Experts and Non-experts

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Summary

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Keywords: Opinion, Expert, Instructions

JEL Classification: D81, L21

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Abstract

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1 Introduction

It is tautological that a manager will expect low productivity from a subordinate he judges to be incompetent. Equally, a subordinate will expect poor results from obeying a superior reputed to be unreliable. While the concern of an employee for being positively evaluated by his manager has been analyzed from various perspectives, (such as influence activities (Milgrom (1988) and the theory of yes-men (Prendergast (1993)), just to quote a few), on the contrary, the leadership role that a manager can exert, just because his competence is highly regarded by his subordinates, has possibly received less attention. That leadership role is the specific focus of the present paper and it is shown to be significant independently of incentive concerns. In particular, the issues addressed by the paper are the following:

a) under which conditions is a manager's credibility crucial for his subordinates' behaviour?

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b) Can the manager's concern about his own reputation affect the instructions he gives to his subordinates?

Especially in large organizations, a person's immediate hierarchical superior is often his official source of information and instructions. Information and instructions concern variables that the receiver knows to be relevant for his productivity, but that can be beyond his scope of direct observation or understanding. In this sense, hierarchical superiors can be said to act in the quality of experts with respect to their subordinates. When the subordinate receives instructions deriving from variables beyond his competence, he cannot but take those instructions very much like the opinion of the sender, rather than decodable and self-explaining data. In this sense, instructions can be considered a very special case of soft information: when even instructions consist of logical and incontrovertible inferences from freely available hard information, the receiver who lacks the knowledge indispensable for repeating the same inferences[1] will face a sort of "ideological" problem. In this special but not infrequent case, cheap talk itself between the sender and the receiver of instructions, i.e. the exchange of non-verifiable messages of any given length or complexity, may be of no particular help in building up the credibility of the sender. On the contrary, short instructions may actually achieve the same results of long messages.

The present paper is just concerned with:

a) the use of the expert's advice by a non-expert decision-maker, and

b) the impact of that use on the reporting of predictions by the expert.

The paper considers the case in which both expert and decision-maker are solidaristic, but the decision-maker can only rely upon his personal assessment of the expert's credibility in taking account of the expert's judgement.

In particular, the non-expert is uncertain about the current state of nature, that can be either low or high in every period. The non-expert has a 50-50 prior that the current state is low. The expert sends to the non-expert a message to be interpreted as the announced probability that the current state of nature is low. The distinctive assumption of the paper is the following: the non-expert considers the expert himself an experiment of uncertain reliability and takes the received messages as the outcomes of such an experiment. Hence, at the beginning of every period, the non-expert will have a density function for the expert's credibility, where a particular level of credibility corresponds to a pair of likelihood functions of the current message, each one conditional on a specific realization of the state of the world. The non-expert will use his density function for the expert's credibility in order to derive the likelihood functions of the current message, conditional on the state of the world. Those functions represent the non-expert's current subjective measure of the expert's credibility, and they are combined with the expert's message in updating the non-expert's prior about the current state. The model of the expert used by the non-expert is known by the expert. At the end of every period, all the agents can observe the realized state of nature, and the non-expert will revise

[1] As an example, I can read the results of my clinical tests, but I am unable to draw any inference from them.

his model of the expert on the basis of the message sent by the expert and the realized state. That is, at the end of each period the non-expert will update his density function for the expert's reliability. In every period, the non-expert will take some action proportional to his posterior probability that the current state is low. It is assumed that in every period the expert aims at minimizing the squared distance between his probability that the current state is low and the non-expert's posterior.

The paper shows that, as long as the non-expert does not consider the expert to be perfectly reliable, the expert will increase his current payoff by reporting a biased message. Distortion will work in the following way: agent E will announce a low-state probability that is smaller than his true belief, when he is less confident than a low state will occur; instead, agent E will announce a low-state probability that is greater than his true belief, when he is more confident than a low state will occur. In other words, agent E will exaggerate his messages in order to make them "loud and clear". The worse is agent E's reputation according to agent N, the greater will be both the distortion in the announced probability and the loss expected by agent E, just because agent N is more insensitive to messages.

In case of repeated interaction, the expert will also be concerned about his reputation in later periods. The paper shows that, in choosing the optimal report of his predictions, the expert will face a trade-off between the current accuracy of the perception of his judgement by the decision-maker and his future credibility in the decision-maker's view. It follows that agent E will keep on exaggerating his report only when his true probability of a low state are sufficiently extreme. Instead, when agent E is sufficiently uncertain about the current state, to exaggerate his announced opinion will adversely affect his expected reputation at the last period. In order to preserve credibility, and so to keep control over future expected losses, agent E will accept a higher expected loss today. As a result, messages will less biased with respect to the true beliefs of the sender.

The rest of the paper is organized as follows. In Section 2, I discuss the related literature, and, in Section 3 I describe the assumptions and the basic model. In Section 4 some preliminary results are obtained. Section 5 is concerned with the one-period interaction and Section 6 with the two-period interaction. In Section 6, I conclude. All proofs are in the Appendix.

2 Related Work

The paper is an attempt to combine contributions from different strands of literature:

1) statistical models about the use of experts and the reporting of predictions;

2) economic models about strategic information transmission and professional advice;

3) the theory of teams and the issue of interaction among agents in informationally decentralized organizations.

In the following I will refer only to the contributions most directly related to the present paper since the relevant strands of literature hold a massive bulk of important models, the extensive review of which would exceed the scope of the present work.

1) The utilization of expert judgement

In French (1986) the expert problem is summarized in following way: a decision-maker needs to assess his subjectivity probability for an event of interest; having little substantive knowledge of the factors affecting the event of interest, the decision-maker asks another person for advice. The consulted person is referred to as an expert. Although the word expert generally means someone reputed to have some special knowledge[2], in that literature an expert is anyone who can give predictions, i.e. anyone who can make probability statements, called judgments or opinions, concerning the event of interest. The problem is: how should the decision-maker incorporate an expert's opinion into his own?

Morris (1974, 1977), Lindley et al (1979), and French (1980) propose a Bayesian modeling approach to the use of experts[3]. The decision-maker should look upon the expert's opinion simply as a piece of data: consulting an expert is like performing an experiment, and just as the results of an experiment are a priori unknown to an experimenter, so the expert's advice is uncertain to the decision maker prior to receiving it. In particular, following Morris (1974), who generalizes the model to uncertain quantities and not just uncertain events, let the probability density function assigned to the uncertain variable x, based on the state of information δ, be denoted by $\{x \mid \delta\}$. Specifically, let $\{x \mid d\}$ and $\{x \mid e\}$ be the decision maker's and the expert's priors. How should the decision maker's prior be altered upon reception of $\{x \mid e\}$? According to Morris (1974), the only restriction to the decision-maker's posterior assessment of the variable x, conditioned on receiving the expert's opinion, is that it is consistent with both his prior knowledge about the variable and his appraisal of the expert. In particular, applying Bayes' theorem, the decision maker's assessment of x conditioned on the fact that the expert's prior is revealed to be $\{x \mid e\}$ will correspond to:

$$\{x \mid \{x \mid e\}, d\} = \frac{\{\{x \mid e\} \mid x, d\} \{x \mid d\}}{\{\{x \mid e\} \mid d\}}$$

where $\{\{x \mid e\} \mid x, d\}$ is the likelihood function, that, as Morris point out, is not the probability of a probability in the classical sense, but is the probability of the event that the expert's prior is $\{x \mid e\}$ given x. In other words, the likelihood function is the model of the expert in the decision-maker's view[4].

[2] Expert is a person who is very knowledgeable about or skilful in a particular area according to the Concise Oxford English Dictionary (2006).

[3] Related works are Morris (1983) and Genest-Schervish (1985).

[4] Morris (1974, p.1238):

> Suppose a decision maker is considering the weather to determine the prospects for a picnic. His view is that there is a 50-50 chance of rain....While

Consequently, the likelihood function is the decision-maker's subjective measure of the expert's credibility[5]. According to Morris (1977), just because the decision-maker interprets the reception of the expert's advice as the outcome of an experiment, a distinction is required between the meaning of an expert's probability assessment to the decision maker and the expert himself: the expert views his probability assessment as a reflection of his state of information, instead, the expert's probability assessment is information to the decision-maker.

The present paper applies Morris' idea of the non-expert's subjective assessment of the expert's reliability to the relationship between a subordinate and his hierarchical superior in a dynamic setting.

As far as the optimal reporting of predictions is concerned, the usual case is that in which both expert and decision-maker are interested in assessing the value of some parameter θ. In particular, the word expert is the label attached to the agent who is going to observe some private new data Y. However, both expert and decision-maker agree upon the conditional distribution for Y given θ for all possible values of θ (Bayarri-DeGroot (1991)). The supposed consensus upon the conditional distribution for private data given the unknown parameter is the indispensable common ground for the interplay between Bayesian players. In this way, expertise is a particular case of asymmetric information[6].

Instead, the present paper moves from the assumption that the knowledge of the decision-maker may be so poor that he may not have a clue about the conditional distribution for Y given θ, but can just formulate his own personal assessment of the expert's credibility. The messages transmitted from superior to subordinate can be seen as a sort of pathological case of soft information in that hard information could be provided, but not understood by the non-expert[7]. If the distinguishing characteristic of the expert is his differential knowledge, and not just his informational advantage, the strategic interaction between expert and decision-maker gets troublesome, as I will discuss later on.

2) Asymmetric information and strategic communication

In the economic literature concerning professional advice, asymmetric infor-

he is waiting for the weather report he ponders how he will use the weatherman's advice. He first reason that the weatherman will state a probability of rain p (shorthand for $\{R \mid e\}$ where R denotes rain and $R\prime$ denotes no rain). The decision maker ... makes a subjective appraisal of the dependence between the expert's advice and the actual weather. Specifically, he asks himself what his assessment of p would be if an honest clairvoyant told him that it will surely rain on his picnic...For any given value of p he can calculate the posterior probability of rain to be:

$$\{R \mid p, d\} = \frac{\{p \mid R, d\}\,\{R \mid d\}}{\{p \mid R, d\}\,\{R \mid d\} + \{p \mid R', d\}\,\{R' \mid d\}}$$

[5] The likelihod function is related to the idea of calibration: according to Lindley (1982), an expert is probability calibrated if the decision maker adopts the expert's opinion for his own. Other concepts of calibration are discussed by DeGroot-Fienberg (1983).

