Industrial Espionage with a Noisy Intelligence

Alex Barrachina*

Yair Tauman**

November 2011

Abstract

We analyze industrial espionage in a model of two firms: a monopoly incumbent, M, and a potential entrant, E, who owns a noisy intelligence system (IS) of a certain precision α . The IS generates a signal on M's action and E decides whether or not to enter based on this signal. We show that if α is commonly known, M is the one who benefits from a perfect IS and E who spies on M prefers a less accurate IS. If however α is a private information of E, the opposite result is obtained. E is best off with a perfect IS and M with a less accurate one.

JEL Classification: C72; D82; L10; L12

Keywords : Espionage; Monopoly; Entry; Asymmetric information; Signaling game.

---

* *University of Valencia and ERI-CES.*

** *IDC Herzliya and Stony Brook University*.

The first author wishes to thank financial support from the *Ministry of Science and Technology* and the European Feder Funds under projects SEJ2007-66581 and ECO-2010-20584. He also would like to thank Amparo Urbano for useful discussions and remarks.

1. Introduction.

We analyze the role of industrial espionage in a model of two firms, a monopoly incumbent (M) and a potential entrant (E). The monopolist wishes to deter E from entering the market. For this purpose M considers a capacity expansion. Under perfect information E stays out if the capacity of M is expanded and enters if M did not expand capacity. Capacity expansion requires investment and E does not observe M's decision of whether or not to invest in capacity. Hence, E enters only if she believes that with high probability the capacity was not expanded.

The entrant E operates an Intelligence System (IS) which set to detect M's action. The IS can send one out of two signals. The signal i indicating that M invests in new capacity and the signal i indicating the opposite. The precision of the IS is α, $1/2 \leq \alpha \leq 1$.

Namely, the signal sent by the IS is correct (it sends the signal i when M invests and sends the signal ni, otherwise) with probability α. If $\alpha = 1$ the IS is a perfect device and E can perfectly detect the action of M. The case $\alpha = 1/2$ is equivalent to not using any intelligence system. Based on the signal received, E decides whether or not (or with what probability) to enter the market.

There are four possible outcomes: (NI, NE), (NI, E), (I, NE), (I, E), where I stands for "invest" and NI stands for "not invest". The interpretation of E and NE is similar. The best outcome for M is the status quo outcome (NI, NE). His second best outcome is (I, NE). M prefers the outcome (I, NE) on (I, E), and if the investment cost not too high, then M prefers the outcome (I, E) on (NI, E). As for E, her best outcome is (NI, E) and it is better for her than either (I, NE) or (NI, NE) (in both cases E obtains zero). The worst outcome for E is (I, E).

In this paper the precision α of the IS is exogenously given. This is the case if a firm has already a spying technology before it encounters a new rival (e.g., a firm that has the ability to plant a Trojan Horse in the computer system of her rivals).

A more realistic scenario is the case where α is a private information of E. But before analyzing this case, we study the benchmark case where the value of α is commonly known. If the investment cost is sufficiently high so that M prefers not to invest even if he knows that E enters, the result is straightforward. It is a dominant strategy for M not to invest and E will enter the market.

Suppose next that the investment cost is such that M prefers to invest if he knows that E enters. Suppose first that E obtains the signal ni. If the IS is not very accurate (α falls below a certain threshold, $\bar{\alpha}$) then with probability 1 E enters (believing with high probability that M did not expand his capacity). However, if the IS is sufficiently accurate (above $\bar{\alpha}$) then, quite surprisingly, E "hesitates" and stays out with a significant probability. Suppose next that E obtains the signal i. If the IS is not very accurate (below $\bar{\alpha}$), E hesitates and enters with a positive probability (less than 1), taking into account the possible mistake of the IS. If the IS is more accurate, E stays out with probability 1.

Let us provide some intuition for these results. If the precision of the IS is relatively high, M who knows α knows that if he does not expand his capacity, E will detect this with high probability and she is likely to enter the market. Hence, M expands capacity with high probability, and the signal ni is less likely to occur. Consequently, when E observes the signal ni, she can no longer rely on its accuracy and she decides to stay out with positive probability. If the precision of the IS is less accurate, M expands capacity with smaller probability, knowing that there is a good chance that his action will not be detected. The signal ni is now more likely to be sent and when E observes it, she enters the market with probability 1.

In equilibrium the unconditional probability that E enters the market decreases, the higher is the precision of IS. Hence, M benefits from a better precision of IS.

Regarding the benefits of the two players, M benefits from the IS more than its owner, E, if the IS is relatively accurate. Whenever α exceeds the threshold, $\bar{\alpha}$, E ends up with zero payoff and she is indifferent between spying on M or not. The optimal accuracy of the IS for E is the threshold value $\bar{\alpha}$ while M is best off with a perfect IS (namely $\alpha = 1$). The implication is that M should subsidize E for building a perfect IS, even though this means that E will be able to perfectly monitor him.

Next we analyze the asymmetric information case where the precision, α, of the IS is the private information of E. The incumbent M knows the distribution of α but does not know the actual realization of α. In particular it covers the case where E does not use an IS ($\alpha = \frac{1}{2}$) but M believes with positive probability that E does operate an IS of a precision $\alpha > \frac{1}{2}$. We find out that while the equilibrium strategies are qualitatively consistent with the common knowledge case, the payoffs of M and E behave in a more intuitive way. Contrary to the complete information case, E obtains positive payoff if α is sufficiently large and this payoff is increasing in α. Furthermore, if M believes that the expected value of α is below the threshold $\bar{\alpha}$, then E obtains positive payoff for all values of α. As for M and contrary to the complete information case, M is best off when E does not spy on him.

Let us briefly review the literature on economic espionage.

A closely related paper is Solan and Yariv (2004) (hereafter SY). The set-up in SY is similar to ours. It provides a general set-up and when applying it to our context the choice of α in SY is costly and it is a strategic variable of E. This choice is made simultaneously with the decision of M to invest or not to invest. The SY paper provides a sort of a "folk theorem" where it characterizes the set of attainable probability distributions over the entries of the payoff matrix which arises in equilibrium for the set of possible cost structures of the IS.

We differ from SY as we focus on the case where α is not a strategic variable of E but rather is exogenously given and it is either the private information of E or commonly known.

Another related paper is Crawford and Sobel (1982) (hereafter CS). The CS paper considers a signaling game of one sender, S, and one receiver, R. The sender has a private information and based on his information he sends a noisy signal to the receiver. The receiver then chooses an action based on the signal she observes. We can think of M in our model as the sender of the signal since his action (to invest or not to invest) automatically induces a noisy signal by the IS. The entrant, E, is the receiver of the signal and based on the signal she decides whether or not to enter. The difference between CS (1982) and the current paper is that in our model the receiver, and not the sender, has the private information (the precision of the IS) and she chooses her action based on both, her private information and the signal she observes.

Let us mention only a few papers that are closely related to us. Provan (2008) has a similar structure to us but it is more computational-based approach, using linear programming solutions for two-person-zero-sum games.

Matsui (1989) considers a two person repeated game where every player has a small probability of perfectly detecting the other player action and revise his strategy accordingly. The paper shows that if the probability is sufficiently small any subgame perfect equilibrium payoff is Pareto efficient.

