approach not only reconciles RMT with PRT, but also provides interpretations for the results of the aforementioned earlier attempts, as we argue in section 5.5. Before presenting our framework in section 5.3, let us give an introduction to both theories.

5.2.2 Relational models theory (RMT)

Relational models theory was introduced by Fiske (1991, 1992) in the field of anthropology to study how people construct their social relationships. RMT posits that people use four elementary models to organize most aspects of most social interactions in all societies. These models are communal sharing (CS), authority ranking (AR), equality matching (EM), and market pricing (MP).

- In CS, people perceive in-group members as equivalent and undifferentiated. CS relationships are based on principles of unity, identity, conformity and undifferentiated sharing of resources. Decision-making is achieved through consensus. CS is typically manifested in close family or friendship bonds, teams, nationalities, ethnicities or between soldiers exposed to stressful conditions.

- In AR relationships, people are asymmetrically ranked in a linear hierarchy. Subordinates are expected to defer, respect and obey high-rankers, who take precedence. Conversely, superiors protect and lead low-rankers. Subordinates are thus not exploited and also benefit from the relationship. Resources are distributed according to ranks and decision-making follows a top-down chain of command.

- EM relationships are based on a principle of equal balance and one-to-one reciprocity. Salient EM manifestations are turn-taking, democratic voting (one person, one vote), in-kind reciprocity, coin flipping, distribution of equal shares, and tit-for-tat retaliation.

- MP is based on a principle of proportionality. Relationships are organized with reference to socially meaningful ratios and rates, such as prices, cost-benefit analyses or time optimization. Rewards and punishment are proportional to merit. Abstract symbols, typically money, are used to represent relative values. MP relationships are not necessarily individualistic; for instance, utilitarian judgments seeking the greatest good for the greatest number are manifestations of MP.

The four relational models (RMs) have in common that they suppose a coordination between individuals with reference to a shared model. To these, Fiske adds two limiting cases that do not involve any other-regarding abilities or coordination (Fiske, 1991, 19-20):

- In asocial interactions, individuals exploit others and treat them as animate objects or means to an end (as in psychopathy, armed robbery, pillage);

- In null interactions, people do not interact at all (they do not actively ignore each other, which still requires a coordination), as can be the case of two inhabitants of the same building who never cross each other's way or fail to notice each other's existence, and thus do not adapt their actions to each other.

Any relationship generally consist in a combination of RMs (Fiske, 1991, 155-168). For example, "roommates may share tapes and records freely with each other (CS), work on a task

at which one is an expert and imperiously directs the other (AR), divide equally the cost of gas on a trip (EM), and transfer a bicycle from one to the other for a price determined by its utility or exchange value (MP)" (Fiske, 1992, 711). Or, "any aspect of the relations between husband and wife can be structured as CS, AR, EM, MP, or any combination of these models across different domains of the marital relationship" (ibid., 712).

The RMs can be seen as "templates" (Fiske, 1992, 711) or "structures" (ibid., 690) with "flexible application" (ibid., 692). RMs, being abstract structures, can be applied in many different ways to any aspect of any social domain. Cultures have their own values or expectations regarding when and how to execute each RM. These cultural paradigms are called "preos" by Fiske (2000). For example, EM can be implemented under the form of equality of treatment, results or opportunity. In different applications of MP, rewards may be proportional to productivity, effort or ability (Fiske, 1992, 712-3). AR relationships may be implemented based on age, education or gender, and can take the form of calling someone by last instead of first name, following orders, or giving precedence. CS expressions include sharing comestibles, dancing in unison, or body contact and sex (Fiske, 2004a, 64). These examples are far from exhaustive: cultural diversity may emerge from each culture specifying differently how, when and where each RM applies (Fiske, 2000, 77 and 79).

The majority of examples of RMs given by Fiske (1991) from various societies around the world are of interactions between two people, and sometimes between two groups. Yet, Fiske also uses RMs to characterize single groups of more than two individuals in which all members use the same relational model in the context of a social activity. For example, if members of a group are all implementing CS when sharing food, it can be called a "CS group" with respect to that activity (Fiske, 1991, 151). Rotating credit associations (Fiske, 1991, 153) or equal distribution of any common resource are typical examples of EM within a group of more than two people. In such situations of homogeneous collective action, a single RM gives an accurate description of what happens between any two members and thus can be used to characterize the group as a whole. That is, a CS group can be entirely described by an ensemble of dyadic CS relationships.

RMT has motivated a considerable amount of research that supports, develops or applies the theory, not only in its original field of social cognition (Fiske et al., 1991; Fiske, 1993, 1995; Fiske and Haslam, 1997), but also in diverse disciplines such as neuroscience (Iacoboni et al., 2004), psychopathology (Haslam et al., 2002), ethnography (Whitehead, 2002), experimental psychology (Brodbeck et al., 2013), evolutionary social psychology (Haslam, 1997), and perceptions of justice (Goodnow, 1998), to name a few. Haslam (2004), Fiske and Haslam (2005) and Whitehead (1993) provide reviews of this research. Moreover, as suggested by Fiske (1991, 210-23), the RMs map onto the four measuring scales defined by Stevens (1946), and their symmetry properties evoke analogous features of neural activity (Bolender, 2008, 2010).

Favre and Sornette (2015) recently introduced a model of social relationships rooted in the observation that each agent (individual or group) in a dyadic interaction can do either the same thing as the other agent, a different thing, or nothing at all. We showed that the relationships

generated by this model aggregate into six exhaustive and mutually disjoint categories of interactions. We argued that these six categories offer suitable abstract representations of the social actions performed by agents implementing the four relational models, and the asocial and null interactions. This representation of social relationships suggests that the RMs form an exhaustive set of all coordinated social relationships.

5.2.3 Plural rationality theory (PRT)

Plural rationality theory (PRT) was initiated by Douglas (1978, 1982) and developed further by several other researchers, notably Thompson et al. (1990). For a review, see Mamadouh (1999). Different authors have given this theory different names, of which cultural theory, grid-group analysis (e.g. Coyle, 1994a, 220), the theory of socio-cultural viability (Thompson et al., 1990, 15:n5), neo-Durkheimian theory (6, 2003), and plural rationality theory (Verweij et al., 2015). The hypotheses at the basis of PRT are summarized by Verweij et al. (2011) and Verweij (2011, 35-8); here we follow this summary but select only the points that we need for our present purposes.

PRT posits that there are only four viable ways of organizing social relations: hierarchy, egalitarianism, individualism and fatalism. Two dimensions underlie this typology: group and grid.

- Group (collectivity, integration) quantifies the extent to which people are incorporated into a larger social unit, fostering group solidarity and group pressure;
- Grid (stratification, regulation) measures the degree of prescribed asymmetry between people, promoting obligations constructed by roles.

Each dimension is assigned high and low values, which results in four patterns of social relations: hierarchy is high group, high grid; egalitarianism is high group, low grid; individualism is low group, low grid; and fatalism is low group, high grid.

PRT further claims that from each pattern of social relationships emerges a compatible so-called cultural bias that specifies, very generally, ways of perceiving, justifying, reasoning, and feeling. This includes perceptions of nature, human nature, time, risk, leadership, justice, blame, and governance. Each cultural bias, in turn, includes values that support and justify its corresponding pattern of social relationships. The idea that each bias comes with a rationality of its own is at the root of the name "plural rational theory." The salient features of the cultural biases are as follows.

- In a hierarchy (high grid, high group), actors relate to each other based on their prescribed relative positions. Superiors and inferiors share ethical values, such as respect for other members, and identify themselves with the collective. Nature, and generally the world, are seen as controllable, and stable within limits that can be determined by certified experts. Perception of time is long-term, supporting thorough planning. Human nature is seen as sinful and thus calling for adequate regulation.

- In egalitarianism (low grid, high group), actors insist that people must start and end up equal. In fact, this principle extends to all living things, including animals and plants. Nature is seen as fragile and intricately interconnected. The earth must be taken care of in the sake of future generations. Solutions to social problems must be urgently implemented to avoid global disasters. Human nature is thought of as fundamentally altruistic, but subject to corruption by status and power.

- In individualism (low grid, low group), actors are and see others as mostly self-interested, without this being seen as a fundamentally bad thing. While egalitarians pursue equality, individualists pursue liberty (Coyle, 1994a, 223). Efficiency, autonomy, individual achievement, skill-based task distribution, entrepreneurial spirit are valued. Accordingly, competitive markets should not be constrained by bureaucratic regulations. Seen as another autonomous actor, nature itself is expected to be resilient, recovering equilibrium on its own upon external perturbations.

- In fatalism (high grid, low group), actors are confined in prescribed asymmetrical roles, as in a hierarchy. But since solidarity is virtually inexistent, actors mostly fend for themselves. Manipulative, unpredictable, deceitful despots are free to exploit a society of isolated individuals whose mutual distrust and amoralism prevents them from standing together. Nature is seen as another unknowable and random actor; time never brings any fundamental change. According to fatalism, there is no meaningful, reliable pattern to be found in anything.

According to PRT's "multiple selves" hypothesis (Thompson et al., 1990, 265-67), people may not fit neatly into the same box in all respects. Instead, they may prefer, or live under, the influence of different cultural biases in different domains of their social life. The PRT literature emphasizes that cultural biases are not personality types (e.g. Thompson, 2008, 19, Rayner, 1992, 106-8). In the present work, we talk about hierarchical, egalitarian, individualistic and fatalistic actors. These terms do not refer to distinct types of people, but instead to individuals or institutions following the principles of a given cultural bias in a given respect. We talk about settings (e.g. an egalitarian setting) to denote social contexts organized along the lines of a grid-group pattern and composed of individuals presumably behaving according to the corresponding cultural bias.

