An Individual-Based Model of Innovation Diffusion Mixing Social Value and Individual Benefit[1]

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The authors propose an individual-based model of innovation diffusion and explore its main dynamical properties. In the model, individuals assign an a priori social value to an innovation which evolves during their interactions with the "relative agreement" influence model. This model offers the possibility of including a minority of "extremists" with extreme and very definite opinions. Individuals who give a high social value to the innovation tend to look for information that allows them to evaluate more precisely the individual benefit of adoption. If the social value they assign is low, they neither consider the information nor transmit it. The main finding is that innovations with high social value and low individual benefit have a greater chance of succeeding than innovations with low social value and high individual benefit. Moreover, in some cases, a minority of extremists can have a very important impact on the propagation by polarizing the social value.

INTRODUCTION

The agent-based model of innovation diffusion described in Deffuant (2001) and Deffuant et al. (2002*b*) was initially targeted on the diffusion of green practices among farmers. We applied it to different types of green practices (e.g., landscape maintenance, reduction of inputs) from different study zones in Europe. In this article, we present an evolution of this model and consider its application to more general processes of innovation

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diffusion like the mobile phone, the Internet, contraception, organic products, genetically modified organisms, and cloning.

We refer to *innovation diffusion* in a sense close to the one proposed
q2 by Valente (1995): “Diffusion of innovations is the spread of new ideas, opinions, or products throughout a society, thus diffusion is a communication process in which adopters persuade those who have not yet adopted to adopt.” More precisely, our model is designed for innovations in which both social values and individual payoff are considered. For instance, farmers give green practices promoted and supported by the European commission a social value according to their opinion about
q3 environmental preservation and the image they have of their work. If they are interested in the green practices, they try to get information to evaluate the individual benefit of adoption, including an evaluation of the work to be done and whether the subsidies cover the costs or not. The final adoption is based on a trade-off between both social value and individual benefit. We believe that such behavior is fairly general and can be extended to other innovations. For instance, in considering the adoption of a mobile phone, a social value can be taken into account as well as more strictly individual benefits or risks for health.

The most popular model of innovation diffusion, the *threshold model* (Granovetter 1978), already considers the trade-off between a social value and an individual benefit from the innovation. In this model, the social value is directly related to the proportion of adopters in the individual’s social network, representing the diffusion as a contagion process (Rogers 1983). When the number of adopters increases in the network of peers, the pressure for adoption increases. The threshold is the proportion of adopters in the individual’s social network that is necessary to convince him or her to adopt. This theory has been applied to very different subjects: farming innovations, family planning practices, medical technology, policy innovation, and language (see Rogers [1983] for a comprehensive review).

Threshold models were particularly used and studied in the social simulation research field, which aims at reproducing social dynamics in computer models (Gilbert and Conte 1995; Bousquet et al. 1993; Gilbert and Troitzsch 1999), because it happens that threshold models fit exactly into the most popular type of social simulation model: automata networks. Automata networks can be used to simulate the threshold model of innovation diffusion or new product growth in marketing. Each automaton represents an individual in a social system, and the links of the graph can represent working relations, friendship, or any type of contact; the binary state of the automaton corresponds to the adoption or nonadoption of the innovation. Blume (1993, 1995) and Ellison (1993) consider automata networks implementing the threshold model, in which the threshold is related to an intrinsic payoff to the considered agent. This leads to the definition of the agent's utility as the sum of an intrinsic payoff and the proportion of the agent's neighbors who adopted the behavior. Several variants of this model can be found (Blume 1993; Young 1998). This framework led to many interesting theoretical and practical results (Young 1999; Weisbuch and Boudjema 1999).

However, our study on agri-environment measures pointed out three strong limitations to threshold models of innovation diffusion:

1. The most important weakness is the hypothesis that people have an a priori knowledge of their individual benefit. This hypothesis is not very realistic for complicated innovations. The analysis of farmers' interviews revealed that only previously interested farmers invested some time to take into account available information and to evaluate their potential individual benefit. In over 350 interviews carried out in nine different sites in Europe, 73% of nonadopters did not look for more information after having heard for the first time about the measures. On the contrary, 70% of adopters did look for information after they first heard about them. Therefore, there is a need to consider the specific dynamics of information propagation.
2. Moreover, the dynamics of mutual influence on social value are more complex than a simple contagion effect. Farmers have more or less strong convictions on their social values, and this affects their influence capacity as well as their open-mindedness to other opinions. A large panel of work related to group polarization (see Moscovici and Doise [1992] for a review) illustrates this complexity.
3. Finally, we noted that the decision is not binary (adoption versus nonadoption). We observed several farmers in an intermediate decision state in which their decision is uncertain.

We tried to incorporate these features in our model while keeping it as simple as possible. Our modeling approach is a hybrid between the cognitive agent approaches in computer science (Conte and Castelfranchi 1995; Ferber 1999; Muller 1996; Conte 1999) and the models of cellular automata networks which are more inspired by physics (Weisbuch 1991; Blume 1993; Young 1998). It builds on earlier versions proposed by Chattoe and Gilbert (1999). The inspiration in sociology relates clearly to the field of innovation diffusion. The main features of the model are the following:

1. The model represents dynamics of discussions in a social network of individuals. Individuals send messages to each other containing their social opinion and their information if available. The discussions are triggered by messages from the media that reach individuals

at random, with a given frequency; the individuals then propagate the discussions in their network. We assume that the information enables individuals to evaluate the individual benefits of adopting an innovation.

2. We assume that individuals have an a priori opinion about the social value of an innovation, even the first time they hear about it. The dynamics on the social values are based on the "relative agreement" model that we studied earlier (Deffuant et al. 2001; Weisbuch et al. 2002; Deffuant et al. 2002*a*). This model shows some similarity with the results described in Moscovici and Doise (1992): it can lead to polarization under the influence of a minority of extremists when there are a lot of discussions.
3. Only individuals having a high social opinion of the innovation pay attention to the information. They use it to perform an evaluation of their potential individual benefit in adoption and transmit it to their associates.
4. Individuals adopt only if a global evaluation, including the social value and the individual benefit, is good enough with some certainty. This implies that all adopters evaluated their potential individual benefit.

We perform a systematic study of the model: we observe the average final number of adopters over several runs for different values of the main parameters—in particular, the definition of the a priori distribution of social values and the function of individual benefit evaluation. The analysis of the results is based on the observation of the social value distribution and the information possession at the end of the simulation. The main results of this analysis are

1. In the model, an innovation with a high social value and a low individual benefit better propagates than an innovation with a low social value and a high individual benefit. The reason is that the propagation of information has a chance of being blocked in the latter case, which prevents people from evaluating their individual benefit.
2. A minority of extremists can strongly modify the adoption, when the density of the social network and the frequency of discussion are high.
3. Low levels of adoption can be due to high uncertainty about the innovation.

q4 Below, we recall the structure of the model and its main hypotheses. We then devote some time to the exploration of the model and analysis of the results. Finally, we propose some conclusions.

