Informational externalities with lump sum sampling

Carole Haritchabalet[1] and **Régis Renault**[2]

Abstract. We consider a game of strategic experimentation where agents are restricted to an all or nothing sampling strategy. The strategic interaction between agents due to informational externalities is affected by the sizes of the experimentation samples and the sensitivity of information to changes in sample sizes. There is experimentation only if the overall sample is large enough. Equilibrium may involve optimal, insufficient or excessive experimentation relative to a second-best welfare benchmark. This unusual over-experimentation result is not necessarily associated with large samples but with a low elasticity of the value of information with respect to the sample size.

JEL Classification : D83, H41.

[1]GREMAQ, Université de Toulouse. E-mail: carole.haritchabalet@univ-tlse1.fr

[2]ThEMA, Université de Cergy-Pontoise, Institut Universitaire de France. E-mail: regis.renault@eco.u-cergy.fr.

We are grateful to Michel Poitevin, anonymous referees, seminar participants at Boston College, ESEM 2001 and EGRIE 2001 for useful comments. The usual disclaimer applies.

1 Introduction

Recent theoretical work studies the dynamic implication of informational externalities when agents may adjust experimentation intensity continuously. Yet, there are many situations where such an adjustment is not feasible or desirable. For instance, when different organizations choose whether to adopt a new technology involving increasing returns or network externalities, a partial adoption may be prohibitively costly. In this paper we study a game of strategic experimentation where agents are restricted to an all or nothing sampling strategy. We investigate how the outcome of strategic interaction and its welfare properties are affected by *i)* the size of the samples that the agents may experiment on and *ii)* the features of the value of the information generated through experimentation (its sensitivity to changes in sample size).

To illustrate our analysis, we focus more specifically on an example that is of particular relevance: the drug approval decisions taken in different countries. No matter how stringent and elaborate a drug approval procedure may be, there always remains some uncertainty about the product's effectiveness and its potential undesirable side effects when a government agency decides whether to allow firms to introduce a new medicine in the market.[1] For instance, regarding post approval risks, Bakke *et al.* (1995) find that from 3% to 4% of newly approved drugs in the US, the UK and Spain over the period 1974-1993 were discontinued for safety reasons. According to a study by the US Accounting Office on a sample of drugs approved by the FDA between 1976 and 1985, 51.5% of these drugs had serious post approval risk resulting in labelling changes or withdrawal. If the drug is approved, its large scale use will help to settle part of the remaining uncertainty. The authorization decision should therefore take into account, not only the information generated by the approval process, but also the value of the information that is generated by an extensive use of the new drug. Furthermore, if a new medicine is introduced in one country, the information thus generated may be used by other countries in making their approval decision. In other words, other countries benefit from an informational externality. Finally, the drug approval decision is to a large extent a binary one. Once a drug is marketed, it should be available for all those who have the specified health condition provided they respect a certain set of rules. In real world situations the choice is not necessarily binary, because the government agency may specify various marketing conditions that will make the drug available for various sub-populations with different health conditions. However the choice

remains a lump sum one.

New medicines are usually not approved simultaneously in all countries under identical marketing conditions. According to Rawson (2000), only 10.5% of the drugs approved in one of five countries from 1996 to 1998 were actually approved in all five (with almost half of them being approved only in one).[2] There are some obvious reasons for this, such as differences in approval procedures or pharmaceutical companies' strategies to file for approval in some countries first. Here we focus on the incentive that some countries may have to adopt a waiting position in order to benefit from an informational externality if the new drug is first approved elsewhere. To this end, we take approval procedures and the laboratory's strategy as given. Nevertheless our analysis provides some insight as to what might influence the choice of a strategy by a drug company. Finally note that our analysis is also relevant for situations where countries choose how restrictive the marketing conditions of an approved drug should be.[3]

We consider a two period model in which each of two countries must independently decide at each period whether to approve the introduction of a new medicine in its market. In deciding whether to approve the medicine in the first period, each country takes into account the expected benefit from introducing the drug given its prior information as well as the value of the information generated once the drug has been introduced. The latter information is public, so that if only one country chooses to approve the drug, the other country also benefits from the additional information. It is valuable to both countries because the approval decision may be reversed: in a second period a country may choose to withdraw the drug or introduce it, based on what has been learned from the drug's consumption in the first period. This option to use first period information to reverse the approval decision in the second period creates a value defined as the value of information. Countries only differ in terms of population size, and thus in the size of the samples over which they may experiment: for each country, the experimentation sample comprises the population of potential users of the drug in the country. They share the same prior information and the same *per capita* benefit from introducing the drug. We consider the case of costly experimentation where the common prior is such that the expected benefit of introducing the drug is negative.

The strategic interaction between agents due to informational externalities is affected by the sizes of the experimentation samples and the sensitivity of information to changes in sample

sizes. We find that there is experimentation only if the total number of potential users of the drug is sufficiently large. If this is the case, then there is always an equilibrium where the larger country experiments. In particular, if the number of potential users of the drug is not too large, this is the only equilibrium since the smaller country always finds it optimal to free ride on the larger country's experimentation. For larger populations of users, the equilibrium outcome depends on the speed at which the marginal value of information from increases the sample size decreases. If it decreases rapidly, then for a very large population of potential users, countries face a coordination problem with two equilibria in which either country experiments and the other free rides, whereas for a relatively smaller user population both would experiment in equilibrium. If the marginal value of information decreases slowly then both countries will experiment.