Finally, while the four cultural biases stand in contradistinction to each other, PRT predicts that attempts to resolve social problems (from urban planning to international conflicts to global warming, going through the whole spectrum of human activities) that do not address the views and goals of all four cultural biases are bound to fail, not only according to the proponents of the neglected biases, but also on their own terms. PRT thus gives a sure recipe for failure, but not a sure recipe for success - taking into consideration all ways of life is a necessary, but not sufficient, condition for success. An important and growing part of the research in PRT consists in case studies documenting failed or successful attempts to resolve social problems and verifying the latter prediction (e.g. Coyle and Ellis, 1994; Verweij and Thompson, 2006; Verweij, 2011).

In the present work, we support our thesis by drawing examples from this literature as well as from the RMT literature.

5.2.4 Aim and scope

It may be helpful to consider our approach in the perspective of earlier attempts to connect RMT with PRT. These typically assume that high group is associated with CS; low group with MP; high grid with AR; and low grid with EM (Triandis, 1995, 50-1, Triandis and Gelfand, 1998; Vodosek, 2009). Accordingly, the combination of high group and high grid (the hierarchical bias) is expected to be associated with CS and AR, but not with other RMs; egalitarianism, with CS and EM; individualism, with EM and MP, and fatalism with AR and MP. As mentioned in section 5.2.1 and reviewed in section 5.5, this and similar one-to-one mappings have brought only partly satisfactory results (Realo et al., 2004; Verweij, 2007; Vodosek, 2009; Brito et al., 2011).

In contrast to these attempts, we propose that there is no one-to-one correspondence between the RMs and PRT's grid and group dimensions, or the cultural biases. Instead, we argue that each cultural bias is compatible with any RM, but not with all of its implementations. Differently said, all RMs can be used to constitute social relationships compatible with a cultural bias. Importantly for empirical research, this means that an association may be found between each RM and any cultural bias.

This view builds on the idea that the implementation of an RM is specified by cultural rules. As Fiske (1992, 713) puts it, "each of the four universal models can be realized only in some culture-specific manner; there are no culture-free implementations of the models. [...] The models cannot be operationalized without specifying application rules determining when and to whom and with regard to what they apply [...]. A major problem for future researchers is the study of how people select a particular implementation of a specific model in any given context. People are probably guided primarily by cultural rules [...]." Our thesis consists in arguing that these cultural implementation rules may be specified, to a certain extent, by the cultural biases of PRT.

In this chapter, our main focus is on how a cultural bias specifies which implementations (or expressions) of each RM may be accepted, preferred, customary or obligatory in social settings associated with this cultural bias. However, the reverse mechanism may also be considered. Namely, particular RMs implementations may evoke, support or constitute a social setting associated with a cultural bias compatible with these implementations. We discuss how to approach this reverse mechanism in section 5.4.2, but examining it in details is beyond the scope of this work.

In section 5.3, we examine how each relational model may be implemented in ways compatible with each cultural bias. We illustrate our points with cases drawn from the RMT and PRT literature.

In section 5.4, we clarify the theoretical hypothesis underlying our framework. Namely, our view is that relational models are tied to relationships between two actors (persons, or groups),

and cultural biases to social networks with characteristic structures. We examine this hypothesis in the context of RMT's recent extensions introducing metarelational models (Fiske, 2011) and moral motives (Rai and Fiske, 2011; Fiske and Rai, 2014). We connect this discussion to the question of how our framework could be built in the other direction, that is, by specifying how specific RM implementations constitute congruent cultural biases.

In section 5.5, we review previous studies (Realo et al., 2004; Verweij, 2007; Vodosek, 2009; Brito et al., 2011) manifesting ambitions similar to ours and interpret their results in the light of our framework. These considerations lead us to suggest directions for empirical research.

5.3 Relational models within each cultural bias

In this section, we consider the four cultural biases in turn and discuss how relational models may be implemented in ways compatible with each bias. We also describe how asocial and null interactions may be perceived by actors in each bias. We consider first the interaction modes that are most salient, so that the order is different within each bias.

5.3.1 Hierarchy (high group, high grid)

The correspondence between the PRT hierarchical ideology and AR relationships is very apparent. A common feature of hierarchical settings and AR relationships is that superiors abide by moral principles and subordinates are not oppressed. According to Fiske (1991, 14), in AR, "Followers are entitled to receive protection, aid, and support from their leaders;" AR "contrasts with pure coercive power [...] subordinates believe that their subordination is legitimate." According to a principle of *noblesse oblige*, "authorities have an obligation to be generous [...] and exhibit pastoral responsibility in protecting and sustaining their subordinates" (Fiske, 1992, 700). In PRT's hierarchical bias, authority is also legitimate, and the hierarchical institution is intended to benefit all of its members. "The top level of authority must never fail to respect the lowest" (Douglas, 2005, 98); "hierarchists believe that human beings are born sinful but can be redeemed by good institutions" (Thompson et al., 1990, 35); the domestic governance ideal of the hierarchical bias is "wise, benevolent" (Verweij, 2011, 56).

Let us now argue that MP (i.e., a relational structure oriented toward the principle of proportionality) is an interaction mode that also suits well the hierarchical bias. This is because MP is particularly convenient for bureaucratic top-down allocation, based on the recommendations of experts recognized as holding authority, and following well-defined rules. In fact, a canonical example of MP in RMT is "bureaucratic cost-effectiveness standards (resource allocation as MP)" (http://www.rmt.ucla.edu, last accessed 2016-03-04). A manifestation of MP is the constitution of a group defined as a "bureaucracy with regulations oriented to pragmatic efficiency" (Fiske, 1992, 695).

An MP-type of thinking is associated with hierarchical actors in numerous case studies carried out in PRT. For example, in the context of the Kyoto protocol intended to address global warming, tradable carbon credits is an MP-type instrument introduced by an institution

identified as highly hierarchical, the United Nations Framework Convention on Climate Change (UNFCCC) (Verweij, 2011, 40-69). Instituting quotas on ethnic minorities in Dutch schools, sport clubs and housing is interpreted as a "quintessentially hierarchical undertaking" by Bovens and Trappenburg (2006, 99). In the context of seat belts legislation, "the hierarchical actors believed that a law would save large numbers of lives [...], conveniently rounded to 1000 lives [...] a year [...] and produced abundant [statistical] evidence to support the belief" (Adams, 2006, 148; see also 152). Finally, the problem of car mobility "has two sides [...]: a demand side (the need for mobility) and a supply side (the infrastructure capacity). [...] These are problems that can be handled in a technocratic way [by a hierarchical actor]" (Hendriks, 1994, 54).

Hierarchy is high group, which "requires a long-term commitment and a tight identification of members with one another as a corporate identity," and makes "the unit more exclusive and conscious of its boundary" (Verweij, 2011, 36 and 35). This sense of shared belonging to a larger, bounded whole is also at the basis of CS: "people attend to group membership and have a sense of common identity [...] what is salient is the superordinate group as such, membership in it, and the boundaries with contrasting outsiders;" people "identify with the collectivity" (Fiske, 1991, 13-4). In that sense, CS relationships support and are supported by the notion of high group in general, and may operationalize this fundamental feature of hierarchy in particular.

Yet, high group and high grid also mean that group pressure and prescribed roles constrain social relationships. In a hierarchical setting, CS relationships thus have to be respectful of and determined by the hierarchy. Furthermore, collective rules (which can change from one hierarchical group to another) determine who can (or must) engage in CS with whom, and which specific implementations thereof are allowed. CS relationships may thus be constituted through rituals that emphasize and are determined by a common identity with the hierarchical system. Dumont (1966, 168-193) gives detailed descriptions of such contact and food rituals in the Indian caste system. Regulating who may or may not have sexual relations is another example of hierarchical intervention in the domain of CS relationships.

Similarly to CS, EM is implemented only with the consent or even under the imposition of the hierarchy. Douglas (2005, 96, 98, 100) insists that competition is restricted in a hierarchy. In this context, EM relationships can be particularly adequate to foster cooperation in specific domains of social life: giving a few expressions of EM, Fiske (1992, 704) notes that each of them "simultaneously builds group (or dyadic) solidarity." For example, Douglas (2005, 99) recounts that in her grandparents' hierarchical home, "No competition was allowed between my sister and myself [...] the general rule was equality between us; we were expected to share presents."

In a hierarchical setting, asocial interactions may be seen as a violation of formal rules of conduct, and may be punished so as to reinforce rules adhesion. This is illustrated by the case of the Internet, where the (very few) hierarchical actors present in this setting "focus more explicitly on things like content-regulation (censorship laws), restrictions on the use of encryption tools, enforcement of copyright laws, ways of combating crackers, apprehending terrorists, defeating drug dealers and so on" (Tranvik and Thompson, 2006, 208). Moreover, according to actors identified as hierarchical by Verweij (2011, 113) in the context of the invasion of Iraq by the

United States in 2003, "Threats to the international order [...] should be dealt with [...] by scrupulously following international law."