[6] Economic contributions following this approach are concerned with the issue of delegation to self-interested experts who are the agents in a principal-agent relationship (for instance, Li-Suen (2004) and Demski-Sappington (1987)).

[7] As an example, I can read the results of my clinical tests, but I am unable to draw any inference from their values.

mation is at the heart of what is commonly known as cheap talk between the sender and the receiver of messages. In Crawford and Sobel (1982), a better informed sender sends a possibly noisy signal to a receiver, who takes an action that determines the welfare of both. The sender has observed the value of a random variable that is modelled as his type. Equilibrium is shown to involve noisy signaling unless the agents' interests coincide. While in Crawford and Sobel the focus is on strategic information transmission by a partisan expert who is interested in biasing the action of a decision-maker, Ottaviani and Sorensen (2006a)[8] consider a professional expert concerned about appearing to be well informed, i.e. concerned with his reputation for ability. The expert observes a private signal generated by a multiplicative linear experiment. The expert's unobserved ability parametrizes the amount of information about the state of the world contained in the expert's signal. After observing the signal, the expert is free to publicly report any message. An evaluator combines the expert's message with the ex-post realization of the state to update the belief regarding the expert's ability. This posterior belief about ability is the expert's reputation and determines her payoff. The quality of the expert's information is evaluated on the basis of the advice given and the realized state of the world. The signal that gives rise to the highest expected reputational payoff is shown to be typically different from the signal actually observed.

The present paper takes from Crawford and Sobel the idea of a partisan expert, in that the expert's expected payoff depends on the decision-maker's actions. However, while in Crawford and Sobel, equilibrium will not involve noisy signals when the agents' interests coincide[9], in the present paper solidarity is shown to be consistent with biased messages. The present paper takes from Ottaviani and Sorensen the idea of reputation concern on the expert's side, that, however, descend from the assumption of both common interest and repeated interaction between expert and decision-maker. In contrast with models of strategic information transmission, the adoption of Morris' approach to the use of expert's advice by the decision-maker makes this paper depart from the usual game-theoretic approach. The reason is that the decision-maker will resort to his own model of the expert and, consistently, the usual game-theoretic concept of types for the experts seems to be only loosely appropriate. In this way, the present paper is an attempt to pursue the intuition that the underlying difference between expert and non-expert is not private information, but differential knowledge.

Credibility in information transmission is analyzed by Sobel (1985) for a case in which an agent, the receiver, must decide whether to trust another, the sender. The last one observes the value of a binary random variable and sends a message to the receiver, who takes a decision affecting the welfare of both

[8]Related papers by the same authors are Ottaviani-Sorensen (2006b) and (2006c). Quite a diiferent approach to the expert problem is taken by the economic lietarure about credence goods. In that case, fraud and cheating are the major problems in the interaction between experts and consumers (for an extensive review, see Dulleck and Kerschbamer (2006)).

[9]Theu show that the amount of information revealed in equilibrium increases as the preferences of the sender and the receiver become aligned.

agents. The problem is that the receiver is uncertain about the preferences of the sender, who can be a "friend" or an "enemy". Repeated interaction between the agents, coupled with verifiable information at the end of each period of interaction, is shown to make it worthwhile for the receiver to build a reputation for truthfulness[10].

The present paper shares the same concern for credibility descending from repeated interaction, but focuses on experts who are uncertain about the realized state of the world, and on receivers who are uncertain about the experts' ability as probability assessors, and not about the senders' preferences. In this way, credibility is more the outcome of reliability than the result of honesty.

In the economic literature, the issue of opinions, and, more specifically, of differences of opinions is often related to the discussion of the common prior assumption and to differential interpretations of public signals. For instance, in Harris and Raviv (1993), traders update their beliefs about an asset's returns using their own likelihood function of the relationship between public signals and the asset's returns. The fact that traders adopt different likelihood functions is common knowledge. Different interpretations of the informative content of public announcements is shown to be consistent with the volumes of trades in speculative markets (Kandel and Pearson (1995)).

3) Hierarchies and informationally decentralized organizations

In the organization literature, hierarchies are built in order to save on information and knowledge costs. In this sense, a superior can be seen as an expert who gives advice regarding stochastic variables to his subordinates. In particular, the theory of teams by Marschak and Radner (1972) is an impressive mechanism aimed at modeling decision rules for interdependent actions of solidaristic but informationally differentiated agents. In that context, information is diversified in that different agents can observe different random variables, all of them having an impact on the optimal team action profile. Marschak and Radner are concerned with the design of the team optimal communication structure. All the internally transmitted information is "soft information", that the authors themselves call instructions in some special cases. Marschak and Radner focus on examples of noisy channels of communication yielding distortions in the transmitted messages. The present paper follows the team approach in that agents' behaviour is affected not by a conflict of interest, but by a particular type of bias impairing the received messages. However, in the present paper, messages can be distorted because they need to be subjectively interpreted by the receivers, and not because they travel along noisy channels,.

The relevance of workers' opinions or ideas is analyzed by Zabojnik (2002). For a case of moral hazard, it is shown that it may be less costly to motivate a worker who is allowed to work on his own ideas, rather than a worker who is forced to follow the ideas of a better informed manager. In Zabojnik both worker and manager observe signals of different quality about the state of the word that was realized, and the comparison is between decentralized vs. centralized decision-making in a framework of conflict of interests. The present paper,

[10] Honesty in informal communication is further analysed by Olszewski (2204).

instead, shows that, notwithstanding solidarity between the agents, the worker will adhere to his manager's instructions as much as the credibility he feels with respect to his superior's competence will let him.

An economic analysis of leadership is the issue of papers such as Rotenberg and Saloner (1993) and Hermalin (1998). Rotenberg and Saloner are concerned with incentive problems and show that leadership style can affect the incentive contracts that can be offered to subordinates. Instead, in Hermalin leadership is distinguished from authority because following a leader is perceived to be a voluntary, rather than coerced, activity of the followers. Manager and workers form a team à la Holmstrom (1982), the performance of which is impaired by its members' shirking, that descent from the team output-sharing agreement. Leadership is analysed as the capacity to induce rational agents to exert effort in situations when the leader has incentives to mislead them. The present paper shares the idea that leadership is more sensitive to trust than authority is. Again, trust and reactivity to instructions are shown to be relevant even in cooperative situations.

Finally, the present paper and Prendergast's (1993) theory of yes men may be interpreted as different faces of the same coin: Prendergast is concerned with the reliability of the subordinate's reports, here the problem lies with the reputation and credibility of the manager.

3 Set-up

The paper is concerned with the relationship between two agents: an expert, labelled E, and a non-expert decision-maker, labelled N. In particular:

Assumption 1 *:*

1) the state of the world at time t, denoted by ω_t, is either low, ω_l, or high, ω_h, for every t spanning from 1 to T.

2) Every period t, agent N chooses the level of some action at no cost.

3) Every period t, before taking action, agent N receives one message p_t from agent E, with $p_t \in [0, 1]$. Message p_t is the probability, announced by agent E, that ω_t is ω_l.

4) Current action and current state yield current output. The expected undiscounted sum of per-period outputs is maximised by the following optimal action rule: choose always the level of current action in constant proportion with respect to the probability that the current state is low.

5) Both agents share the same objective in 4) and are aware of the optimal action rule.

6) Only after the current action has already been implemented, both the agents observe the realization of the state of the world for the same period.

Under Assumption 1, for T periods agent N and agent E are engaged in a joint activity. That joint activity yields per-period outputs that depend on both the current state and the current action. The set of states is binary.

Agent N is a decision-maker in that he has complete control over the relevant action, while agent E is an expert in that he is the source of messages stating the probability of a particular state for the current period.

The agents share a common objective and know the action rule optimal for that common aim. In particular, the optimal current action is simply proportional to the probability that the current state is low.

The assumption that the agents are solidaristic and know the optimal action rule serves the purpose of focusing attention on the interplay between agent N's beliefs and agent E's messages. That interplay may have a dynamic evolution since both the agents are supposed to observe the realization of the state of the world at the end of every period.

In particular, from Assumption 1, agent N will choose the current action in the correct proportion with respect to his posterior probability that the current state is ω_l. The matter just lies in agent N's beliefs, that satisfy the following Assumption.

Assumption 2 *:*

1) At the beginning of every period, agent N's prior probability that the current state is low is always equal to 0.5.

2) Agent N considers a message p_t as the outcome of the random variable P_t in the sample space $[0,1]$. Moreover, agent N believes that all messages from a particular expert are characterized by a unique parameter α from the parameter set A such that $pr\left(p_t, \omega_t = \omega_x \mid \alpha\right)$ is well defined for every α, p_t and x, with $x = l, h$. Finally, agent N believes that the messages of the same expert at different times form a random sample, conditional on the realization of the same state of the world: provided the true state is always ω_x and messages come from the same expert from time 1 to time n, then $P_1, P_2, ...P_n$ are i.i.d. with common likelihood function $l\left(p \mid \omega_x, \alpha\right)$, where $l\left(p \mid \omega_x, \alpha\right)$ is always non-negative for $p \in [0,1]$, and $\int_0^1 l\left(p \mid \omega_x, \alpha\right) dp$ is equal to 1.

3) At the initial period, agent N considers agent E an experiment of unknown parameter α, where α belongs to the non-singular parameter set A. Agent N believes that his advisor's parameter is a drawing from the distribution function G_1 of α, with corresponding non-degenerate density function $g_1\left(\alpha\right)$ on the parameter set A.

Under Assumption 2, the relationship between agent E and agent N springs from agent N's uncertainty about the current state of the world. Agent N's uncertainty is substantial for two reasons. First, agent N's prior probability that the current state is low is always 0.5; hence, agent N believes that the states at different periods are stochastically independent, and his uncertainty is the highest at the beginning of every period. Second, agent N looks at an expert as a source of messages with a systematic and unknown component represented by parameter α.

