Eurasian Journal of Economics and Finance, 6(1), 2018, 16-24
DOI: 10.15604/ejef.2018.06.01.002

EURASIAN JOURNAL OF ECONOMICS AND FINANCE

www.eurasianpublications.com

R&D INVESTMENTS AND SPILLOVERS UNDER ENDOGENOUS ABSORPTIVE CAPACITY: COMPETITIVE R&D CANNOT TAKE FULL-ADVANTAGE OF COMPLEMENTARITY IN ABSORPTIVE CAPACITY WHILE COOPERATIVE R&D CAN

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Abstract

We show that the setting up of general conditions on complementarity in absorptive capacity gives rise to different, if not opposite Nash equilibrium outcomes to those found when absorptive capacity is assumed to be determined only by the similarity of R&D orientations. Firms that cooperate in R&D can take full-advantage of complementarity in R&D by adopting firm-specific R&D paths, which appears to contradict findings and predictions of existing theoretical literature on R&D and spillovers. Oddly, firms competing in R&D cannot gain the most from the potential of complementarity in knowledge by not choosing firm-specific R&D approaches in equilibrium under even milder conditions, which is contrary to another prediction of existing related models.

Keywords: Absorptive Capacity, Complementarities, R&D, Knowledge Spillovers

JEL Classifications: L13, O31, O33

1. Introduction

The notion of absorptive capacity is essential to understand knowledge spillovers between firms carrying out R&D and new knowledge acquisition (Cohen and Levinthal, 1989; 1990). Absorptive capacity consists of a firm's capabilities of acquisition and assimilation of external knowledge and its transformation and exploitation capabilities. The absorptive capacity of a firm has two components related to knowledge sharing and knowledge diversity across individuals. Some overlap of knowledge across individuals is necessary for internal communication, but there are some benefits to diversity of knowledge structures across individuals which are similar to the benefits to diversity of knowledge within individuals. Cognitive elements which enhance absorptive capacity are similarity and complementarity of different but related bits of knowledge. The similarity and diversity dimensions of knowledge are critical determinants of learning. Knowledge diversity strengthens assimilative abilities, but also facilitates the innovative process by enabling individuals to make new associations and linkages.

R&D not only generates new information, as economists conventionally think of R&D, but also enhances a firm's ability to assimilate and exploit existing information. Recognition of the dual role of R&D means that one thinks that R&D generates new knowledge and also enhances the learning capacity of the firm. Absorptive capacity depends crucially on the learning experience of the firm which, in turn, may be developed and enhanced by in-house R&D activities. The firm's absorptive capacity is constituted by the development of a stock of prior knowledge. A significant benefit of R&D is thus its contribution to this knowledge base. The foundations of the concept of absorptive capacity were originally designed in the context of firm theory.

There is strong empirical evidence supporting the view that R&D increases a firm's absorptive capacity. Jaffe (1986) has obtained results suggesting that high R&D US firms benefit most in terms of productivity from their spillover pool. One influence on the firms' R&D program that is examined by Jaffe (1986) is spillovers of R&D from other firms. It is shown that the productivity of firms' R&D is increased by the R&D of "technological neighbors," though neighbors' R&D lowers the profits and market value of low-R&D-intensity firms. Cohen and Levinthal (1989) themselves have also presented some empirical evidence in favor of the absorptive capacity hypothesis using the Federal Trade Commission's Line of Business data and the Klevorick *et al*.'s (1987) survey data. The empirical results by Cohen and Levinthal (1989) suggest that the characteristics of knowledge that affect the ease of firm learning may represent an important class of determinants of R&D investments. The factors that affect the character and ease of learning include the degree to which knowledge is targeted to a firm's needs and the character of knowledge within each of the scientific and technological fields upon which innovation depends. The paper by Klevorick *et al.* (1987) describes the results of an inquiry into appropriability conditions in more than one hundred manufacturing industries. As a sampling frame, the lines of business defined by the Federal Trade Commission were used in the paper. There were 650 respondents to the survey representing 130 lines of business, with ten or more responses from eighteen industries and five to nine from twenty-seven industries. The sample was reasonably representative of firms performing R&D, though small start-up ventures were underrepresented.