Null interactions are not viable within a hierarchy. As Douglas (1992, 226) writes, "Since no one can be eliminated, all have to be assigned places in the system [...] people can drop down, but not out." Hence, the exclusion of a member (which is an imposed null interaction) is likely to be a last resort. In general, null interactions can take the form of indifference toward out-members and operationalize the boundaries of a hierarchy.

5.3.2 Egalitarianism (high group, low grid)

Egalitarian settings clearly support and are supported by EM relationships. Equality between members of an egalitarian group is maintained through EM relationships. EM relationships can nearly be said to constitute the norm of egalitarian settings. There is however an expression of EM that may not be the first choice in egalitarianism, namely the one-person, one-vote standard, since egalitarian actors rather favor consensus decision making (e.g. Verweij, 2011, 83). Still, egalitarians may have to resort to the one-person, one-vote principle when reaching a consensus is not realistic (as, for example, in a large group).

Some combinations of EM may be compulsory in egalitarianism, for example equality of opportunity and outcome. Only the former will not do, as we see in section 5.3.3 that equal opportunity alone corresponds to individualism. Egalitarianism seeks to prevent any form of discrimination from the beginning to the end of any process.

CS relationships are also largely compatible with the egalitarian ideology. For example, as mentioned above, egalitarian decision-making process is by consensus (Verweij, 2011, 83), which is precisely the way decisions are reached in CS relationships (Fiske, 1992, 695). Moreover, mutual aid follows the same principle in PRT's egalitarianism and CS. Indeed, communism is interpreted by PRT as corresponding to the egalitarian way of life (Thompson et al., 1990, 155-7). The communist maxim "From each according to his ability, to each according to his needs" parallels CS mutual aid, also based on respective abilities and needs (Fiske, 1992, 693). Finally, in egalitarianism, actors see "man as essentially caring" and trust each other (Verweij et al., 2006, 4), while CS is seen as "generating kindness, generosity" (Fiske, 1991, 14); "people have a sense of solidarity" (Fiske, 1991, 13). This last point is linked to high group being particularly conducive to CS relationships, as we argued in section 5.3.1. In general, the egalitarian bias guides implementations of CS in the sense that there is a group pressure to implement specific CS relationships (high group), and these relationships are seen as appropriate or obligatory between all members indiscriminately (low grid).

Egalitarianism is mostly non-conducive to AR relationships, as the asymmetry that is both a precondition and a consequence of AR relationships fundamentally contradicts the egalitarian ideology. Yet, for a large group to reach any collective goal, some degree of stratified organization operationalized by AR relationships is often unavoidable. This is pointed out by Mars (2008, 367), talking about an egalitarian group: "any form of authority is resented", yet "All organisations, however egalitarian, 'co-operative' and enclavic they may be, none the less need a degree

of order and control." In Mars' study, egalitarian actors come up with an idea that reconciles the implementation of AR relationships with egalitarianism: "to have 'rolling co-ordinators' who would each hold office for a month at a time" (369). Rotating chairmanships is mentioned by Fiske (1992, 703) as an EM scheme for group choice. This constitutes an interesting combination of AR and EM under the same umbrella of egalitarianism. In general, egalitarian leadership (implementing AR) is charismatic: a leader is chosen among and by her peers based on her charisma, and is followed voluntarily (Verweij, 2011, 57 and 92).

Since MP offers an equity principle justifying unequal allocation (e.g. reward proportional to contribution), it can seem fully incompatible with egalitarianism. Moreover, individualistic and hierarchical actors are inclined to adopt MP-based reasonings to implement their own views (see sections 5.3.1 and 5.3.3), which egalitarian actors outright oppose.

However, there are expressions of MP that are actually fully compatible with egalitarian principles. These are for example so-called fair trade, and barter. Fair trade addresses inequalities of wealth between nations by attempting to help producers in developing countries. Barter (moneyless exchange) provides the opportunity to acquire second-hand, home-made or homegrown products. This is in line with egalitarian environmental concerns and preference for low consumption: "we must all tread lightly on the Earth" (Verweij, 2011, 37); the egalitarian economic ideal is "minimal and local production and consumption" (ibid., 90). An egalitarian barter system would be such that anyone can enter it (equality of opportunity) and such that everyone benefits (equality of outcome). One can find various barter systems online; these often promote mutual enrichment and community building.

Other examples of MP expressions compatible with egalitarian principles are microcredit aimed at empowering women in developing countries, or policies according to which the rich should pay more taxes than the poor, proportionally to a reference point such as fortune or income. Cost-benefit calculations (corresponding to MP) may also be carried out within contexts favored by egalitarian actors, such as the development of renewable energies.

The main conditions on egalitarian MP thus include equal opportunities to enter deals, and equally beneficial outcomes for all parties. Mars (2008, 370) illustrates this idea concerning the use of an MP-type instrument in an egalitarian setting: "To avoid drawing too obvious a parallel with [...] individualist practices, however, this re-introduction of the levy had to be cloaked in the rhetoric of egalitarianism;" in the end, the preferred solution would be such that "Everyone would [...] benefit."

Asocial interactions are seen as possibly pathological by egalitarian actors; criminals should be helped and oriented toward harmonious reintegration. The lengths through which actors abiding by egalitarian principles are ready to go to include asocials are documented by Swedlow (1994, 76-7) in the context of a mental health facility, the Kingsley Hall.

As in a hierarchical setting, the ideal of group cohesiveness renders null interactions not viable within an egalitarian group. Null interactions are imposed only under the form of last resort exclusion. Residents of the aforementioned egalitarian Kingsley Hall (Swedlow, 1994, 77), despite feeling "severely threatened" by the behavior of one of them, would still wonder "what

would happen to him if we told him to leave?"

5.3.3 Individualism (low group, low grid)

Individualism may appear to rely more insistently on MP than on any other RM. This may be largely due to MP being particularly well suited to immediate individual optimization. Indeed, MP-based bargain, contract or agreement directly between the involved parties allows each party to minimize her cost/benefit ratio. In PRT case studies, examples abound of individualist actors being equated with companies obviously functioning mainly on the basis of MP (Coyle and Ellis, 1994; Verweij and Thompson, 2006; Verweij, 2011). Indeed, MP "is a relationship mediated by values determined by a market system" (Fiske, 1991, 15) and companies are precisely built to function as individualist actors in a competitive market.

However, MP relationships are not fundamentally self-interested. "MP relationships need not be selfish, competitive, maximizing, or materialistic - any of the four models may exhibit any of these features. MP relationships are not necessarily individualistic" (http://www.rmt.ucla.edu, last accessed 2016-03-04). We argue in sections 5.3.1 and 5.3.2 that specific variations of MP are compatible with the hierarchical and egalitarian biases, which are at odds with the individualist bias. Conversely, any other interaction mode may serve self-interest, and can thus be made compatible with the individualistic bias.

In PRT, individualism favors the principle of equal opportunity (Verweij, 2011, 57), an expression of EM. However, let us stress that the principle of free competition then takes over, resulting in inequalities (of wealth, for example), something that individualistic actors would accept (but not egalitarian ones). Another EM scheme, the "one person, one vote" electoral process allows individualistic actors to vote in line with their perceived best interests. Moreover, individualistic actors may be prone to use EM in an alliance with selected peers in order to attain their personal goals. This is illustrated by the collusion of two groups in the context of the Russian transition to capitalism (Intriligator et al., 2006), whose analysis suggests that it followed an extreme individualistic logic. Finally, another example of individualistic EM, inspired by Coyle (1994a, 224), is that of rock climbers taking turns belaying each other, not necessarily in order to manifest any kind of perceived equality, but simply in order to practice the sport for themselves.

AR, like any other RM, comes in a number of variations. These include prestige rankings, as in sports team standings, and expertise-based leadership: "roommates may [...] work on a task at which one is an expert and imperiously directs the other (AR)" (Fiske, 1992, 711). These instantiations of AR are compatible with the individualistic ideology; prestige rankings valorize individual achievement, while following an expert's advice can serve self-interest.

Other instantiations of AR, such as that based on the idea of a superior commanding an inferior, go against autonomy, the core value of individualism. Yet, if an individualistic actor estimates that entering such an AR relationship will be beneficial to herself, she may just do so. In fact, in individualism, concrete outcomes tend to matter more than deep principles underlying relationships. It may thus easily occur for an individualistic actor to hold a different view than

the other party as to what principles the relationship fundamentally follows. As long as it is worth her while to do so, an individualistic actor may just play along the rules preferred by her counterparty, thus avoiding a time- and energy-consuming conflict.

PRT abounds in examples of individualistic actors (typically companies) associating with hierarchical groups (typically governments). This individualism-hierarchy alliance can be so common and strong that it has been called "the establishment" (Thompson et al., 1990, 88). It is illustrated by Hendriks (1994, 56), who also uses the term "establishment," in the context of traffic policy projects. In general, this relationship can be interpreted as AR (from the hierarchical actor's viewpoint), MP (from the individualistic actor's viewpoint), or even EM (e.g. if the actors maintain equality in some respect). An example of relationship that may be interpreted as either expertise-based AR, or MP, is that of an individualist governmental party seeking the expert advice of McKinsey on the clean-up of the Rhine (Verweij, 2011, 193).