The double crossing phenomenon is the focus of Ho (2008). Espionage is used there to learn the rival's private information. Unlike Ho (2008), espionage in our paper and in Solan and Yariv (2004) and Matsui (1989), is used to obtain information about the rival's action. We do not allow for double crossing in our model or for the possibility of a player to take costly action to reduce the reliability of the intelligence system of his rival –and interesting topic for future study.

Whitney and Gaisford (1999) study a duopoly competition between two companies (Airbus and Boeing as an example) where one company (or both) spy on the other company in attempt to learn its technology and as a result to be able to lower its own marginal cost. The intelligence system can result with either a pure success or a pure failure and it does not generate any noise. The outcome of the IS is assumed to be common knowledge. The benefit from the IS is very different whether they compete in prices or in quantities. In a recent paper, Billand, Bravard, Chakrabarti and Sarangi (2009) study espionage in a Cournot model of several firms with differentiated goods. Their model is of symmetric information where firms observe the full espionage activity before choosing their quantity levels.

Finally, our paper is similar in spirit to Biran and Tauman (2009) (BT). The context of the BT paper is different and deals with the role of intelligence in nuclear deterrence. The preferences of the players in BT are different and so are the results.

For further discussion of the literature see also Solan and Yariv (2004).

2. The basic model.

There are two firms, M and E. The Incumbent Firm, M, is a monopolist and E is a potential entrant. In an attempt to deter E from entering M considers whether to invest or not to invest in a new capacity. E has an Intelligence System (IS) that monitors the action of M. The IS sends a noisy signal, one of the two signals i or ni. The signal i indicates that M invests and the signal ni indicates that M does not invest. The IS sends the right signal with probability α and the wrong signal with probability $1-\alpha$. For simplicity we assume that the precision, α, of the IS is independent of the action of M. It is assumed w.l.o.g that $\frac{1}{2} \le \alpha \le 1$. If $\alpha = \frac{1}{2}$, the IS is of no relevance and if $\alpha = 1$, the IS is perfect.

The following tree summarizes the above:

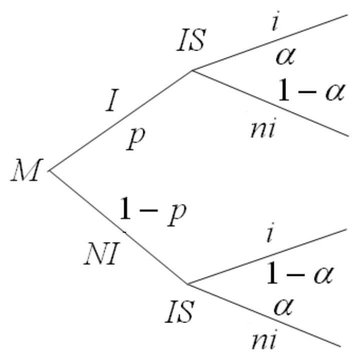

Figure 1

Based on the signal received E decides whether or not to enter the market.

The following table describes the payoffs of the two firms based on their possible actions:

M \ E	E	NE
I	b, -1	c, 0
NI	0, 1	1, 0

Figure 2

Where

$$0 < b < c < 1 \qquad \text{(AS1)}[1]$$

3. The case where α is commonly known.

We first focus on the case where α is common knowledge. In particular, M knows that E spies on him with an IS of precision α. Let us start with the two extreme cases where $\alpha = 1/2$ and $\alpha = 1$.

The case $\alpha = 1/2$ is basically the case where E does not operate an IS on M, and the strategic game between M and E is described in Figure 2. This game has a unique Nash equilibrium in which: M invests with probability $\frac{1}{2}$ and E enters the market with probability $\frac{1-c}{1-c+b}$, which is decreasing in both b and c. Namely, the higher is the payoff of M from expanding his capacity the lower is the probability that E enters. The payoff of E is zero (E is indifferent between entering and not entering), and the payoff of M is $\frac{b}{1-c+b}$ (which increases in b and c).

The second case is $\alpha = 1$ and M's action is perfectly detected by E. In this case, E chooses her action based on M's action. This game can be described by the following tree:

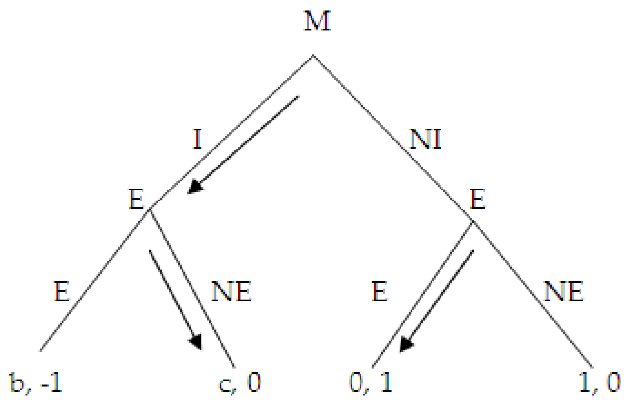

Figure 3

[1] The case where $b < 0$ is trivial as I is strictly dominated by NI.

The backward induction is the unique Nash equilibrium. M expands his capacity and E does not enter the market. This outcome yields a higher payoff for M than the equilibrium outcome for $\alpha = \frac{1}{2}$. The payoff of E is zero in both there two cases. Hence, only M benefits from a perfect IS. The entrant, who spies on M and who is able to perfectly monitor M's action (before taking her action) does not benefit at all from using it. This result follows by the assumption that is α commonly known.

The general case $\frac{1}{2} < \alpha < 1$.

The entrant has four pure strategies. A pure strategy of E is a pair (x, y) where both x and y are in $\{E, NE\}$, x is the action of E if she observes the signal ni and y is her action if she observes the signal i. The following figure describes the game, G_α, between M and E in strategic form (see Figure 1 and Figure 2):

M \ E	(E, E)	(E, NE)	(NE, E)	(NE, NE)
I	$b, -1$	$\alpha c + (1-\alpha) b, -1+\alpha$	$\alpha b + (1-\alpha) c,\ -\alpha$	$c, 0$
NI	$0, 1$	$1-\alpha, \alpha$	$\alpha, 1-\alpha$	$1, 0$

Figure 4

For instance, the strategy (E, NE) of E is to enter the market if the signal is ni and not to enter if the signal is i. The strategy (E, E) is to enter the market irrespective of the signal.

Note that the strategy (NE, E) of E is strictly dominated by her strategy (E, NE), since $\alpha > \frac{1}{2}$. Therefore the strategy (NE, E) can be removed, and the resulting game is:

		E \ M	(E, E)	(E, NE)	(NE, NE)
p	I		$b,-1$	$b+(c-b)\alpha,\ -1+\alpha$	$c,0$
1-p	NI		$0,1$	$1-\alpha,\alpha$	$1,0$

Figure 5

Let $\bar{\alpha} = \max\left[\frac{1}{2}, \frac{1-b}{1-b+c}\right]$. This parameter plays a central role in our analysis.

We first analyze the case where $1-c \le b$. Namely (see Figure 3), the cost of making a mistake for M is larger when E enters than when E does not enter. In this case $\bar{\alpha} = \frac{1}{2}$.

Proposition 1. Suppose that $1-c \le b$. Then the game has a unique Nash equilibrium. (1) The Entrant does not enter the market if the signal is i and randomizes between entering and not entering if the signal is ni. The Incumbent randomizes between expanding and not expanding its capacity. (2) The probability that the Incumbent expands his capacity is increasing in α. The probability that the Entrant enters the market is decreasing in α. (3) The expected payoff of the Incumbent increases in α. The expected payoff of the Entrant is zero.