INDIVIDUAL-BASED MODEL OF INNOVATION DIFFUSION

We first propose a global picture of the model. Then, we give more details about the state variables and the dynamics.

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General Overview

The principles of the model are the following:

1. Individuals are related to each other through a social network, which can be more or less dense. The network is a particular type of small world network (Watts and Strogatz 1998; Milgram 1967) with a majority of links (95%) corresponding to geographic proximity (under a given distance threshold), and others (5%) drawn at random. In this article, we do not investigate a precise influence of the network structure, but rather rough results related to the density of links. We could have used totally random networks and gotten similar results.[2]
2. We assume that the mass media regularly send messages about the innovation, reaching individuals at random. People who receive the messages tend to discuss the innovation with their colleagues, and we model a propagation of the discussions in the social network. In agent-based terminology, this propagation of the discussions (explained is greater detail below) rules the scheduling of the interactions.
3. The state of an individual contains a social value with an uncertainty, an information state (which is a Boolean), and other variables. A discussion is modeled as a message exchange only about the social value and the information state.
4. The innovation is interpreted within an existing social context, and it is given an a priori social value, which is more or less positive. For the sake of simplicity, we assume that the initial social value is drawn from a normal distribution. The mean and standard deviation of this distribution allow us to define innovations with on average an a priori high or low social value, more or less homogeneously distributed in the population.
5. We postulate that individuals influence each other's social values when they have discussions. The model of social value influence is inspired by previous research (Nowak and Vallacher 1998; Axelrod 1997). However, the originality of this part of the model is the use of continuous variables for the opinions and the introduction of an uncertainty interval around these opinions. More convinced people

[2] We studied more precisely the influence of different types of small world networks on the relative agreement model in Amblard and Deffuant (2004).

(more certain), who are more influential, can be modeled. If these more convinced individuals are initialized with extreme opinions, the model reproduces some aspects of the polarizations observed in Moscovici and Doise (1992; see Deffuant et al. [2001], Weisbuch et al. [2002], and Deffuant et al. [2002*a*] for more details).

6. To take into account the results of our study on the adoption of agri-environmental measures, the individuals having a low a priori social opinion about the innovation do not consider the available information and therefore do not transmit it. On the other hand, individuals having a high a priori social opinion pay attention to the information and tend to integrate it (their Boolean value changes to true) and to transmit it (it is supposed that this information is not strategic). We particularly want to investigate the consequences of this attitude toward information on the final adoption level.
7. When interested individuals (having a high social opinion) get information, they evaluate the potential individual benefit of adoption. Here, to simplify the model, we draw the individual benefit from a normal distribution.[3] When we vary the mean and the standard deviation of this distribution, we represent innovations that are more or less beneficial for the individuals, with a more or less homogeneous distribution of this benefit in the population.

We now proceed to a more complete presentation of the model.

State Variables of an Individual

An individual is described by the following state variables, with their type in parentheses:

1. *Social opinion* (real number).—The social opinion can be negative or positive, initially drawn from a normal distribution $N(m_s, \sigma_s)$.
2. *Social opinion uncertainty* (real number).—The term uncertainty is used for convenience. In fact, this value represents a mix between uncertainty, conviction, and openness to the opinion of others. For the sake of simplicity, it is the same value U for every individual, except for extremists who have a much smaller value.
3. *Individual benefit* (*nil* or real number).—Initialized with the value *nil*, it is drawn from a normal distribution $N(m_s, \sigma_i)$ when the individual evaluates his or her potential benefit.
4. *Individual benefit uncertainty* (*nil* or real number).—Initialized with

[3] In the model we applied to agri-environmental measures, the individual benefit evaluation was performed with an economic model, taking as inputs the characteristics of the farm and the requirements of the agri-environmental measure.

the value *nil*, it is the same for every individual when the individual evaluates his or her potential benefit.

5. *Global opinion* (real number).—If the individual benefit is *nil*, it is equal to the social opinion. If not, it is the average of the social opinion and the individual benefit.
6. *Global opinion uncertainty* (real number).—If the individual benefit uncertainty is *nil*, it is equal to the social opinion uncertainty. If not, it is the average of the social opinion uncertainty and the individual benefit uncertainty.
7. *Information* (*yes* or *no*).—This variable expresses whether the individual is able to evaluate his or her individual benefit and transmit the information.
8. *Interest* (*no*, *maybe*, or *yes*).—The value of this variable is based on the global opinion and uncertainty.
9. *Decision* (*not concerned, information request, no adoption, preadoption, adoption*).—The value of this variable is based on the interest value and the information state.

During discussions, individuals exchange messages containing the values of the following state variables: social opinion, social opinion uncertainty, and information. The social opinion and its uncertainty are modified during discussions according to the relative agreement model (see below). The rules modifying the information state are also specified below. These modifications can change the interest and the decision states, as will be explained. The propagation of the discussions (scheduling of interactions) is also described.

Decision Process

The decision state is based on the interest and the information states. The interest state can take three values (*no, maybe, yes*), based on the global opinion (see fig. 1):

1. If the global opinion plus the global opinion uncertainty is negative (respectively positive), then the interest is *no*.
2. If the global opinion minus the global opinion uncertainty is positive, then the interest is *yes*.
3. Otherwise, the interest is *maybe*.

The interest states are essential in the dynamics of the information and decision states. The decision state is rules by the state diagram of figure 2. The decision process takes into account the interest state and the information state of the individual. When the individual has no information,

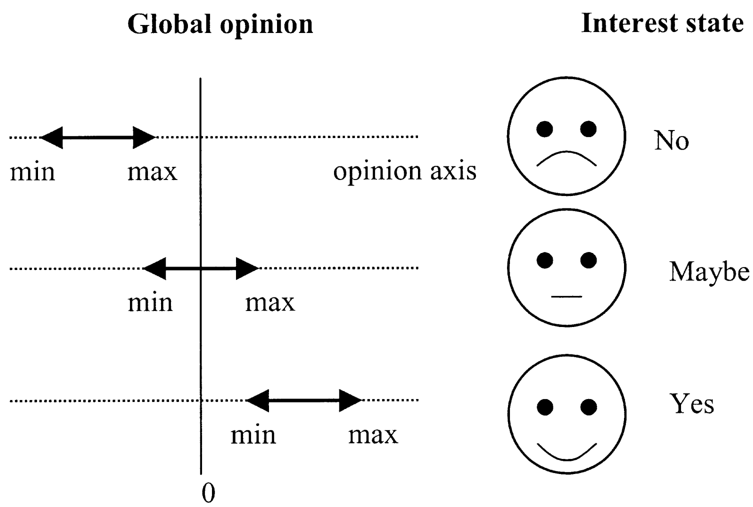


FIG. 1.—Definition of the interest state. The global opinion and uncertainty are equal to the social value and uncertainty if the individual benefit is not computed. If the individual benefit is computed, the global opinion is the average of the social opinion and individual benefit, and the global uncertainty is the average of the corresponding uncertainties. The global opinion plus or minus the global uncertainty is compared to zero. This comparison defines the interest state.