Competitive contexts, such as individual sports (e.g. racing), or competition for professional status, provide instructive examples of individualistic settings. Such competitions are often seen as fair only if participants start as equals (on the same line for a race, with the same education level for professionals); this is EM. However, the process culminates in asymmetrical rankings glorifying those at the top for their achievements (AR). It may also result in the attribution of some form of reward proportional to the degree of these achievements, for example a yearly bonus (MP). These manifestations of EM, AR and MP fall under the same umbrella of a process thought of in individualistic terms. This example illustrates that thinking simultaneously in terms of relational models and cultural biases may help understand the combination of relational models in dynamical processes, and the presence of apparently contradictory values in the same cultural bias.

In an individualistic perspective, CS relationships cannot be supervised or imposed by collective principles, as in hierarchy and egalitarianism. Instead, individualists may freely constitute CS relationships based on their personal inclinations, and expect others to do the same. For example, as regards "sex between consenting adults, individualists will be against allowing the government to intervene" (Dake, 1991, 66). In the same spirit, a CS relationship may be given up if it stops bringing personal enjoyment or benefits. Yet, Olli (2012, 220), interviewing an individualistic household, notes "how strong the family loyalties are," which however "is not a counter indicator of the individualistic way of organizing." Olli adds that PRT "actually does not say that the loyalties are weak. It says that the group pressure is weak, and that the obligations constructed by roles are weak" (n171). Individualists may thus engage in loyal CS relationships, but only with selected others, and feel entitled to orient these relationships toward the satisfaction of their own wishes or needs, while giving others the same right. Conformity to and identification with a group may occur, but again only because individualists choose this for themselves.

While the above points evoke relationships between two people, CS relationships can also be constituted between individualistic groups: for example, while the acquisition of a company by another is MP, the merging itself is an expression of CS, whereby the two companies pool their

resources and literally become one. At the same time, the two companies' departments may be newly positioned relatively to each another in a global organigram depicting AR relationships. The agreement between the companies may have consisted in negotiating this reorganization based on the interests and expertise of the respective departments, in an individualistic way. This is another example of a combination of RMs (MP, CS, AR) along a process globally guided by the individualistic bias.

In an individualistic setting, free riding can be seen as fair game, so that asocial interactions may be expected. Consequently, actors may find it normal to take individual measures against free riding, e.g. by owning a gun (Kahan et al., 2006), contracting an insurance or hiring a lawyer. Victims of asocial interactions may be inclined to seek justice for themselves through revenge. At the same time, individualistic actors may defend asocials' freedom: indeed, they grant others the same right to freedom as themselves. Swedlow (1994, 81-5) reviews the individualistic view on the mentally ill, according to which people should not be committed in a mental health institution against their will, apparently no matter how dangerously asocial their sickness may make them.

Null interactions are common and do not carry the heavily loaded meaning of last resort exclusion present in hierarchy and egalitarianism. Instead they denote ordinary, voluntary withdrawal from relationships seen as unproductive. As Coyle (1994a, 223) puts it, "freedom entails the choice not to participate, be it by not voting in politics, [...] or by withdrawing from social contact altogether."

5.3.4 Fatalism (low group, high grid)

Fatalism, being by definition unfavorable to social coordination, should actually mostly hinder the constitution of relational models. Instead, the asocial interaction may dominate social life in fatalistic settings. In what has become a classic illustration of fatalism (Thompson et al., 1990, 223), Banfield (1958, 10) introduces the concept of "amoral familism" to describe a peasants society in southern Italy. Amoralism is at the basis of asocial interactions: indeed, moral rules are shared social constructs, and asocial interactions are characterized by the absence of any shared directive model (Fiske, 1991, 20, Rai and Fiske, 2011). The pervasive presence of asocial interactions in fatalism is illustrated throughout Banfield's account. Another illustration of how fatalistic actors expect interactions to be asocial by default is given by Verweij (2011, 135-7). He suggests that some actors observing or involved in the Rwandan genocide interpreted it through the lens of the fatalistic cultural bias. For example, according to the (implausible) fatalistic story told by these actors, "everybody committed genocide" (ibid., 135).

Null interactions are also very common in fatalistic settings. Fatalistic actors have also been called "isolates" (e.g. Douglas, 1992, 105, Douglas, 2005, 114). Mitterrand, described by Verweij (2011, 168:n185) as a fatalistic leader, actively promoted null interactions among his staff; "they were not encouraged to get together (in fact they were discouraged from developing joint viewpoints)." Such imposed null interactions can ensure the submission of oppressed actors by preventing them from coordinating any kind of revolt. France's inaction in Rwanda (Verweij,

2011, 159) can also be seen as illustrating the prevalence of null interactions in fatalism. The isolation of fatalistic actors is illustrated by Olli (2012, 246): in a fatalistic household, one spouse has friends but does not invite them home and "emphasizes the separateness of their lives," and the other has no friends. In general, null interactions sustain the status quo that constitutes the fatalistic norm; the fatalistic perception of time is "undifferentiated: same old, same old" (Verweij, 2011, 57).

Social stratification (high grid) evokes AR but, as suggested by our treatment of low-grid biases (sections 5.3.2 and 5.3.3), we do not associate AR exclusively with high grid. In fact, a fatalistic setting is rather unfavorable to the constitution of AR relationships, because these suppose the common acceptance of social norms, a feature mostly unsupported by low-group environments. We thus suggest that in most cases, asymmetrical relationships (e.g. fatalistic leadership) actually instantiate the asocial interaction, possibly under the pretense of functioning through regular AR relationships. The possible confusion between AR and asocial is noted by Fiske (1992, 702), though the other way around: "Because Westerners often fail to distinguish between coercive force and AR as a relationship, they tend to see many AR interactions as illegitimate."

The role of asocial interactions as substitutes for genuine AR relationships is illustrated, for example, by slave culture, which Ellis (1994) argues to be fatalistic. Slavery is the result of asocial oppression, while the relationship master-slave could be falsely equated with AR, especially by the masters themselves. Also, fatalistic leadership has been qualified as "unpredictable, secretive, ruthless, cunning" and illustrated by the governance style of French President Mitterrand (Verweij, 2011, 57, 174), which corresponds to the asocial interaction, and not AR.

That being said, AR relationships may still be constituted. A superior may support her protégé for as long as this appears to be in her self-interest, while the willing follower benefits from a relationship she perceives as legitimate (at least temporarily). However, like other RMs constituted in a low-group setting, the relationship is not constrained or determined by collectively shared rules. Instead, it is viable only as long as both parties individually estimate it to be useful to themselves, which in fatalism can randomly cease to be the case at any time. The randomness and unpredictability of relationships in fatalism is exemplified by the fatalistic domestic governance ideal described as a "personal rule (fiefdom); at best benevolent dictator" (Verweij, 2011, 56).

Fiske (1992, 708) gives several examples of MP that can be compatible with the fatalistic ideology, noting that "many writers have confused MP with asocial interactions. Some of the most egregious evils of MP are prostitution, capture and sale of people into slavery, the killing of indigenous inhabitants to open land up for economic exploitation, child labor, and colonial systems of forced labor. Mercantile wars fought for markets and sources of raw materials are also high on the list, as is the violence that is intrinsic to the businesses of drug dealing, loan sharking, and extortion."

Moreover, Verweij (2011, 38) suggests that fatalistic actors seek "relative (rather than absolute) gain," which can be seen as an implementation of zero-sum MP (what someone gains is

what someone else loses). Also, MP is present by default whenever goods are sold and bought, which can hardly be avoided in modern societies. Yet, in the village studied by Banfield (1958, 44-5), consumption is kept down to a minimum. In general, agreeing on fair prices can be next to impossible in fatalism, leaving room, again, only to the asocial interaction (e.g. by setting abusive prices). In Banfield's account, landlords and tenants give up on an MP relationship out of mutual distrust (ibid., 93). Furthermore, the employer-employee relationship could be MP but instead turns into the asocial interaction ("the worker is usually cheated", ibid., 93). Let us note that the latter case could be seen as a violation of MP, which still implies an MP-type of reasoning. Finally, fatalistic MP may take the form of corruption (ibid., 102-3).

Fatalistic mutual distrust is unfavorable for CS relationships, which in principle require frequent interactions and considerable trust and commitment. In order to overcome this mutual distrust, CS relationships (especially their initiation) may take extreme forms, such as violent blood rituals. This might serve to raise the stakes in an attempt to ensure loyalty in a non-conducive environment. In general, characteristic features of fatalistic CS relationships are that they may be short-lived, unreliable and dependent on changing circumstances. Or, they may actually endure, but under the constant threat of being broken off. The ancient proverb "the enemy of my enemy is my friend" may be an illustration of such a self-interested, contextual, temporary and dubious form of solidarity.

It is quickly done to defect in an EM relationship, especially if it entails the reciprocal exchange of favors over time. The mostly fatalistic peasants interviewed by Banfield (1958, 121) consider that EM, if used, has to be applied strictly: "Even trivial favors create an obligation and must be repaid." Such relationships are thus avoided: "You would needlessly create an obligation which you would have to repay." An expression of EM that can be common in fatalism is in-kind retribution (tit-for-tat), a canonical example of EM that does not require any agreement from the involved parties. Fiske (1992, 705) mentions that "Retaliatory feuding and vengeance are often based on EM."

5.3.5 Summary

Our approach consists in arguing that each RM may be implemented in a way compatible with each cultural bias, and offering examples of such implementations. Importantly, this implies that an association may be found between each RM and each cultural bias. In other words, there is no one-to-one mapping between the RMs and the group-grid dimensions or the cultural biases.