Proof. See Appendix.

Since $b \ge 1-c$ the penalty of M for not expanding capacity if E enters is relatively high. Thus M invests in capacity expansion with relatively high probability. Actually, this probability is shown to be equal to the precision α of the IS and since $\alpha > \frac{1}{2}$ E expects to observe the signal i with higher probability than the signal ni. As a result, E stays out for sure if she observes the signal i and E hesitates if she observes the less expected signal ni. In the latter case E mixes her two pure actions. The higher is the precision α of the IS the higher is the probability that M invests and the higher is the probability that E stays out. Hence, the expected payoff of M increases with α and the expected payoff of E is zero.

We conclude that for $1-c \le b$ even if the IS is cost free, E has no incentive to use IS since her payoff is zero irrespective of the quality α.

We next deal with the case where $1-c>b$. In this case $\bar{\alpha}>\frac{1}{2}$ and the equilibrium outcome depends on whether $\alpha<\bar{\alpha}$ or $\alpha>\bar{\alpha}$.

Proposition 2. Suppose that $1-c>b$. The game has a unique Nash equilibrium. In equilibrium (1) If E observes the signal ni she enters the market with probability 1 if $\alpha<\bar{\alpha}$ and she randomizes her two actions if $\alpha>\bar{\alpha}$. If E observes the signal i she randomizes her two actions if $\alpha<\bar{\alpha}$ and stays out with probability 1 if $\alpha>\bar{\alpha}$. (2) The probability that E enters the market is decreasing in α for all $\alpha\in\left(\frac{1}{2},1\right)$. (3) The probability that M expands capacity is decreasing in α for $\frac{1}{2}<\alpha<\bar{\alpha}$ and it is increasing in α for $\bar{\alpha}<\alpha<1$. (4) The expected payoff of M is increasing in α, for all α, and the expected payoff of E is increasing in α for $\frac{1}{2}<\alpha<\bar{\alpha}$ and it is zero for all α, $\bar{\alpha}<\alpha<1$. (5) If $\alpha=\bar{\alpha}$, E enters the market with certainty if she observes the signal ni and E stays out with certainty If she observes the signal i. M has a continuum of best reply strategies.

Proof. See Appendix.

The proposition implies that E is better off the higher is the precision of the IS as long as it is smaller than $\bar{\alpha}$ (see Figure 6). The incumbent firm is best off with a perfect IS, even thought that means perfect monitoring of his actions. Let Π_E be the equilibrium expected payoff of E.

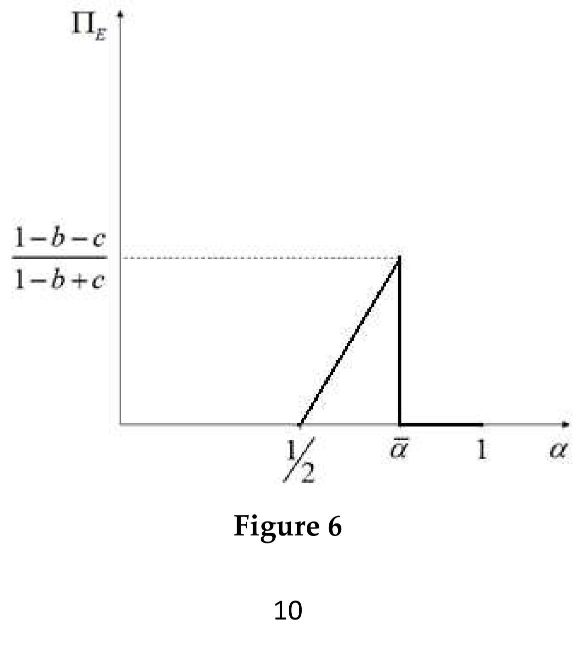

Figure 6

Let us provide intuition for these results. If the precision α of the IS is sufficiently large ($\alpha > \bar{\alpha}$), M who knows α knows that his action will be correctly detected with high probability. He therefore expects that if he does not expand his capacity, E is likely to enter. Hence, M expands his capacity with high probability which can be shown to be α. Consequently, the signal ni is not likely to occur. If E observes this signal, she should not trust its accuracy and should update her belief about M's action. As a result, she does not enter with positive probability. On the other hand, E expects the signal i and when she observes it, she trusts its accuracy and does not enter with probability 1.

If the precision of the IS is not too accurate ($1/2 < \alpha < \bar{\alpha}$), M assigns significant probability that his action will not be accurately detected. Therefore, in an attempt to conceal his action, M mixes his two strategies I and NI, both with significant probabilities ($1-\alpha$ and α respectively). Thus both signals i and ni have reasonable likelihood to occur. However the signal ni is more likely than the signal i since $\alpha > 1-\alpha$. As a result E enters with probability 1 if the signal is ni and randomizes her action if the signal is i.

An increase in the quality α of the IS increases the reliability of the signal generated. Hence, when E observes the signal i she enters the market with lower probability and M is better off. Less intuitive is the fact that as α increases M invests with lower probability and reduces the probability of the signal i. However, we argue that this decreases the probability that E enters. This behavior of M has two opposite effects on M's payoff. The negative effect is the increase of the probability of the signal ni, which contributes to the increase of the probability that E enters (E enters with probability 1 when she observes the signal ni). On the other hand, it decreases the conditional probability that E enters given i, which contributes to the decrease of the probability that E enters. It turns out that the latter effect outperforms the negative effect and as a result the unconditional probability that E enters decreases with α.

4. Asymmetric information about the precision of IS.

In this section we assume that the precision α of the IS is the private information of its owner, E. The incumbent, who doesn't know α assigns a continuous density probability $f(\alpha)>0$ to every α, $\frac{1}{2}\le\alpha\le 1$ and $\int_{\frac{1}{2}}^{1} f(\alpha)\,d\alpha=1$. In other words, E knows the game G_α which is actually being played while M doesn't know what game is being played. But M knows that α is chosen according to $f(\alpha)$, and this is commonly known. Denote by Γ this game.

Let u_M and u_E be the utilities of the two firms from the various outcomes. As in the previous section (see Figure 2), it is assumed that

$$\begin{array}{ll} u_M(I,E)=b & u_E(I,E)=-1 \\ u_M(I,NE)=c & u_E(I,NE)=0 \\ u_M(NI,E)=0 & u_E(NI,E)=1 \\ u_M(NI,NE)=1 & u_E(NI,NE)=0 \end{array}$$

Let $E(\alpha)=\int_{\frac{1}{2}}^{1}\alpha\, f(\alpha)\,d\,\alpha$ be the expected value of α. Namely $E(\alpha)$ is the expected quality of the IS from the perspective of the uninformed M.

The next proposition shows that the strategic behavior of the two players in the asymmetric information case is qualitatively similar to the case where the precision of the IS is common knowledge.

Proposition 3. Suppose that $E(\alpha)\neq\overline{\alpha}$. Then Γ has a unique perfect Bayesian equilibrium.