and by hypothesis, a benefit and uncertainty of value *nil*, there are two possibilities:

1. If the individual's interest state is *no*, then the decision state is *not concerned*. In this case, the individual does not pay attention to the information he or she may receive.
2. If the individual's interest state is *maybe* or *yes*, then the decision state is *information request.* In this case, when the individual receives a message with information, he or she has the probability ω of understanding and using it for the evaluation of personal benefit. To simplify, the value of the personal benefit is drawn from the normal distribution $N(m_i, \sigma_i)$, and the uncertainty is supposed fixed.

As soon as an individual evaluates his or her individual benefit, the decision state changes, and depending on the interest state of the individual, two possibilities appear again:

1. If the individual's interest state is *no* or *maybe*, then the decision state becomes *no adoption*. This means that the individual benefit was negative enough to drive down the global interest. This state is not definitive because messages with very high social opinions may change the interest state to *yes*.

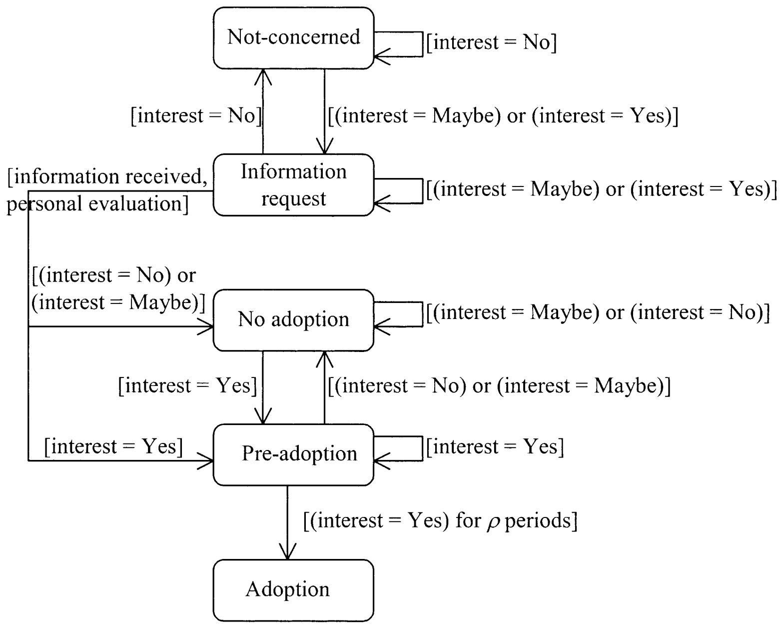


FIG. 2.—State diagram of the decision process. The squares represent the states and the comments near the arrows the conditions for the transitions. The interest state rules the attitude toward the information and also the final decision once the individual has an opinion about the personal consequences of adoption.

2. If the individual's interest state is *yes*, then the decision state becomes *preadoption*: the individual is ready to adopt, but takes reflection time to be sure of the decision. During this period, social influences may change his or her interest to *no* or *maybe*, and by consequence, the decision state to *no adoption*.

Finally, if the individual remained interested during a given number of time steps, noted ρ, he or she adopts, and the decision state becomes *adoption*.

The "Relative Agreement" Model, Ruling the Influence on the Social Values

During pair interactions, the social opinion and uncertainty are modified according to the relative agreement (RA) model of social influence (Deffuant et al. 2002). The main features of this model are the following:

1. Opinions with low uncertainty are more influential.
2. When the overlap between the segments formed by the opinion plus

and minus the uncertainty is too small, there is no influence.

q7 More precisely, let us consider opinion segments $s_i = [x_i - u_i,\ x_i + u_i]$ and $s_j = [x_j - u_j, x_j + u_j]$ (see fig. 3). We define the agreement of individual i with j (it is not symmetric) as the overlap of s_i and s_j, minus the nonoverlapping part. The overlap h_{ij} is given by

$$h_{ij} = \min(x_i + u_i,\ x_j + u_j) - \max(x_i - u_i,\ x_j - u_j). \tag{1}$$

The nonoverlapping width is

$$2 \cdot u_i - h_{ij}. \tag{2}$$

The agreement is the overlap minus the nonoverlap:

$$h_{ij} - (2 \cdot u_i - h_{ij}) = 2 \cdot (h_{ij} - u_i). \tag{3}$$

The relative agreement is the agreement divided by the length of segment s_i:

$$\frac{2 \cdot (h_{ij} - u_i)}{2 \cdot u_i} = \frac{h_{ij}}{u_i} - 1. \tag{4}$$

If $h_{ij} > u_i$, then the modifications of x_j and u_j by the interaction with i are multiplied by the relative agreement:

$$x_j :\ = x_j + \mu \cdot \left(\frac{h_{ij}}{u_i} - 1\right) \cdot (x_i - x_j), \tag{5}$$

$$u_j :\ = u_j + \mu \cdot \left(\frac{h_{ij}}{u_i} - 1\right) \cdot (u_i - u_j), \tag{6}$$

where μ is the rate of the dynamics. If $h_{ij} \leq u_i$, there is no influence of i on j.

We studied the properties of this model (see Deffuant et al. 2001; Deffuant 2001), in particular, with a population including extremists (Deffuant et al. 2002*a*). This study exhibits some conditions under which the majority of the population, initially moderate, becomes extremist. We also studied the influence of various social network structures on the convergence type (Amblard and Deffuant 2004). In the present model, the initial distribution of opinions is drawn from a normal distribution instead of a uniform one. This modifies a bit the global behavior of the model, as shown in below.

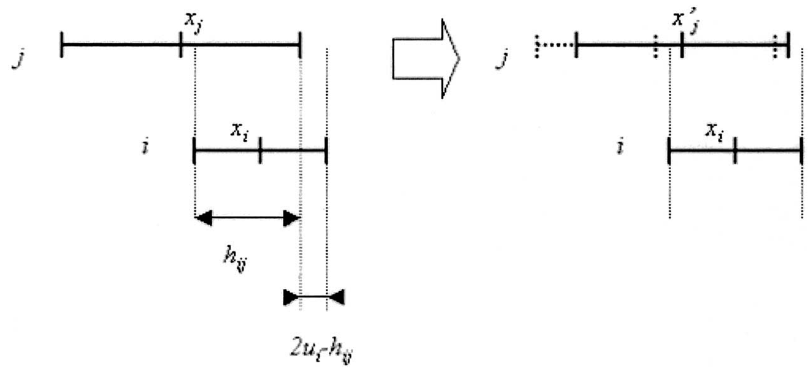


FIG. 3.—Individual i (opinion x_i and uncertainty u_i) influences individual j (opinion x_j and uncertainty u_j). h_{ij} is the overlap between segments i and j, and $2u_i - h_{ij}$ is the nonoverlapping part of segment j. On the right, the dotted lines represent the segment before interaction, the plain lines after interaction.

