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Hide or Show?

Endogenous Observability of Private Precautions Against Crime When Property Value is Private Information

Florian Baumann* Philipp Denter† Tim Friehe‡

November 2013

Abstract

This paper analyzes a contest in which defenders move first, have private information about the value of the objects they are trying to protect, and determine the observability of their defense efforts. The equilibrium consistent with the intuitive criterion depends on the distribution of defender types, the magnitude of the difference between defender types, and the asymmetry between defender and aggressor regarding the valuation of the objects at stake in the contest. Our setting captures key characteristics of the interaction between households and thieves, focusing on the classic distinction between observable and unobservable private precautions against crime. An analysis of welfare implications determines that a setting in which information about the value of the protected objects is private results in a better outcome than a complete-information scenario.

Keywords: Contest; Private Information; Timing; Crime; Private Precaution Against Crime

JEL-Code: D62, D82, K42

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1 Introduction

1.1 Motivation and main results

In many circumstances in which parties struggle over resources, defenders determine their defense efforts before aggressors decide on their appropriation efforts. There are numerous examples of this timing, including the creation of firewalls to protect business secrets. There is often evidence of the so-called “first-mover advantage”, which suggests that it is beneficial for defenders to make their defense efforts known to aggressors (Yildirim 2005). However, this preference for leading in the contest may no longer apply when the value of the objects defenders are trying to protect varies across defenders and is private information. In this case, defense effort could signal information about the object value to aggressors, such that higher defense effort might invite higher rather than lower appropriation effort. As a result, in complex settings, defenders must trade off the pros and cons of making their defense efforts observable; they may ultimately prefer to hide their defense efforts in an attempt to discourage assumptions about the value of the protected objects on the part of aggressors.

These trade-offs are analyzed in the present contribution, which takes the context of private precautions against crime as a prime example at hand. In the real world, households invest in safety measures, and this investment can be made observable or not. For instance, some alarm systems utilize easily detectable cameras, while others do not. Similarly, there are often substitutable ways to protect property that differ with respect to observability. For example, a safe can lower the probability of a thief obtaining a valuable object, as can iron bars on the windows preventing entry into the building. The presence of a safe inside the home cannot be known by the thief prior to the commission of the burglary, and therefore this constitutes an ex-ante unobservable precaution measure. The opposite holds for the barred windows, which represent an observable investment in precaution.¹ When thieves

¹Another example is a fire-arm for defensive use: Such a weapon can be concealed (unobservable precau-

observe high defense efforts, they may be discouraged from investing heavily in appropriation effort. However, it is conceivable that defense expenditures may in fact encourage thieves when there is asymmetric information on the valuables in the house. In view of the important classic distinction between observable precautions against crime and unobservable measures, we develop an analysis that yields the defender's choice between the two options as an endogenous outcome. This represents a radical divergence from the literature, as previous contributions have exogenously imposed the observability of safety investments and then developed results contingent upon this assumption (see Ben-Shahar and Harel 1995, Clotfelter 1977, 1978, Hylton 1996, Hotte and van Ypersele 2008, Shavell 1991). Without a doubt, private precautions against crime are a key determinant of the prevalence of crime in equilibrium (e.g., Ehrlich 1996). Thus, it comes as no surprise that private precautions against crime are extremely important in practice. For instance, Shavell (1991) estimates that private precaution expenditures are at least of the same order of magnitude as public expenditures. Despite its significance in terms of magnitude and crime control, private protection has received much less scholarly attention than public law enforcement measures (Cook and MacDonald 2010).

Our paper analyzes a contest in which the defender moves first, has private information about the "contest prize", and chooses whether or not to make the defense effort observable to the aggressor. In other terms, the game we consider is a correlated-values game characterized by incomplete information, since the aggressor cannot observe the contest prize (i.e., the defender's type). There will be imperfect information if the defender decides to make her defense effort unobservable to the aggressor, which implies that the aggressor will choose contest effort based on a conjecture about the defense effort rather than an observation of it. The strategic interaction between the defender and the aggressor can be characterized as a Cournot-Nash play when the defense effort is unobservable, and as a Stackelberg play

tion) or worn openly (observable precaution).