(1) If $E(\alpha)>\overline{\alpha}$, there exists $\overline{p}_1$, $\frac{1}{2}<\overline{p}_1<1$ such that M expands his capacity with probability $\overline{p}_1$. If the signal is ni, E does not enter the market if $\alpha<\overline{p}_1$ and she enters if $\alpha>\overline{p}_1$. If the signal is i, E does not enter the market irrespective of the precision α of the IS.

(2) If $E(\alpha) < \bar{\alpha}$, there exists $\overline{p}_2$, $0 < \overline{p}_2 < \frac{1}{2}$, such M expands his capacity with probability $\overline{p}_2$. If the signal is ni, E enters the market irrespective of the precision α of the IS. If the signal is i, E does not enter the market if $\alpha > 1 - \overline{p}_2$ and she enters the market if $\alpha < 1 - \overline{p}_2$.

Proof. See Appendix.

The next two figures illustrate the results of proposition 3:

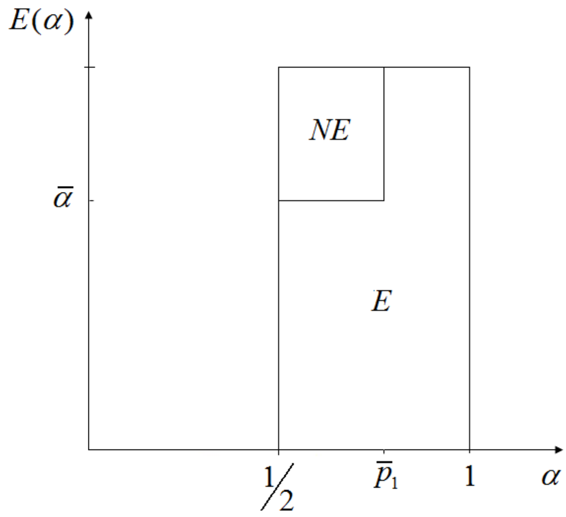

Figure 7: The decision of E when the signal is ni

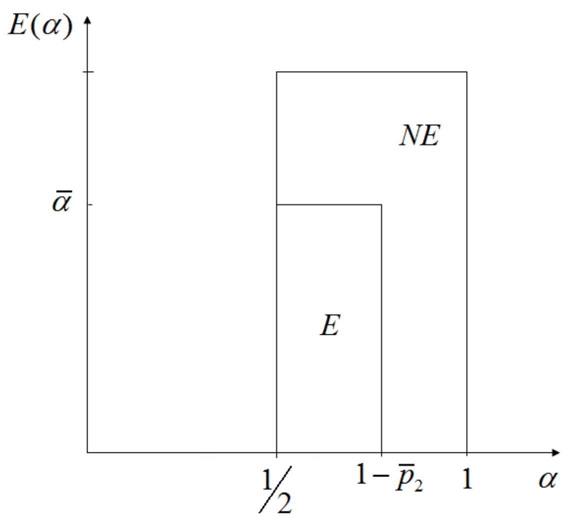

Figure 8: The decision of E when the signal is i

Unlike the case where α is commonly known, the equilibrium strategy of E of type α is a pure action (enter or not enter the market with probability 1). The action of E depends on both the expected and the actual precision of the IS. If the expected precision of IS does not exceed $\overline{\alpha}$, E following the signal ni will enter the market irrespective of the actual precision. Furthermore, E will enter the market even if she receives the signal i and if the actual precision α is relatively small ($\alpha < 1-\overline{p}_2$), otherwise she will not enter the market. If on the other hand, the expected precision of the IS exceeds $\overline{\alpha}$, E following the signal ni will enter the market if the actual precision is relatively high ($\alpha > \overline{p}_1$) and will not enter the market otherwise.

This result is quite consistent with the case where α is commonly known. When α is commonly known, the actual precision and the expected precision are the same. If it does not exceed $\overline{\alpha}$, E, following the signal ni, will enter the market with probability 1. If it exceeds $\overline{\alpha}$, E following ni will randomize between entering and not entering. In the asymmetric information case the mixing is obtained by varying the pure action of E as a function of α. Namely, E of type α enters the market if $\alpha > \overline{p}_1$ and stays out if $\alpha < \overline{p}_1$.

Next we analyze the expected payoff of the entrant. Let $\pi_E(\alpha)$ be the equilibrium expected payoff of E when the precision of the IS is α.

The next proposition provides a significant change from the symmetric information case.

<u>Proposition 4.</u> Consider the equilibrium of Γ. Then,

(1) Suppose that $E(\alpha) > \overline{\alpha}$. Then for all α in the interval $\left(\tfrac{1}{2}, \overline{p}_1\right)$ E does not enter the market, irrespective of the signal received, and $\pi_E(\alpha)$ is zero in this interval. For all α in $\left(\overline{p}_1, 1\right)$, $\pi_E(\alpha)$ is strictly increasing.

(2) Suppose that $E(\alpha) < \overline{\alpha}$. Then for all α in the interval $\left(\tfrac{1}{2}, 1-\overline{p}_2\right)$ E enters the market, irrespective of the signal sent by the IS, and $\pi_E(\alpha)$ is a positive constant in this interval. On the other hand, for all α in $\left(1-\overline{p}_2, 1\right)$, $\pi_E(\alpha)$ is strictly increasing.

Proof. See Appendix.

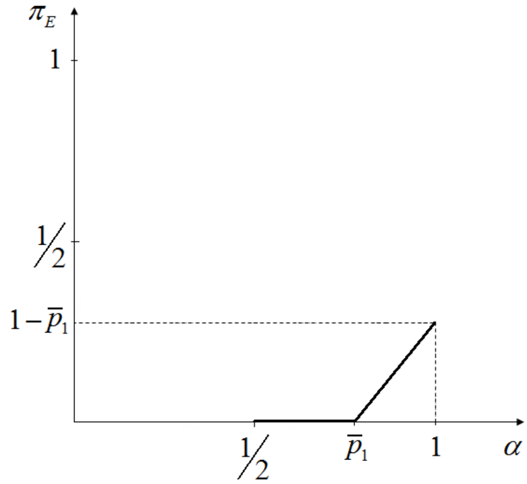

Figure 9: The expected payoff of E when $E(\alpha) > \overline{\alpha}$

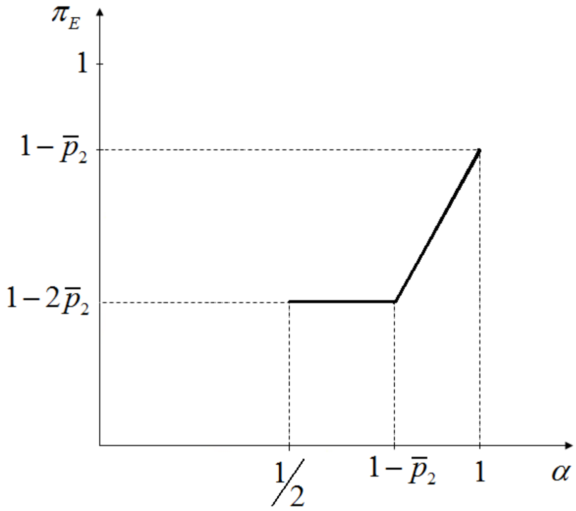

Figure 10: The expected payoff of E when $E(\alpha) < \overline{\alpha}$

In contrast to the common knowledge case, Proposition 4 shows that in the asymmetric case E is always best off with a perfect IS. The payoff of E as function of α is constant up to a certain α (depending on whether or not $E(\alpha) > \overline{\alpha}$) and there after it is strictly increasing. In the case where α is commonly known, the payoff of E if $b + c \geq 1$ is zero for all $\frac{1}{2} \leq \alpha \leq 1$, and if $b + c < 1$ it increases up to $\overline{\alpha}$ and drops to zero the after.