Empirical evidence shows that the complementarity between internal R&D and R&D from external sources has a relevant role in the absorption of knowledge that leaks out by firms that undertake R&D, and consequently in the innovative performance of firms (see e.g. Backmann *et al.* 2015; Abecassis-Moedas and Mahmoud-Jouini, 2008). Abecassis-Moedas and Mahmoud-Jouini (2008) have proposed a conceptual framework of the source-recipient knowledge complementarity and its impact on the new product development performance. In a dyadic perspective, the source-recipient knowledge complementarity plays an important role in the transformation and exploitation of source knowledge. The main result is that the complementarity between the recipient and the source knowledge is a critical aspect of the absorption process and therefore of the new product development performance. Furthermore, given that innovations are usually developed by project teams, absorptive capacity, as a construct, may be usefully applied at the team level. Consequently, the study by Backmann *et al.* 2015 developed a measure for team-level absorptive capacity, investigated the potential influencing factors, and examined its relationship to team effectiveness in terms of product innovativeness in an interorganizational context. Building on the theory of homophily and information and decision-making theories, knowledge complementarity between the recipient and the partner organization teams was identified as a likely antecedent of team absorptive capacity. With regard to this antecedent of team absorptive capacity, the results showed an inverted U-shaped relationship with partners' knowledge complementarity. Backmann *et al.* 2015 demonstrate that absorptive is indeed related to team effectiveness outcomes in an interorganizational context, which underlines the importance of team-level absorptive capacity for product innovation management.

Absorptive capacity and the relationship between absorptive capacity and cooperation have been examined by the management and organization literature (Mowery *et al.* 1996; 1998). R&D alliances and in-house R&D are usually viewed by this literature as complementary strategies rather than alternatives. The internal research process can be significantly improved by successful alliances, as useful new ideas are generated outside the organization. Additionally, alliances with other firms will enable the firm to view differently some issues which, because of the established routines, may be difficult to do with only in-house R&D. A R&D alliance can thus be seen as another source of absorptive capacity besides in-house R&D. The

R&D alliance in effect expands a firm's own absorptive capacity by making the absorptive capacity from the in-house R&D of the firm's partner available to the firm.

The increasing uncertainty and complexity of engaging in innovative activity suggests that cooperation among autonomous firms commanding specialized complementary assets and sources of knowledge may be crucial to innovative success (Teece, 1986). The successful commercialization of innovations requires that the know-how be utilized together with other capabilities or assets. Marketing, competing manufacturing and after sales support are services which are almost always needed. Such services are often obtained from specialized complementary assets. Colombo *et al*. (2006) derive an empirical model to address the question of why new technology-based firms cooperate. The econometric estimates, based on a large sample of Italian young high-tech firms that are observed from 1994 to 2003, provide strong evidence supporting a key intuition of Teece's (1986) work: the combination of specialized complementary assets appears to be a key driver of the formation of exploitative commercial alliances by new technology-based firms.

However, the game-theoretical literature on R&D investment and absorptive capacity does not address the role played by the complementarity component of absorptive capacity in the selection of firms' R&D strategies, namely their R&D orientations and their levels of R&D investment (Kamien and Zang, 2000; Weithaus, 2005). The theoretical economic literature on R&D, technological knowledge spillovers and absorptive capacity assumes that only the similarities in R&D approaches chosen by firms enhance the absorptive capacity of each firm by increasing the connectedness between firms. Both studies by Kamien and Zang (2000), and Wiethaus (2005) implicitly treat technological distance as only a problem for a firm's innovation performance instead of also an opportunity.

In this paper, we generalize the models of Kamien and Zang (2000) and Weithaus (2005) by hypothesizing that the absorptive capacity of each firm is also affected by complementarity in knowledge. The similarity of knowledge and the variety of knowledge in absorptive capacity are, in turn, determined by firms' R&D orientations. The relevance of the predictions of Kamien and Zang's (2000) and Weithaus' (2005) models might be undermined as their assumptions on absorptive capacity do not consider the effects of knowledge complementarity on the absorption of external R&D results and consequently on the innovative performance of firms.