Let $pr(\omega_l \mid p, \alpha)$ denote agent N's posterior probability that ω_t is ω_l, given p_t equal to p and α, i.e.:

$$pr(\omega_l \mid p, \alpha) = \frac{l\,(p \mid \omega_l, \alpha)}{l\,(p \mid \omega_l, \alpha) + l\,(p \mid \omega_h, \alpha)} \tag{1}$$

The α parameters are a measure of the alignment of agent N's beliefs to the opinion stated by agent E because they satisfy the following condition:

Condition 1 *: the parameters α_i and α_j are connected by the binary relation R_1, denoted by $\leq_1$, such that:*
1) $\alpha_j \leq_1 \alpha_i$ if and only if:

$$|p - pr(\omega_l \mid p, \alpha_i)| \leq |p - pr(\omega_l \mid p, \alpha_j)| \qquad \vee\, p \in [0, 1]$$

2) $\alpha_j <_1 \alpha_i$ if and only if $\alpha_j \leq_1 \alpha_i$ and $\alpha_i \nleq_1 \alpha_j$
3) $\alpha_j =_1 \alpha_i$ if and only if $\alpha_j \leq_1 \alpha_i$ and $\alpha_i \leq_1 \alpha_j$

From Assumption 2 point 2), all the messages received by the same expert are supposed to be random variables with identical density function, $l\,(p \mid \omega_x, \alpha)$, conditional on the true state ω_x and parameter α. Under Condition 1, the α parameter is a measure of reliability in that it is related to the distance between agent N's posterior beliefs and agent E's messages. In particular, if $\alpha_j <_1 \alpha_i$, then, for some message p, $|p - pr(\omega_l \mid p, \alpha_i)|$ will be lower than $|p - pr(\omega_l \mid p, \alpha_j)|$: agent N's beliefs will be closer to the opinion from α_i than to the messages from α_j. In this sense, if $\alpha_j <_1 \alpha_i$, agent N will associate greater trust/reliability to α_i than to α_j.

Let $\tilde{\alpha}$ denote the particular parameter satisfying the following condition:

$$pr(\omega_l \mid p, \tilde{\alpha}) = p \qquad \vee\, p \in [0, 1] \tag{2}$$

In other words, given $\tilde{\alpha}$, agent N will adopt the received message as his own belief. Parameter $\tilde{\alpha}$ corresponds to the case of perfect calibration. It follows that $\tilde{\alpha} \geq_1 \alpha$ for every α in A.

Finally, say that a set C is completely ordered by a binary relation $\leq$ if and only if: a) $c_j < c_i$ or b) $c_i < c_j$ or c) $c_j = c_i$, for every $c_j, c_i \in C$. The following Assumption will be made:

Assumption 3 *:*
1) the parameter set A is completely ordered by relation R_1 from Condition 1
2) the parameter $\tilde{\alpha}$ in (2) belongs to A
3) $l\,(p \mid \omega_l, \alpha)$ is a continuous, differentiable and nondecreasing function of p
4) $l\,(p \mid \omega_h, \alpha) = l\,(1 - p \mid \omega_l, \alpha)$ for every p and α

Under Assumption 3, any two α parameters can be related through R_1 in terms of opinion reliability in the sense explained just above. Moreover, Assumption 3 specifies some properties of the likelihood functions $l\left(p \mid \omega_x, \alpha\right)$. In particular, agent N will believe that the probability, conditional on α, that p is announced at time t is positively related to the level of p when the current state is low, while it is negatively related to the level of p when the current state is high.

Now, consider the following condition for the weak property of monotone likelihood ratio:

Condition 2 *: the parameters α_i and α_j are connected by the binary relation R_2, denoted by $\leq_2$, such that :*

1) $\alpha_j \leq_2 \alpha_i$ if and only if:

$$\frac{l\left(p_k \mid \omega_l, \alpha_i\right)}{l\left(p_k \mid \omega_l, \alpha_j\right)} \geq \frac{l\left(p_z \mid \omega_l, \alpha_i\right)}{l\left(p_z \mid \omega_l, \alpha_j\right)} \qquad \forall\ p_k > p_z \tag{3}$$

2) $\alpha_j <_2 \alpha_i$ if and only if $\alpha_j \leq_2 \alpha_i$ and $\alpha_i \nleq_2 \alpha_j$

3) $\alpha_j =_2 \alpha_i$ if and only if $\alpha_j \leq_2 \alpha_i$ and $\alpha_i \leq_2 \alpha_j$

The following Lemma shows that relation R_2 is compatible with relation R_1. In particular:

Lemma 1 *: when A is completely ordered by relation R_2 from Condition* 2*, then $\alpha_j <_2 \alpha_i$ will imply that $\alpha_j <_1 \alpha_i$*

Proof. In the Appendix. ■

Given Lemma 1, the following Assumption will be made:

Assumption 4 *: the parameter set A is completely ordered by relation R_2 from Condition* 2

Given Lemma 1 and Assumption 2 point 3), let the distribution function G_1 of α in be defined on the parameter set A completely ordered by either R_1 or R_2.

The model of the expert adopted by agent N will correspond to the distribution of parameter α. Agent E's reputation will be represented by agent N's density function for parameter α. The reputation for credibility enjoyed by agent E will determine the relationship between agent E's message and agent N's posterior probability that the current state is low. At time t, given $g_t\left(\alpha\right)$, agent N will believe that the probability that agent E announces p_t equal to p, conditional on the current state ω_t being ω_l, denoted by $l\left(p \mid \omega_l, g_t\left(\alpha\right)\right)$, is equal to:

$$l\left(p \mid \omega_l, g_t\left(\alpha\right)\right) = \int_A l\left(p \mid \omega_l, \alpha\right) g_t\left(\alpha\right) d\alpha \tag{4}$$

The credibility of agent E's messages for agent N is a necessary intermediary step for the computation of agent N's posterior probability that the current state ω_t is ω_l, given $p_t = p$, i.e.:

$$pr\left(\omega_l \mid p, g_t(\alpha)\right) = \frac{l\left(p \mid \omega_l, g_t(\alpha)\right)}{l\left(p \mid \omega_l, g_t(\alpha)\right) + l\left(p \mid \omega_h, g_t(\alpha)\right)} \tag{5}$$

From (4), since at the end of period t the realization of the state of the world for the same period, ω_t, is public information, agent N will update his model of agent E for period $(t+1)$. Agent N will compute a new density function of α, $g_{t+1}(\alpha \mid \omega_x, p)$, that is equal to:

$$g_{t+1}(\alpha \mid \omega_x, p) = \frac{g_t(\alpha)\, l\left(p \mid \omega_x, \alpha\right)}{l\left(p \mid \omega_x, g_t(\alpha)\right)} \quad \text{given } \omega_t = \omega_x \text{ and } p_t = p \tag{6}$$

As far as agent E is concerned, the following Assumption will be made:

Assumption 5 *: agent E knows agent N's prior probability that ω_t is ω_l, and the density functions $g_1(\alpha)$ and $l(p \mid \omega_x, \alpha)$ for every ω_x and α. Every period t agent E can attach a probability $\bar{p}_t$ to the event that ω_t is ω_l.*

Under Assumption 5 , agent E can compute agent N's posterior probability that the current state is low, i.e. $pr\left(\omega_l \mid p, g_t(\alpha)\right)$ in (5). Hence, agent N's behaviour will be perfectly predictable by agent E, who can treat agent N as a sort of Stackelberg follower. In other words, agent E will have correct second order beliefs with respect to agent N. Contrarily to most models of expert behaviour, agent E's true probability that the current state is low, $\bar{p}_t$, will be interpreted just as agent E's confidence that the current state is low. In this sense, the α parameters will be relevant for agent E in as much as they affect agent N's beliefs, and not because they represent the rank through which agent E measures his own information.

Let $V\left(p_t \mid g_t(\alpha)\right)$ denote the squared difference between $\bar{p}_t$ and agent N's posterior probability that ω_t is ω_l, given $p_t = p$ and $g_t(\alpha)$ in (5), i.e.:

$$V\left(p_t \mid g_t(\alpha)\right) = \left[\bar{p}_t - pr\left(\omega_l \mid p, g_t(\alpha)\right)\right]^2 \tag{7}$$

Finally, let $\mathbf{p}_t$ denote the vector of messages from time t to time T, i.e.:

$$\mathbf{p}_t = \left(p_t, p_{t+1}, ..., p_T\right) \tag{8}$$

Given Assumption 1, solidarity between the agents and knowledge of the optimal action rule will make agent E concerned with the distance between his true probability $\bar{p}_t$ that the current state is low and agent N's probability of the same event. Indeed, that distance is related to the difference between the optimal action according to agent E and the optimal action according to agent N. It follows that agent E's expected payoff at time t, denoted by $\pi_t(\mathbf{p}_t)$, can be represented by the following function:

$$\pi_t(\mathbf{p}_t) = -\left\{ V\left(p_t \mid g_t(\alpha)\right) + E\left[\sum_{j=t+1}^{T} V\left(p_j \mid g_j(\alpha)\right)\right]\right\} \tag{9}$$

4 Preliminary results

The following Lemma shows that under the monotone likelihood ratio property the following results hold:

1) when the current state is low, the probability that a message lower than p is announced will never be greater conditional on α_i than conditional on α_j if $\alpha_j \leq_2 \alpha_i$;

2) agent N will interpret higher α as more informative experiments;

3) provided ω_l has occurred at time t, the posterior density function of α conditional on higher messages at time t will dominate in the sense of first order stochastic dominance the posterior density function of α conditional on lower messages at time t.