The next proposition describes the equilibrium payoff of M.

Proposition 5. Consider the equilibrium of Γ. Then,

(1) If $E(\alpha) > \bar{\alpha}$, $\pi_M(\alpha)$ is constant for $\frac{1}{2} < \alpha < \bar{p}_1$. For $\bar{p}_1 < \alpha < 1$, $\pi_M(\alpha)$ is strictly decreasing if $\frac{1}{2} < \bar{p}_1 < \frac{1}{1-b+c}$, and it is strictly increasing if $\frac{1}{1-b+c} < \bar{p}_1 < 1$.

(2) If $E(\alpha) < \bar{\alpha}$, $\pi_M(\alpha)$ is constant for $\frac{1}{2} < \alpha < 1 - \bar{p}_2$ and is strictly decreasing for $1 - \bar{p}_2 < \alpha < 1$.

Proof. See Appendix.

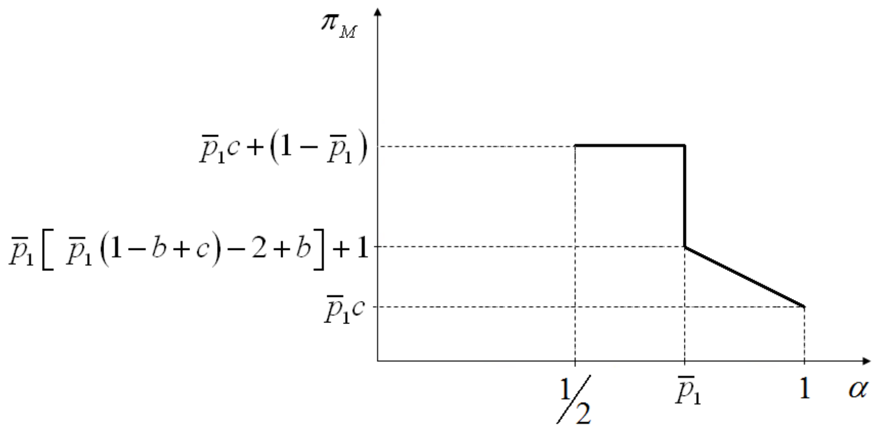

Figure 11: The expected payoff of M when $E(\alpha) > \bar{\alpha}$ **and** $\frac{1}{2} < \bar{p}_1 < \frac{1}{1-b+c}$

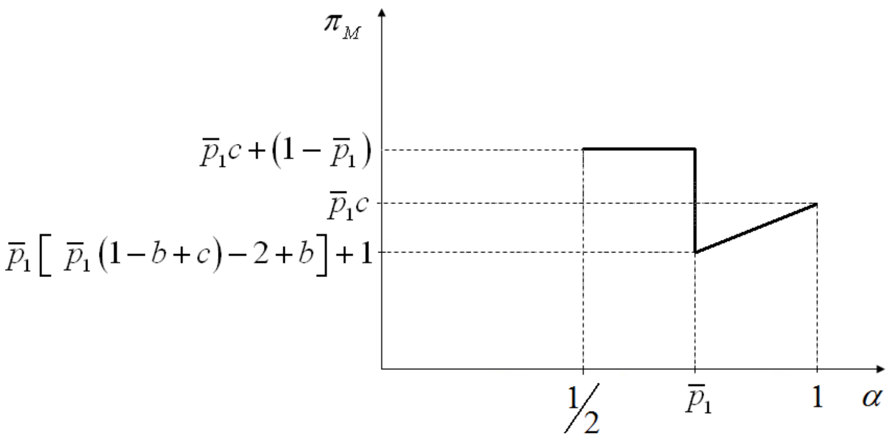

Figure 12: The expected payoff of M when $E(\alpha) > \bar{\alpha}$ **and** $\frac{1}{1-b+c} < \bar{p}_1 < 1$

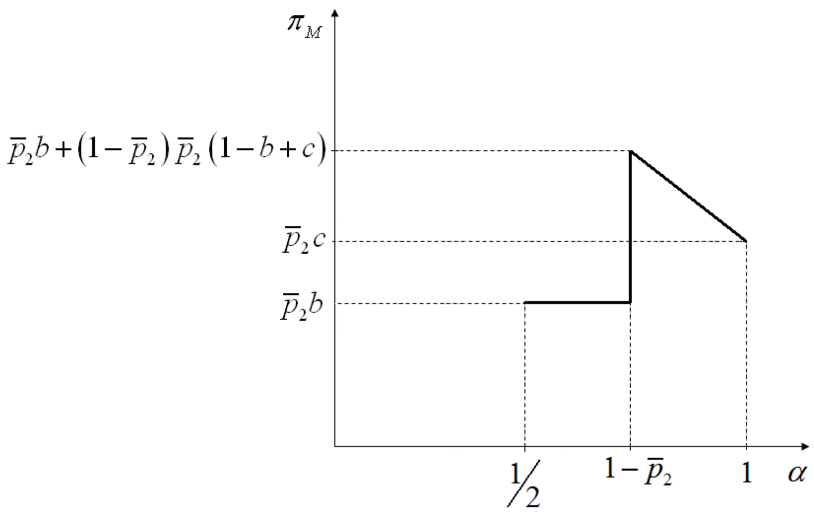

Figure 13: The expected payoff of M when $E(\alpha) < \bar{\alpha}$

In the common knowledge case M is always best off when E perfectly detects his action. The asymmetric case yields different results. Up to a certain value of α the ex-post expected payoff of M is constant. If M believes that the expected precision of the IS is relatively high he is best off when E does not spy on him or if the IS has a low accuracy. If however M believes that the expected precision of the IS is low, M prefers E to spy on him, but with an IS which is not perfect. Actually, the closer α is to $1-\bar{p}_2$ (from above) the better is M. E always prefers the perfect IS.

References

1. Billand, P., Bravard, C., Chakrabarti, S. and Sarangi, S. (2009) “Spying in Multi-market Oligopolies”, Louisiana State University, Department of Economics Working Papers Series, Working Paper 2009-11.

2. Biran, D. and Tauman, Y. (2009) “The Decision to Attack a Nuclear Facility: The Role of Intelligence”, Working Paper.

3. Crawford, V. and Sobel, J. (1982) “Strategic Information Transmission”, *Econometrica* 50:6, 1431–1451.

4. Ho, S.J (2008) “Extracting the Information: Espionage with Double Crossing”, *Journal of Economcs*, 93:1, 31-58.

5. Matsui, A. (1989) “Information Leakage Forces Cooperation”, *Games and Economic Behavior*, 1:1, 94-115.

6. Provan, J.S. (2008) "The Use of Spies in Strategic Situations: Preliminary Report." Technical Report UNC/STOR/07/01

7. Solan E. and Yariv, L. (2004) “Games with espionage”, *Games and Economic Behavior*, 47:1, 172-199.

8. Whitney, M. E. and Gaisford, J. D. (1999) “An Inquiry Into the Rationale for Economic Espionage”, *International Economic Journal*, 13: 2, 103-123.