We compare the equilibrium outcome to a second best social welfare benchmark whereby the social planner is also restricted to lump sum sampling: the social planner chooses between no experimentation, experimentation in either country or experimentation in both countries. Strategic experimentation may be optimal, insufficient or excessive. The most striking conclusion of our welfare analysis is clearly that restricting experimentation decisions to be lump sum may induce excessive experimentation in equilibrium, which departs from the under-experimentation result that is typically obtained when experimentation may be adjusted continuously. In the present setting, over-experimentation arises in situations where only the larger country experiments whereas it would have been socially optimal to experiment in the smaller country alone. It is not necessarily associated with large samples. For intermediate sample sizes, a sufficient condition for over-experimentation is that the value of information is not too elastic with respect to the sample size and that sample sizes do not differ too much.

Previous work on strategic experimentation with informational externalities include Hendricks and Kovenock (1989), Rob (1991), Bolton and Harris (1999) and Cripps, Keller and Rady (2005). Our work is closest to the work of Hendricks and Kovenock (1989). In their two period framework, players are restricted to an all or nothing experimentation decision, they have identical experimentation sample sizes but they differ in their prior on the value of the investment. In their setting, one experiment is sufficient to generate all the information, so that a player would not experiment knowing for sure that the other does. The asymmetry in priors induces a bayesian game where experimentation may be excessive or insufficient. Rob (1991)

considers an entry game with a large population of identical players who learn about the profitability of the market from previous entry. The entry decision is binary but since investments are identical in size, it is not possible to observe the type of excessive experimentation that we emphasize. Finally, Bolton and Harris (1999) and Cripps, Keller and Rady (2005) consider continuous time settings with continuous experimentation decisions.[4] They find that experimentation is insufficient.[5] This is analogous to standard results in public goods provision games where costs are private and benefits are public. Using such a continuous time set up in our lump sum experimentation problem would enrich the analysis by allowing for more elaborate strategies in which the timing of drug approval would depend on the result of experimentation by others.

We describe the model in the next section and provide some benchmark results on the social optimum and the non cooperative outcome for continuous sampling. Section 3 characterizes the outcome of the non cooperative strategic interaction when sample sizes are lump sum. Section 4 provides a welfare evaluation of the non cooperative outcome. The last section concludes.

2 The model

Consider two countries, SMALL and LARGE (M and L for short), who are contemplating authorizing a new drug. However they cannot perfectly assess the benefits from introducing the new medicine. We assume that the product review yields the same prior on the value of the medicine. We take this prior as given and focus on the additional information that is generated once the product is marketed, and on how this information may be used to re-evaluate a previous decision. A country that had previously chosen to authorize may decide to withdraw while a country that had initially denied approval may reverse its decision. We therefore consider a two period framework. We say that a country experiments if it grants approval in the first period.

The *per capita* benefits over one period are measured by the *per capita* social surplus denoted s which is the realization of a real valued random variable S defined over a set of states of nature Ω. In the state of nature $\omega \in \Omega$, authorizing the new drug in one period is optimal if and only if this surplus is positive. The value of $S(\omega)$ is a measure of *per capita* total welfare in state ω as evaluated by the public authority. It is of course affected by the therapeutic characteristics and

undesirable effects of the new medicine but also reflects the authority's attitude towards risk, political considerations, the functioning of the health care system, and so on.

The decision criterion for each country is the expected surplus: in a static setting, the new medicine is approved if $E(S) \equiv \bar{s} \geq 0$. This static viewpoint however does not allow for taking into account staggered approval decisions or withdrawals of previously authorized products based on the post-approval information. In our two period setup, each country must independently decide whether or not to approve the new medicine in the first period. The outcome of experimentation is publicly observed. In the second period, a country that approved in the first period decides whether to confirm approval or withdraw the medicine, whereas a country that did not approve in the first period decides whether to approve it (based on the information generated by the first period experimentation if any). We concentrate on the interesting case where $\bar{s} < 0$ so that experimentation is costly and the drug would not be introduced in a static setting.

2.1 Second period analysis and the value of information

We first consider the second period decisions as a function of the information generated by first period experimentation. This in turn will allow us to characterize the value of that information as a function of the size of the experiment.

If at least one country experiments, all countries have the opportunity to observe the value of a random variable $X^n \equiv (X_1, ..., X_n)$ that is related to the surplus S. The observation of X^n provides some information about the value of S. The dimension n reflects the scale of the experiment, which is related for instance to the size of the population concerned: the larger the size of the countries or the number of countries where the drug is approved, the larger n is. A higher dimension induces better quality information in a sense we define below. We assume that the conditional distribution of X^n when $S = s$ can be specified for each possible value $s \in \mathbb{R}$.

We denote $p(./x^n)$ ($\mathbb{R} \to \mathbb{R}$), the posterior density of S after an n-dimensional experiment x^n, $f^n(./s)$ ($\mathbb{R}^n \to \mathbb{R}$) the conditional density of X^n, and $f^n(.)$ ($\mathbb{R}^n \to \mathbb{R}$) the non conditional density of X^n. We have

$$p(./x^n) = \frac{f^n(x^n/s)p(s)}{\int_{\mathbb{R}} f^n(x^n/s)p(s)ds}.$$

In period two, a country decides to extend approval or, if it had not approved the drug in period one, to approve it, if and only if the posterior *per capita* expected surplus $E(S/x^n)$ is positive. Without experimentation, the drug would not be approved in period 2 since $\bar{s} < 0$, and thus *per capita* surplus would be zero. Thus *per capita* value of information generated by an n-dimensional experiment equals the *ex ante* expected second period *per capita* surplus (prior to observing X^n) given by

$$I^n \equiv \int_{\mathbb{R}^n} f^n(x^n) \max\{E(S/x^n), 0\} dx^n.$$

The above expression measures the expected benefit from taking a decision after observing X^n rather than deciding on the basis of prior beliefs on the new medicine.