in the case of observable contest effort by the defender. Accordingly, the defender's choice between unobservable and observable defense effort is strategically equivalent to the defender choosing between a contest with simultaneous effort investments by both players and a sequential contest structure (e.g., Gibbons 1992). Based on this equivalence, the decision between observable and unobservable defense effort will be captured in our model by the defender's choice to invest at stage 1 or stage 2, where aggressors observe decisions made in stage 1 and always determine their own effort in stage 2. In other words, the decision regarding observability is represented by the defender's decision concerning the timing of the game – that is, the choice between a sequential-move game and a simultaneous-move game. Moreover, we assume that each attacker is randomly assigned to one defender (as in Lacroix and Marceau 1995) and that attackers observe the effort decisions made in stage 1 by all defenders (i.e., attackers observe whether there are any defenders who invested in stage 1 as well as the amount invested).²

We establish that defenders always make their defense efforts observable when there is complete information about the defender's type (allowing aggressors to determine their efforts based on the observation of defender efforts); however, asymmetric information about the defender's type can induce other configurations in equilibrium, such as the opposite scenario in which all defender types decide to make their defense efforts unobservable to the aggressors. More generally, we establish that the choices made by different defender types with respect to the level and the observability of defense efforts in equilibrium depend in a very intuitive way on the distribution of defender types, the magnitude of the difference between defender types, and the asymmetry between defender and aggressor regarding the valuation of the protected objects. For example, when the asymmetry in the valuation of the

²The random assignment allows us to focus on informational issues, abstracting from the possibility of diverting crime (as in, e.g., Lacroix and Marceau 1995). In a related paper, Baumann and Friehe (2013), we instead focus on the effects on the privately optimal investment in private precaution against crime that arise due to the possibility of diversion.

contest prize increases, defenders will be more likely to make their defense efforts observable, because the advantage of leading in Stackelberg play relative to engaging in simultaneous Cournot-Nash play increases with the difference in the respective valuations of winning the contest.

In addition to the positive description of decision-making, we also consider welfare implications. In many scenarios, welfare-maximizing policy-makers seek to remove information asymmetries, but face difficulties in doing so. In our model, the goal of removing asymmetric information would likewise prove unattainable in most cases. However, when we compare the decentralized equilibrium when there is incomplete information to the equilibrium under complete information, we arrive at the conclusion that incomplete information actually improves welfare by lowering societal costs (defined as either the sum of contest efforts or the sum of both contest efforts and the expected loss in value due to the potential transfer of the contested object to the attacker).³ Turning to the competing parties, it is obviously the case that some parties may gain from asymmetric information, while others lose. For example, for defenders with the most valuable objects to protect, complete information represents the worst possible scenario.

1.2 Relation to the literature

In our study, we analyze the defender's choice between unobservable and observable defense effort by means of its strategic equivalence to the decision of whether or not to move first in a contest. The setting considered is particularly interesting due to the presence of asymmetric information between contestants. The practical application of this model is the classic distinction between unobservable and observable precautions against crime. Accordingly, our paper is related to contributions on timing and sequential choice in contest-like situations

³Note that minimizing the sum of both contest efforts and the expected loss in value due to the potential transfer of the contested object to the attacker is equivalent to maximizing the sum of expected payoffs.

and to research addressing private protection against crime.

With respect to the former line of inquiry, this paper has ties to Baik (1994), Baik and Shogren (1992), Fu (2006), Hoffmann and Rota-Graziosi (2012), Konrad and Leininger (2007), Leininger (1993), Morgan (2003), and Nitzan (1994), all of whom study endogenous timing in contests. Baik and Shogren (1992) and Leininger (1993) establish that the equilibrium sequence is such that the so-called underdog moves first and the so-called favorite moves second when both parties decide about timing. This terminology dates back to Dixit (1987), who defines the favorite (underdog) as the party in a two-player contest with an equilibrium winning probability of more (less) than one-half in the simultaneous-move contest. Our complete-information benchmark diverges from this timing prediction, as our attacker cannot move first.⁴ Morgan (2003) analyzes a scenario in which the timing decision must be made before the valuation of winning the contest is realized, finding that a sequential structure emerges in equilibrium despite participants being homogenous *ex ante*. In contrast, Fu (2006) allows only one competing party to learn the value of the contest prize before determining effort but after deciding on timing, finding that the uninformed party moves first in sequential-move equilibria. This outcome is ruled out in our analysis, since we are interested in the scenario in which defenders (who are naturally better-informed) cannot choose contingent on attacker effort. Whereas we focus on the emergence of sequential or simultaneous moves, Powell (2007) studies the case in which a defender always chooses observable effort first but must protect two different objects, the values of which are the private information of the defender. He establishes that the defender will in many scenarios pool resources so as to not signal any information about the respective contest prizes to the attacker. In our analysis, different defender types interact non-cooperatively, which rules out pooling under