The objective of our work is to assess the impact upon equilibrium outcomes of a firm's absorptive capacity with a complementarity component between own and external R&D. We would like to show the lack of robustness of the Nash equilibria in R&D approaches found in Kamien and Zang's (2000) and Weithaus' (2005) models once absorptive capacity includes an additional component of complementarity.

We show that the setting up of general conditions on complementarity in absorptive capacity in those theoretical frameworks gives rise to different, if not opposite Nash equilibrium outcomes to those found when absorptive capacity is assumed to be determined only by the similarity of R&D orientations. Firms that cooperate in R&D can take full advantage of complementarity in R&D by adopting firm-specific R&D paths that enhance firms' capabilities to explore technological possibilities, which appears to contradict Kamien and Zang's (2000) findings, and so would contradict Weithaus' (2005) predictions, according to which firms choose identical R&D paths. Oddly, firms competing in R&D cannot gain the most from the potential of complementarity in knowledge by not choosing firm-specific R&D approaches in equilibrium under even milder conditions than in the former case of R&D cooperation, which is contrary to another prediction of the Kamien and Zang's (2000) and Weithaus' (2005) models according to which firms choose idiosyncratic R&D approaches.

The remaining of the paper is organized as follows. In section 2, the hypotheses of the game-theoretical model are presented and the structure of the model is described. Section 3 presents the equilibrium results under R&D competition and R&D cooperation. Finally, section 4 concludes the paper.

2. Model

In this section, a simple duopoly model can be established to underline the role of complementarity between in-house R&D and external R&D in endogenous absorptive capacity and R&D investments. The timeline of the three-stage games of Kamien and Zang (2000) and Weithaus (2005) that we adopt here is the following. In the first stage, the two firms choose simultaneously their R&D approaches and in the second stage, their R&D investment levels. We consider two alternative versions of the model concerning firms' decisions on the two elements of every R&D strategy, that is, the choices of R&D orientations and R&D investment levels under competition and under cooperation. The output level of each duopolist is chosen non-cooperatively in the last stage of the game. We assume that firms are maximizing their profits when they choose their R&D strategies and output levels.

In this model, the absorptive capacity of a firm is given by two elements, the similarity in knowledge, and so connectedness between firms that undertake R&D as assumed in Kamien and Zang (2000) and Weithaus (2005), and the complementarity between own R&D and external R&D. One implication of the introduction of the complementarity hypothesis in absorptive capacity is that the innovative performance of a firm is expected to be higher than when absorptive capacity is only affected by the similarity in knowledge, for given choices of R&D orientations by firms. It is the introduction of the complementarity element of knowledge that turns our model into an extended version of the absorptive capacity's model of Weithaus (2005).

A minimal setting change of the Kamien and Zang's (2000) and Weithaus' (2005) models so that the positive effects of complementarity in absorptive capacity are taken into account is via the impact of R&D results on the innovative performance of each firm. In order to compare the equilibrium outcomes in our generalized framework with those obtained in the original models of Kamien and Zang (2000) and Weithaus (2005), it is enough to assume that the marginal productivity of a firm's own R&D results increases in the complementarity between R&D approaches of the competing firms in the product market.

The innovative performance of a firm is represented in this paper by the reduction of the unit cost of production of the firm resulting from investments in R&D as follows

$$X_i = \left(1 + \varphi(\delta_i, \delta_j)\right)x_i + \beta(1 - \delta_i)\left(1 - \delta_j\right)x_j, \text{ with } i = 1, 2,\ \ i \neq j. \quad (1)$$

The effective level of R&D effort of firm i, X_i depends on its own R&D investment, x_i and also on the R&D investment of the other firm, x_j through knowledge spillovers. R&D activities are associated with positive spillovers. The knowledge of a firm leaks to its rival at an exogenous rate $0 \leq \beta \leq 1$. The absorption of external knowledge by firm i depends on the choices of R&D approaches, or technological distances $0 \leq \delta_i \leq 1$ and $0 \leq \delta_j \leq 1$ by firms i and j, respectively. The similarity of knowledge in the absorptive capacity of a firm is given by $\beta(1 - \delta_i)\left(1 - \delta_j\right)$.