Let us show that I^n is an increasing function of n.

$$\begin{aligned} I^{n+1} &= \int_{\mathbb{R}^{n+1}} f^{n+1}(x^{n+1}) \max\{E(S/x^{n+1}), 0\} dx^{n+1} \\ &= \int_{\mathbb{R}^n} f^n(x^n) \int_{\mathbb{R}} g_{n+1}(x_{n+1}/x^n) \max\{E(S/x^n, x_{n+1}), 0\} dx_{n+1} dx^n, \end{aligned}$$

where $g_{n+1}(./x^n)$ denotes the density of X_{n+1} conditional on $X^n = x^n$. Using the convexity of the max function and Jensen's inequality, we have $I^{n+1} \geq I^n$ (where we use $E(S/x^n) = \int_{\mathbb{R}} g_{n+1}(x_{n+1}/x^n) E(S/x^n, x_{n+1}) dx_{n+1}$).

We henceforth assume that the size of the experiment only depends on the size of the potential number of prescriptions in the geographic area where the drug is approved in the first period. This size is now allowed to take any positive real value to simplify the exposition. Let $\theta > 0$ denote the size of the overall potential number of prescriptions (hereafter PNP) in both countries. The country LARGE is assumed to be the larger and its share in overall PNP is denoted $\lambda \in [1/2, 1]$. If there is an experiment on a fraction λ of overall PNP, the *per capita* value of information is then $I(\lambda\theta)$. The value of the second period game for each country is thus given by $I(\lambda\theta)$ times the country's PNP.

Specifying the prior distribution and the joint distribution of the signals generated by the experimentation would allow for providing a closed form expression of the value of information. We rather keep these distributions unspecified and make general assumptions that are consistent with results in the literature. We assume that the marginal impact of increasing the sample size on the *per capita* value of information is decreasing and tends to zero when the sample

size becomes very large.[6] This reflects the intuition that if the drug has been experimented with on a large PNP, the incremental information that could be generated from increasing the size of the experiment becomes rather limited.[7] We finally assume that I is twice continuously differentiable, with $I'(0) > -\bar{s}$ at zero. The degree to which the value of information is concave turns out to be critical for the analysis. The relevant measure of concavity here is the elasticity of the slope $\sigma(x) = -xI''(x)/I'(x)$. For x small, we have the following result (which is obviously true if the second derivative of I has a finite limit at 0).[8]

Lemma 1 *Since $I(0) = 0$, $\sigma(x) < 1$ for x sufficiently close to 0.*

For larger values of x, σ may exceed one. To simplify the analysis we assume the following.

Assumption 1 *If $\sigma(x) > 1$ for some x, then $\sigma(x') > 1$ for all $x' > x$.*

If the returns to experimentation do not decrease too rapidly, then σ remains below one even for very large population sizes. This would be the case for instance if I is given by a power function, $I(x) = x^\alpha$, with $0 < \alpha < 1$ and thus $\sigma(x) = 1 - \alpha < 1$ is constant. If on the contrary returns to experimentation decrease rapidly, then σ eventually exceeds 1 as the sample size increases. For instance, this happens for $I(x) = 1 - e^{-\alpha x}$ with $\alpha > 0$ and thus $\sigma(x) = \alpha x$ is linear and increasing.

2.2 First period game

We now consider the first period game in which each country independently chooses whether to authorize the drug for the current period. When a country experiments, it incurs the *per capita* cost of experimentation given by the negative expected *per capita* surplus $\bar{s}$. For each country, the *per capita* payoff in the first period game is an intertemporal payoff: it is the sum of the *per capita* cost of experimentation and the *per capita* value of information which is a function of the size of the total first period experiment (we abstract from discounting to simplify notations, but the value of information may be interpreted as a discounted second period expected surplus).

Strategies and payoffs may be summarized by the following matrix where LARGE chooses a line and SMALL chooses a column:

	$\bar{e}_M$		e_M	
$\bar{e}_L$	0	0	$\lambda\theta I((1-\lambda)\theta)$	$(1-\lambda)\theta(\bar{s}+I((1-\lambda)\theta))$
e_L	$\lambda\theta(\bar{s}+I(\lambda\theta))$	$(1-\lambda)\theta I(\lambda\theta)$	$\lambda\theta(\bar{s}+I(\theta))$	$(1-\lambda)\theta(\bar{s}+I(\theta))$

where e_i and $\bar{e}_i$ indicate experimentation and no experimentation by country i respectively, $i \in \{L, M\}$.

Our objective is to derive the equilibrium of this game and study how it is affected by changes in the overall PNP θ, and the share of the large country in this overall PNP, λ.

2.3 Continuous choice of sample sizes

Although, our main focus is the case where sample sizes are lump sum, we first present as a benchmark what would happen if sample sizes could be chosen continuously. First consider the social optimum. Suppose that for a given total PNP θ, it is possible to choose any sample size $\gamma\theta$ where we may pick $\gamma \in [0, 1]$. Overall surplus is given by $\gamma\theta\bar{s} + \theta I(\gamma\theta)$. From our assumptions this overall surplus is a strictly concave function of γ which becomes decreasing for γ large enough so that it is maximized for a unique γ^*. The derivative for $\gamma = 0$ is $\theta\bar{s} + \theta^2 I'(0)$: we obtain $\gamma^* = 0$ if and only if $\theta \leq -s/I'(0)$. Otherwise we have $\gamma^* > 0$ and the first order condition is:

$$\theta\bar{s} + \theta^2 I'(\gamma^*\theta) \geq 0 \tag{1}$$

with equality if $\gamma^* < 1$.