Appendix

Proof of Proposition 1. It is easy to verify that when $b+c \geq 1$ (in which case $\bar{\alpha} = \frac{1}{2}$), the unique Nash equilibrium strategy of M is $(\alpha, 1-\alpha)$, namely M invests with probability α, and E plays (E, NE) with probability

$$q = \frac{1-c}{\alpha(1-b+c)+b-c}$$

and plays (NE, NE) with probability $1-q$. Clearly, $\Pi_E = 0$ and $\Pi_M = \frac{\alpha(2c-b)+b-c}{\alpha(1-b+c)+b-c}$.

■

Proof of Proposition 2. Suppose that $b+c<1$. It is easy to verify that the unique Nash equilibrium strategy of M is to invest with probability p, s.t.

$$p(\alpha) = \begin{cases} 1-\alpha, & \frac{1}{2} < \alpha < \bar{\alpha} \\ \alpha, & \bar{\alpha} < \alpha < 1 \end{cases}$$

As for E, if $\frac{1}{2} < \alpha < \bar{\alpha}$, she plays (E, E) with probability q^*, where

$$q^* = \frac{1-b-\alpha(1+c-b)}{1-\alpha(1+c-b)} \tag{A1}$$

and plays (E, NE) with probability $1-q^*$. If $\bar{\alpha} < \alpha < 1$, E plays (E, NE) with probability $\hat{q}$, where

$$\hat{q} = \frac{1-c}{\alpha(1-b+c)+b-c} \tag{A2}$$

and plays (NE, NE) with probability $1-\hat{q}$. It can be easily verified that

$$\Pi_M = \begin{cases} \frac{(1-\alpha)b}{1-\alpha(1+c-b)}, & \frac{1}{2} < \alpha < \bar{\alpha} \\ \frac{\alpha(2c-b)+b-c}{\alpha(1-b+c)+b-c}, & \bar{\alpha} < \alpha < 1 \end{cases}$$

and

$$\Pi_E = \begin{cases} 2\alpha - 1, & \tfrac{1}{2} < \alpha < \bar{\alpha} \\ 0, & \bar{\alpha} < \alpha < 1 \end{cases}$$

If $\alpha = \bar{\alpha}$, the game has multiple equilibrium points: M invests with probability $\tilde{p}$ where $\frac{c}{1-b+c} \le \tilde{p} \le \frac{1-b}{1-b+c}$, and E plays (E, NE) purely. In this case $\tilde{\Pi}_M = \frac{c}{1-b+c}$ and $\tilde{\Pi}_E \in \left[0, \frac{1-b-c}{1-b+c}\right]$.

Next let us prove that the unconditional probability that E enters is decreasing in α. Consider first the case $\tfrac{1}{2} < \alpha < \bar{\alpha}$. In equilibrium the Entrant enters the market with probability 1 if the signal is ni, and with probability q^* if the signal is i. Hence

$$Prob(E) = Prob(ni) + q^* Prob(i)$$

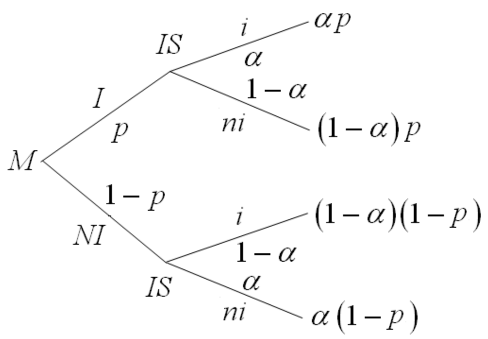

Figure 14

where $p = 1 - \alpha$. By Figure 14,

$$Prob(ni) = p(1-\alpha) + (1-p)\alpha = (1-\alpha)^2 + \alpha^2$$

and

$$Prob(i) = p\alpha + (1-p)(1-\alpha) = 2(1-\alpha)\alpha$$

By (A1)

$$Prob(E) = \frac{1 + 2b\alpha^2 - \alpha(1+c+b)}{1 - \alpha(1+c-b)}$$

Since $[2 - (1+c-b)\alpha]\alpha - 1 = -(\alpha-1)^2 + (b-c)\alpha^2 < 0$,

$$\frac{\partial Prob\left(E\right)}{\partial\alpha}=\frac{2b\left[\left[2-(1+c-b)\alpha\right]\alpha-1\right]}{\left[1-\alpha(1+c-b)\right]^{2}}<0$$

Next assume that $\bar{\alpha}<\alpha<1$. In equilibrium the Entrant does not enter the market if the signal is i, and she enters with probability $\hat{q}$ if the signal is ni. Hence

$$Prob\left(E\right)=\hat{q}Prob(ni)+0Prob(i)$$

Using Figure 14 (but now $p=\alpha$) we have

$$Prob\left(ni\right)=p\left(1-\alpha\right)+\left(1-p\right)\alpha=2\left(1-\alpha\right)\alpha$$

By (A2)

$$Prob\left(E\right)=\frac{2\left(1-c\right)\left(1-\alpha\right)\alpha}{\alpha(1-b+c)+b-c}$$

and it is decreasing in α since

$$\frac{\partial Prob\left(E\right)}{\partial\alpha}=\frac{-2\left(1-c\right)\left[\left(\alpha-1\right)^{2}(c-b)+\alpha^{2}\right]}{\left[\alpha(1-b+c)+b-c\right]^{2}}<0$$

■

Proof of Proposition 3. Suppose that M chooses I with probability p and NI with probability $1-p$. Using Figure 14,

$$Prob_{E}\left(I\middle|\alpha,i\right)=\frac{\alpha\,p}{\alpha\,p+\left(1-\alpha\right)\left(1-p\right)}$$

$$Prob_{E}\left(NI\middle|\alpha,i\right)=\frac{\left(1-\alpha\right)\left(1-p\right)}{\alpha\,p+\left(1-\alpha\right)\left(1-p\right)}$$

$$Prob_{E}\left(I\middle|\alpha,ni\right)=\frac{\left(1-\alpha\right)p}{\left(1-\alpha\right)p+\alpha\left(1-p\right)}$$

$$Prob_{E}\left(NI\middle|\alpha,ni\right)=\frac{\alpha\left(1-p\right)}{\left(1-\alpha\right)p+\alpha\left(1-p\right)}$$

Let $\Pi_{E}\left(E\middle|\alpha,i\right)$ be the expected payoff of E if the signal is i and she enters the market. Then,

$$\Pi_E\left(E\middle|\,\alpha,i\right)=Prob_E\left(I\middle|\,\alpha,i\right)u_E\left(I,E\right)+Prob_E\left(NI\middle|\,\alpha,i\right)u_E\left(NI,E\right)= \\ =\frac{1-p-\alpha}{\alpha\,p+\left(1-\alpha\right)\left(1-p\right)} \tag{A3}$$

Similarly

$$\Pi_E\left(E\middle|\alpha,ni\right)=\frac{\alpha-p}{\left(1-\alpha\right)p+\alpha\left(1-p\right)}$$

$$\Pi_E\left(NE\middle|\,\alpha,i\right)=0 \tag{A4}$$

$$\Pi_E\left(NE\middle|\,\alpha,ni\right)=0$$

Given p , by (A3) and (A4), if E receives the signal i she prefers E on NE iff

$$\frac{1-p-\alpha}{\alpha\,p+\left(1-\alpha\right)\left(1-p\right)}>0$$

or equivalent iff $\alpha<1-p$.