In this representation of a firm's effective R&D effort, the new element to theoretical literature is the additional component of absorptive capacity due to complementarity, $\varphi(\delta_i, \delta_j)$. The complementarity of knowledge $\varphi(\delta_i, \delta_j)$ results from the adoption of different but related R&D approaches by firms and increases the innovative performance of firms. Complementary bits of knowledge are different from each other but make a good combination. This additional component of the effective R&D effect is actually both determined endogenously through firm's decisions and exogenously by the environment of the industry. The amount of prior knowledge existing in the industry and the extent to which new industry knowledge improves the innovative performance of firms are some of the exogenous factors explaining the potential of knowledge complementarity.

The existence of complementarity in absorptive capacity and its effects for firm performance is hypothesized here as follows: for $i = 1, 2,\ \ i \neq j$,

(i) $\varphi'_{\delta_i}(\delta_i, \delta_j) = 0$, $\varphi'_{\delta_j}(\delta_i, \delta_j) = 0$, if either $\delta_i = 0$ or $\delta_j = 0$;
(ii) $\varphi'_{\delta_i}(\delta_i, \delta_j) > 0$, $\varphi'_{\delta_j}(\delta_i, \delta_j) > 0$, if both $\delta_i > 0$ and $\delta_j > 0$. (2)

The benefits of complementarity between internal and external R&D are realized only if firms choose specific R&D orientations, $\delta > 0$. The marginal productivity of a firm's own R&D in its effective R&D efforts do not change if firms fail to take advantage of the potential of complementarity in absorptive capacity by choosing identical R&D approaches, $\delta = 0$. In the symmetrical case in particular, $\varphi(\delta, \delta) > 0$ for $\delta > 0$ whereas $\varphi(0,0) = 0$ is consistent with the idea that complementarity between own R&D and external R&D, if it exists, brings benefits to firms carrying out R&D.

In the next section, we address the question of whether, after making hypothesis (ii) in (2), a Nash equilibrium in the initial stage of a game with complementarity in absorptive capacity imply the full exploitation of the complementarity potential by firms, through the choice of idiosyncratic R&D approaches $\delta = 1$, or even the realization of some of this complementarity potential, which is possible by not selecting a purely broad R&D approach $\delta = 0$ or anything close it.

3. Results

Here we focus our discussion on the equilibrium outcomes in the first stage of the game where companies choose independently or cooperatively their R&D orientations. The analytical deduction of equilibrium outcomes in the independent and cooperative cases is shown in the Appendix.

A cooperative solution in the first stage of a game with complementarity in absorptive capacity is $\delta^* = 1$ if $\varphi'_{\delta_i} > 1$, $i = 1, 2$. In equilibrium, firms take full-advantage of this knowledge complementarity with the choice of firm-specific R&D orientations. The connectedness between the two firms just disappears when they simultaneously choose idiosyncratic R&D orientations. The necessary condition for the existence of this symmetric equilibrium is, in turn, $\varphi'_{\delta_i} \geq \beta(1 - \delta_j)$, $i \neq j$. This means that, at the margin, the contribution of greater variety brought by a more specific orientation has to outweigh the marginal cost of less similarity brought about by the choice of less technological proximity. The existence of sufficient complementarity in the model leads expectably to the emergence of a cooperative Nash equilibrium different from the one determined in the original Kamien and Zang's (2000) and Weithaus' (2005) frameworks, that is, identical R&D orientations $\delta^* = 0$. The potential for knowledge complementarity just disappears when firms simultaneously choose purely broad R&D orientations.

We find that cooperating firms adopt firm-specific R&D approaches. The R&D approaches selected by firms determine several different research paths to be followed simultaneously by different firms in the R&D process, as firms decide cooperatively not to "step on toes" of others doing similar design and development work. Each firm deals with different, mutually exclusive knowledge domains from which potentially useful new information may emerge.

There can be a negative externality in research which is analogous to congestion on a highway. It is possible that, at some point in time, the duplication and overlap of research reduce the marginal product of research in generating innovations. Current research may duplicate existing research and hence lower the productivity of research. This may arise out of patent races, where multiple firms run parallel research programs in the hope of being the first to succeed at creating and introducing into the market a new product or a new production process. The externality associated with duplication is referred to as the "stepping on toes" effect in Cameron (1998) and Jones (1998).