We now consider the non cooperative solution where each country chooses its sample size independently. Let $\gamma_M\theta$ and $\gamma_L\theta$ denote the sample sizes selected by SMALL and LARGE respec-

tively. We must have $\gamma_M \in [0, 1-\lambda]$ and $\gamma_L \in [0, \lambda]$. When one country selects a sample size $\gamma_i\theta$, it pays a cost of $\gamma_i\theta\bar{s}$. The benefit depends on both countries' experimentation. The value of information generated by an experimentation of size $(\gamma_M + \gamma_L)\theta$ is $I((\gamma_M + \gamma_L)\theta)$. Surpluses are thus given by

$$\lambda\theta I(\gamma\theta) + \gamma_L\theta\bar{s} \quad \text{for LARGE,} \tag{2}$$

$$(1-\lambda)\theta I(\gamma\theta) + \gamma_M\theta\bar{s} \quad \text{for SMALL} \tag{3}$$

where $\gamma = \gamma_M + \gamma_L$. Surplus derivatives are

$$\lambda\theta^2 I'(\gamma\theta) + \theta\bar{s} \quad \text{for LARGE} \tag{4}$$

$$(1-\lambda)\theta^2 I'(\gamma\theta) + \theta\bar{s} \quad \text{for SMALL.} \tag{5}$$

Since $\lambda > 1/2$, (4) exceeds (5) so that, surplus derivatives cannot simultaneously be equal to zero. This means that $\gamma_M \in (0, 1-\lambda)$ and $\gamma_L \in (0, \lambda)$ cannot be an equilibrium. Moreover, if (5) is at least zero then (4) is strictly positive, which implies that if SMALL is to experiment at all then LARGE experiments over its entire population. Otherwise the equilibrium outcomes are no experimentation or experimentation by LARGE alone.[9] Observe that the derivative of the overall surplus is strictly greater than (4). Thus in any equilibrium with experimentation, condition (1) holds with strict inequality and equilibrium experimentation is insufficient unless both countries experiment on their entire population. This is because each country bears all the costs of increasing its sample size but only receives part of the benefits.

In this paper we consider a situation where each country is restricted to experiment over its entire sample size if it experiments at all. Although it is still true that a country privately bears the cost of experimentation while benefits are public, the restriction to an all or nothing decision may lead to over-experimentation that would not arise with a continuous choice of experimentation.

3 Strategic interaction

We first derive the Nash equilibria of the game as a function of overall PNP, θ and LARGE's share in the overall PNP, λ. Let us characterize LARGE's best response as a function of parameter

values. If SMALL does not experiment then it is optimal for LARGE to experiment if and only if

$$I(\lambda\theta) \geq -\bar{s}. \tag{6}$$

From Equation (6) and since I is strictly increasing we may define

$$\hat{\theta}(\lambda) = \frac{I^{-1}(-\bar{s})}{\lambda}, \tag{7}$$

which is the smallest potential number of prescriptions such that LARGE would choose to experiment alone. Similarly, the smallest PNP such that SMALL would choose to experiment alone is $\hat{\theta}(1-\lambda)$. Clearly, $\hat{\theta}$ is strictly decreasing and strictly convex in λ and we have $\hat{\theta}(\lambda) \leq \hat{\theta}(1-\lambda)$.

If SMALL experiments then LARGE prefers joint experimentation over free riding if and only if

$$J(\lambda, \theta) \equiv \bar{s} + I(\theta) - I((1-\lambda)\theta) \geq 0. \tag{8}$$

We have the following result.

Lemma 2 *Under Assumption 1, for any $\lambda \in (0,1)$, the benefit from joint experimentation given by $J(\lambda, \theta)$ is quasiconcave in θ and it is strictly increasing for θ low enough.*

If both λ and θ are large enough, then the benefit from joint experimentation over free riding for the large country is necessarily strictly positive. There is however no guarantee that a large overall PNP would make this benefit strictly positive if the two countries are close in size (λ close to $1/2$).

Because our analysis focuses on experimentation behavior, we assume that its value is sufficiently high relative to its cost $-\bar{s}$ so that for any $\lambda \in [1/2, 1]$, there exist some values of θ such that joint experimentation is strictly preferred to free riding by the large country. From Lemma 2, the set of such θ is an open interval which we denote $(\underline{\theta}(\lambda), \bar{\theta}(\lambda))$, where the bounds set the left-hand side of (8) to zero. The left-hand side of (8) is increasing in θ at $\underline{\theta}$ and decreasing in θ at $\bar{\theta}$. Since it is also strictly increasing in λ, the bounds $\underline{\theta}$ and $\bar{\theta}$ are respectively decreasing and increasing functions of λ. Note that we do not rule out the possibility that $\bar{\theta}(\lambda)$ be infinite, a situation which could arise when returns to experimentation do not decrease too quickly, so that even when countries are very large, each of them prefers joint experimentation to free riding. In particular this happens if $\sigma < 1$ throughout.

Finally, since marginal returns to experimentation are decreasing, the added benefits from experimenting in one country are less if the other country is also experimenting than if it is not. The left-hand side of (6) is therefore larger than $J(\lambda, \theta)$. This in turn implies that for any λ, the smallest overall PNP for which LARGE is ready to experiment alone is less than the smallest overall PNP for which it prefers joint experimentation to free-riding, $\hat{\theta}(\lambda) < \underline{\theta}(\lambda)$.

Note that free riding is preferred to joint experimentation either because overall population is too small ($\theta < \underline{\theta}$) or too large ($\theta > \bar{\theta}$): in the first case, the incremental benefit from joint experimentation is too small because the country doing this additional experimentation is too small ; in the second case, these benefits are too small because the other country is so large that returns to additional experimentation are very low (this arises only when returns to experimentation decrease sufficiently fast).

Insert Figure 1.