Propagation of the Discussions

We assume that the media regularly send messages to the population. At each time step, individuals chosen at random receive the media message, which triggers a cascade of discussions, propagating in the network in the following time steps. We assume that the first individuals who receive the message from the media tend to discuss it with their neighbors, who themselves then tend to discuss it with their neighbors at the next time step, and so on. We assume that this tendency to discuss decreases linearly with the time elapsed after the reception of the message from the media by the individual who initialized the cascade.

Let t_0 be the time step at which an individual i_0 receives an information message from the media. At time step $t_0 + t$, all the individuals reached by the discussion during the time interval t from individual i_0 (i_0 included) send messages to a proportion of their neighbors which is given by

$$p(t) = \begin{cases} 1 - \gamma \cdot t & \text{while } 1 - \gamma \cdot t > 0 \\ 0 & \text{if } 1 - \gamma \cdot t \leq 0, \end{cases} \tag{7}$$

where $0 < \gamma < 1$ is a parameter of the model, which rules the tendency of the population to discuss the innovation. When γ is close to one, the discussions do not propagate. On the contrary, when γ is close to zero, the discussions tend to propagate far in the network; the number of discussions triggered by one individual receiving a message from the institution first increases and then decreases progressively.

EXPLORATION OF THE MODEL

We explore the model with an experimental design on a subset of parameters, the others being fixed: we run the models several times for these values and compare the results. In the first step, we analyze the evolution of the social opinion distribution. We use this first step to explain the variations of the final proportion of adopters and informed individuals.

Experimental Design

This experimental design focuses on

1. initial distribution of the social opinion and the distribution of personal evaluation;
2. parameters affecting the evolution of the social opinion and the propagation of information (the average size of the individual's social network, the frequency of information diffusion by the institution).

This decision comes from larger investigations on the model, which we omit here for the sake of simplicity.

Fixed parameters.—We fixed the main parameters of the internal dy-
q9 namics, because this is not our main focus in the experiment (see table 1). In particular, we kept the population size equal to 1,000 individuals. Previous investigations showed that the main features of the dynamics are not sensitive to population size above 50 individuals.

Moreover, we fixed the standard deviation of the individual benefit evaluation distribution, the uncertainty of this evaluation, and the uncertainty of the extremists (if any). The values are discussed below.

Varying values of the experimental design.—To simplify the presentation, we distinguish two parts in the experimental design (see table 2). The first part is related the parameters ruling the type of convergence of
q10 the social opinion distribution (see table 3):

1. The density of the network and the frequency of the media messages are aggregated into a single variable with two values (*high* or *low*). The value *high* means that at each time step, each individual has a probability of 0.4 of receiving an information message from the media, and each individual has four associates on average in the social network. The value *low* means that at each time step, each individual has a probability of 0.1 of receiving an information message from the media, and each individual has one associate on average in the social network.
2. The standard deviation σ_s of the initial distribution of social opinion has two possible values: 0.1 or 0.3.
3. There can be no extremists or 15% of extremists in the population. In the latter case, the extremists are the 15% of individuals having the highest social opinions.
4. The uncertainty of the moderate (or all the individuals of the population when there are no extremists), denoted U, has two possible values: 0.05 or 0.3.

The second part of the experimental design relates to the mean values of the initial distribution of the social opinions (m_s) and the mean value of the distribution from which the evaluation of the individual benefit (m_i) is drawn. We want to study more particularly different combinations of these values (for instance, an innovation having on average an a priori high social value in the population, but on average a low individual benefit). The considered combinations are given in table 4.

All the combinations between both parts of the experimental design are considered, which leads to 128 parameter configurations. A run of a simulation lasts 500 steps, which ensures a stabilization of all the state variables. We perform 20 runs for each parameter configuration, which

TABLE 1
FIXED VALUES OF THE DYNAMICS PARAMETERS

Variable	Value
Ω (the probability of transmitting the knowledge necessary to the economic evaluation of the measure)	.5
γ (discussion propagation)	.3
μ (intensity of the social influence)	1
ρ (reflection time necessary for the adoption decision)	15 time steps
N (number of individuals in the population)	1,000

makes 2,560 simulations in total. We compute then the average state of the population after 500 steps (proportion of adopters, informed individuals, individuals in different interest states, etc.) over the 20 runs.

Types of Evolution of the Social Opinion Distribution

In the first stage, we consider the evolution of the social opinion distribution when the parameters of the first part of the experimental design vary. The other part of the experimental design has no influence on the type of evolution of this distribution.

The results yield a typology which is very close to the one proposed in Deffuant et al. (2002*b*). The main difference is the introduction of two types: one in which the opinions remain stable over time (because of a very sparse network), and a mixed case between central and one extreme convergence.

1. The individuals keep their social opinion and uncertainty is almost unchanged during the whole process. We call this case "stable convergence" (fig. 4).
2. The social opinion of all the individuals converges toward the initial average opinion; the evolution of the population tends toward a

TABLE 2
FIXED VALUES OF THE EXPERIMENTAL DESIGN RELATED TO THE OPINIONS

Variable	Value
σ_i (SD of the individual benefit distribution)	.1
u_i (uncertainty of the individual benefit evaluation)	.01
u_e (uncertainty of the extremists' social opinion)	.01

TABLE 3
Variables Ruling the Type of Convergence of the Social Opinion

Network Media	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
σ_s	0	.1	0	.3	0	.1	0	.3	0	.1	0	.3	0	.1	0	.3
Extreme	0				.15				0				.15			
U	.05								.3							

TABLE 4
Average of the Initial Distribution of Social Opinions and of the Distribution from Which the Individual Benefit Is Drawn

	m_s							
	−.2		−.15		.15		.2	
m_i ...	−.15	.15	−.2	.2	−.2	.2	−.15	.15

consensus on the initial average opinion. We call this case "central convergence" (fig. 5).

3. A large part of the population has its social opinion which improves dramatically and converges to the values of the positive extreme of the initial distribution, with a small uncertainty. We call this case "extreme convergence" (fig. 6).
4. A mixed case occurs where a part of the population is attracted by the extremists, and the other part has a central convergence. We call this case "central extreme convergence" (fig. 7).