In order to insure against the costs of failure, research management often initiate several independent research projects with the same objective. In a R&D process involving many possible research paths and trial and error, it is reasonable for each firm to pursue several research avenues simultaneously, and the differences among firms being in the greater emphasis each firm places on one research path over the others (Kamien *et al.* 1992). The spillover effects in this vision of the R&D process take the form of each firm learning something about the others' experiences. Under R&D cooperation, firms will always choose to completely share their information. As a result, the cost of duplicating fruitful and fruitless approaches is avoided.

A number of pioneering studies explore the economic performance of the parallel path R&D approach to innovation (Nelson, 1961; Peck and Scherer, 1962). The problem of choosing among alternative research paths to a given objective in the presence of a high level of uncertainty is a difficult one. Technological change is characterized by major uncertainties so that it is usually unclear ex-ante whether a particular technical approach will be successful. In such situations, some firms will hesitate to invest at all in R&D, while others may adopt technical approaches that ultimately prove wrong. In the literature of economics, the research investment strategies incorporating this dispersion of technical approaches are called "parallel path" strategies.

According to Nelson (1961), parallel development of alternative designs seems called for when several competing designs have been proposed and there is considerable uncertainty with respect to which is best, and when much additional information can be gained from prototype testing. If the early stage development costs are small, it may be economical not to choose one design or contractor for an R&D job on the basis of first estimates, but rather to run multiple projects, cutting down the list of competing projects as estimates improve. In this model of uncertain hardware development, learning occurs within each research approach. Nelson (1961) considers cost-reducing and time-reducing benefits of running approaches concurrently when internal learning takes place. During World War II, the United States Manhattan Project supported five alternative methods of separating the needed fissionable material. According to Peck and Scherer (1962), an extraordinary combination of uncertainties and the non-market environment in which the defense industry functions, are the two fundamental explanations for the unique ways of doing business in the defense sector, and for the differences between defense and civilian markets.

Let us now deal with competition in R&D. An identical perturbation as before, $\varphi_{\delta_i}^{'} > 1$, $i = 1, 2$, made in the initial assumptions of the Kamien and Zang's (2000) or Weithaus' (2005) framework would not imply a similar equilibrium outcome $\delta^* = 1$ when firms compete in R&D. Unexpectedly, the introduction of complementarity in absorptive capacity destroys the non-cooperative Nash equilibrium $\delta^* = 1$ determined in the Kamien and Zang's (2000) and Weithaus' (2005) models. A small perturbation $\varphi_{\delta_i}^{'} > 0$, $i = 1, 2$ in any such framework is enough for the new equilibrium in R&D approaches to be $\delta^* < 1$. The necessary condition for the existence of the symmetric equilibrium $\delta^* = 1$ is not satisfied since the positive direct effect of complementarity in absorptive capacity is completely dominated by the negative strategic effect in the neighborhood of $\delta^* = 1$, $\varphi_{\delta_i}^{'} x_i - (1 + \varphi)\, dx_j^* / d\delta_i < 0$. This means that each competitor i faces a trade-off in its choice of a R&D approach between more exploration of technological possibilities and appropriability of own R&D on the one hand, and more assimilation and absorption of external knowledge on the other hand. That is to say, each firm faces a trade-off between similarity and complementarity when comes to the choice of a R&D approach.

From the perspective of firms, similarity and variety of R&D approaches seem to be in conflict with each other. The important challenge for firms' management is therefore to balance between similarity and diversity of R&D approaches. The intermediate levels of δ chosen by firms in non-cooperative equilibrium reveal that firms do strick such a balance between similarity and variety.

Nooteboom *et al.* (2007) test the relation between cognitive distance and innovation performance of firms engaged in technology-based alliances. The key finding is that the hypothesis of an inverted U-shaped effect of cognitive distance on innovation performance of firms is confirmed in the case of explorative learning. The optimal cognitive distance at the mean value of technological capital is 38.4 on a scale between zero and hundred. The key contribution that their paper makes is that it shows the opposed effects of small versus large distances in cognition, and the implications of this combined effect for firm performance. The authors have interpreted cognitive distance in terms of differences in technological knowledge between firms.