In particular, let $L(p \mid \omega_l, \alpha)$ denote the distribution function associated to $l(p \mid \omega_l, \alpha)$, i.e.:

$$L(p \mid \omega_l, \alpha) = \int_0^p l(m \mid \omega_l, \alpha)\, dm$$

The following can be proved:

Lemma 2 *:*
1) given $\alpha_i >_2 \alpha_j$, $L(p \mid \omega_l, \alpha_i) \leq L(p \mid \omega_l, \alpha_j)$ *for every* p
2) experiment α_i *is sufficient for experiment* α_j*.*
3) given $g_t(\alpha)$, $\alpha_i > \alpha_j$ *and* $p_k > p_z$*, then* $g_{t+1}(\alpha)$ *in* (6) *is such that:*

$$\frac{g_{t+1}(\alpha_i \mid \omega_l, p_k)}{g_{t+1}(\alpha_i \mid \omega_l, p_z)} \geq \frac{g_{t+1}(\alpha_j \mid \omega_l, p_k)}{g_{t+1}(\alpha_j \mid \omega_l, p_z)} \tag{10}$$

$$\begin{array}{rcll} G_{t+1}(\alpha \mid \omega_l, p_k) & \leq & G_{t+1}(\alpha \mid \omega_l, p_z) & \forall\alpha \\ G_{t+1}(\alpha \mid \omega_h, p_k) & \geq & G_{t+1}(\alpha \mid \omega_h, p_z) & \forall\alpha \end{array} \tag{11}$$

Proof. In the Appendix. ■

In order to handle an easier notation, let agent N's posterior probability that ω_t is ω_l, given p_t and $g_t(\alpha)$, in (5), be represented by the function $k_t(p_t \mid g_t(\alpha))$, i.e.:

$$pr(\omega_l \mid p_t, g_t(\alpha)) = k_t(p_t \mid g_t(\alpha)) \tag{12}$$

Under Assumption 3 points 3) and 4), $k_t(p_t \mid g_t(\alpha))$ in (12) is non-decreasing in p_t.

Let $\breve{A}$ denote the subset of A such that $l(p \mid \omega_l, \alpha)$ is increasing in p, i.e.:

$$\breve{A} = \{\alpha \mid l(p_k \mid \omega_l, \alpha) > l(p_z \mid \omega_l, \alpha) \text{ for every } p_k > p_z\} \tag{13}$$

The following Lemma shows that, provided some condition on the prior density function of α are satisfied, $k_t(p_t \mid g_t(\alpha))$ will always be strictly positive, lower than 1 and invertible. Moreover, $k_t(p_t \mid g_t(\alpha))$ will not be lower (higher) than p_t if p_t is lower (higher) than 0.5. Finally, provided ω_l has occurred at time t, the higher the message at time t, the greater will be the range of the domain of the inverse function k_t^{-1}. When $G_t(\alpha)$ dominates $G_t'(\alpha)$ in the sense of first order stochastic dominance, the range of the domain of the inverse function k_t^{-1} will be smaller under $G_t'(\alpha)$ than $G_t(\alpha)$. In particular:

Lemma 3 *: provided $g_t(\alpha)$ is non-degenerate on $\tilde{\alpha}$ and is positive for some α in $\check{A}$, then:*

1) $k_t(p_t \mid g_t(\alpha)) \in (0,1)$

2) $k_t(p_t \mid g_t(\alpha))$ is increasing in p_t, and so invertible.

3) $k_t(p_t \mid g_t(\alpha)) \geq p_t$ for every p_t in $(0, 0.5)$ and $k_t(p_t \mid g_t(\alpha)) \leq p_t$ for every p_t in $(0.5, 1)$

4) provided $G_t(\alpha) \leq G_t'(\alpha)$ for every α, then:

$$k_t(0 \mid g_t(\alpha)) < k_t(0 \mid g_t'(\alpha)) \leq k_t(1 \mid g_t'(\alpha)) < k_t(1 \mid g_t(\alpha)) \tag{14}$$

5) for every $p_k > p_z$:

$$\begin{aligned} k_{t+1}(0 \mid g_{t+1}(\alpha \mid \omega_l, p_k)) &< k_{t+1}(0 \mid g_{t+1}(\alpha \mid \omega_l, p_z)) \\ k_{t+1}(1 \mid g_{t+1}(\alpha \mid \omega_l, p_k)) &> k_{t+1}(1 \mid g_{t+1}(\alpha \mid \omega_l, p_z)) \end{aligned} \tag{15}$$

Proof. In the Appendix. ■

5 Message Rule for One Period Ahead

In the one-period case, agent E will announce p_T in order to minimize the distance between his own probability that the current state is low and agent N's posterior belief. Hence, from (7), (9) and (12), agent E will solve the following problem:

$$\min_{p_T} V(p_T \mid g_T(\alpha)) = [\bar{p}_T - k_T(p_T \mid g_T(\alpha))]^2 \tag{16}$$

Let $k_T^{-1}(\bar{p}_T \mid g_T(\alpha))$ denote the inverse function of $k_T(p_T \mid g_T(\alpha))$. Let p_T^* denote the solution to the problem in (16). The following can be proved:

Proposition 1 *: provided $g_T(\alpha)$ is positive for some α in $\check{A}$ in (13), agent E will adopt the following message rule:*

$$\begin{aligned} p_T^* &= 0 && \text{if } \bar{p}_T \in [0, k_T(0 \mid g_T(\alpha))] \\ p_T^* &= k_T^{-1}(\bar{p}_T \mid g_T(\alpha)) && \text{if } \bar{p}_T \in (k_T(0 \mid g_T(\alpha)), k_T(1 \mid g_T(\alpha))) \\ p_T^* &= 1 && \text{if } \bar{p}_T \in [k_T(1 \mid g_T(\alpha)), 1] \end{aligned} \tag{17}$$

Proof. In the Appendix. ■

Corollary 1 *: 1)*

$$V\left(p_T^* \mid g_T(\alpha)\right) > 0 \qquad \text{if } \ \bar{p}_T \notin \left(k_T\left(0 \mid g_T(\alpha)\right), k_T\left(1 \mid g_T(\alpha)\right)\right)$$

2) given $G_t(\alpha) \leq G_t'(\alpha)$ for every α, then:

$$E\left[V\left(p_T^* \mid g_T(\alpha)\right)\right] < E\left[V\left(p_T^* \mid g_T'(\alpha)\right)\right] \tag{18}$$

3) under the message rule in (17)*, it will be that:*

$$\begin{array}{lcll} p_T^* & < & \bar{p}_T & \text{if } \ \bar{p}_T \in \left(0, k_T\left(k_T\left(0 \mid g_T(\alpha)\right) \mid g_T(\alpha)\right)\right] \\ p_T^* & \leq & \bar{p}_T & \text{if } \ \bar{p}_T \in \left(k_T\left(k_T\left(0 \mid g_T(\alpha)\right) \mid g_T(\alpha)\right), 0.5\right) \\ p_T^* & = & \bar{p}_T & \text{if } \ \bar{p}_T = 0.5 \\ p_T^* & \geq & \bar{p}_T & \text{if } \ \bar{p}_T \in \left(0.5, k_T\left(k_T\left(1 \mid g_T(\alpha)\right) \mid g_T(\alpha)\right)\right) \\ p_T^* & > & \bar{p}_T & \text{if } \ \bar{p}_T \in \left(k_T\left(k_T\left(1 \mid g_T(\alpha)\right) \mid g_T(\alpha)\right), 1\right) \end{array} \tag{19}$$

4) when $g_T(\alpha)$ is positive for some α such that:

$$\frac{l\left(p_k \mid \omega_l, \tilde{\alpha}\right)}{l\left(p_z \mid \omega_l, \tilde{\alpha}\right)} > \frac{l\left(p_k \mid \omega_l, \alpha\right)}{l\left(p_z \mid \omega_l, \alpha\right)} \qquad \text{for every } p_k > p_z \tag{20}$$

then:

$$\begin{array}{lcll} p_T^* & < & \bar{p}_T & \text{if } \ \bar{p}_T \in (0, 0.5) \\ p_T^* & > & \bar{p}_T & \text{if } \ \bar{p}_T \in (0.5, 1) \end{array} \tag{21}$$

Proof. In the Appendix. ■

Proposition 1 shows that agent N's posterior belief will be perfectly aligned to agent E's true belief only if agent E's true probability belongs to the open interval between $k_T\left(0 \mid g_T(\alpha)\right)$ and $k_T\left(1 \mid g_T(\alpha)\right)$. Otherwise, agent E will prefer to announce one of the extreme values that his messages can take.

From Corollary 1, distortion in the announced probability from agent E's true probability will always occurs for some values of agent E's beliefs, notwithstanding solidarity between the agents. Moreover, distortion will always prevail, except for the case in which $\bar{p}_T = 0.5$, if some α parameters satisfy the strong property of monotone likelihood ratio.

Distortion will work in the following way: agent E will announce a low-state probability that is smaller than his true belief, when he is less confident than a low state will occur; instead, agent E will announce a low-state probability that is greater than his true belief, when he is more confident than a low state will occur. The reason is this: when agent N does not certainly believe that agent E is perfectly calibrated, then agent E will exaggerate his messages in order to make them "loud and clear".

The worse is agent E's reputation according to agent N, i.e. the worse is the distribution function of α in the sense of first order stochastic dominance, the greater will be both the distortion in the announced probability and the loss expected by agent E, just because agent N is more insensitive to messages.

6 Message Rules for Two Periods Ahead

For the two-period case, at $(T-1)$ agent E will work out his optimal message rules for both period $(T-1)$ and T. From (8), (7), (9) and (12), agent E will plan to announce $\mathbf{p}_{T-1}$ in order to solve the following problem:

$$\begin{aligned} &\min_{\mathbf{p}_{T-1}} V\left(p_{T-1} \mid g_{T-1}(\alpha)\right) + \\ &+\bar{p}_{T-1} E\left[V\left(p_T \mid g_T(\alpha) \mid \omega_l, p_{T-1}\right)\right] + \\ &+\bar{q}_{T-1} E\left[V\left(p_T \mid g_T(\alpha) \mid \omega_h, p_{T-1}\right)\right] \end{aligned} \tag{22}$$

where $\bar{q}_{T-1} = (1-\bar{p}_{T-1})$.