Our findings from sections 5.3.1 to 5.3.4 are summarized in table 5.1. This table shows the four cultural biases and lists how the RMs may be implemented within each bias, based on the examples we offer in sections 5.3.1 to 5.3.4. Let us stress that table 5.1 does not provide an exhaustive list of the various possible implementations of the RMs in each bias. This is impossible in principle, as each RM can be expressed in an indefinite number of ways. Table 5.1 illustrates and summarizes our thesis that all RMs have implementations compatible with each cultural bias.

	Fatalism	**Hierarchy**
High grid	**CS:** unreliable ; extreme initiations (e.g. blood rituals) **AR:** unreliable mentor-protégé relationship; **EM:** strict reciprocity; tit-for-tat **MP:** evil, amoral **Asocial:** default state **Null:** prevents changes	**CS:** abiding by collective rules (e.g. food rituals in caste system; intolerance of same-sex relationships) **AR:** legitimate authority (based on prescribed roles) **EM:** cooperation **MP:** top-down allocation **Asocial:** violation of rules; punished **Null:** exclusion
	Individualism	**Egalitarianism**
Low grid	**CS:** whatever involved parties want for themselves; merging companies **AR:** expertise-based; prestige ranking **EM:** equal opportunity; one-person-one-vote; alliance **MP:** contract, bargain (individual optimization) **Asocial:** expected; triggers self-defense **Null:** voluntary withdrawal	**CS:** consensus decision-making; abiding by collective rules emphasizing absence of discrimination **AR:** charisma-based; rotating chair(wo)manship **EM:** equal opportunity *and* outcome; hinders discrimination **MP:** such that everyone benefits (e.g. barter, microcredit) **Asocial:** pathological; helped toward reintegration **Null:** exclusion
	Low group	High group

Table 5.1: *This table summarizes the examples of implementations of RMs compatible with each cultural bias given in sections 5.3.1-5.3.4. This suggests that an association may be found between each RM and each bias. This table also describes how asocial and null interaction may be perceived within each cultural bias. We list RMs in the conventional order used in RMT.*

Our approach can be positioned in PRT by drawing a parallel with the way cultural biases are characterized in case studies. Namely, a table is often given which lays out features of each bias in a relevant social context. For example, Olli (2012, 63, 88) lists characteristics of household organization, Verweij (2011, 56-7) focuses on global governance, and Coyle (1994b, 35) on environmental and land-use cultures. To such tables, one could add a row labeled "relational models" and fill it with the boxes of table 5.1 (or add one row for each RM, the asocial and null interactions).

From the RMT viewpoint, our thesis can be seen as an attempt to build on the fact that RMs are operationalized in accordance with cultural implementation rules specifying when, to

whom and with regard to what they apply (Fiske, 1992, 713, Fiske, 2000). Cultural biases do not specify all details about RM implementations, but they can be seen as a typology of implementation rules. Namely, each RM can be implemented in indefinitely many ways, but these ways can be categorized into the four cultural biases, according to the mutual compatibility between a given RM implementation and a cultural bias.

5.4 Underlying theoretical basis

5.4.1 Different levels of analysis

Using a number of concrete examples to support our claim, we argue above that the following connection holds between RMT and PRT: any relational model may have a number of expressions compatible with each cultural bias. A cultural bias restrains the range of congruent RM implementations, but does not preclude any RM altogether.

We now justify this idea at a theoretical level by proposing that a relational model is attached to a relationship between two actors (that can be persons or groups), whereas a cultural bias emerges from a larger pattern of social relationships. By larger pattern, we mean a set of nodes (actors) and links (social ties), as in graph or network theory. While this representation is in fact not new, it is nonetheless problematic, as we now discuss.

The idea that cultural biases emerge from patterns of social relationship is at the basis of PRT, but it is not fully solved. Thompson et al. (1990, 11-13) describe what such patterns should look like for each category of the typology, but only textually. 6 et al. (2006, 47) and Olli (2012, 19) propose one type of network for each quadrant of the grid-group diagram, but without rending explicit how the grid and group axes relate to quantities that can be measured on networks. Gross and Rayner (1985), for their part, define measurements of both the grid and group dimensions on networks, which they illustrate graphically. However, they do not offer a generic type of network for each quadrant of the grid-group diagram.

Missing in PRT is thus a coherent network representation, which would for example offer well-defined grid-group axes giving rise at their extreme ends to ideal structures (i.e. patterns of social relationships), relating in clear ways to cultural biases. The absence of such a representation is linked to the issue that it is actually not clear how cultural biases derive from the grid and group dimensions. The latter problem is notably reviewed by Olli (2012, 283-93).

Attempting to resolve these issues in PRT is beyond the scope of the present work. For the time being, we assume that it is possible to define measures of grid and group on social networks, giving rise to certain network structures that clearly support and are supported by cultural biases. This assumption justifies the idea that cultural biases are attached to different types of networks. So far, we have not directly focused on this theoretical idea. Instead, we have defended a rather empirical consequence of this idea, namely that specific RM expressions are compatible with the ideology associated with the larger social structure that these relationships inhabit and contribute to create.

Even if the aforementioned issues were solved in PRT, the proposition that RMs apply to

single ties and cultural biases to networks would still not be straightforward, in the context of either PRT or RMT. At first sight, it may appear to overlook several facts:

1. PRT may be argued to apply to relationships between two actors as well; for example a "hierarchist relationship" may be seen as a relationship whose features and actors' views are consistent with the hierarchical bias and associated high-grid, high-group pattern;

2. RMT has been extended to describe the combinatorics of relational models through the introduction of "metarelational models" (Fiske, 2011), thus going toward describing networks;

3. According to another extension of RMT, relationship regulation (Rai and Fiske, 2011; Fiske and Rai, 2014), each RM generates a distinct "moral motive," i.e. a set of moral values, which evokes cultural biases.

Thus, both theories have something to say about each of several levels: individual and institutional sets of values, perceptions, etc.; relationships between two individuals or groups; and structures of social networks.

Of the above points, the simplest to address is the one about PRT possibly applying to relationships between two actors. It is indeed the case that a network (a set of nodes connected by links) can be so small as to include just a pair of nodes connected by a single link. In that sense, PRT can talk about, say, an egalitarian relationship, meaning that the constitution of this relationship supports and is supported by the principles of the egalitarian bias. According to our framework, RMT provides a more precise characterization of this relationship: namely, it can be structured in the ways given by the four relational models, implemented in ways compatible with the egalitarian bias.

The first point thus raises no contradiction to our theoretical hypothesis. The two other points are treated in the next sections, and argued not to constitute contradictions to our hypothesis either.

5.4.2 Metarelational models: micro-macro vs macro-micro approach

Fiske (2011) studies the combinatorics of social relationships, which examines how combinations of relationships may be implied, required or prohibited. For instance, relationships between parent and children may inform relationships between children. This situation can be represented as a three-node network, composed of one parent and two children, with the two parent-child links entailing or prohibiting a child-child relationship. Moreover, in a dyad, two kinds of relationships may require or preclude each other. For example, AR and MP may typically be combined in the relationship between an employer and employee (Fiske, 2011, 10).

Fiske (2011) calls these combinations of relationships "metarelational models" (MeRMs) and defines six elementary MeRMs occurring either in dyads or triads. MeRMs are thus represented as two- or three-node networks. Fiske also offers two combination mechanisms, recursive embedding and temporal dynamics, which correspond to integrating (or summing) over people and

time, respectively. Recursive embedding allows the construction of larger social networks, using the elementary MeRMs as building blocks.

The framework we introduce in this chapter connects PRT and RMT in a macro-micro manner. That is, we start from the cultural biases, and derive in a deductive manner the forms that the RMs can take within the biases. Understanding inductively the micro-macro process of how relationships aggregate to create a larger social structure associated with a cultural bias is a different problem. In order to solve the question of the connection of PRT and RMT in this direction, one may have to find associations between the MeRMs and PRT's patterns of social relationships associated with cultural biases. As discussed above, this would require initially adopting a network-like representation for each quadrant in the grid-group diagram.

It may be relevant to note that the latter process is an instance of the micro-macro upscaling problem, which is fundamental in physics, material sciences, biology, economics, sociology, traffic flow, and so on (Anderson, 1972; Wilson, 1979; Sornette, 2004). The micro-macro problem is not solved in general. In fact, it is solved in general terms only in the statistical physics of critical phase transitions at equilibrium, through the theory of the renormalization group (Wilson, 1979).

In the present case, the analysis is made even more difficult by the fact that the whole system is regulated by micro-macro and macro-micro feedback loops, i.e. cycles going both ways between the micro (individual) and the macro (social structure and culture) levels. This is another way to say that culture influences individuals and relationships at the same time as individuals and relationships are the constituents of culture.

In summary, the elementary MeRMs may be seen as a first step toward solving the micro-macro upscaling problem in the context of social relationships. Our framework, on the other hand, emphasizes the macro-micro process connecting PRT and RMT.

5.4.3 Morality: relationship regulation and "virtuous violence"

In recent years, RMT was extended into a theory of relationship regulation (Rai and Fiske, 2011) and "virtuous violence" (Fiske and Rai, 2014). This recent extension fully develops ideas expressed earlier by Fiske (1991, 130-3).

According to relationship regulation theory, each RM generates a distinct *moral motive*, respectively unity (CS), hierarchy (AR), equality (EM) and proportionality (MP). The related principle of virtuous violence holds that much or most violence derives from these fundamental motives and may thus be perceived as morally correct. In a nutshell, violence may be seen as rightly inflicted when it is perceived as protecting the group (unity), responding to authorized orders (hierarchy), maintaining balance (equality) or respecting proportionality in relevant social relationships (proportionality).