The equilibrium may then be summarized as shown in Figure 1. The figure depicts $\hat{\theta}(\lambda)$, $\underline{\theta}(\lambda)$ and $\bar{\theta}(\lambda)$ (with thick lines) which are used to determine the large country's behavior. When $\theta < \hat{\theta}(\lambda)$, not experimenting is a dominant strategy for LARGE. When $\theta \in [\hat{\theta}(\lambda), \underline{\theta}(\lambda)]$ or $\theta > \bar{\theta}(\lambda)$, experimentation is optimal for LARGE if and only if SMALL does not experiment. Finally, if $\theta \in [\underline{\theta}(\lambda), \bar{\theta}(\lambda)]$, experimentation is a dominant strategy for LARGE. We complete the picture by drawing $\hat{\theta}(1-\lambda)$, $\underline{\theta}(1-\lambda)$ and $\bar{\theta}(1-\lambda)$ (with thin lines) which are used to determine the small country's behavior. These curves are extensions of the large country's curves ($\hat{\theta}(\lambda)$, $\underline{\theta}(\lambda)$ and $\bar{\theta}(\lambda)$ for $\lambda < 1/2$, tipped upside down because the argument is $1-\lambda$ instead of λ. These curves may be used to identify regions where either experimentation or no experimentation is a dominant strategy for SMALL and regions where SMALL experiments if and only if LARGE does not experiment. For each parameter region, the figure indicates the equilibrium strategy profiles.[10]

In our discussion of the equilibrium outcome, we first concentrate on the case where returns to experimentation do not decrease too rapidly, so that $\bar{\theta}$ is infinite (the two curves $\bar{\theta}(\lambda)$ and $\bar{\theta}(1-\lambda)$ should then be ignored on the figure). Then for a low overall PNP size ($\theta < \hat{\theta}(\lambda)$), not experimenting is a dominant strategy for both countries : we obtain that the unique equilibrium

involves no experimentation. If, on the contrary, overall user population is sufficiently large ($\theta > \underline{\theta}(1-\lambda)$), then experimentation is a dominant strategy and both countries experiment. For intermediate values of θ, there is always an equilibrium in which LARGE experiments alone. It is the unique equilibrium when, either experimenting is a dominant strategy for LARGE, ($\theta > \underline{\theta}(\lambda)$) or, not experimenting is a dominant strategy for SMALL ($\theta < \hat{\theta}(1-\lambda)$). In particular, the first condition always holds if populations are sufficiently dissymmetric in size (for λ large). In contrast, if PNP sizes are sufficiently close (λ close to 1/2), then there is a parameter region where $\hat{\theta}(1-\lambda) < \theta < \underline{\theta}(\lambda)$, and each country prefers experimentation if and only if the other country does not experiment. There are then two pure strategy equilibria, each involving experimentation by one of the two countries.

If returns to experimentation decrease sufficiently fast so that $\bar{\theta}$ is finite, the outcome is only modified for a large total PNP. Only one country experiments if the overall population is so large that experimenting is no more a dominant strategy for SMALL ($\theta > \bar{\theta}(1-\lambda)$). Then, either experimenting is still a dominant strategy for LARGE ($\theta < \bar{\theta}(\lambda)$) and the equilibrium is unique with LARGE experimenting, or experimenting is no more a dominant strategy for LARGE ($\theta > \bar{\theta}(\lambda)$) and there are two equilibria with either country experimenting. The following proposition summarizes the main features of the equilibrium outcome.

Proposition 1 *There always exists an equilibrium in pure strategy and we have the following.*

1. *If θ is small enough ($\theta < \hat{\theta}(\lambda)$) there is no experimentation.*
2. *If $\theta \geq \hat{\theta}(\lambda)$, there always exists an equilibrium where* LARGE *experiments.*
3. *There is joint experimentation either for large user populations ($\theta > \underline{\theta}(\lambda)$) if I is not too concave or for intermediate user populations ($\underline{\theta}(1-\lambda) < \theta < \bar{\theta}(1-\lambda)$) if I is concave enough.*
4. *The game is a coordination game where either country experiments in equilibrium if countries are similar in size and user populations are not too large (λ close to 1/2 and $\hat{\theta}(1-\lambda) < \theta < \underline{\theta}(\lambda)$) or if user populations are very large ($\theta > \bar{\theta}(\lambda)$) and I is very concave.*

Our results show that if there is experimentation then it is likely that the larger country is experimenting. The only cases where SMALL should be expected to be experimenting alone are either when the population of potential users is not too large and country sizes are similar enough or when the population of potential users is very large and marginal returns to experimentation decrease sufficiently quickly. Finally, a large population of potential users does not necessarily imply that both countries experiment: this is the case only if marginal returns to experimentation do not decrease too fast.

4 Welfare

In this section we compare the outcome of non-cooperative strategic interaction with some social welfare benchmarks. As we pointed out at the end of section 2, if sample sizes could be chosen continuously then strategic interaction would typically result in under experimentation and experimentation would never be excessive relative to the first-best benchmark.

In our welfare analysis of lump sum sampling, we adopt a second-best approach, whereby the only options available to the social planner are, no approval, approval in either country or approval in both. It is straightforward to apply some standard externality arguments to compare the equilibrium outcome and the second-best socially optimum solution. When a country chooses or not to experiment, it bears all of the additional costs but enjoys only part of the extra benefits. The following results are immediate consequences of this simple reasoning.

1. If a country weakly prefers experimenting alone to no experimentation then experimenting in this country is strictly socially preferable to no experimentation.

2. If a country weakly prefers joint experimentation to free-riding then joint experimentation is strictly socially preferable to experimenting in the other country alone.

Strategic interaction may result in too little experimentation, the right level of experimentation or excessive experimentation. We now explore these three possibilities.

4.1 Too little experimentation

It is not too surprising that the simple externality arguments used above allow us to identify various regions where experimentation is insufficient. This is the case for instance when no country experiments and θ is close to $\hat{\theta}(\lambda)$ (experimenting in the large country would then be preferable). This is also the case when only one country experiments and θ is slightly below $\underline{\theta}(1-\lambda)$ or slightly above $\bar{\theta}(1-\lambda)$ (around the bell shaped area in the middle of the figure). Then experimentation in both countries would be preferable since both countries "nearly" prefer joint experimentation to free riding. Finally, under-experimentation is also possible when the smaller country experiments alone (we will provide an example of this below, see endnote 11).