That is, if E receives the signal i she will enter if $\alpha<1-p$ and she will not enter if $\alpha>1-p$. If $\alpha=1-p$ E is indifferent between entering and not entering the market.

Similarly, if E receives the signal ni she enters the market iff

$$\frac{\alpha-p}{\left(1-\alpha\right)p+\alpha\left(1-p\right)}>0$$

or equivalently iff $\alpha>p$.

We can write now the best reply strategy of E as a function of the signal she receives.

$$s_E\left(i\,|\,\alpha,\,p\right)=\begin{cases} NE & p>\frac{1}{2},\quad \frac{1}{2}<\alpha\le 1 \\ E & p\le\frac{1}{2},\quad \frac{1}{2}<\alpha<1-p \\ NE & p\le\frac{1}{2},\quad 1-p<\alpha\le 1 \\ \text{any strategy} & p\le\frac{1}{2},\quad \alpha=1-p \end{cases} \tag{A5}$$

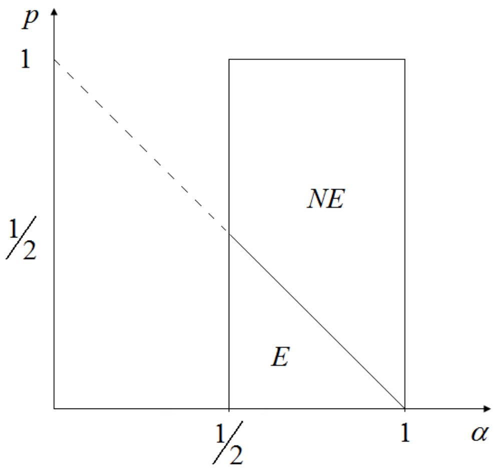

Figure 15: $s_E\left(i\,|\,\alpha,\,p\right)$

Next,

$$s_E\left(ni\,|\,\alpha,\,p\right)=\begin{cases} E & p<\frac{1}{2},\quad \frac{1}{2}<\alpha\le 1 \\ NE & p\ge\frac{1}{2},\quad \frac{1}{2}<\alpha<p \\ E & p\ge\frac{1}{2},\quad p<\alpha\le 1 \\ \text{any strategy} & p\ge\frac{1}{2},\quad \alpha=p \end{cases} \tag{A6}$$

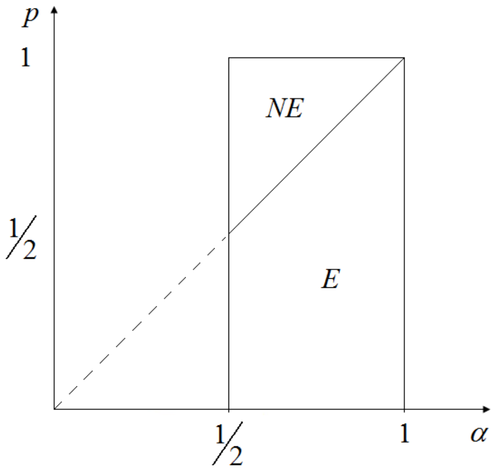

Figure 16: $s_E\left(ni \mid \alpha, p\right)$

(1) Suppose that $E(\alpha) > \bar{\alpha}$ where $\bar{\alpha} = \dfrac{1-b}{1-b+c}$. Consider first the case where M expands his capacity with probability $\dfrac{1}{2} < p < 1$. Let $E\Pi_M(p)$ be the expected payoff of M. By (A5) and (A6)

$$E\Pi_M(p) = p\left[\int_{\frac{1}{2}}^{1} \alpha\, u_M(I, NE)\, f(\alpha)\, d\alpha + \int_{\frac{1}{2}}^{p} (1-\alpha)\, u_M(I, NE)\, f(\alpha)\, d\alpha + \int_{p}^{1} (1-\alpha)\; u_M(I, E)\, f(\alpha)\, d\alpha\right] +$$

$$+(1-p)\left[\int_{\frac{1}{2}}^{p} \alpha\; u_M(NI, NE)\, f(\alpha)\, d\alpha + \int_{p}^{1} \alpha\; u_M(NI, E)\, f(\alpha)\, d\alpha + \int_{\frac{1}{2}}^{1} (1-\alpha)\, u_M(NI, NE)\, f(\alpha)\, d\alpha\right]$$

Since $u_M(I, E) = b,\;\; u_M(I, NE) = c,\;\; u_M(NI, E) = 0$ and $u_M(NI, NE) = 1$

$$E\Pi_M(p) = p\left[c\int_{\frac{1}{2}}^{1} \alpha f(\alpha)\, d\alpha + c\int_{\frac{1}{2}}^{p} (1-\alpha)\, f(\alpha)\, d\alpha + b\int_{p}^{1} (1-\alpha)\, f(\alpha)\, d\alpha\right] +$$

$$+(1-p)\left[\int_{\frac{1}{2}}^{p} \alpha f(\alpha)\, d\alpha + \int_{\frac{1}{2}}^{1} (1-\alpha)\, f(\alpha)\, d\alpha\right]$$

Since $\int_{\frac{1}{2}}^{1} f(\alpha)\, d\alpha = 1$

$$E\Pi_M(p) = p\left[c + (b-c)\int_{p}^{1} (1-\alpha) f(\alpha)\, d\alpha\right] + (1-p)\left[1 - \int_{p}^{1} \alpha\, f(\alpha)\, d\alpha\right] \tag{A7}$$

Note that E observes neither the mixed strategy played by M nor his actual action. She only observes the signal sent by the IS. Hence, if M unilaterally deviates from his mixed strategy $(p, 1-p)$ to any other strategy, the strategy of E (as a function of her type α and the signal observed) does not change, but the probabilities of the signals do change. In equilibrium, M should be indifferent between playing $(p, 1-p)$ and playing either one of his pure strategies, since $0 < p < 1$. That is

$$E\Pi_M(0) = E\Pi_M(1) \tag{A8}$$

By (A7) and (A8)

$$c + (b-c)\int_p^1 (1-\alpha) f(\alpha)\, d\alpha = 1 - \int_p^1 \alpha\, f(\alpha)\, d\alpha \tag{A9}$$

Let

$$g(p) \equiv c - 1 + (b-c)\int_p^1 (1-\alpha) f(\alpha)\, d\alpha + \int_p^1 \alpha\, f(\alpha)\, d\alpha$$

be defined for all $\frac{1}{2} \le p \le 1$. Since $f(\alpha)$ is continuous in α, $g(p)$ is continuously differentiable in p. Also

$$g\left(\frac{1}{2}\right) = -1 + b + (1-b+c)\, E(\alpha)$$

By our assumption $E(\alpha) > \frac{1-b}{1-b+c}$, hence $g\left(\frac{1}{2}\right) > 0$. Since $g(1) = c - 1 < 0$ by the Mean Value Theorem there is $\bar{p}_1$, $\frac{1}{2} < \bar{p}_1 < 1$, such that $g(\bar{p}_1) = 0$.