The moral motives, being sets of values (which do not apply only to violence), may seem to identify with the cultural biases of PRT. In fact, we argue that moral motives relate to cultural biases in the same way as relational models. That is, each moral motive can be activated within each cultural bias, being tied to a relational model whose specific expression is compatible with the cultural bias.

For example, the moral motive of equality can be pursued in a variety of different contexts. Ensuring equality of opportunity is likely to be seen as an obligation in both egalitarianism and individualism; however, guaranteeing equality of outcome may be seen as compulsory in egalitarianism, and at the same time undesirable or even morally wrong in individualism. The same moral motive thus applies to different social aspects depending on the cultural biases within which it is enacted.

The latter reasoning is no different than the ones carried out in sections 5.3.1-5.3.4. Overall, the moral motives, being tied to social relationships, follow the same rules as relational models, relatively to cultural biases. Namely, thinking simultaneously in terms of moral motives and cultural biases allows one to understand more precisely how moral values can be enacted within cultural contexts.

Interestingly, Rai and Fiske (2011, 67) note how cultural settings valuing freedom are associated with restriction of AR and expansion of MP:

"In some cultures, freedom - autonomy, independence - is a core moral and political value. [...] Future research should explore how restriction of AR has combined by expansion of MP to form the integrated psychocultural construct of freedom. In particular, how does 'freedom' interact with other moral motives to restrict the scope of some social-relational (and consequently moral) obligations, such that beyond these boundaries people can and *should* pursue their own interests without regard to the needs and desires of others and any attempts to forcibly impose social-relational obligations are regarded as illegitimate."

It appears that this quote makes a point similar to the development we make in section 5.3.3, where we discuss how PRT's individualism (pursuing freedom) selects compatible implementations of RMs (of which AR and MP); by extension, this also concerns moral motives.

Rai and Fiske (2011, 67) also note the coupling of the hierarchy and unity moral motives in religious contexts, in line with the ideas expressed in section 5.3.1 concerning the coexistence of AR and CS in PRT's hierarchical setting: "[...] Unity violations may sometimes become coupled with motives for Hierarchy in religiously based concerns where individuals cast Unity-violating acts as disobedience to God's will or injury to God's flock."

Morality is also a concern on the PRT side. For example, Chai and Wildavsky (1994) and Lockhart and Franzwa (1994) examine the relationship between morality, violence and culture. Moreover, Bruce (2013) introduces a model unifying PRT, Jonathan Haidt's moral foundations theory (Haidt, 2007) and Richard Shweder's tripartite theory of morality (Schweder et al., 1997). This suggests that our framework could be used in future research to elaborate on how social-relational contexts interact with morality, and on possible connections between different theories of morality.

5.5 Review of previous studies and suggestions for empirical research

5.5.1 Vodosek (2009): RMT and Triandis' constructs (1995)

Our framework sheds light on the attempt carried out by Vodosek (2009) to test hypotheses expressed by Triandis (1995, 50-1) and Triandis and Gelfand (1998) concerning the relationship between relational models and the constructs introduced by Triandis (1995, 1996). Triandis defines four types of social settings, namely vertical individualism, horizontal individualism, vertical collectivism and horizontal collectivism. The correspondence between cultural biases and these constructs is suggested by Verweij et al. (2014, 87-9). In line with this, we identify vertical collectivism with hierarchy, horizontal collectivism with egalitarianism, horizontal individualism with individualism, and vertical individualism with fatalism.

Triandis (1995, 50-1) and Triandis and Gelfand (1998) hypothesize that vertical relations correspond to AR, horizontal ones to EM, individualism to MP and collectivism to CS. This results in the association of two RMs with each construct, as shown in table 5.2. This table also shows the results of Vodosek's test of these hypotheses, under the form of presence or absence of association.

Vertical individualism (Fatalism)	**Vertical collectivism (Hierarchy)**
AR: yes MP: no	AR: yes CS: yes
Horizontal individualism (Individualism)	**Horizontal collectivism (Egalitarianism)**
EM: no MP: no	EM: yes CS: yes

Table 5.2: *This table summarizes the hypotheses expressed by Triandis (1995, 50-1) and Triandis and Gelfand (1998), and shows the results of Vodosek's tests of these hypotheses (2009). We write "yes" when a significant association is found by Vodosek (confirming a hypothesis expressed by Triandis et al.) and "no" otherwise. We assume that vertical individualism corresponds to fatalism, vertical collectivism to hierarchy, horizontal individualism to individualism, and horizontal collectivism to egalitarianism.*

Our framework predicts that it is possible to find significant associations between any RM and each cultural bias, as long as the expression of the RM is compatible with the bias. For example, CS may be associated with hierarchy, but not if it is expressed as consensus decision making, an implementation of CS that happens to be incompatible with the hierarchical bias.

It is thus relevant to explain the few absences of association shown in table 5.2, which all concern EM or MP. The items used by Vodosek (2009, 128) for these two RMs are the following.

EM1: Group members typically divide things up into shares that are the same size.

EM2: Group members often take turns doing things.

EM3: When group members work together, they usually split the work evenly.

EM4: Group members make sure that the group's workload is shared equally.

EM5: The group makes decisions by a simple majority vote.

MP1: Group members calculate what their payoffs are in this group and act accordingly.

MP2: Group members divide things up according to how much they have paid or contributed.

MP3: Group members make decisions according to the ratio of the benefits they get and the costs to them.

MP4: Group members choose to participate in the group when it is worth their while to do so.

Overall, the absence of association of EM and MP with low group biases may be due to all EM and MP items mentioning "group" or "group members," while the notion of by-default group membership is contrary to low group settings.

More precisely, regarding EM items, the main issue may be that, in individualism, people are not bound to apply EM to all task or resource distribution problems. They do so only if it makes sense in a given situation and in the view of the individuals involved. Individualistic task distribution is thus rather skill-based. Based on interviews in an individualistic household, Olli (2012, 219) notes that "The division of housework is quite flexible [...] Equality is not created by spending an equal number of hours on household tasks, [...] tasks are allocated to the person who has the better skills and more time to do them."

Item EM5, expressing the one person, one vote principle, may evoke individualism, but the formulation "The group makes," evoking collectivism, may have induced participants to reject this item in association with individualism. Finally, some of these items imply a notion of collective supervision (e.g. EM4) contrary to low group.

In relation to individualism, a common issue with MP items is that they all evoke collective action or decision. Even MP1 and MP3, which at first sight should appeal to individualistic self-interest, still imply that a payoff results from acting specifically in or with the group. Also, the calculation aspect present in MP1-4 may imply that such calculations constitute the only appropriate strategy. In fact, individualistic actors feel free to act based on their personal preferences, without necessarily justifying them on the basis of a cost/benefit ratio.

Overall, it is thus possible that the framing of the EM and MP items induced participants to reject any association between EM, MP, and individualism. Even with due consideration of this framing effect, one may still have difficulty finding any striking association between any RM and the individualistic bias because of the relative RM-flexibility of individualists, as argued in section 5.3.3. Individualistic actors constitute their relationships along the lines of the RMs, but feel free to pick the RM and the specific implementation thereof that suit them best individually

(as long as these also suit the other directly involved parties). Designing generic RM items that happen to suit individualists in general may thus be challenging. We come back to this point in section 5.5.5.

As in individualism, the absence of association between MP and fatalism may be due to the mention of "group members" and the implication that these members agree on shared MP schemes. This is in principle incompatible with fatalists' isolation and lack of coordination. We argue in section 5.3.4 that fatalistic MP is mostly amoral, or appears under the form of failed (violated) MP.

Vodosek's results aggregate items relating to the same RM, but it is interesting to note that even where associations were found, some specific items should not correlate with the cultural setting. For example, CS is generally found to correlate with hierarchy, but one of the CS items is "The group makes decisions together by consensus" (Vodosek, 2009, 128). This is not a hierarchical view; it rather evokes the egalitarian bias. We thus hypothesize that this particular CS item was not associated with vertical collectivism.

Our analysis thus helps explain Vodosek's results, in particular the absence of association between EM, MP and low-group cultural biases. Based on our framework, we suggest that associations can potentially be found between each RM and each cultural bias, but that in practice this depends on the specific formulation of the RMs.

5.5.2 Verweij (2007): critique of RMT

Verweij (2007) reviews the similarities of PRT and RMT, as well as their respective shortcomings and strengths. Particularly interesting in the light of our framework is his suggestion that the relational models appear to be "somewhat overlapping" (p. 10), which he illustrates with the following examples.

"[...] in competitive markets (i.e., transactions that resemble the 'ideal markets' of neo-classical economics), actors are certainly 'equal, but distinct peers': none of them has more market power than any of the others, and none of them can hope to earn a higher wage, or make a larger profit, than the others. Yet, these markets not only fulfill the conditions of equality matching, but also of market pricing." (p. 10)

In our approach, this situation appears to correspond to an instance of EM (equal opportunity) within an individualistic setting (competitive markets). It is no contradiction that such markets simultaneously function on the basis of MP in (many) other respects; on the contrary, this idea is supported by our framework. This case is particularly reminiscent of the examples given in section 5.3.3 of entire processes guided by a given cultural bias and encompassing several distinct RMs at different stages. The other points raised by Verweij happen to follow a similar logic.