⁴Yildirim (2005) qualifies the results obtained by Baik and Shogren (1992) and Leininger (1993) by showing that the underdog only investing effort early in the game and the favorite only investing late in the game can never be the equilibrium outcome in a contest setting in which both contestants can invest both early and late.

the intuitive criterion.⁵

Our model analyzes potential victims' private protection investments when property values differ between potential victims and these values are private information. In this regard, we contribute by establishing conditions for having either observable or unobservable private precautions against crime. This stands in sharp contrast to the literature, in which the observability of private protection is exogenously imposed as a general rule (see, e.g., the recent contribution by Hotte and van Ypersele 2008). In this literature, research has often centered on the question of whether or not private investment in precautions against crime is socially excessive (see, e.g., Ben-Shahar and Harel 1995, Hui-Wen and Png 1994, Hylton 1996, Shavell 1991). Reasons for the discrepancies between private and social incentives with respect to investments in private protection against crime include the diversion effect (due to thieves observing high levels of precaution at one household and consequently moving to an alternative target) and the possibility that society regards criminals' benefits from crime as social benefits. Hotte and van Ypersele (2008) is related to our study in that the authors discuss heterogeneous defenders and consider a contest-like structure to represent the household/thief interaction. However, they presume that the property value is perfectly observable, ruling out the informational effects that take center stage in the present contribution. The novelty of our paper is the finding that the informative value of private protection for potential offenders co-determines the privately optimal observability of precautions.

Our central result with regard to welfare is that in our model, incomplete information improves on the complete-information outcome. This finding is in line with contributions on industrial organization that have established that asymmetric information may in many cases be welfare-superior to complete information (e.g., Barros 1997, Baumann and Friehe 2010, Kessler 1998). In the present paper, the driving force is that asymmetric information

⁵For a recent survey on contributions in the contest literature dealing with imperfect and incomplete information, see Wärneryd (2012).

softens competition between contestants. Denter et al. (2011) come to a similar conclusion, albeit via a different setup: In examining the implications of mandatory transparency in lobbying contests with private values, they show that mandating transparency is often detrimental to society. Our study finds that a similar result applies in situations with correlated values and endogenous observability of effort.

The structure of the paper is as follows: Section 2 describes the model. Section 3 determines the equilibrium outcome as a function of the model parameters. In Section 4, we briefly address the welfare repercussions of asymmetric information in comparison to symmetric information, and Section 5 concludes the study.

2 The model

We consider a setting in which risk-neutral attackers are randomly matched with an equal number of risk-neutral defenders. In each pair of individuals, the defender D_j and the attacker A compete for an object in a contest by investing effort (d_j and a , respectively, where $j = L, H$). The defender population can be divided into two types, based on the value of the objects being defended (denoted J , $J = L, H$). This value may be either low or high, $L < \lambda L = H$, $\lambda \in (1, 4)$.⁶ A share q of defenders defend objects of value L , and the remaining share of $1 - q$ defend objects of value H . The attacker values the object less than the defender, $(1 - \rho)J$, $\rho \in (0, 1/2)$. In the application of our model to real-world theft, this asymmetry can be explained as representing the personal significance of objects for their owners or the difficulty thieves face in fencing stolen property, for example.⁷

The defender succeeds in defending the object with probability p , which is determined

⁶The upper bounds for λ and ρ (to follow) will ensure interior solutions for parties' effort levels.

⁷See, for example, the literature on the endowment effect, such as the seminal paper by Kahneman et al. (1990) or Gintis (2007), which makes use of a contest setting.

by the parties' respective efforts in the following way:

$$p(a, d_j) = \frac{d_j}{d_j + a} \quad (1)$$

for strictly positive effort.⁸ Since we restrict our analysis to risk-neutral individuals, the level of p may just as well be interpreted as the share of the value that stays with the defender. With regard to the so-called contest-success function, we consider what has become known as the Tullock contest.⁹

The parties' expected payoffs are given by

$$\pi_{D_j} = pJ - d_j \quad (2)$$

$$\pi_A = (1 - p)J(1 - \rho) - a. \quad (3)$$

Defenders and attackers thus share the same marginal effort cost equal to one, focusing the asymmetry on the term ρ .