Table 5 shows the type of social opinion distribution evolution obtained for the different parameter configurations of the first part of the experimental design. The stable configuration systematically appears when the number of discussions is *low* (media and network). The extremists' effect appears of course only when extremists are present and particularly when σ_s/U is small, which is in agreement with the results obtained with a uniform initial distribution of social opinion. The central convergence

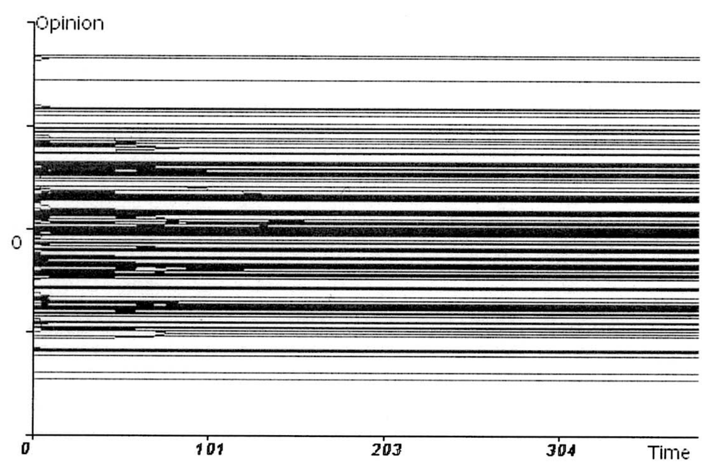


Fig. 4.—Trajectories of the individuals' social opinions in the case of "stable convergence" for the parameter values $U = 0.05$, $\sigma_s = 0.3$, no extremists, media network = *low*.

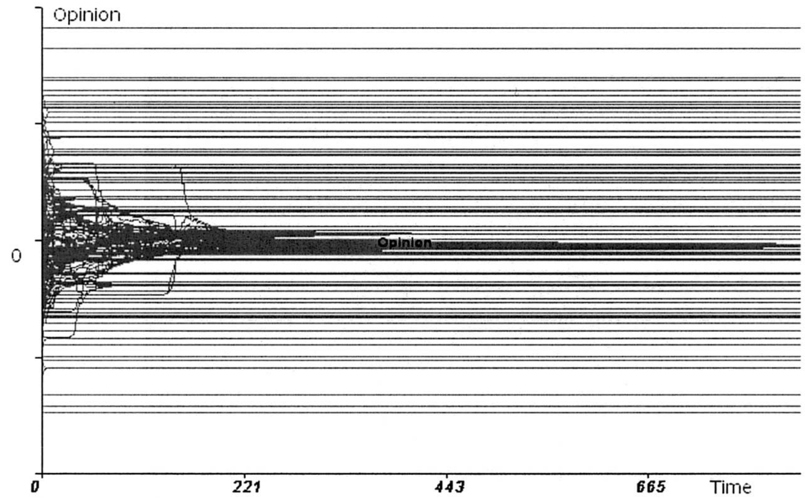


FIG. 5.—Trajectories of the individuals' social opinions in the case of "central convergence" for the parameter values $U = 0.3$, $\sigma_s = 0.3$, no extremists, media network = *high*.

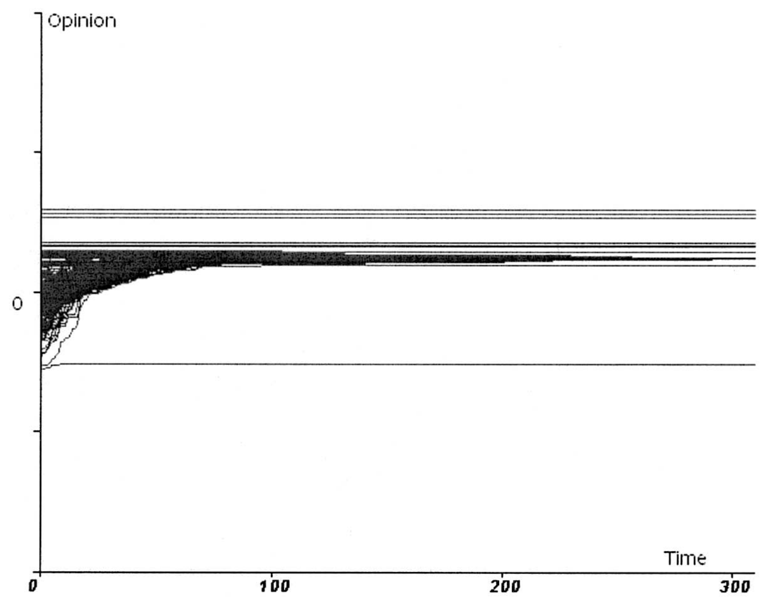


FIG. 6.—Trajectories of the individuals' social opinions in the case of "shift to positive extremism" for the parameter values $U = 0.3$, $\sigma_s = 0.1$, extremists = 15%, media network = *high*. The extremists (15% of the population) have horizontal trajectories in the upper part of the figure.

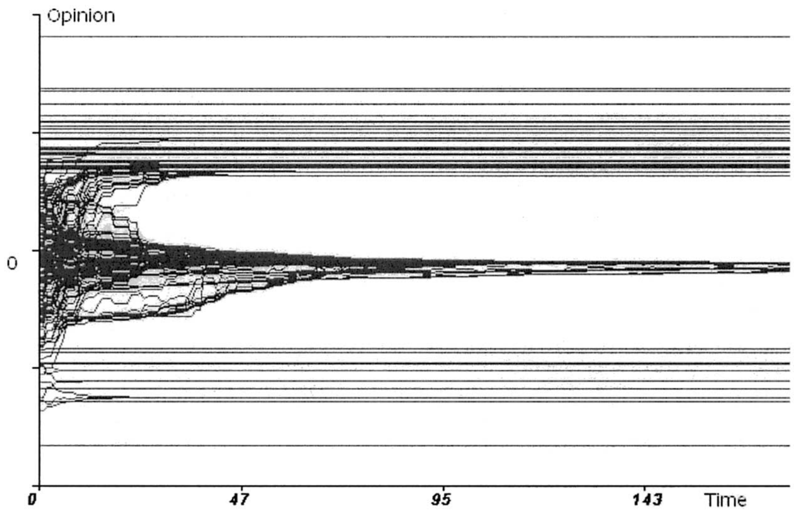


FIG. 7.—Trajectories of the individuals' social opinions in the case of "central extreme convergence" for the parameter values $U = 0.3$, $\sigma_s = 0.3$, extremists = 15%, media network = *high*. The extremists (15% of the population) have horizontal trajectories in the upper part of the figure.

takes place when there are no extremists and a high number of discussions (media and network). The central extreme takes place in intermediate situations. These results can be analyzed more carefully and explained with more details, but that is not our objective in this article.