4.2 The right level of experimentation

It is also straightforward to identify parameter regions where experimentation is optimal. When both countries experiment in equilibrium then it is clearly the second-best social optimum. Experimentation is a dominant strategy for both countries, which implies that experimenting in both dominates all other options. Obviously experimentation is also optimal if λ is close to 1, since LARGE then internalizes all costs and benefits. From the analysis with continuous sampling in Section 2, we also know that if the total number of users is sufficiently small, and $I'(0)$ is finite, no experimentation is optimal (and it is also the equilibrium outcome). Finally, when marginal returns to experimentation decrease sufficiently fast so that σ becomes less than 1, it is possible that for θ very large one of the two equilibria is optimal. For instance, for $I(\theta) = 1-e^{-\theta}$, we have $\gamma^* = -\ln(-\bar{s}/\theta)/\theta$ which tends to zero as θ goes to infinity, so that the equilibrium where SMALL experiments yields the second-best optimum (when SMALL experiments, no experimentation is socially dominated so that there is no over-experimentation). Our analysis below will show that optimal experimentation is also possible in the other region with multiple equilibria, where country sizes are intermediate (for $\hat{\theta}(1-\lambda) < \theta < \underline{\theta}(\lambda)$).

4.3 Excessive experimentation

It would be fairly straightforward to establish an over-experimentation result if the equilibrium outcome were compared to a first-best benchmark where sample size is adjusted continuously: then the first-best optimum may prescribe experimentation over a small fraction of the overall PNP so that if LARGE experiments in equilibrium, with λ close to 1, experimentation is excessive. But it is somewhat less obvious that it can happen relative to our second best benchmark. Some of our previous results may be used to establish necessary conditions for excessive experimentation. We have seen that when both countries experiment, it is a socially optimal outcome and also that experimentation by SMALL in equilibrium implies that no experimentation is socially dominated. Hence, there is over-experimentation only in an equilibrium where the large country experiments alone. Since experimentation by LARGE implies that no experimentation is socially dominated, there is over-experimentation only if LARGE experiments and the social optimum prescribes that only SMALL experiments.

The analysis with continuous sampling provides some additional insight by considering how the first best socially optimal sample size γ^* relates to $1 - \lambda$. Overall surplus being strictly concave in γ, a sufficient condition for over-experimentation when LARGE experiments alone is that $(1 - \lambda) > \gamma^*$. This condition guarantees that the second best social optimum involves experimentation in the small country alone.

Intuition suggests that the potential for over-experimentation would be largest for large user populations. It turns out that this depends upon how concave the value of information is. In particular, if $\sigma < 1$, there is optimal experimentation when θ is large (in this case, there is joint experimentation in equilibrium). As the following proposition shows, over-experimentation for large user populations does happen if returns to experimentation decrease sufficiently quickly. More strikingly, it also shows that over-experimentation may occur even if overall PNP is not very large.

Proposition 2 *Sufficient conditions for over-experimentation in equilibrium are:*

1. *Overall* PNP θ *is sufficiently large and* γ^* *tends to zero as* θ *tends to infinity;*

2. *Overall* PNP θ *is sufficiently close to* $\hat{\theta}$ *with* $\theta > \hat{\theta}$ *and the value of information is not too*

elastic with respect to the sample size:

$$\varepsilon \equiv \frac{xI'(x)}{I(x)} < 1 - \lambda \ \ \forall\, x \geq 0.$$

The first item corresponds to a situation where, as overall PNP becomes sufficiently large, the first-best optimum, γ^*, falls below the smaller PNP, $1-\lambda$. When the value of information is very concave so that σ becomes larger than 1 for θ large, then standard comparative statics shows that γ^* necessarily falls when the overall PNP is large. From equation (1) we have $d\gamma^*/d\theta = \gamma^*/\theta(\sigma(\gamma^*\theta)^{-1} - 1)$. The possibility that γ^* tends to zero as θ tends to infinity is illustrated by the example used in the discussion of optimal experimentation where $I(\theta) = 1 - e^{-\theta}$. For θ large enough, since γ^* tends to zero, experimentation by LARGE is excessive while the equilibrium with only SMALL experimenting yields socially optimal experimentation. To discuss the second part of the proposition it is useful to consider an isoelastic value of information $I(\theta) = \theta^{\varepsilon}$. Here γ^* is always increasing with θ since $\sigma = 1 - \varepsilon < 1$ so that there is never over-experimentation with a large overall user population. However, if $\varepsilon < 1/2$, Proposition 2 tells us that there is over-experimentation in equilibrium if the two countries are sufficiently close in size so that $\varepsilon < 1 - \lambda$.[11] If the difference between the two countries is indeed small, then the extent of over-experimentation is limited. However, if the value of information is very inelastic, then Proposition 2 applies even if a large share of the overall PNP is in the large country, so that the excess in experimentation is significant.

5 Concluding remarks

We have investigated the consequences of restricting agents to lump sum sampling in a strategic experimentation context. Our results show that if there is experimentation, it is likely that the larger agent is experimenting and we should observe that small agents free ride on large ones. If each agent could select a sample size, we would have a standard private provision of public good problem where strategic interaction typically leads to under-experimentation. Instead, we find that there may be over-experimentation as compared to a second-best welfare benchmark in situations where the larger agent experiments alone whereas it would be optimal that the smaller agent experiments alone. In particular, over experimentation may arise even if sample

sizes are not very large provided that returns to experimentation are not too sensitive to changes in the size of the experimentation.