The timing of the game we analyze is as follows: At stage 0, there is the random assignment of one attacker to each defender. In stage 1, all defenders simultaneously choose their level of defense effort and whether or not they want to make their effort investment observable to the attacker. Attackers observe decisions made by all defenders in stage 1; that is, they observe the level of defense effort when a defender has opted for observability, but they cannot observe the effort level exerted when a defender has chosen to make it unobservable. In the real-world application, this would correspond to the ability of thieves to detect observable precautions: They can determine which houses have made observable investments, but they must also take into account the existence of measures that are unobservable ex-ante. In stage 2, attackers choose their effort level. The game concludes with a move by nature, determining the outcome of the contest according to (1) and the competing parties' payoffs.

⁸We focus on interior solutions only, because this is the more interesting case. See, for instance, Leininger (1993) for a discussion of boundary solutions in sequential contests.

⁹This is the most widely applied contest-success function; see, e.g., Konrad (2009).

3 The analysis

In this section, we will first examine the complete-information scenario as our benchmark and then present the solution to the game under incomplete information. We start with a description of the outcomes for the different decisions regarding the observability of effort, discussing the equilibrium emerging from each decision. The scenario of interest here involves one party defending something of value against another party. In such settings, the attacker usually chooses effort after the defender. As explained above, the strategic interaction between the defender and the aggressor can be characterized as a Cournot-Nash play when the defender decides to make defense effort unobservable, and as a Stackelberg play in the case of observable contest effort on the part of the defender. There are four feasible combinations: (1,1) all D_L and all D_H make their efforts observable, (2,2) all D_L and all D_H make their effort investments unobservable, (1,2) all D_L make efforts observable and all D_H hide their effort investments, and (2,1) all D_L hide their effort investments and all D_H make their efforts observable. In addition, there is the possibility of a mixed-strategy equilibrium. In such a case, it will be assumed that all defenders of a given type behave in the same way in all contingencies.

3.1 Complete information

We now briefly establish defender and attacker decisions when both contestants know the object value J . First, we will determine the effort and payoff levels for given effort observability decisions, and then the defenders' decisions of whether or not to make their defense efforts observable will be considered. We will proceed in the same fashion in the next section, in which incomplete information about the value of the resources at stake will be examined.

The attacker seeks to maximize his expected payoff for a given or conjectured level of

defender effort d_j ,

$$\max_a \pi_A = (1 - p(a, d_j))J(1 - \rho) - a, \quad (4)$$

and will choose to respond to defense effort d_j with

$$a = \sqrt{(1 - \rho)Jd_j} - d_j. \quad (5)$$

When the defender has decided to make effort *unobservable*, the privately optimal defense effort level should

$$\max_{d_j} \pi_{D_j} = p(a, d_j)J - d_j, \quad (6)$$

which will be true for

$$d_j = \sqrt{Ja} - a. \quad (7)$$

The case in which defense effort is unobservable (hereafter indicated by U) thus leads to the following equilibrium effort and expected payoff levels:

$$a_j^U = \frac{(1 - \rho)^2 J}{(2 - \rho)^2} \quad (8)$$

$$d_j^U = \frac{(1 - \rho)J}{(2 - \rho)^2} = \frac{a^U}{1 - \rho} \quad (9)$$

$$\pi_{A_j}^U = \frac{(1 - \rho)^3 J}{(2 - \rho)^2} \quad (10)$$

$$\pi_{D_j}^U = \frac{J}{(2 - \rho)^2}. \quad (11)$$

Our consideration of the fact that an object appropriated from someone else carries a somewhat lower value (i.e., our assumption $\rho > 0$) implies that the defender is the favorite in Dixit's (1987) terminology, as the defender wins with a probability greater than one-half (because $d_j^U > a_j^U$).