Final Proportions of Adopters and Informed Individuals

We focus now on the final proportions of adopters and of individuals possessing the information, considering both parts of the experimental design. The typology introduced in the previous paragraph will help us to interpret the results. We distinguish different cases of combinations proposed in the second part of the experimental design.

The mean of the initial social opinion and the individual benefit evaluation distributions are both negative.—In figure 8, we consider the negative couples of the distribution means $m_s = -0.2$ and $m_i = -0.15$ or $m_s = -0.15$ and $m_i = -0.2$. The diffusion of information is generally lower when $m_s = -0.2$, but this does not lead to significant differences in the proportion of adopters. We note that the proportion of adopters is most of the time very low (between 0 and 2%), which is not surprising. However, the model can lead to a non-negligible number of adoptions (around 10%) when the standard deviation of the initial distribution of

TABLE 5

Type of Social Opinion Distribution Evolution

	Social Opinion Evolution															
	Stable	Central	Stable	Stable	Stable	Central + Extreme	Stable	Stable	Central	Central	Stable	Central	Stable	Extreme	Stable	Central + Extreme
Network media	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
σ_s	0	1	0	3	0	1	0	3	0	1	0	3	.1		.3	
Extreme	0				.15				0				.15			
U	.05								.3							

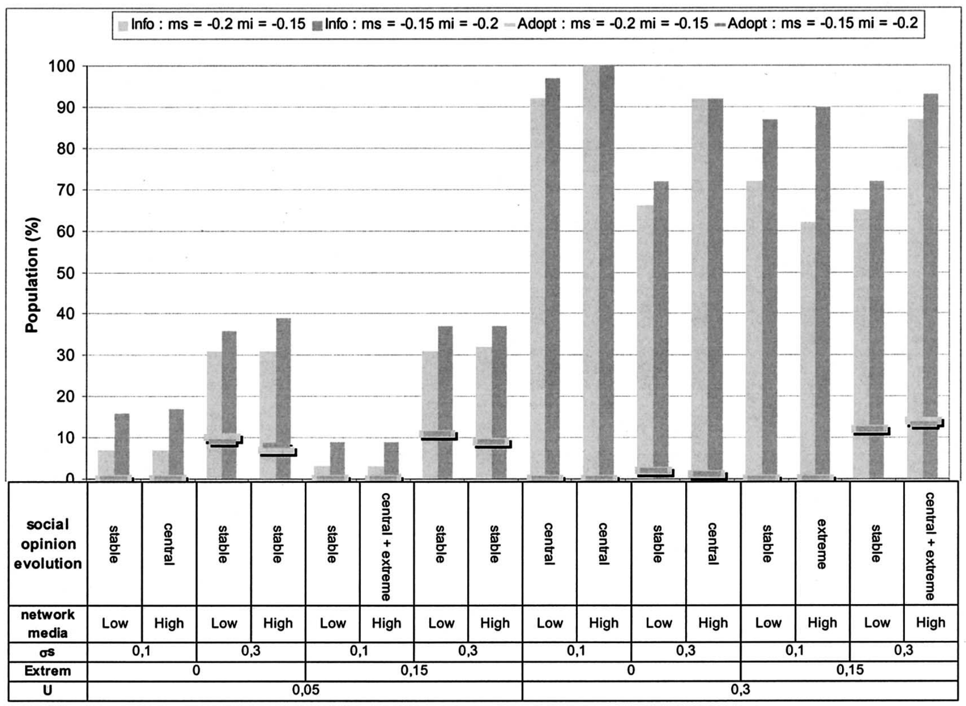


FIG. 8.—Final adoption (horizontal lines) and information (vertical bars) proportions when both the initial mean of the social distribution and the individual benefit are negative. The results are the average over 20 replications.

social opinions is large, and a bit more when there is an extremist effect. The large standard deviation initializes some individuals with an a priori high social opinion, and the extremist effect increases slightly their number.

Figure 9 gives an example of the evolution of the proportion of adopters, informed individuals, and of the different interest states on a particular run for a particular parameter configuration with extremists. The number of uncertain individuals decreases rapidly when the number of informed individuals increases, because the evaluation of the individual benefit is negative, which decreases the global opinion when it is evaluated. The slight increase of interested individuals at the beginning is due to the extremists (here the evolution of the social opinion distribution is "extreme central convergence."

We can enhance this extremist effect by increasing the uncertainty of the social opinion U to 0.7. In this case, one can reach more than 50% of adoption at the end of the simulation. One could relate these dynamics to innovations that were initially very badly perceived except by a convinced minority and finally had a good diffusion because of the influence of this minority. One can think of sects or religious movements for instance, which were initially persecuted and therefore represented a risk for the early converted (negative personal evaluation). But these early converted were convinced enough of the innovation's social value to neglect the personal risk.

The mean of the initial social opinion and the personal evaluation distributions are both positive.—Figure 10 shows the final proportion of adopters and informed individuals for the couples $m_s = 0.15$ and $m_i = 0.2$, or $m_i = 0.15$. We note that the results are very similar for both couples. When the uncertainty of the social opinion is low ($U = 0.05$), the proportion of adoption is quite high (more than 70%). A small uncertainty associated with a positive value of the opinion leads easily to an interest state of *yes*. One can relate these dynamics to innovations that have a good social image and are also valuable from a strictly personal point of view. The mobile phone could be put in this category.

However, when the initial distribution of social opinion has a large standard deviation (0.3), we notice that the final adoption proportion is lower, as well as the proportion of informed individuals. As illustrated by figure 11, which presents the time evolution of the population in a particular run for this parameter configuration, this is due to the fact that a proportion of individuals have an initial negative social opinion (they are not interested) and therefore do not get the information and do not evaluate their individual benefit. If they did, they would probably become interested or uncertain, because the individual benefit is positive.