Given Proposition 1, since the optimal message rule for period T corresponds to (17), the problem in (22) can be replaced by the following one:

$$\begin{aligned} &\min_{p_{T-1}} \left[\bar{p}_{T-1} - k_{T-1}\left(p_{T-1} \mid g_{T-1}(\alpha)\right)\right]^2 + \\ + \quad &\bar{p}_{T-1}\left[Q_l\left(p_{T-1}\right) + S_l\left(p_{T-1}\right)\right] + \bar{q}_{T-1}\left[Q_h\left(p_{T-1}\right) + S_h\left(p_{T-1}\right)\right] \end{aligned} \tag{23}$$

where:

$$\begin{aligned} &Q_x\left(p_{T-1}\right) \\ = &\int_0^{k_T\left(0 \mid g_T\left(\alpha \mid \omega_x, p_{T-1}\right)\right)} \left[\bar{p}_T - k_T\left(0 \mid g_T\left(\alpha \mid \omega_x, p_{T-1}\right)\right)\right]^2 f\left(\bar{p}_T \mid \bar{p}_{T-1}\right) d\bar{p}_T \end{aligned}$$

$$\begin{aligned} &S_x\left(p_{T-1}\right) \\ = &\int_{k_T\left(1 \mid g_T\left(\alpha \mid \omega_x, p_{T-1}\right)\right)}^{1} \left[\bar{p}_T - k_T\left(1 \mid g_T\left(\alpha \mid \omega_x, p_{T-1}\right)\right)\right]^2 f\left(\bar{p}_T \mid \bar{p}_{T-1}\right) d\bar{p}_T \end{aligned}$$

with $x = l, h$.

From (23) and Lemma 3 point 5), the opinion announced by agent E at time $(T-1)$ will have both a direct impact on agent N's beliefs at time $(T-1)$, and an indirect impact on the reputation enjoyed by agent E at time T. Credibility will be relevant for agent E in as much as it fosters the future alignment of agent N's beliefs to agent E's stated opinions.

Condition 3 *:*

$$\begin{aligned} &\left|\frac{\vartheta k_T\left(0 \mid g_T\left(\alpha \mid \omega_l, p_{T-1}\right)\right)}{\vartheta p_{T-1}}\right| \int_A l\left(p_{T-1} \mid \omega_l, \alpha\right) d\alpha \\ \geq \quad &\frac{\vartheta k_T\left(0 \mid g_T\left(\alpha \mid \omega_h, p_{T-1}\right)\right)}{\vartheta p_{T-1}} \int_A l\left(p_{T-1} \mid \omega_h, \alpha\right) d\alpha \\ \forall p_{T-1} \quad \in \quad &[0, 0.5) \end{aligned}$$

Let $\tilde{p}_{T-1}$ denote the solution to the problem in (23). The following can be proved:

Proposition 2 *: provided $g_T(\alpha)$ is positive for some α in $\check{A}$ in* (13)*, if Condition 3 holds, agent E will adopt the following message rule at $(T-1)$:*

$$
\begin{array}{lllr}
\tilde{p}_{T-1} & = & 0 & \text{if } \bar{p}_{T-1} \in [0, z] \\
\tilde{p}_{T-1} & < & \bar{p}_{T-1} & \text{if } \bar{p}_{T-1} \in (z, 0.5) \\
\tilde{p}_{T-1} & = & 0.5 & \text{if } \bar{p}_{T-1} = 0.5 \\
\tilde{p}_{T-1} & > & \bar{p}_{T-1} & \text{if } \bar{p}_{T-1} \in (0.5, y) \\
\tilde{p}_{T-1} & = & 1 & \text{if } \bar{p}_{T-1} \in [y, 1]
\end{array}
$$

where:

$$
\begin{array}{lll}
0 & < & z < k_{T-1}(0 \mid g_{T-1}(\alpha)) \\
1 & > & y > k_{T-1}(1 \mid g_{T-1}(\alpha))
\end{array}
\tag{24}
$$

Proof. In the Appendix. ■

Corollary 2 *: the message rule in Proposition 2 will be such that:*

$$
\begin{array}{lllr}
\tilde{p}_{T-1} & > & p^*_{T-1} & \text{if } \bar{p}_{T-1} \in (z, 0.5) \\
\tilde{p}_{T-1} & < & p^*_{T-1} & \text{if } \bar{p}_{T-1} \in (0.5, y)
\end{array}
$$

where p^*_{T-1} is the optimal message rule for the one-period case proved by Proposition 1.

Proof. In the Appendix. ■

As Proposition 2 shows, in the two-period case, agent E may face a trade-off between leading agent N to have correct posterior belief in the first period, and improving his own reputation in the second period. It follows that agent E will keep on exaggerating his report only when his true probability of a low state are sufficiently extreme.

As Corollary 2 proves, distortion at $(T-1)$ will be less severe than it would be if it were the last period of interaction. Indeed, when agent E is sufficiently uncertain about the current state, to exaggerate his announced opinion will adversely affect his expected reputation at the last period. In order to preserve credibility, and so to keep control over future expected losses tomorrow, agent E will accept a higher expected loss today.

Then, repeated interaction will make agent E concerned about the reliability of his reports. As a result, messages will less biased with respect to the true beliefs of the sender.

Propositions 1 and 2 are illustrated through the following example.

Example 1 *Suppose that:*
1) $A \in [0,1]$
2) $g_t(\alpha) : E_t[\alpha] = \mu_t \quad Var_t(\alpha) = \sigma_t^2$
3) $l(p_t \mid \omega_l, \alpha) = 1 - \alpha(1 - 2p_t)$
4) $l(p_t \mid \omega_h, \alpha) = 1 + \alpha(1 - 2p_t)$
Hence:

$$
\begin{aligned}
& k_t(p_t \mid g_t(\alpha)) \\
= & \frac{\int_A [1 - \alpha(1 - 2p_t)] g_t(\alpha) d\alpha}{\int_A [1 - \alpha(1 - 2p_t)] g_t(\alpha) d\alpha + \int_A [1 + \alpha(1 - 2p_t)] g_t(\alpha) d\alpha} \\
= & \frac{1 - \mu_t(1 - 2p_t)}{2}
\end{aligned}
$$

From Proposition 1, in the one-period case the message rule will be the following:

$$
\begin{aligned}
p_T^* &= 0 & if \quad \bar{p}_T \in \left[0, \frac{1-\mu_T}{2}\right) \\
p_T^* &= \frac{2\bar{p}_T - 1 + \mu_T}{2\mu_T} & if \quad \bar{p}_T \in \left[\frac{1-\mu_T}{2}, \frac{1+\mu_T}{2}\right] \\
p_T^* &= 1 & if \quad \bar{p}_T \in \left(\frac{1+\mu_T}{2}, 1\right]
\end{aligned}
\tag{25}
$$

For the two-period case, given:

$$
\begin{aligned}
g_T(\alpha \mid \omega_l, p_{T-1}) &= \frac{[1 - \alpha(1 - 2p_{T-1})] g_{T-1}(\alpha)}{1 - \mu_{T-1}(1 - 2p_{T-1})} \\
E[\alpha \mid g_T(\alpha \mid \omega_l, p_{T-1})] &= \frac{\mu_{T-1} - (1 - 2p_{T-1})\left(\sigma_{T-1}^2 + \mu_{T-1}^2\right)}{1 - \mu_{T-1}\left(1 - 2p_{T-1}\right)}
\end{aligned}
$$

$$
\begin{aligned}
g_T(\alpha \mid \omega_h, p_{T-1}) &= \frac{\left[1 + \alpha\left(1 - 2p_{T-1}\right)\right] g_{T-1}(\alpha)}{1 + \mu_{T-1}(1 - 2p_{T-1})} \\
E[\alpha \mid g_T(\alpha \mid \omega_h, p_{T-1})] &= \frac{\mu_{T-1} + \left(1 - 2p_{T-1}\right)\left(\sigma_{T-1}^2 + \mu_{T-1}^2\right)}{1 + \mu_{T-1}\left(1 - 2p_{T-1}\right)}
\end{aligned}
$$

it will be that:

$$
\begin{aligned}
& k_T(0 \mid g_T(\alpha \mid \omega_l, p_{T-1})) \\
= & \frac{1 - 2\mu_{T-1}(1 - p_{T-1}) + (1 - 2p_{T-1})\left(\sigma_{T-1}^2 + \mu_{T-1}^2\right)}{2\left[1 - \mu_{T-1}(1 - 2p_{T-1})\right]}
\end{aligned}
\tag{26}
$$

$$
k_T(0 \mid g_T(\alpha \mid \omega_h, p_{T-1})) = \frac{1 - 2\mu_{T-1}p_{T-1} - (1 - 2p_{T-1})\left(\sigma_{T-1}^2 + \mu_{T-1}^2\right)}{2\left[1 + \mu_{T-1}(1 - 2p_{T-1})\right]}
\tag{27}
$$

From Proposition 2, the first derivative of (23) *will be equal to:*

$$-2\left[\bar{p}_{T-1}-\frac{1-\mu_{T-1}\left(1-2p_{T-1}\right)}{2}\right]\mu_{T-1}+ \tag{28}$$
$$+2\bar{p}_{T-1}\frac{\sigma_{T-1}^{2}}{\left[1-\mu_{T-1}\left(1-2p_{T-1}\right)\right]^{2}}\left[M_{l}\left(p_{T-1}\right)-N_{l}\left(p_{T-1}\right)\right]+$$
$$-2\bar{q}_{T-1}\frac{\sigma_{T-1}^{2}}{\left[1+\mu_{T-1}\left(1-2p_{T-1}\right)\right]^{2}}\left[M_{h}\left(p_{T-1}\right)-N_{h}\left(p_{T-1}\right)\right]$$

From $(26)-(27)$ *it follows that:*

$$\begin{array}{lcll} k_T\left(0 \mid g_T\left(\alpha \mid \omega_l, p_{T-1}\right)\right) & > & k_T\left(0 \mid g_T\left(\alpha \mid \omega_h, p_{T-1}\right)\right) & \text{if } p_{T-1}\in[0,0.5) \\ k_T\left(1 \mid g_T\left(\alpha \mid \omega_l, p_{T-1}\right)\right) & < & k_T\left(1 \mid g_T\left(\alpha \mid \omega_h, p_{T-1}\right)\right) & \text{if } p_{T-1}\in[0,0.5) \end{array}$$

Consider the following message p_{T-1}^{*} *from* (25)*:*

$$p_{T-1}^{*}=\frac{2\bar{p}_{T-1}-1+\mu_{T-1}}{2\mu_{T-1}}\ <0.5$$

It follows that:

$$\bar{p}_{T-1}=\frac{1-\mu_{T-1}\left(1-2p_{T-1}^{*}\right)}{2}<0.5$$

Since $\dfrac{1}{\left[1-\mu_{T-1}\left(1-2p_{T-1}\right)\right]}>\dfrac{1}{\left[1+\mu_{T-1}\left(1-2p_{T-1}\right)\right]}$, *Condition 3 is satisfied.* (28) *is lower than zero and* $\tilde{p}_{T-1}$ *is strictly greater than* p_{T-1}^{*}.