Instead, if the defender makes defense effort *observable*, this implies that she selects a locus somewhere on the aggressor's reaction function. That is, the best response of the attacker (5) will be anticipated by the defender, who accordingly seeks to

$$\max_{d_j} \pi_{D_j} = \frac{\sqrt{d_j}}{\sqrt{(1-\rho)J}} J - d_j. \quad (12)$$

The contest with observable defense effort (hereafter indicated by O) entails the following equilibrium effort and expected payoff levels:

$$a_j^O = \frac{(1-2\rho)J}{4(1-\rho)} \quad (13)$$

$$d_j^O = \frac{J}{4(1-\rho)} = \frac{a^O}{1-2\rho} \quad (14)$$

$$\pi_{A_j}^O = \frac{(1-2\rho)^2 J}{4(1-\rho)} \quad (15)$$

$$\pi_{D_j}^O = \frac{J}{4(1-\rho)}. \quad (16)$$

In strategic terms, defenders can choose between the Stackelberg play and the Cournot-Nash play by choosing between observable and unobservable defense efforts. We find that the contest with observable defense effort always results because

$$\pi_{D_j}^O = \frac{J}{4(1-\rho)} > \frac{J}{(2-\rho)^2} = \pi_{D_j}^U \iff \rho^2 > 0. \quad (17)$$

In other terms, the asymmetry between defender and attacker due to $\rho > 0$ makes the sequential structure preferable for the defender. The defender has a first-mover incentive that comes at the detriment of the attacker (i.e., $\pi_{D_j}^O > \pi_{D_j}^U$ and $\pi_{A_j}^O < \pi_{A_j}^U$). Given that we do not permit the underdog (i.e., the attacker) to commit to effort ex-ante, we obtain in equilibrium that the favorite prefers to move first rather than simultaneously. When the favorite moves first, he overcommits effort relative to the simultaneous-move scenario in order to induce lower equilibrium effort by the underdog (see, e.g., Baik and Shogren 1992); this is evident in $d_j^O > d_j^U$ and $a^O < a^U$. The total contest effort is lower in the simultaneous-move contest than in the sequential game in which the defender (i.e., the favorite) moves first; this follows from

$$a_j^U + d_j^U - (a_j^O + d_j^O) = \frac{(1-\rho)J}{2-\rho} - \frac{J}{2} = \frac{-\rho J}{2(2-\rho)} < 0. \quad (18)$$

Thus, in our setting, the decentralized decision-making concerning effort observability is not in accordance with efficiency concerns in terms of effort expenditures. This stands in contrast to the standard setting with endogenous moves, in which the underdog moves first in equilibrium (see, e.g., Leininger 1993). At the end of the paper, we will return to welfare considerations in greater detail.

3.2 Incomplete information: Analysis for given observability

As argued above, there are four feasible combinations of defender observability decisions: (1,1) all D_L and all D_H make defense efforts observable, (2,2) all D_L and all D_H make defense efforts unobservable, (1,2) all D_L choose observable efforts while all D_H make their efforts unobservable, and (2,1) all D_L choose to conceal their effort levels while all D_H make their efforts observable. Note that ‘1’ (‘2’) denotes the case in which a given defender type makes effort (un-)observable, given that the scenarios with observable and unobservable effort is analytically equivalent to settings with sequential and simultaneous moves, respectively. In this section, we follow Dixit (1987) in analyzing the outcomes of various exogenous arrangements with respect to the observability of defense effort; we establish observability decisions in equilibrium in the following section.

3.2.1 Both defender types make defense efforts observable

In Combination (1,1), all defender types select observable defense efforts. As a result, the observability decision itself does not convey type information to the attacker. However, it may be the case that the effort level will reveal information about a defender’s type.

If we denote the probability that the attacker assigns to facing a defender of type D_L with μ , we can state that the attacker will seek to maximize her expected payoff by choosing effort according to

$$\max_a \pi_A = (1 - p(a, d))(1 - \rho)\{\mu L + (1 - \mu)H\} - a, \tag{19}$$

and will choose to respond with

$$a = \sqrt{(1 - \rho)\{\mu L + (1 - \mu)H\}}d - d \quad (20)$$

to defender effort d . The best response of the attacker is intuitively decreasing in μ .

If both defender types choose defense efforts that are tailored to their type and effort investments are observable (i.e., d_L^O and d_H^O), then the attacker can deduce the value of the object the defender is trying to protect. In this case, we would obtain $\mu(d_L^O) = 1$ and $\mu(d_H^O) = 0$. The associated expected payoffs for defenders would be given by $\pi_{D_j}^O$. However, this cannot be an equilibrium outcome, because defender D_H would be tempted to imitate defender D_L in order to compete with a less aggressive attacker. Indeed, choosing d_L^O when $\mu(d_L^O) = 1$ promises a payoff of

$$\pi_{D_H} = \frac{L(2\lambda - 1)}{4(1 - \rho)} > \pi_{D_H}^O = \frac{\lambda L}{4(1 - \rho)} \quad (21)$$

for defender D_H , where $H = \lambda L$.