Next

$$\begin{aligned} g'(p) &= -(b-c)\, f(p) - (1-b+c)\, p\, f(p) = \\ &= \left[-(1-b+c)\, p - (b-c)\right] f(p) \end{aligned}$$

Since $f(p) > 0$

$$g'(p) > 0 \text{ iff } p < \frac{c-b}{1-b+c}$$

Since $\frac{c-b}{1-b+c}<\frac{1}{2}$, $g(p)$ is decreasing for $\frac{1}{2}\le p<1$. Since $g\left(\frac{1}{2}\right)>0$ and $g(1)<0$ then g crosses the p-axis only once. Therefore $\overline{p}_1$ is the unique solution of $g(p)=0$ and therefore of (A9).

Next observe that M has no equilibrium strategy $(\overline{p}, 1-\overline{p})$ such that $0<\overline{p}\le\frac{1}{2}$ and $E(\alpha)>\frac{1-b}{1-b+c}$. Otherwise (A9) should be replaced by

$$c+(b-c)\int_{\frac{1}{2}}^{1}(1-\alpha)f(\alpha)\,d\alpha=1-\int_{\frac{1}{2}}^{1}\alpha\, f(\alpha)\,d\alpha$$

This implies that

$$E(\alpha)=\frac{1-b}{1-b+c},$$

a contradiction. We conclude that whenever $E(\alpha)>\frac{1-b}{1-b+c}$ the game Γ has a unique equilibrium.

(2) Suppose next that $E(\alpha)<\frac{1-b}{1-b+c}$. Consider first the case where M expands his capacity with probability p, $0<p<\frac{1}{2}$. Similarly to the previous case

$$E\Pi_M(p)=p\left[\int_{\frac{1}{2}}^{1-p}\alpha\, u_M(I,E)\,f(\alpha)\,d\alpha+\int_{1-p}^{1}\alpha u_M(I,NE)\,f(\alpha)\,d\alpha+\int_{\frac{1}{2}}^{1}(1-\alpha)\;u_M(I,E)\,f(\alpha)\,d\alpha\right]+$$
$$+(1-p)\left[\int_{\frac{1}{2}}^{1}\alpha\, u_M(NI,E)\,f(\alpha)\,d\alpha+\int_{\frac{1}{2}}^{1-p}(1-\alpha)u_M(NI,E)\,f(\alpha)\,d\alpha+\int_{1-p}^{1}(1-\alpha)\,u_M(NI,NE)\,f(\alpha)\,d\alpha\right]$$

Since $u_M(I,E)=b,\;\; u_M(I,NE)=c,\;\; u_M(NI,E)=0$ and $u_M(NI,NE)=1$

$$E\Pi_M(p)=p\left[b+(c-b)\int_{1-p}^{1}\alpha f(\alpha)\,d\alpha\right]+(1-p)\left[\int_{1-p}^{1}(1-\alpha)\,f(\alpha)\,d\alpha\right]\tag{A10}$$

In equilibrium where $0<p<1$ we have

$$E\Pi_M(0)=E\Pi_M(1)\tag{A11}$$

By (A10) and (A11) we have

$$b+(c-b)\int_{1-p}^{1} \alpha f(\alpha)\, d\alpha = \int_{1-p}^{1} (1-\alpha) f(\alpha)\, d\alpha \tag{A12}$$

Let

$$m(x) \equiv b+(c-b)\int_{x}^{1} \alpha f(\alpha)\, d\alpha - \int_{x}^{1} (1-\alpha) f(\alpha)\, d\alpha$$

be defined for all $\frac{1}{2} \le x \le 1$. Clearly $m(x)$ is continuous and differentiable. Since

$E(\alpha) < \frac{1-b}{1-b+c}$,

$$m\left(\frac{1}{2}\right) = (1-b+c)\, E(\alpha) + (b-1) < 0$$

Also

$$m(1) = b > 0$$

In addition

$$m'(x) = \left[1-(1-b+c)\, x\right] f(x)$$

Since $f(x) > 0$

$$m'(x) > 0 \text{ iff } x < \frac{1}{1-b+c}$$

Hence m increases for $\frac{1}{2} \le x < \frac{1}{1-b+c}$ and decreases for $\frac{1}{1-b+c} < x \le 1$. Since $m\left(\frac{1}{2}\right) < 0$ and $m(1) > 0$ then m intersects the x-axis only once. Namely, there is a unique $\bar{x}$ such that $m(\bar{x}) = 0$ and $\frac{1}{2} < \bar{x} < 1$. Thus there exists $\bar{p}_2$, $0 < \bar{p}_2 < 1$, such that $\bar{p}_2$ is the unique solution of (A12), and $\bar{p}_2 < \frac{1}{2}$ which is consistent with our assumption.

Next it is easy to verify (similarly to the previous case) that there is no equilibrium where $p \ge \frac{1}{2}$ and $E(\alpha) < \frac{1-b}{1-b+c}$. We conclude that whenever $E(\alpha) < \frac{1-b}{1-b+c}$ the game Γ has a unique equilibrium.

It is also easy to verify that there is no equilibrium where M is playing a pure strategy.

■

Proof of Proposition 4. By (A5), (A6) and Proposition 3 it is easy to verify that

$$\pi_E(\alpha)=\begin{cases} 1-2\overline{p}_2 \quad , & E(\alpha)<\overline{\alpha},\ \frac{1}{2}<\alpha<1-\overline{p}_2 \\ \alpha-\overline{p}_2 \quad , & E(\alpha)<\overline{\alpha},\ 1-\overline{p}_2<\alpha<1 \\ 0 \quad , & E(\alpha)>\overline{\alpha},\ \frac{1}{2}<\alpha<\overline{p}_1 \\ \alpha-\overline{p}_1 \quad , & E(\alpha)>\overline{\alpha},\ \overline{p}_1<\alpha<1 \end{cases}$$

and the proof follows immediately.

■

Proof of Proposition 5. By (A5), (A6) and Proposition 3 it is easy to verify that

$$\pi_M(\alpha)=\begin{cases} \overline{p}_2 b \quad , & E(\alpha)<\overline{\alpha},\ \frac{1}{2}<\alpha<1-\overline{p}_2 \\ \left[\ \overline{p}_2(1-b+c)-1\right]\alpha+1-\overline{p}_2(1-b) \quad , & E(\alpha)<\overline{\alpha},\ 1-\overline{p}_2<\alpha<1 \\ \overline{p}_1 c+(1-\overline{p}_1) \quad , & E(\alpha)>\overline{\alpha},\ \frac{1}{2}<\alpha<\overline{p}_1 \\ \left[\ \overline{p}_1(1-b+c)-1\right]\alpha+1-\overline{p}_1(1-b) \quad , & E(\alpha)>\overline{\alpha},\ \overline{p}_1<\alpha<1 \end{cases}$$

and the proof follows immediately.

■