"Similarly, in many Japanese markets [...], each major company is closely related - in an almost paternalistic way - to a set of smaller competitors, suppliers and retail firms. When profits and prices fall or cheaper alternatives become available, the large company at the centre of the network will not abandon the peripheral enterprises, but instead offer them advice as

to how to reorganise their companies and even forms of temporary financial support. These practices constitute authority ranking and market pricing at the same time." (p. 10)

The organization of Japanese markets in this example appears to be highly hierarchical and built on the basis of AR relationships, while the intervention of the larger company follows an MP logic. This is a typical example of an MP-based resource allocation determined in a top-down hierarchical manner (section 5.3.1). Need-based advice and support may even correspond to CS under a form consistent with hierarchical implementation rules.

Finally, mentioning the fatalistic society described by Banfield (1958), Verweij notes the folllowing:

"[...] a particular form of equality matching is also prevalent when social relations are characterised by extreme levels of inter-personal distrust and jealousy. [...] no cooperation will take place if anyone benefits more from the collective effort than the others. Fiske calls such relations 'asocial relationships' [...] Still, a perverse form of equality matching is characteristic of such null relationships." (p. 10)

This is actually compatible with the implementation of strict or "perverse" EM in a fatalistic setting otherwise favoring asocial and null interactions, as we proposed in section 5.3.4.

Our approach is thus able to answer Verweij's points by reframing his examples in terms of distinct RMs coexisting with each other, but not overlapping, within larger social settings characterized by PRT's cultural biases.

5.5.3 Brito et al. (2011): RMT and families, friendships and work

Our approach may also provide an interpretation to the findings of another empirical study. Brito et al. (2011) examine the question of which RMs are present within different social contexts. They find that relationships within families are mainly of the CS and AR types, friendships show all RMs except for AR, and work organizations correlate with MP and AR.

In the light of the study of household organization performed by Olli (2012), and of PRT case studies in general, we would expect families, work organizations and friendships to differ from each other in ways that may be described by cultural biases. Yet, Brito et al. do not evaluate the cultural bias of social contexts from the viewpoint of PRT or any related theory. They appear to assume that in terms of favored RMs, and in the context of their study, all families are similar, as well as all work settings, and so on. In the context of our framework, this limits the interpretation that we can make of their findings, but their study presents interesting points, among which are the following.

One of Brito et al.'s findings is that EM is generally correlated with CS (p. 423), which would make sense in our framework if the cultural bias happens to be egalitarian or hierarchical. Indeed, in these cases, the same actors who interact on the basis of one of these two RMs are more likely to interact on the basis of the other as well.

Brito et al. encountered difficulties with a few MP items that correlated with each other, but badly with other MP items (p. 417). One of these problematic items is: "What you get from this person is directly proportional to how much you give them" (p. 431). Interestingly,

this statement can fairly easily be imagined to be true of love, violence, attention, time, respect, effort, (im)politeness, and so on, and be valid in many contexts, including home, work and friendships. What it expresses is generally a mechanism of positive feedback, which can apply to many different behaviors or emotions. Hence, it seems rather devoid of content and potentially correlated with any social context. From the perspective offered by our framework, we would thus argue that it is actually a very appropriate item for MP: it can be expected to correlate with any social context, in line with the view we express in the present chapter that all RMs may be present in any cultural bias. However, Brito et al's reached an opposite conclusion: in fact, they removed this item from their analysis (p. 417). In contrast, the MP items that they kept mention payment, payoff, costs, rationality, or regulations, which all evoke the context of work more than anything else. It is thus no surprise that these other items correlated well with work, and only partly with friendships.

5.5.4 Realo et al. (2004): RMT and collectivism

Realo et al. (2004) examine associations between RMs and collectivist attitudes, understood in the sense of Triandis (1995, 1996) and Triandis and Gelfand (1998). They look for associations between RMs and different contexts, namely family (familism), peers (companionship) and society (patriotism). Realo et al.'s approach and conclusion are very similar to our own. On a theoretical basis, Realo et al. express the following opinions, questioning the possibility of a one-to-one mapping between RMs and cultural settings in the same way we do:

"[...] a simple one-to-one link between Fiske's elementary forms of sociality and collectivism-individualism can be questioned [...] one-to-one relationships between cultural syndromes and elementary constituents of human relations are unrealistic: relational models theory is not a taxonomy of cultures. Instead, the models are abstract and open [...]" (p. 784)

"[...] we expect that individuals scoring high on collectivism will use the whole range of elementary forms of sociality to organize their different relationships, or even the different aspects of the same relationship. We believe that there is not necessarily a one-to-one association between the major cultural dimensions and the elementary models of social relations." (p. 785)

Realo et al.'s thesis is supported by their results. They do not give the twenty-three items they used to measure the RMs, so we cannot attempt any precise interpretation. Overall, they state that:

"[...] the relationships between the use of the relational models and the collectivist attitudes were far from strict one-to-one associations. It is quite clear that people scoring low on collectivism do not always use MP and not in all situations; neither are 'collectivists' rigidly fastened to the use of CS, not even in their family relations. In most of the hypothetical situations, both people scoring low and high on collectivism tended to use all four models as dictated by general cultural norms, the logic of the situation, and their personal history." (p. 789)

This is clearly in line with the view we develop in this chapter.

These comments on previous works suggest further possible ways to test our hypotheses and design empirical research, which is the topic of the next section.

5.5.5 Further testing of our hypotheses: empirical research design

Our framework suggests that associations may potentially be found between each cultural bias and each RM. In sections 5.3.1-5.3.4, we support this thesis by providing a number of examples mostly drawn from PRT case studies, but also from the RMT literature. The fact that we found various supporting illustrations (and no contradicting ones) can be seen as a first successful test of our hypotheses. Additional tests could be carried out as follows.

First, one may perform case studies (as in PRT) and identify manifestations of cultural biases and RMs at the same time. In contrast, in the present work, we typically identify RMs a posteriori in PRT case studies completed by others who presumably did not have our framework in mind. When attempting to identify RMs in live situations, the constitutive media for each RM given by Fiske (2004a, 64) may be useful. For example, sharing comestibles, dancing and body contact are some of the most emotionally evocative constitutive media for CS; icons or people set above or in front of others are constitutive media for AR, and so on.

Incidentally, this approach may bring insights into PRT case studies. By clarifying counter-intuitive associations, it may help determine with greater confidence the cultural bias(es) at work within a social context. For example, it may help make sense of individualistic or hierarchical actors insisting on equality of, respectively, opportunity, or same-rank people, for example. Such expressions of EM are coherent with the individualism or hierarchical bias, respectively; they are not counter indicators thereof, and do not necessarily amount to actors borrowing the rhetoric of egalitarianism. This principle also holds for other RMs in other biases, such as implementations of MP in egalitarian settings, and so on.

Second, one may perform survey-based analyses similar to the ones carried out by Vodosek (2009); Brito et al. (2011) and Realo et al. (2004). That is, survey questions could be aimed at assessing both cultural biases and relational models in given social contexts and relationships, in order to test whether associations correspond to those of table 5.1.

This approach, however, is not guaranteed to succeed. For one thing, reservations have been expressed regarding survey-based tests of PRT (Verweij et al., 2011, Olli, 2012, 208, Verweij et al., 2014). For another, it may be challenging to find sufficiently generic items evoking RMs compatible with cultural biases. For example, observing elaborate food rituals whose details heavily depend on the participants' status in a hierarchical system can be interpreted as an expression of "hierarchical CS," i.e. an implementation of CS compatible with the hierarchical cultural bias. Yet, finding a generic survey item evoking hierarchical CS may be problematic. There are indefinitely many possible expressions of each RM, and different hierarchical social systems may use different specific implementations of CS. In general, one can expect that hierarchical CS relationships are respectful of and determined by the hierarchy; differently said, in a hierarchical setting, group pressure and prescribed roles constrain CS relationships. But expressing this abstract principle in a survey may not bring the intended results, because people are not necessarily aware in these terms of their own social relationships.

Therefore, case study research might be more appropriate than survey-based methods in order to further test our hypotheses. Nevertheless, if one wants to go about surveys, one should

test for 24 constructs: (4 RMs + 1 asocial + 1 null) × 4 cultural biases, and define 5 or 6 items for each construct. Starting points to define questions could be Dake (1991), Boyle and Coughlin (1994), Vodosek (2009) or Brito et al. (2011) and Olli (2012, 308). For example, the item "I support a tax shift so that burden falls more heavily on corporations and people with large incomes" (Dake, 1991, 69) may test for "egalitarian MP," and "Everyone should have an equal chance to succeed and fail without government interference" (Olli, 2012, 308) may test for "individualistic EM."

5.6 Conclusion

Our framework proposes that each relational model may be expressed in a way compatible with each cultural bias. A cultural bias restrains the range of congruent RM implementations, but does not preclude any RM altogether. We support this idea by offering examples drawn from the literature of both RMT and PRT. This implies that associations may be found between any RM and each cultural bias, and that there is no one-to-one mapping between RMT and PRT.

At a theoretical level, our thesis is based on the hypothesis that PRT and RMT apply to different levels of analysis: a relational model is attached to a social relationship (i.e. a tie between two actors), whereas a cultural bias emerges from a larger pattern of social relationships (i.e. a social network). From this representation derives the idea that social relationships instantiating relational models are compatible with the ideology associated with the larger social structure they inhabit, support and constitute. Future work shall address this theoretical representation, in particular by offering network types for each cultural bias.