Once the attacker acknowledges these mimicking incentives and pools the two defender types (i.e., chooses $\mu(d_L^O) = q$), this is naturally detrimental for defender L , since the attacker will be more aggressive towards him. In order to rule out mimicking by a defender D_H , defender type D_L may choose to distort defense effort downwards in order to distance themselves from defender type D_H . This distorted effort \tilde{d} that enables the separation of the two defender types follows from

$$\frac{\tilde{d}}{\sqrt{L(1 - \rho)\tilde{d}}}H - \tilde{d} = \frac{H}{4(1 - \rho)}, \quad (22)$$

where the left-hand side represents the expected payoff for defender D_H , should she choose to imitate \tilde{d} and be rewarded by the most favorable belief of the attacker (i.e., $\mu(\tilde{d}) = 1$), and the right-hand side gives the payoff from choosing d_H^O (which implies $\mu(d_H^O) = 0$). Solving (22), we obtain

$$\tilde{d} = \frac{\lambda L[2(\lambda - \sqrt{\lambda(\lambda - 1)}) - 1]}{4(1 - \rho)} < d_L^O. \quad (23)$$

Very intuitively, the difference between defender types drives the extent of the distortion required for separation, such that \tilde{d} decreases with λ . Naturally, the larger the difference in property values, the more attractive it is for a defender D_H to be mistaken for a defender D_L (as this implies lower aggressor effort). For instance, when $\lambda \rightarrow 1$, we obtain the undistorted defense effort of defender type D_L , d_L^O .

When the attacker observes \tilde{d} , he expects $\mu(\tilde{d}) = 1$, because he knows that such low defense effort is a dominated strategy for defenders of type D_H (since they can secure the payoff represented on the right-hand side of (22) by behaving according to their type in a complete-information setup). Consequently, the aggressor chooses an appropriation effort of $\tilde{a} = \sqrt{(1 - \rho)L\tilde{d}} - \tilde{d}$. The implied level of expected payoffs for defenders of type D_L is given by

$$\tilde{\pi}_{D_L} = \frac{\left(\lambda[1 - 2(\lambda - \sqrt{\lambda(\lambda - 1)})] + 2\sqrt{\lambda[2(\lambda - \sqrt{(\lambda - 1)\lambda}) - 1]} \right) L}{4(1 - \rho)}. \quad (24)$$

This is greater than the level of expected payoffs that results when defender type D_L chooses a defense effort above \tilde{d} when this induces $\mu = 0$, where this payoff is given by $L/(4\lambda(1 - \rho))$ (since the term in parentheses in (24) exceeds $1/\lambda$ for $\lambda > 1$).

The preceding argumentation permits the conclusion that the following beliefs are consistent with the intuitive criterion (Cho and Kreps 1987):

$$\mu(d) = \begin{cases} 0 & \text{if } d > \tilde{d} \\ 1 & \text{if } d \leq \tilde{d}. \end{cases} \quad (25)$$

These conditions will be referenced throughout the remainder of the paper. Observing a defense effort less than or equal to \tilde{d} will therefore convince the attacker that the defender is trying to protect an object of value L .

For Combination (1,1), this completes the establishment of the Perfect Bayesian Nash Equilibrium that relies on the intuitive criterion with respect to the attacker's beliefs.

Lemma 1 *Assume that both defender types make their effort levels observable, and that*

aggressors hold the beliefs specified in (25). Then, defender type D_L selects \tilde{d} , faces \tilde{a} , and earns $\tilde{\pi}_{D_L}$. Defender type D_H chooses d_H^O , faces a_H^O , and earns π_H^O .

In this combination, defender D_L is worse off than in the complete-information scenario. The distortion benefits the attacker when she is competing with a defender of type D_L . Defender D_H is not adversely affected by the presence of asymmetric information.

3.2.2 Both defender types make defense efforts unobservable

In Combination (2,2), all defenders choose unobservable defense efforts. In this scenario, neither the observability decision nor the effort level can be informative for the attacker, who must therefore use $\mu = q$ and conjectured effort levels. In other words, the attacker chooses effort against the distribution of the defender types, who choose their defense effort levels d_j given the attacker effort, as in (7) (see Wärneryd 2000). The equilibrium defense effort levels will differ from those derived for the case of complete information due to this variation in the behavior of the attacker.