In our analysis of drug approval decisions, we have ignored the strategic behavior of private agents such as patients, physicians or firms.[12] In particular, we have assumed that a pharmaceutical company seeks approval simultaneously in both countries whereas it may choose to seek approval in different countries sequentially. In this case, it is clear that it would prefer to ask for approval in large countries first. Furthermore, if the drug is expected to be approved in all countries, then there is no point for the firm not to seek approval simultaneously. Thus our predictions on the outcome of strategic interaction would not be affected apart from cases where there is an equilibrium with the small country experimenting alone. In that case, the sequential choice by the firm selects the equilibrium where the large country experiments. These conclusions on pharmaceutical firms' behavior should be taken with care since it does not account for long run interactions between drug approval decisions and research and development strategies in the pharmaceutical industry.

Two comments are in order regarding the relationship of our results to those in the literature on overprovision of public goods. First, it is rather straightforward to construct a game matrix representing a public good provision problem with lump sum actions where the outcome involves overprovision. This is the point made by Buchanan and Kafoglis (1963) in their reciprocal example. Our contribution is to derive general conditions in the context of strategic experimentation under which such a game matrix may arise. These conditions pertain to underlying parameters such as sample sizes and to the properties of the benefits from experimentation. Previous literature has also pointed out that overprovision results could be obtained only with some non convexities in underlying preferences or technologies (see Diamond and Mirrlees, 1973, for instance). Potential application of our model to the adoption of new technologies exhibiting increasing returns or network externalities provide instances of such non convexities yielding overprovision of a public good. An illustration of this is provided by the introduction of new surgical procedures in hospitals (see the study by Escarce (1996) on the adoption of laparoscopic cholecystectomy). Then if the two technologies are used together, the organization must incur two fixed costs and therefore, if it decides to switch, it would do it for the whole activity. This may result in over experimentation if the new technology could have been introduced in a somewhat smaller organization. The large organization could not replicate the same level of

experimentation without incurring both fixed costs. It may also be costly for an organization to introduce a new technology with network externalities. Think for instance of adopting a new computer operation system or a new management software. Then the adoption decision is clearly a binary one and it may be the case that the technology is introduced in a large organization whereas it would have been optimal to introduce it in a smaller one where the cost of potential disruptions would have been less severe.

One limitation of our analysis is that it is inherently static because the timing of decisions such as continuation, withdrawal or introduction in the example of drug approval decisions is exogenous. In practice, such decisions could be taken at any time once some experimentation has been carried out. Future research should be devoted to embedding the lump sum experimentation problem analyzed in the present paper in a dynamic setting that could provide predictions as to the timing of the agents reactions to the results of experimentation given that those reactions are restricted to being lump sum jumps.

References

[1] Anderson, S. P. and R. Renault (2003), 'Efficiency and Surplus Bounds in Cournot Competition', *Journal of Economic Theory, 113,* 253-264.

[2] Bakke, O. M., Manocchia, M. de Abajo, F., Kaitin, K. I. and L. Lasagna (1995), Drug Safety Discontinuation in the United Kingdom, the United States and Spain from 1974 through 1993: a Regulatory Perspective', *Clinical Pharmacology and Therapeutics, 59(1)*, 108-117.

[3] Bolton P. and C. Harris (1999), 'Strategic Experimentation', *Econometrica, 67,* 349-374.

[4] Buchanan J. and M. Kafoglis (1963), 'A Note on Public Good Supply', *The American Economic Review, 53,* 403-414.

[5] Chade H. and E. Schlee (2002), 'Another Look at the Radner-Stiglitz Nonconcavity in the Value of Information', *Journal of Economic Theory, 107,* 421-452.

[6] Claxton K. (1998), 'Bayesian Approaches to the Value of Information: Implications for the Regulation of New Pharmaceuticals', *Health Economics Letters, 2,* 22-28.

[7] Cripps M., Keller G. and S. Rady (2005), 'Strategic Experimentation with Exponential Bandits', *Econometrica, 73,* 39-68.

[8] Décamps, J.P. and T. Mariotti (2004), 'Investment timing and learning externalities', *Journal of Economic Theory, 118,* 80-102.

[9] Diamond P. and J. Mirrlees (1973), 'Aggregate Production with Consumption Externalities', *The Quarterly Journal of Economics, 87,* 1-24.

[10] Escarce J. J. (1996), 'Externalities in Hosptials and Physician Adoption of a New Surgical Technology: An Exploratory Analysis', *Journal of Health Economics, 15,* 715-734.

[11] Hendricks, K. and D. Kovenock (1989), 'Asymmetric Information, Information Externalities, and Efficiency: the Case of Oil Exploration', *Rand Journal of Economics, 20,* 164-182.

[12] Malueg, D. and S. Tsutsui (1997), 'Dynamic R&D competition with learning', *RAND Journal of Economics, 28,* 751-772.

[13] Moscarini G. and L. Smith (2002), 'The Law of Large Demand for Information', *Econometrica, 70,* 2351-2366.

[14] Radner R. and J. Stiglitz (1984), 'A Nonconcavity in the Value of Information", in *Bayesian Models of Economic Theory* (Boyer M. and R. Kihltsrom, Eds), 33-52, Elsevier, Amsterdam.

[15] Rawson, N. S. B. (2000), 'Time Required for Approval of New Drugs in Canada, Australia, Sweden, the United-Kingdom and the United-States in 1996-1998', *Canadian Medical Association Journal, 162(4),* 501-504.

[16] Rob R. (1991), 'Learning and Cpacity Expansion under Demand Uncertainty', *Review of Economic Studies, 58,* 655-675.

[17] The United-States General Accounting Office (1990), 'FDA drug review: post approval risks 1976-85', Document Number GAO/PEMD-90-15.