Our framework can inform empirical research, by clarifying the social relationships that can be expected in different social contexts assessed through the typology of PRT. It also helps interpret previous (one-to-one) reconciliation attempts, and opens up paths for future research. Overall, by attempting to connect two theories of constrained relativism, our hope is to strengthen that movement and facilitate future research in this domain.

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Chapter 6

Conclusion: Merging social theories and individual decision making models, using insights from physics

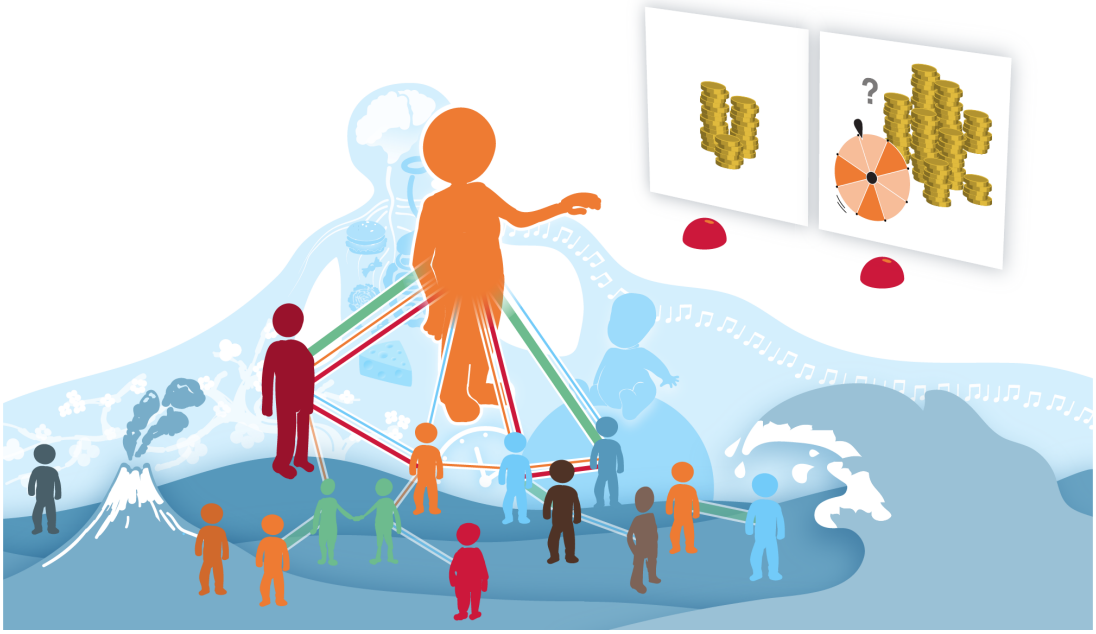

Figure 6.1: *One cannot isolate a person from his or her social relationships and culture in the same way that one can isolate an atom from an aggregate. Models of individual decision making should integrate social components.*

We have modeled and quantified aspects of individual decision making, social relationships, population dynamics and cultural contexts. This provided insights into the social and cultural factors that may influence individual behavior, in particular individual decision making under risk and uncertainty.

PRT and RMT's claim that there are multiple ways to be "rational," or to justify our values, preferences or actions, suggests that the decisions made by different people may be consistent with different models of decision making, without there being a single overarching model. Our view is that theories of individual behavior should integrate multiple models that address the influence of social relationships and culture on an inherently sociable human nature (Fiske, 2000).

Coming back to chapter 2, QDT could be one of these multiple models, or could itself include multiple models, providing a flexible framework taking into account the influence of social relationships on individual decision making. The utility and attraction factors of QDT (the two terms whose sum gives the probability of choosing an option) may be thought of as encapsulating, among other variables, cultural biases and preferences for certain forms of social relationships (or implementations of relational models). Developing multiple forms of these factors (for example one for each cultural bias or for each relational model) may be an adequate starting point to refine QDT at the individual level. This would lead to a partly case-based theory, with different cases relating to different modes of thought influenced by social surroundings.

In the experiment from chapter 2, figure 2.5 suggests that a participant may make many random choices, under the belief that the lottery is rigged, that she is generally unlucky, or generally that there is no point in making any calculation or prediction according to any scientific model. Alternatively, she may follow her intuition, gut feelings, or rules of her personal designing or choosing. Or, she may take calculated risks according to rules determined by experts, possibly leading her to systematically select the option with the highest expected value. Another possibility would be for the participant to be concerned about not appearing to be greedy, which may lead to suboptimal decisions in terms of expected value maximization. These various strategies may be associated with relational models and cultural biases, following the idea that an individual's perceptions and behavior are influenced by the type of decision making process and attitude toward risks that prevail in her social circles and culture.

These speculations illustrate the idea that the decisions made by individuals following different rules may not be meaningfully aggregated and compared to a single model. To address this, it would be of high interest to study and compare individual decisions and determine whether a few representative patterns can be found. In turn, we would expect cross-cultural analyses to show associations between individual choice patterns and culture (Hofstede and McCrae, 2004). Testing these ideas would require to examine individual results (such as those shown in figure 2.5) for a sufficiently large number of subjects belonging to different cultures. Within the framework of QDT, one may thus be able to develop tailored forms of the utility and attraction factors for specific patterns of choices. Under certain conditions, some of these forms may reduce QDT

to other decision theories such as prospect theory, thus yielding, in effect, multiple models of decision making.

These views are in line with those of Ostrom (2007, 13-4), who advocates for "a broader theory of human behavior" and argues that "Multiple models are consistent with a theory of boundedly rational human behavior." Interdisciplinarity may be key in this endeavor. In this spirit, we let our reasonings throughout this thesis benefit from insights arising from the field of complex systems. Indeed, many concepts surrounding complexity appear to apply to social life and may guide the reasoning to express novel ideas and hypotheses. We see it as insightful to express this correspondence here.

A complex system is composed of a large number of elements interacting with each other in such a way that the behavior of the collective is qualitatively different from (i.e., follows different rules than) the behavior of the parts. Anderson (1972) summarized this idea by saying that "more is different."

Complex systems are intrinsically threefold interdisciplinary: the micro level is concerned with individual elements (e.g. atoms) and their interactions, and belongs to one discipline of science (e.g. quantum mechanics). The macro level, made of emerging collective objects (e.g. ferromagnets), belongs to another discipline (e.g. solid state physics). The mechanisms linking micro to macro belong to a third discipline (e.g. statistical mechanisms). The system may be regulated by micro-macro and macro-micro feedback loops, i.e. cycles going both ways between the micro and the macro levels. Moreover, levels of complexity may be embedded in each other so that each level constitutes the micro scale of a higher level and the macro scale of a lower one (Anderson, 1972).

In parallel with this, social systems can be seen as complex systems of many interacting actors constituting collectives manifesting emergent phenomena such as culture, language or religion. Individual elements may be people, and then the macro collective is a group. In this case, the group culture influences individuals and relationships at the same time as individuals and relationships are the constituents of this culture. This triggers micro-macro together with macro-micro feedback loops. The same picture can be drawn one level higher, that is, constituents may be thought of as representing groups (or institutions, or nations) interacting with each other, thus forming a collective of groups.

A difficulty with the micro-macro picture in the social sciences is as follows. In physics, micro interactions and individual behavior depend on a limited number of measurable features of the elementary constituents, such as, for atoms, mass, electric charge, spin, etc. The behavior of an element (e.g. its trajectory in a known environment) and interactions between two elements are determined by discoverable laws that are functions of these features (and may be deterministic or probabilistic).

In social systems, micro interactions (e.g. relational models) and individual behavior (e.g. decisions under risk) depend on individual characteristics including past experience, age, gender, physical features, emotions, beliefs, and so on. Not only are these individual characteristics potentially unlimited in number, but not all of them can be readily measured. Even if they

could, there is no known law describing the relation between them and the propensity of an individual to engage into a specific social interaction, show a certain behavior or make a given decision.

Moreover, individuals are heavily, if not primarily, influenced by the macro collective (culture) they are embedded in, and constantly so, even when observed "in isolation" in experimental settings. One cannot, in fact, isolate people from their culture in the same way that one can isolate atoms from an aggregate. People carry their culture (and associated cultural biases) with them so that it becomes one of their primary individual features, though a composite and malleable one (unlike, for example, their age).

These considerations are linked to the problem of reproducibility in the social sciences. When the system under study involves people (as opposed to particles, molecules, or simpler organisms), one cannot entirely isolate it and control the experimental setting. As a result, one cannot reproduce the exact conditions of an experiment performed at an earlier time or by another research group. This hinders the development of social theories that would reach the same level of scientific consensus as in the natural sciences.

In other words, a person is a more complicated "object" than a particle. In fact, an individual is itself a complex entity, in the sense that the brain can be described as a complex system of neurons from which emerge macro phenomena such as consciousness, senses, epileptic seizures, and so on (Tononi and Edelman, 1998; Chialvo, 2006; Hesse and Gross, 2014). When we are dealing with people and societies, we are thus building on several levels of complexity that are far from being well understood.

Overall, we support the view that the mechanisms of complex systems described by the physical sciences can bring valuable insights to the social sciences. Along this line of reasoning, we are interested in promoting interdisciplinarity in the form of increased communication between different disciplines of the social sciences, between adherents of different theories, and between the social sciences and other sciences, in particular physical, computer, and mathematical sciences.

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Publications

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