7 Conclusions

The paper shows that the opinion announced by an expert can be distorted from his true beliefs in the interaction with a solidaristic non-expert. The time horizon of interaction is proved to have an impact on the level of bias in messages.

The basic interaction analysed in the paper between an expert and a decision-maker can represent the relationship between a manager and his subordinate when instructions are issued from the former to the latter. Often, indeed, the subordinate cannot but take instructions very much like the opinion of the sender, and opinions are always objectionable.

The model may be extended in different ways. Two directions of future research are the analysis of many activities and so of different types of action, and the case of a non-binary set of states of the world[11].

[11] An additional problem is the coherent combination of experts' opinions. For an extensive review of the subject, see Genest-Zidek (1986) and Clemen-Winkler (1999).

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9 Appendix

Proof. of Lemma 1:

Given $\alpha_i, \alpha_j \in A$, let B_{ij} and C_{ij} be the sets defined as follows:

$$\begin{aligned} B_{ij} &= \{p \mid l(p \mid \omega_l, \alpha_i) < l(p \mid \omega_l, \alpha_j)\} \\ C_{ij} &= \{p \mid l(p \mid \omega_l, \alpha_i) > l(p \mid \omega_l, \alpha_j)\} \end{aligned} \tag{29}$$

Given $\alpha_i \neq_1 \alpha_j$, there will be one p at least such that $l(p \mid \omega_l, \alpha_i) \neq l(p \mid \omega_l, \alpha_j)$, since $\int_0^1 l(p \mid \omega_x, \alpha)\, dp = 1$ for every α. Given continuity of $l(p \mid \omega_l, \alpha)$ for every α, the sets defined in (29) are non-empty and non-singular for any

$\alpha_i \neq_1 \alpha_j$. Hence:

$$\begin{aligned} p_B &\in B_{ij} \text{ and } p_C \in C_{ij} \\ &\to \frac{l(p_C \mid \omega_l, \alpha_i)}{l(p_C \mid \omega_l, \alpha_j)} > 1 > \frac{l(p_B \mid \omega_l, \alpha_i)}{l(p_B \mid \omega_l, \alpha_j)} \end{aligned} \tag{30}$$

Given (30)

$$\alpha_j <_2 \alpha_i \to p_B < p_C \tag{31}$$

Let α_{2L} denote the particular parameter satisfying the following condition:

$$\alpha_{2L} \leq_2 \alpha \qquad \forall \alpha \in A \backslash \alpha_{2L}$$

Let α_m denote the particular parameter satisfying the following condition:

$$l(p \mid \omega_l, \alpha_m) = 2 \qquad \forall p \in [0,1] \tag{32}$$

Suppose $\alpha_{2L} <_2 \alpha_m$. Given (30)

$$p_B \in B_{m2L} \text{ and } p_C \in C_{m2L} \to \frac{l(p_C \mid \omega_l, \alpha_m)}{l(p_B \mid \omega_l, \alpha_m)} = 1 > \frac{l(p_C \mid \omega_l, \alpha_{2L})}{l(p_B \mid \omega_l, \alpha_{2L})}$$

Given (31), $l(p \mid \omega_l, \alpha_{2L})$ should be decreasing for some p, contrarily to Assumption 3 point 3). Hence, $\alpha_m \leq_2 \alpha_{2L}$. If $\alpha_m \in A$, then $\alpha_m =_2 \alpha_{2L}$. If $\alpha_m \notin A$, then $\alpha_m <_2 \alpha_{2L}$.

Consider any $\alpha_i >_2 \alpha_m$. Since:

$$\begin{aligned} p_B &\in B_{im} \text{ and } p_C \in C_{im} \to \frac{l(p_C \mid \omega_l, \alpha_i)}{l(p_B \mid \omega_l, \alpha_i)} > 1 = \frac{l(p_C \mid \omega_l, \alpha_m)}{l(p_B \mid \omega_l, \alpha_m)} \\ &\to l(p_C \mid \omega_l, \alpha_i) > l(p_B \mid \omega_l, \alpha_i) \end{aligned}$$

it follows that:

$$l(p \mid \omega_l, \alpha) \text{ is increasing for some } p \text{ for every } \alpha \neq \alpha_m \tag{33}$$

Hence:

$$\begin{aligned} l(p \mid \omega_l, \alpha_j) - l(p' \mid \omega_l, \alpha_j) &> 0 \to \\ l(p \mid \omega_l, \alpha_i) - l(p' \mid \omega_l, \alpha_i) &> 0 \quad \vee \alpha_i >_2 \alpha_j \end{aligned}$$

Given $\alpha_i >_2 \alpha_j$

$$\begin{aligned} p_B &\in B_{ij} \to 1 > \frac{l(p_B \mid \omega_l, \alpha_i)}{l(p_B \mid \omega_l, \alpha_j)} \geq \frac{l(p \mid \omega_l, \alpha_i)}{l(p \mid \omega_l, \alpha_j)} \quad \forall p < p_B \\ &\to l(p \mid \omega_l, \alpha_j) > l(p \mid \omega_l, \alpha_i) \quad \forall p < p_B \\ &\to p \in B_{ij} \end{aligned} \tag{34}$$

Let $\hat{p}$ and $\check{p}$ denote the lowest and the highest p such that:

$$l(p \mid \omega_l, \alpha_j) = l(p \mid \omega_l, \alpha_i)$$

From (34):
$$\alpha_i >_2 \alpha_j \rightarrow B_{ij} = [0, \hat{p}) \text{ and } C_{ij} = (\check{p}, 1] \tag{35}$$
Hence:
$$l\,(0 \mid \omega_l, \alpha_i) \geq 0 \rightarrow l\,(0 \mid \omega_l, \alpha_j) > 0 \qquad \forall \alpha_j <_2 \alpha_i \tag{36}$$
Consider $\tilde{\alpha}$. By definition, $l\,(0 \mid \omega_l, \tilde{\alpha}) = 0$ and $l\,(p \mid \omega_l, \tilde{\alpha}) > 0$ for every p in $(0, 1]$. Suppose that $\alpha_j >_2 \tilde{\alpha}$ for some $\alpha_j \in A$. In that case, (36) would be violated. Hence:
$$\tilde{\alpha} >_2 \alpha \qquad \vee\, \alpha \in A \backslash \tilde{\alpha} \tag{37}$$
Since the sum of continuous functions is a continuous function, and the ratio of continuous functions is a continuous function, provided the denominator function is never zero, then $pr(\omega_l \mid p, \alpha)$ is a continuous function of p, from (36) – (37).

Moreover, $pr(\omega_l \mid p, \alpha)$ is a nondecreasing function of p such that $pr(\omega_l \mid 1, \alpha)$ is greater than $pr(\omega_l \mid 0, \alpha)$ for every $\alpha \neq \alpha_m$ from (33).

Let M be the closed set of p between 0.5 and 1. Then:
$$\begin{aligned} \alpha_j &< {}_2\alpha_i \\ &\rightarrow \frac{l\,(p \mid \omega_l, \alpha_i)}{l\,(p \mid \omega_l, \alpha_j)} \geq \frac{l\,(p \mid \omega_h, \alpha_i)}{l\,(p \mid \omega_h, \alpha_j)} \quad \vee\, p \in M \\ &\rightarrow pr(\omega_l \mid p, \alpha_i) \geq pr(\omega_l \mid p, \alpha_j) \quad \vee\, p \in M \end{aligned}$$

$$\begin{aligned} \alpha_j &< {}_2\alpha_i \text{ and } pr(\omega_l \mid p, \alpha_i) > pr(\omega_l \mid p, \alpha_j) \\ &\rightarrow pr(\omega_l \mid p', \alpha_i) > pr(\omega_l \mid p', \alpha_j) \quad \vee\, p' \in (p, 1] \quad \vee\, p \in M \end{aligned}$$

$$\begin{aligned} \alpha_j &< {}_2\alpha_i \\ &\rightarrow pr(\omega_l \mid p, \alpha_i) > pr(\omega_l \mid p, \alpha_j) \quad \vee\, p \in M \cap C_{ij} \end{aligned} \tag{38}$$

Let N be the closed set of p between 0 and 0.5. It can be shown that:
$$\begin{aligned} \alpha_j &< {}_2\alpha_i \\ &\rightarrow pr(\omega_l \mid p, \alpha_j) > pr(\omega_l \mid p, \alpha_i) \quad \vee\, p \in N \cap B_{ij} \end{aligned} \tag{39}$$

Given (37), (38) and (39):
$$\alpha_i >_2 \alpha_j \rightarrow \alpha_i >_1 \alpha_j$$

■

Proof. of Lemma 2:

Point 1): given $\alpha_i >_2 \alpha_j$ and (29), from Lehmann (1986, p.85), given a nondecreasing function ψ of p, if $b = sup_{B_{ij}} \psi\,(p)$ and $c = inf_{C_{ij}} \psi\,(p)$, then

$c - b \geq 0$ and:

$$\begin{aligned}
& \int_P \psi(p) \left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right] dp \\
= & \int_{B_{ij}} \psi(p) \left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right] dp + \\
& + \int_{C_{ij}} \psi(p) \left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right] dp
\end{aligned}$$

From the weighted mean-value theorem for integrals, since $\left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right]$ never changes sign in B_{ij} and C_{ij}, then:

$$\begin{aligned}
& \int_{B_{ij}} \psi(p) \left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right] dp \\
= & \psi(p_B) \int_{B_{ij}} \left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right] dp \qquad p_B \in B_{ij}
\end{aligned}$$

$$\begin{aligned}
& \int_{C_{ij}} \psi(p) \left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right] dp \\
= & \psi(p_C) \int_{C_{ij}} \left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right] dp \qquad p_C \in C_{ij}
\end{aligned}$$