Thus, firms competing in R&D do not fully realize the potential of complementarity in absorptive capacity and prefer instead to adopt R&D orientations that are eventually more similar to each other than different. However, there is still a worse scenario regarding absorptive capacity and its effects on the firm performance. In the Weithaus' (2005) framework extended with the complementarity hypothesis in absorptive capacity in (2), the only equilibrium when $\varphi_{\delta_i}^{'} > 0,\ i = 1, 2,$ take small values is the choice of identical R&D approaches at the opposite extreme, $\delta^* = 0$, or a δ^* quite close to zero when the extent of technological spillovers β is rather large. Oddly, firms competing in R&D realize virtually none of the technological possibilities existing in knowledge complementarity in this case.

4. Conclusion

In this paper, we have focused on R&D complementarity and its effects upon R&D outcomes in the independent and cooperative cases. In order to do this, we have developed a three-stage game in which firms first choose their R&D orientations, then how much to invest in R&D, and finally their Cournot outputs. Firms compete with each other in the final product market. Firms can reduce their unit costs of production by realizing R&D investments. We have fully endogenized knowledge complementarity through the firms' choices of their R&D approaches at the first stage of the game.

Empirical evidence shows that knowledge complementarity is an important element of absorptive capacity, and our game-theoretical framework takes this into account in the assumptions made therein. The equilibrium outcomes of our extended model call into question the conclusions of existing economic theory on R&D investments and absorptive capacity, based on the assumption that absorptive capacity increases endogenously only through the similarity of R&D orientations chosen by firms. We have drawn two different conclusions from those found in the Kamein and Zang's (2000) and Weithaus' (2005) models regarding the choices of R&D approaches and their effects on the innovative performance of firms, one of which may be considered as odd. Our model shows that firms competing in R&D cannot take full advantage of the potential of complementarity in absorptive capacity whereas cooperating firms can. This is a reversal of established results in the theoretical literature on R&D investments, knowledge spillovers and absorptive capacity.

The theoretical findings presented here have considerable implications for both theory and practice, for future economic research and managerial decisions regarding how learning and innovative performance of firms can be enhanced through the mediating role of absorptive capacity in settings with R&D investments and knowledge spillovers. Our results suggest that firms should seek to adopt R&D cooperation strategies if they want to take full advantage of the complementarity element in absorptive capacity and thereby improve their innovative performance. Otherwise, if they decide to compete in R&D, they risk taking little or no advantage of the potential offered by complementarity between internal and external sources of R&D.

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Appendix

In this appendix, we concentrate successively on the competitive and cooperative solutions of the game, both in the initial stage of the selection of R&D approaches and in the second stage of the choice of R&D investment levels, to deduce the symmetric stage Nash equilibria.

Given the equilibrium output level in the third stage of the game, $q_i = 1/3\ \left(a - A + 2X_i - X_j\right)$, for $i = 1, 2,\ \ i \neq j$, where a and A are positive constants and X_i is given by (1), the profit function of firm i in the second-stage of a non-cooperative game may be expressed as $\pi_i = q_i^2 - \gamma/2\ x_i^2$, where γ is a positive parameter.

The first-order condition for a maximum of π_i with respect to x_i (interior solution) given the R&D orientation profile (δ_i, 1) implies the equilibrium level of R&D investment $x_i^*(\delta_i, 1) = 4(a - A)(1 + \varphi)/(9\gamma - 4(1 + \varphi)^2)$.

In the first stage, the first-order condition is $\partial\pi_i/\partial\delta_i = 2q_i\left(\partial q_i/\partial\delta_i + \partial q_i/\partial x_j\ dx_j^*/\partial\delta_i\right) = 0$ as, by the envelope theorem, $\partial\pi_i/\partial x_i = 0$. For the R&D orientation profile (δ_i, 1), $\partial q_i/\partial\delta_i = 1/3\ \varphi'_{\delta_i}x_i$ and $\partial q_i/\partial x_j = -1/3\ (1 + \varphi)$. Thus, $\partial\pi_i/\partial\delta_i\,(\delta_i, 1) = 1/3\left(\varphi'_{\delta_i}x_i - (1 + \varphi)\,dx_j^*/d\delta_i\right)$.