Notes

[1] The current regulation of new drugs demands arbitrary amounts of information. As a result, Claxton (1998) shows that existing drug approval procedures do not convey sufficient information about the product's effectiveness.

[2] The five countries were the Australia, Canada, Sweden, UK and the US.

[3]For instance, the appetite suppressant molecule Dexfenfluramine which was approved by the FDA in 1996 had been in use in Europe for a decade under very stringent conditions. The widespread use of the drug in the US and Canada after 1996 generated enough information about the risk of primary pulmonary hypertension to prompt a quick removal of the drug in all countries after 1997. The FDA's 1996 decision clearly generated a significant informational externality for European countries.

[4]Other references on similar settings include Décamps and Mariotti (2004) or Malueg and Tsutsui (1997).

[5]Although Bolton and Haris (1999) stress that dynamic strategic interaction tends to exacerbate the incentives to experiment, this effect is never strong enough to yield over-experimentation.

[6]This assumption applies to the *per capita* value of information and it may well be the case that the marginal impact of increasing the PNP on the total value of information is increasing.

[7]Radner and Stiglitz (1984) have pointed out a nonconcavity problem in the value of information: they present examples in which information exhibits increasing marginal returns,

so the value of information is clearly not always concave. This nonconcavity result has been recently extended by Chade and Schlee (2002). They show that if the nonconcavity is difficult to rule out in a general model, it is always possible to construct examples that yield a concave value of information. In particular, if we measure the quantity of information by the number of independent observations from an experiment (as it is the case in our model), Moscarini and Smith (2002) show that the marginal value of information falls as the number of observations increases for a large enough sample size.

[8]Proofs are available upon request.

[9]The analysis here is similar to that of a public good contribution game with quasilinear preferences where there would be upper bounds on individual contributions.

[10]There is no situation with an equilibrium where both experiment along with an equilibrium where neither experiments. This is due to the decreasing marginal return to experimentation which rules out a situation where it would be optimal for one country to systematically mimic the other one. This property also guarantees the existence of a pure strategy equilibrium.

[11] The argument in the proof of Proposition 2 may easily be adapted, reversing the inequalities, to show that the elasticity of I being larger than one half is a sufficient condition for insufficient experimentation with SMALL experimenting in equilibrium.

[12]The extent of experimentation in a country that chooses to approve the drug may depend on how patients and physicians behave if they realize that the newly approved medicine yields negative surplus. If private costs are similar to public costs, strategic behavior by users would exacerbate under-experimentation. Because of health insurance, private costs are somewhat

smaller than public costs and we should then expect massive under experimentation. The difference between public and private costs may also be important if costs are mostly production costs and the negative expected surplus is due to uncertainty about potential benefits. Then, following approval, the drug might be used extensively even though its potential benefits are limited in expectation. In such a situation our over-experimentation result would still hold.

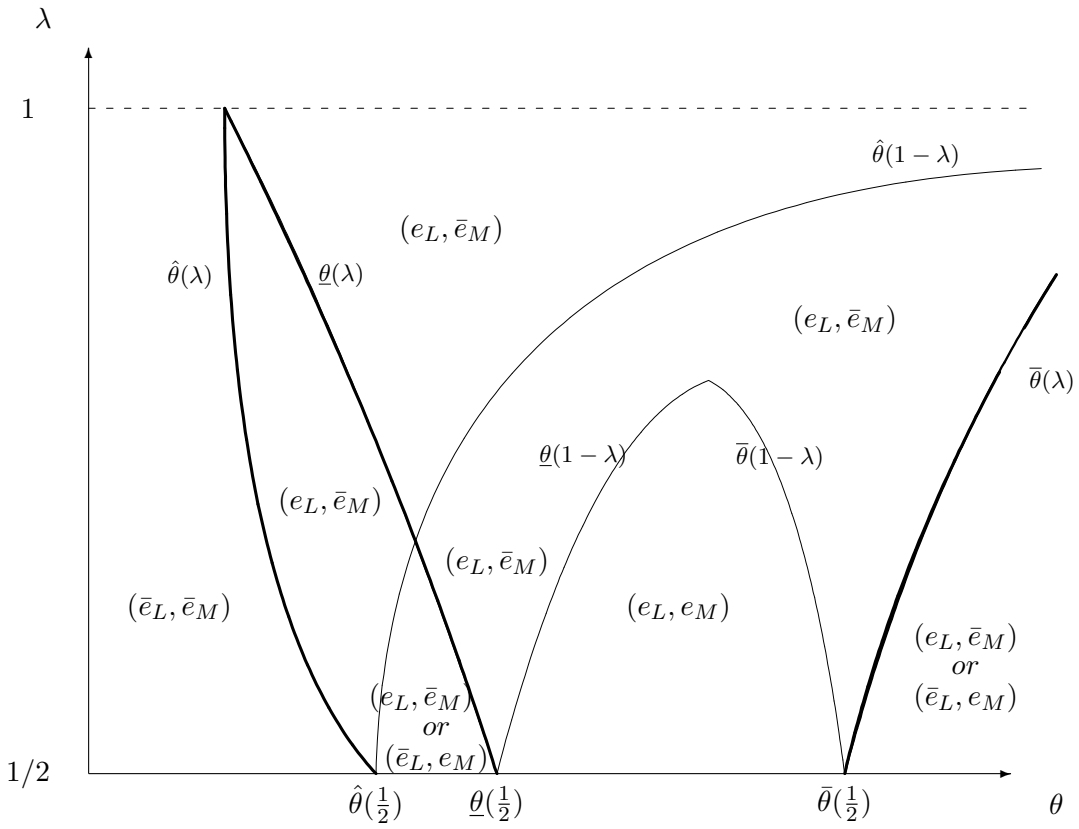

Figure 1: Equilibrium