Since:

$$\begin{aligned}
& \psi(p_B) \int_{B_{ij}} \left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right] dp \\
\geq & \; b \int_{B_{ij}} \left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right] dp \\
& \psi(p_C) \int_{C_{ij}} \left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right] dp \\
\geq & \; c \int_{C_{ij}} \left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right] dp
\end{aligned}$$

$$\begin{aligned}
& b \int_{B_{ij}} \left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right] dp + \\
& c \int_{C_{ij}} \left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right] dp \\
= & \; (c - b) \int_{C_{ij}} \left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right] dp \geq 0
\end{aligned}$$

it follows that:

$$\begin{gathered}
\int_P \psi(p) \left[l(p \mid \omega_l, \alpha_i) - l(p \mid \omega_l, \alpha_j) \right] dp \geq 0 \rightarrow \\
E\left[\psi(p) \mid \omega_l, \alpha_i \right] \geq E\left[\psi(p) \mid \omega_l, \alpha_j \right]
\end{gathered} \tag{40}$$

Consider a nondecreasing function φ of p such that:

$$\begin{aligned}\varphi(p) &= 1 \quad \text{if } p > \bar{p} \\ \varphi(p) &= 0 \quad \text{otherwise}\end{aligned}$$

From (40):

$$L(p \mid \omega_l, \alpha_i) \leq L(p \mid \omega_l, \alpha_j) \quad \text{for every } p \tag{41}$$

Point 2): under Assumption 3 points 3) and 4), $\dfrac{l(p \mid \omega_l, \alpha)}{l(p \mid \omega_h, \alpha)}$ is nondecreasing in p for every α. Hence:

$$\begin{aligned}\int_0^t l(p \mid \omega_l, \alpha)\, dp &: \quad \text{error of the I type fixed at } t \qquad (42) \\ \int_t^1 l(p \mid \omega_h, \alpha)\, dp &= \int_0^{1-t} l(p \mid \omega_l, \alpha)\, dp\text{: error of the II type given } t\end{aligned}$$

Given $\alpha_i >_2 \alpha_j$, consider experiment k such that:

$$\begin{aligned}l(p \mid \omega_l, k) &= l(p \mid \omega_l, \alpha_j) \qquad (43) \\ l(p \mid \omega_h, k) &= l(p \mid \omega_h, \alpha_i)\end{aligned}$$

Blackwell (1953)[12] shows that experiment β is more informative than experiment γ, denoted by $\beta \supset \gamma$, if and only if at every level t the error of the II type with β is less than or equal to the corresponding error with γ. Compare experiment k to experiment α_j. From (41) and (43) it follows that:

$$\begin{aligned}\int_0^t l(p \mid \omega_l, k)\, dp &= \int_0^t l(p \mid \omega_l, \alpha_j)\, dp \qquad (44) \\ \int_t^1 l(p \mid \omega_h, k)\, dp &= \int_0^{1-t} l(p \mid \omega_l, \alpha_i)\, dp \leq \int_0^{1-t} l(p \mid \omega_l, \alpha_j)\, dp \\ &\to k \supset \alpha_j\end{aligned}$$

Now, compare experiment k to experiment α_i:

$$\begin{aligned}\int_t^1 l(p \mid \omega_h, k)\, dp &= \int_t^1 l(p \mid \omega_h, \alpha_i)\, dp \\ \int_0^t l(p \mid \omega_l, \alpha_i)\, dp &\leq \int_0^t l(p \mid \omega_l, k)\, dp = \int_0^t l(p \mid \omega_l, \alpha_j)\, dp \quad \text{from (41)} \\ &\to \alpha_i \supset k \supset \alpha_j\end{aligned}$$

Point 3): consider two density functions of α, $g(\alpha)$ and $g'(\alpha)$ such that $\dfrac{g(\alpha)}{g'(\alpha)}$ is nondecreasing in α. Let D and E be sets defined as follows:

$$\begin{aligned}D &= \{\alpha \mid g(\alpha) < g'(\alpha)\} \\ E &= \{\alpha \mid g(\alpha) > g'(\alpha)\}\end{aligned}$$

[12] DeGroot (1962, 1979) provides a detailed analysis of the concept of sufficient experiments.

Given a nondecreasing function ψ of α, if $d = sup_D \psi(\alpha)$ and $e = inf_E \psi(\alpha)$, then $e - d \geq 0$ and:

$$\begin{aligned} & \int_A \psi(\alpha)\left[g(\alpha) - g'(\alpha)\right] d\alpha \\ = & \int_D \psi(\alpha)\left[g(\alpha) - g'(\alpha)\right] d\alpha + \int_E \psi(\alpha)\left[g(\alpha) - g'(\alpha)\right] d\alpha \end{aligned}$$

From the weighted mean-value theorem for integrals, since $[g(\alpha) - g'(\alpha)]$ never changes sign in D and in E, then:

$$\begin{aligned} & \int_D \psi(\alpha)\left[g(\alpha) - g'(\alpha)\right] d\alpha \\ = & \ \psi(\alpha_D) \int_D \left[g(\alpha) - g'(\alpha)\right] d\alpha \qquad \alpha_D \in D \end{aligned}$$

$$\begin{aligned} & \int_E \psi(\alpha)\left[g(\alpha) - g'(\alpha)\right] d\alpha \\ = & \ \psi(\alpha_E) \int_E \left[g(\alpha) - g'(\alpha)\right] d\alpha \qquad \alpha_E \in E \end{aligned}$$

Since:

$$\begin{aligned} \psi(\alpha_D) \int_D \left[g(\alpha) - g'(\alpha)\right] d\alpha & \geq d \int_D \left[g(\alpha) - g'(\alpha)\right] d\alpha \\ \psi(\alpha_E) \int_E \left[g(\alpha) - g'(\alpha)\right] d\alpha & \geq e \int_E \left[g(\alpha) - g'(\alpha)\right] d\alpha \end{aligned}$$

$$\begin{aligned} & d \int_D \left[g(\alpha) - g'(\alpha)\right] d\alpha + e \int_E \left[g(\alpha) - g'(\alpha)\right] d\alpha \\ = & \ (e - d) \int_E \left[g(\alpha) - g'(\alpha)\right] d\alpha \geq 0 \end{aligned}$$

it follows that:

$$\begin{gathered} \int_A \psi(\alpha)\left[g(\alpha) - g'(\alpha)\right] d\alpha \geq 0 \rightarrow \\ E\left[\psi(\alpha) \mid g(\alpha)\right] \geq E\left[\psi(\alpha) \mid g'(\alpha)\right] \end{gathered}$$

Consider a nondecreasing function φ of α such that:

$$\begin{aligned} \varphi(\alpha) &= 1 \quad \text{if } \alpha > \bar{\alpha} \\ \varphi(\alpha) &= 0 \quad \text{otherwise} \end{aligned}$$

Hence:

$$\frac{g(\alpha)}{g'(\alpha)} \text{ nondecreasing in } \alpha \rightarrow G(\alpha) \leq G'(\alpha) \quad \text{for every } \alpha \tag{45}$$

Given $\alpha_i >_2 \alpha_j$ and $p_k > p_z$, and:

$$\frac{g_{t+1}(\alpha \mid \omega_l, p_k)}{g_{t+1}(\alpha \mid \omega_l, p_z)} = \frac{l(p_k \mid \omega_l, \alpha)}{l(p_z \mid \omega_l, \alpha)} \frac{\int_A l(p_z \mid \omega_l, \alpha) g_t(\alpha) d\alpha}{\int_A l(p_k \mid \omega_l, \alpha) g_t(\alpha) d\alpha}$$

it follows that:

$$\frac{l(p_k \mid \omega_l, \alpha_i)}{l(p_z \mid \omega_l, \alpha_i)} \geq \frac{l(p_k \mid \omega_l, \alpha_j)}{l(p_z \mid \omega_l, \alpha_j)} \rightarrow (10) \quad \rightarrow \quad (11)$$

■

Proof. of Lemma 3:
Points 1) and 2): provided $g_t(\alpha)$ is non-degenerate on $\tilde{\alpha}$, then from (36):

$$\begin{array}{ccc} 0 & < & k_t(0 \mid g_t(\alpha)) \\ 1 & > & k_t(1 \mid g_t(\alpha)) \end{array}$$

Provided $g_t(\alpha) > 0$ for some α in $\check{A}$, then $k_t(p_t \mid g_t(\alpha))$ is increasing in p_t. Hence, $k_t(p_t \mid g_t(\alpha))$ is invertible.
Point 3): under R_2:

$$\frac{l(1-p \mid \omega_l, \tilde{\alpha})}{l(p \mid \omega_l, \tilde{\alpha})} = \frac{1-p}{p} \geq \frac{l(1-p \mid \omega_l, \alpha)}{l(p \mid \omega_l, \alpha)} \quad \vee p \in (0, 0.5), \vee \alpha <_2 \tilde{\alpha}$$

Hence:

$$(1-p)\int_A l(p \mid \omega_l, \alpha) g_T(\alpha) d\alpha \geq p \int_A l(p \mid \omega_h, \alpha) g_T(\alpha) d\alpha \quad \vee p \in (0, 0.5)$$

Point 4): given $\alpha_i >_2 \alpha_j$ and (35), then:

$$\begin{array}{l} l(0 \mid \omega_l, \alpha) \text{ is decreasing in } \alpha, \ \vee \alpha \neq \alpha_m \\ l(0 \mid \omega_h, \alpha_i) \text{ is increasing in } \alpha, \ \vee \alpha \neq \alpha_m \end{array}$$

where α_m is defined in (32). It follows that:

$$\begin{array}{ccc} \int_A l(0 \mid \omega_l, \alpha) g(\alpha) d\alpha & < & \int_A l(0 \mid \omega_l, \alpha) g'(\alpha) d\alpha \\ \int_A l(0 \mid \omega_h, \alpha) g(\alpha) d\alpha & > & \int_A l(0 \mid \omega_h, \alpha) g'(\alpha) d\alpha \end{array} \qquad (46)$$

(14) follows from (46).
Point 5): (15) follows from (10) and (14). ■

Proof. of Proposition 1:
from Lemma 3 points 1) and 2), $V(p_T \mid g_T(\alpha))$ is:
a) always positive and decreasing in p_T if $\bar{p}_T < k_T(0 \mid g_T(\alpha))$
b) always zero if $p_T = k_T^{-1}(\bar{p}_T \mid g_T(\alpha))$ and $\bar{p}_1 \in [k_T(0 \mid g_T(\alpha)), k_T(1 \mid g_T(\alpha))]$

c) always positive and increasing in p_T if $\bar{p}_T > k_T(1 \mid g_T(\alpha))$.
Consequently, (17) is the optimal message rule of agent E. ■