Let us consider the Nash equilibrium $\delta^* = 1$ of Kamien and Zang's (2000) and Weithaus' (2005) models. We want to show that, given hypothesis (ii) in (2), $\partial\pi_i/\partial\delta_i\,(1,1) < 0$, which destroys the previous equilibrium in the framework of absorptive capacity with knowledge complementarity. At (δ_i, 1), we get $dx_j^*/\partial\delta_i = 4(a - A)\varphi'_{\delta_i}(9\gamma + 4(1 + \varphi)^2)/(9\gamma - 4(1 + \varphi)^2)^2$. Thus, using this result, and after simplifications, we get $\partial\pi_i/\partial\delta_i\,(1,1) = -4\varphi'_{\delta_i}(1 + \varphi)^3$.

Thus, if $\varphi'_{\delta_i} > 0$, the first-order condition for profit maximization in the first stage is no longer satisfied for $\delta = 1$ as $\partial\pi_i/\partial\delta_i\,(1,1) < 0$, which will shift the critical value of δ_i to the left, $\delta_i^* < 1$. By continuity arguments regarding $\partial\pi_i/\partial\delta_i\,(\delta,\delta)$, this function will be also negative in the left-hand neighborhood of $\delta = 1$. In the extension of the Weithaus' (2005) model, however, a small variation $\varphi'_{\delta_i}(\delta,\delta)$ for any $\delta > 0$, so that $\varphi(\delta,\delta)$ has as result equally small values, causes function $\partial\pi_i/\partial\delta_i\,(\delta,\delta)$ to be all the way negative in the unit interval of R&D orientations for a low or medium β. A critical value of δ such that $\partial\pi_i/\partial\delta_i\,(\delta,\delta) = 0$ takes values very close to zero only for rather high β's.

Let us now consider the cooperative game in δ and x. In the second stage of the game, we deduct the optimal investment level $\hat{x}$, considering the symmetric case $\delta_i = \delta_j$: $Max_x\ \pi_i(x,x)$ given common δ, which implies $\partial\pi_i/\partial x = 0$. In the first stage, putting this result into the objective function π_i, we deduct the optimal value for R&D orientations in the symmetric case too: $Max_\delta\ \pi_i(\delta,\delta)$ given $\hat{x}(\delta,\delta)\ \Leftrightarrow\ Max_\delta\ q^2 - \gamma/2\ \hat{x}^2$, with $q_i = 1/3\ (a - A + X)$ and $X = (1 + \varphi(\delta,\delta) + \beta(1 - \delta)^2)\hat{x}$. This is equivalent to $Max_\delta\ X(\delta,\delta)$, so the first-order condition is $\partial X/\partial\delta\,(\delta,\delta) = \left(-2\beta(1 - \delta) + \varphi'_\delta(\delta,\delta)\right)\hat{\mathrm{x}} = 0$.

Thus, $\delta^* = 1$ is a cooperative solution under cooperative R&D only if $-2\beta(1 - \delta) + \varphi'_\delta(\delta,\delta) \geq 0$ for every $(\beta,\delta)\ \Leftrightarrow\ \varphi'_\delta(\delta,\delta) \geq 2\beta(1 - \delta)$ everywhere. Given that $\varphi'_\delta(\delta,\delta) = \varphi'_{\delta_i}(\delta,\delta) + \varphi'_{\delta_j}(\delta,\delta)$ in the symmetrical case, $\varphi'_\delta(\delta,\delta) = 2\varphi'_{\delta_i}(\delta,\delta)$ and so the necessary condition for an equilibrium is $\varphi'_{\delta_i} \geq \beta\left(1 - \delta_j\right)$. A sufficient condition for $\delta^* = 1$ is $\varphi'_\delta > 2$, for every (β,δ), which can be rewritten as $\varphi'_{\delta_i} > 1$. Note that the Nash equilibrium for the cooperative game of the models of Kamien and Zang (2000) and Weithaus (2005) $\delta^* = 0$ is also an equilibrium for the cooperative game with complementarity in knowledge given hypothesis (i) in (2), as $-2\beta(1 - \delta) + 0 \leq 0$.