With a larger uncertainty ($U = 0.3$), people tend to hesitate (decision

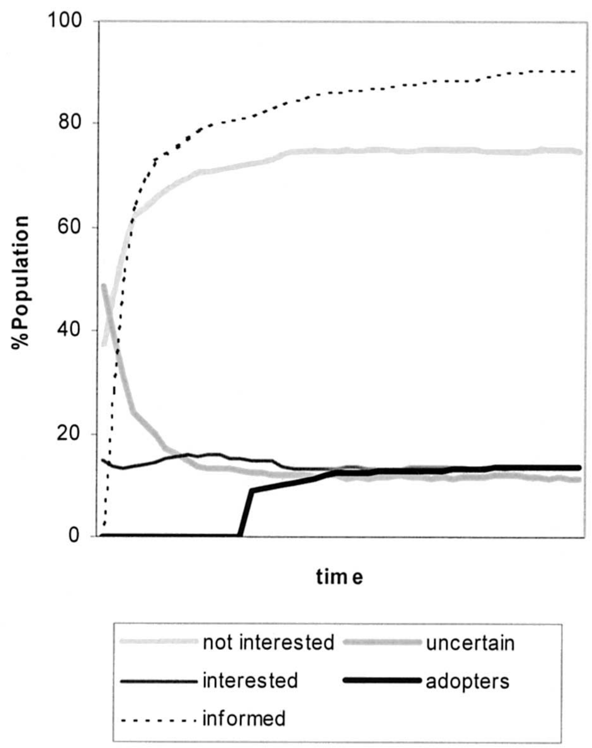
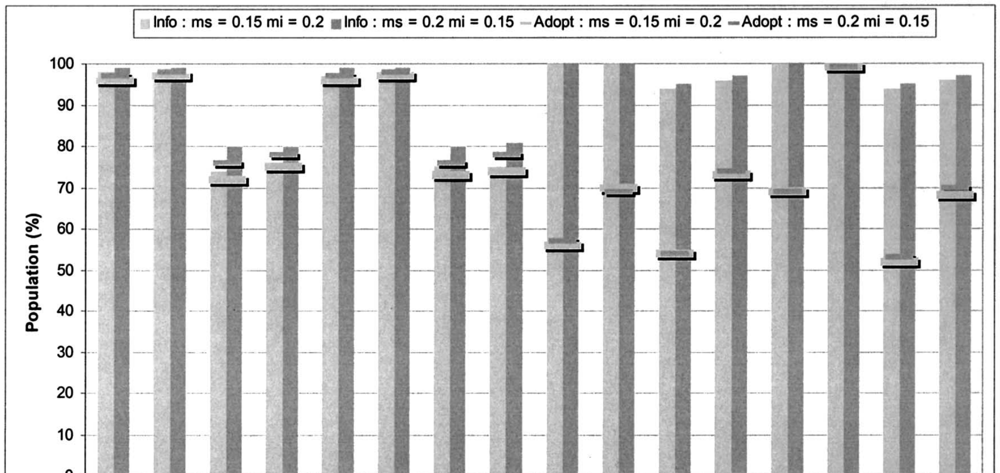


FIG. 9.—Example of evolution of the proportion of individuals in the different interest states, informed and adopters. $m_s = -0.2$ and $m_i = -0.15$. $U = 0.3$, $\sigma_s = 0.3$, 15% extremists, media network = *high*.

state = *maybe*), which generates a high level of information, but a lower adoption proportion. It can be only around 50% that the evolution of the social opinion is stable. This can be related to innovations that have globally high social value, but with a high uncertainty; they could also be very bad. One can think of the introduction of genetically modified organisms in agriculture, for instance. Although it is agreed that these innovations can generally bring improvements in the yield and resistance of the plants, the possible negative consequences on the global ecosystem are unknown and feared. Note that an extremist effect can lead to about 100% adoption, compared to 70% without the extremist effect (when $U = 0.3$ and $\sigma_s = 0.1$).

Intermediate cases.—We now consider the intermediate couples $m_s = -0.2$ and $m_i = 0.15$, or $m_s = 0.15$ and $m_i = -0.2$. These parameter configurations allow us to underline the asymmetry of the model between



social opinion evolution	stable	central	stable	stable	stable	central + extreme	stable	stable	central	central	stable	central	stable	extreme	stable	central + extreme
network media	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
σs	0,1		0,3		0,1		0,3		0,1		0,3		0,1		0,3	
Extrem	0				0,15				0				0,15			
U	0,05								0,3							

FIG. 10.—Final adoption (horizontal lines) and information (vertical bars) proportions when both the initial mean of the social distribution and the individual benefit are positive. The results are the average over 20 replications.

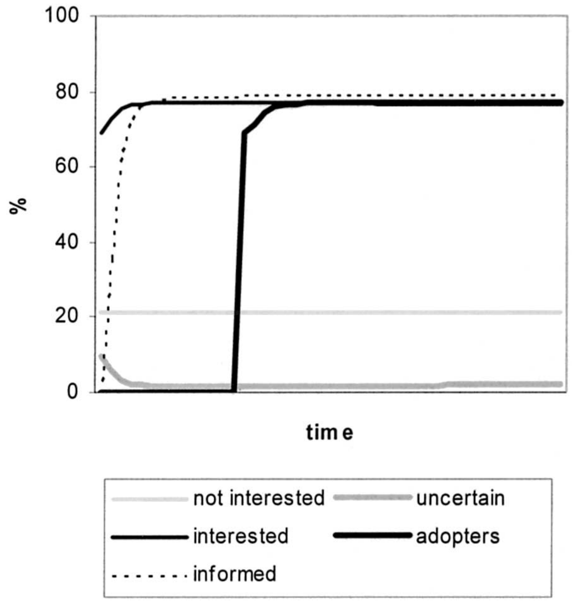
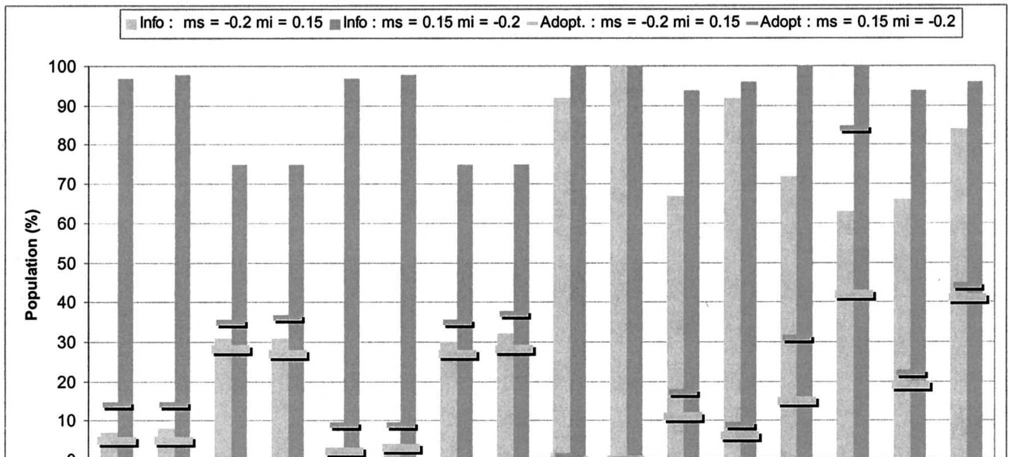


FIG. 11.—Example of evolution of the proportion of individuals in the different interest states, informed and adopters. $m_s = 0.2$ and $m_i = 0.15$. $U = 0.05$, $\sigma_s = 0.3$, no extremists, media network = *high*.

the social and the personal opinions. This asymmetry is due to the hypothesis that the social opinion governs the initial interest state.