Proof. of Corollary 1:
Point 1): it follows from (17).
Point 2): (18) follows from Lemma 3 point 4)
Point 3): (19) follows from Lemma 3 point 3).
Point 4): given Lemma 3 point 3), under (20):

$$\frac{l(1-p \mid \omega_l, \tilde{\alpha})}{l(p \mid \omega_l, \tilde{\alpha})} = \frac{1-p}{p} > \frac{l(1-p \mid \omega_l, \alpha)}{l(p \mid \omega_l, \alpha)} \quad \vee\, p \in (0, 0.5)$$

It follows that:

$$(1-p)\int_A l(p \mid \omega_l, \alpha)\, g_T(\alpha)\, d\alpha > p\int_A l(p \mid \omega_h, \alpha)\, g_T(\alpha)\, d\alpha \quad \vee\, p \in (0, 0.5)$$

$$\begin{array}{rcll} k_T(p_t \mid g_T(\alpha)) & > & p_t & \vee\, p_t \in [0, 0.5) \\ k_T(p_t \mid g_T(\alpha)) & < & p_t & \vee\, p_t \in (0.5, 1] \end{array} \tag{47}$$

(21) is the consequence of (47). ■

Proof. of Proposition 2:
The first derivative of (23) is:

$$\begin{aligned} &-2\frac{\vartheta k_{T-1}(p_{T-1} \mid g_{T-1}(\alpha))}{\vartheta p_{T-1}}\left[\bar{p}_{T-1} - k_{T-1}(p_{T-1} \mid g_{T-1}(\alpha))\right] + \\ &-2\frac{\vartheta k_T(0 \mid g_T(\alpha \mid \omega_l, p_{T-1}))}{\vartheta p_{T-1}}\bar{p}_{T-1} M_l(p_{T-1}) + \\ &-2\frac{\vartheta k_T(1 \mid g_T(\alpha \mid \omega_l, p_{T-1}))}{\vartheta p_{T-1}}\bar{p}_{T-1} N_l(p_{T-1}) + \\ &-2\frac{\vartheta k_T(0 \mid g_T(\alpha \mid \omega_h, p_{T-1}))}{\vartheta p_{T-1}}\bar{q}_{T-1} M_h(p_{T-1}) + \\ &-2\frac{\vartheta k_T(1 \mid g_T(\alpha \mid \omega_h, p_{T-1}))}{\vartheta p_{T-1}}\bar{q}_{T-1} N_h(p_{T-1}) \end{aligned} \tag{48}$$

where:

$$\begin{aligned} & M_x(p_{T-1}) \\ = & \int_0^{k_T(0 \mid g_T(\alpha \mid \omega_x, p_{T-1}))} \left[\bar{p}_T - k_T(0 \mid g_T(\alpha \mid \omega_x, p_{T-1}))\right] f(\bar{p}_T \mid \bar{p}_{T-1})\, d\bar{p}_T \end{aligned}$$

$$\begin{aligned} & N_x(p_{T-1}) \\ = & \int_{k_T(1 \mid g_T(\alpha \mid \omega_x, p_{T-1}))}^{1} \left[\bar{p}_T - k_T(1 \mid g_T(\alpha \mid \omega_x, p_{T-1}))\right] f(\bar{p}_T \mid \bar{p}_{T-1})\, d\bar{p}_T \end{aligned}$$

with $x = l, h$

From Lemma 3 point 2):

$$\frac{\vartheta k_{T-1}\left(p_{T-1} \mid g_{T-1}\left(\alpha\right)\right)}{\vartheta p_{T-1}} > 0$$

From Lemma 3 point 4):

$$p_{T-1} \in [0, 0.5) \rightarrow M_l\left(p_{T-1}\right) < M_h\left(p_{T-1}\right) < 0, \quad N_l\left(p_{T-1}\right) > N_h\left(p_{T-1}\right) > 0$$

From Lemma 3 point 5):

$$\begin{aligned} \frac{\vartheta k_T\left(0 \mid g_T\left(\alpha \mid \omega_l, p_{T-1}\right)\right)}{\vartheta p_{T-1}} &< 0 \\ \frac{\vartheta k_T\left(0 \mid g_T\left(\alpha \mid \omega_h, p_{T-1}\right)\right)}{\vartheta p_{T-1}} &> 0 \end{aligned}$$

Under Assumption 3 point 4):

$$k_T\left(1 \mid g_T\left(\alpha \mid \omega_x, p_{T-1}\right)\right) = \left[1 - k_T\left(0 \mid g_T\left(\alpha \mid \omega_x, p_{T-1}\right)\right)\right]$$

Hence, Condition 3 implies that:

$$\begin{aligned} & \frac{\vartheta k_T\left(1 \mid g_T\left(\alpha \mid \omega_l, p_{T-1}\right)\right)}{\vartheta p_{T-1}} \int_A l\left(p_{T-1} \mid \omega_l, \alpha\right) d\alpha \\ \geq & \left|\frac{\vartheta k_T\left(1 \mid g_T\left(\alpha \mid \omega_h, p_{T-1}\right)\right)}{\vartheta p_{T-1}}\right| \int_A l\left(p_{T-1} \mid \omega_h, \alpha\right) d\alpha \qquad \forall p_{T-1} \in [0, 0.5) \end{aligned}$$

consequently:

$$\begin{aligned} & -\left|\frac{\vartheta k_T\left(1 \mid g_T\left(\alpha \mid \omega_l, p_{T-1}\right)\right)}{\vartheta p_{T-1}}\right| M_l\left(p_{T-1}\right) \int_A l\left(p_{T-1} \mid \omega_l, \alpha\right) d\alpha + \\ & + \frac{\vartheta k_T\left(1 \mid g_T\left(\alpha \mid \omega_l, p_{T-1}\right)\right)}{\vartheta p_{T-1}} N_l\left(p_{T-1}\right) \int_A l\left(p_{T-1} \mid \omega_l, \alpha\right) d\alpha \\ > & -\frac{\vartheta k_T\left(0 \mid g_T\left(\alpha \mid \omega_h, p_{T-1}\right)\right)}{\vartheta p_{T-1}} M_h\left(p_{T-1}\right) \int_A l\left(p_{T-1} \mid \omega_h, \alpha\right) d\alpha + \\ & + \left|\frac{\vartheta k_T\left(1 \mid g_T\left(\alpha \mid \omega_h, p_{T-1}\right)\right)}{\vartheta p_{T-1}}\right| N_h\left(p_{T-1}\right) \int_A l\left(p_{T-1} \mid \omega_h, \alpha\right) d\alpha \\ \forall p_{T-1} \in & [0, 0.5) \end{aligned} \tag{49}$$

Since:

$$\begin{aligned} & -\left|\frac{\vartheta k_T\left(0 \mid g_T\left(\alpha \mid \omega_l, p_{T-1}\right)\right)}{\vartheta p_{T-1}}\right| M_l\left(p_{T-1}\right) + \\ & + \frac{\vartheta k_T\left(1 \mid g_T\left(\alpha \mid \omega_l, p_{T-1}\right)\right)}{\vartheta p_{T-1}} N_l\left(p_{T-1}\right) \text{ is decreasing in } p_{T-1} \end{aligned}$$

$$-\frac{\vartheta k_T\left(0 \mid g_T\left(\alpha \mid \omega_h, p_{T-1}\right)\right)}{\vartheta p_{T-1}} M_h\left(p_{T-1}\right)+$$
$$+\left|\frac{\vartheta k_T\left(1 \mid g_T\left(\alpha \mid \omega_h, p_{T-1}\right)\right)}{\vartheta p_{T-1}}\right| N_h\left(p_{T-1}\right) \text{ is increasing in } p_{T-1}$$

when $p_{T-1} \in [0, 0.5)$, it follows that:

a) when $p_{T-1} \in [0, 0.5)$, there exists a z such that:

$$\begin{aligned}
\bar{p}_{T-1} \quad & \frac{\vartheta k_T\left(0 \mid g_T\left(\alpha \mid \omega_l, p_{T-1}\right)\right)}{\vartheta p_{T-1}} M_l\left(p_{T-1}\right)+ \\
& +\bar{p}_{T-1} \frac{\vartheta k_T\left(1 \mid g_T\left(\alpha \mid \omega_l, p_{T-1}\right)\right)}{\vartheta p_{T-1}} N_l\left(p_{T-1}\right) \\
= \quad & -\bar{q}_{T-1} \frac{\vartheta k_T\left(0 \mid g_T\left(\alpha \mid \omega_h, p_{T-1}\right)\right)}{\vartheta p_{T-1}} M_h\left(p_{T-1}\right)+ \\
& -\bar{q}_{T-1} \frac{\vartheta k_T\left(1 \mid g_T\left(\alpha \mid \omega_h, p_{T-1}\right)\right)}{\vartheta p_{T-1}} N_h\left(p_{T-1}\right)+ \\
& +\left[k_{T-1}\left(p_{T-1} \mid g_{T-1}(\alpha)\right)-\bar{p}_{T-1}\right] \frac{\vartheta k_{T-1}\left(p_{T-1} \mid g_{T-1}(\alpha)\right)}{\vartheta p_{T-1}} \quad \text{evaluated at } p_{T-1}=z
\end{aligned}$$

b) when $p_{T-1} \in [0, 0.5)$:

$$\bar{p}_{T-1} \in [z, 0.5) \rightarrow \bar{p}_{T-1} > \tilde{p}_{T-1}$$

The proof is analogous for the case in which $p_{T-1} \in (0.5, 1]$. ■

Proof. of Corollary 2:

From (49) it follows that:

$$\bar{p}_{T-1} \in \left[k_{T-1}\left(0 \mid g_{T-1}(\alpha)\right), 0.5\right) \rightarrow \tilde{p}_{T-1} > k_{T-1}^{-1}\left(\bar{p}_{T-1} \mid g_{T-1}(\alpha)\right)=p_{T-1}^*$$

■

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