In figure 12, we note the couples lead to significantly different adopter proportions and even more different proportions of informed individuals. Especially for small values of the social opinion uncertainty ($U = 0.05$), the proportion of informed individuals is lower than 40% when $m_s = -0.2$ and higher than 70% when $m_s = 0.15$. The reason is that when the social opinion is negative and the standard deviation of the social opinion is small, the information propagates poorly because the interest state tends to be *no*. In case 2, for the social opinion uncertainty $U = 0.05$, the proportion of individuals having the information is very close to the adoption proportion, indicating that it is the limiting factor. On the contrary, in case 1, the information is possessed by almost the whole population (at least 80%). It is therefore the difference of propagation of information which explains the difference between these cases. Such a difference of dynamics can be related to the difficulty of diffusing innovations that have a low cultural acceptability, even though they can bring a significant improvement of individual well-being. Think about the condom, for example, which is not adopted because of its bad cultural image in some



social opinion evolution	stable	central	stable	stable	stable	central + extreme	stable	stable	central	central	stable	central	stable	extreme	stable	central + extreme
network media	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
σs	0,1		0,3		0,1		0,3		0,1		0,3		0,1		0,3	
Extrem	0				0,15				0				0,15			
U	0,05								0,3							

FIG. 12.—Final adoption (horizontal lines) and information (vertical bars) proportions when the initial mean of the social distribution and the individual benefit are of opposite signs. The results are the average over 20 replications.

African societies, even though a large part of the population is HIV positive.

On the other hand, one can find examples of well-diffused behaviors which have negative consequences on individual well-being because of their good social image. For instance, different types of risky behaviors diffuse among young people in modern societies because they are very fashionable within the group, or play the role of necessary rituals of acceptence within the group.

However, the preponderance of the social opinion has limits, and when the personal evaluation becomes too negative compared to the social benefit, the diffusion is also very limited. For example, when $m_s = 0.15$ and $m_p = -0.2$, the diffusion culminates around 35%, except when there is an extremist effect, which brings adoption up to 70%. In the latter case, as illustrated by a particular simulation in figure 13, the number of interested individuals increases rapidly while the number of uncertain individuals decreases because of the extreme convergence of the social opinion. For many individuals, this high social value compensates for the negative individual benefit.

DISCUSSION AND CONCLUSION

We proposed an extension of the threshold model of innovation diffusion. We maintained two main hypotheses of the threshold models, which are

1. a strong distinction between a social influence and a personal intrinsic payoff of the adoption,
2. a decision of adoption based on a trade-off between both aspects of the innovation.

We introduced several supplementary hypotheses which were suggested by our study on the diffusion of agri-environmental measures. In particular, we considered a continuous social opinion and an uncertainty (which can also be interpreted as conviction and broadmindedness), and particular dynamics of social influences based on this uncertainty. These dynamics offer the possibility of simulating the diffusion of extreme opinions in a population. We also introduced a variable of information about the innovation, which is necessary to make the evaluation of the intrinsic payoff. Moreover, we supposed that the attitude toward this information depends on the social opinion.

We are conscious that many of the assumptions behind the model are highly debatable: the choice of the social dynamics, the dynamics of discussion, the strong separation between social and personal opinions, the type of social networks, and more. We made several of these choices with

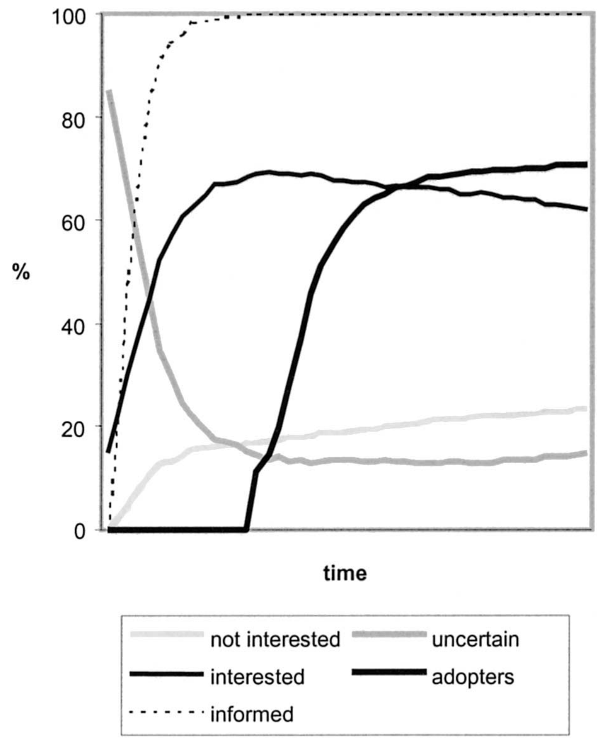


FIG. 13.—Example of evolution of the proportion of individuals in the different interest states, informed and adopters. $m_s = 0.15$ and $m_i = -0.2$. $U = 0.3$, $\sigma_s = 0.1$, 15% extremists, media network $=$ *high*.

poor or without empirical justification, and sociologists or psychologists might see them as strong and artificial simplifications. We consider these proposals as first approximations which can be refined or totally changed in light of empirical evidence.

However, one can criticize the model from an opposite point of view: it may appear too complicated to be efficiently related to quantitative data. We also partially accept this criticism. Our attempts to relate the initial distribution of opinions and uncertainties with empirical data from questionnaires (see Deffuant 2001) were not entirely satisfactory. We also had some difficulty in attributing concrete values to some parameters of the dynamics. In this respect, the threshold model is easier to deal with.

Nevertheless, the richness and the interpretability of the different dynamical behaviors of the model seem to us good arguments in its favor. The interpretability indicates that the complexity of the model remains humanly tractable, and that the model helps to bring a new way of understanding complex social phenomena. Is that not what we ask from a model?

Let us recall the features identified from the experimental design:

1. The extremist effect can lead to a significant diffusion of innovations which were initially, on average, badly evaluated socially and for personal well-being. This extremist effect is also identified for innovations that have an average positive value.
2. A large uncertainty can lead to innovations that trigger the interest of many people but diffuse poorly.
3. A low social opinion can block the diffusion of innovations that bring an individual benefit because it prevents good diffusion of information.

These features illustrate the richness of the model and the potential to relate it to specific innovations. In particular, the influence of the social opinion on the diffusion of information is a feature that explains the difficulty of diffusing innovations that have a low social image, even though they bring an objectively significant improvement to individual well-being. Therefore, we argue that the model presents a new and meaningful typology of innovation diffusion. We consider these properties of the model to represent interesting progress compared to the initial threshold model. Moreover, this typology may offer the possibility of grounding the model in data coming from particular concrete examples of innovation diffusion, even if the values of some parameters may have to be tested by exploration of the parameter space.

The structure of this model could also be used to model more specific social diffusion phenomena, such as political votes or the purchase of specific products. In these cases, the role of social opinion messages in the media (which were not considered in our design experiment) as well as the social network structure would be interesting subjects of research.

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