The emergent equilibrium effort levels are given by

$$a^{22} = \frac{L(1-\rho)^2(\sqrt{\lambda}(1-q) + q)^2}{(2-\rho)^2} \quad (26)$$

$$d_L^{22} = \frac{L(1-\rho)(\sqrt{\lambda}(1-q) + q)(2 - (1-\rho)\sqrt{\lambda}(1-q) - \rho(1-q) - q)}{(2-\rho)^2} \quad (27)$$

$$d_H^{22} = \frac{L(1-\rho)(\sqrt{\lambda}(1-q) + q)(\sqrt{\lambda}(1 + (1-\rho)q) - (1-\rho)q)}{(2-\rho)^2} \quad (28)$$

and imply expected payoffs for defender types as follows:

$$\pi_L^{22} = \frac{L \left(2 - \left(\rho(1-q) + q + (1-q)\sqrt{\lambda}(1-\rho) \right) \right)^2}{(2-\rho)^2} \quad (29)$$

$$\pi_H^{22} = \frac{L \left(\sqrt{\lambda}(1 + q(1-\rho)) - (1-\rho)q \right)^2}{(2-\rho)^2}. \quad (30)$$

We can summarize decision-making in this combination as follows:

Lemma 2 *Assume that both defender types make their efforts unobservable. Then, defender type D_j selects d_j^{22} , faces a^{22} , and earns π_j^{22} .*

Very intuitively, it holds that the defender D_H gains from the incomplete information in the present setting, in comparison to the outcome that results under complete and imperfect information (i.e., $\pi_H^{22} > \pi_H^U$). This results because the attacker is relatively less aggressive towards defender D_H . The contrary is true for defender D_L (i.e., $\pi_L^{22} < \pi_L^U$), since the attacker is relatively more aggressive towards defender D_L than in the complete but imperfect information scenario. However, with complete information, both defender types would choose observable effort, such that we would find perfect information in equilibrium. In comparison to this outcome, defenders of type D_H may be better or worse off in Combination (2,2). On the one hand, they gain from pooling with defenders of type D_L ; on the other hand, they lose from forfeiting their first-mover advantage. Defenders of type D_L are definitely worse off than with complete and perfect information: They suffer from being pooled with type D_H defenders and from not being able to take advantage of moving first.

3.2.3 Defender type D_L (D_H) makes efforts observable (unobservable)

In Combination (1,2), defender type D_L (D_H) chooses (un-)observable defense effort. Aggressors note the observability decisions of all defender types, but only effort levels for defenders of type D_L are visible. Importantly, the observability of defender D_L 's effort conveys informative value for all attacker-defender pairs, as we will explain in the following analysis.

The defender type D_L acknowledges the mimicking incentives of the defender type D_H , given that any observable effort exertion will be evaluated by the attacker according to the beliefs (25). This means that effort set at the privately optimal level for defender D_L under complete information (i.e., d_L^O) will convince the attacker that the defender has highly valued objects to protect. In order to ensure that the attacker understands that defender D_L is protecting only value L , he selects \tilde{d} . In this case, defenders who make their defense

efforts unobservable will be recognized as a defender of type D_H . Consequently, attackers who observe that some defenders have chosen \tilde{d} but who themselves are playing against a defender whose effort is unobservable will choose a_H^U .

Lemma 3 *Assume that defender type D_L (D_H) makes defense effort observable (unobservable) and that aggressors hold the beliefs specified in (25). Then, defender type D_L selects \tilde{d} , faces \tilde{a} , and earns $\tilde{\pi}_{D_L}$. Defender type D_H selects d_H^U , faces a_H^U , and earns π_H^U .*

This combination implies that the defender D_L is worse off relative to the complete-information case, since defense effort is distorted downwards. The defender D_H is adversely affected to the extent that she selects unobservable defense effort, as she prefers observable effort investments under complete information.

3.2.4 Defender type D_L (D_H) makes effort unobservable (observable)

In Combination (2,1), defender type D_H (D_L) chooses (un-)observable defense effort. The defender type D_H must take attackers' beliefs (as specified in (25)) into account. The attacker will mistake a defender of type D_H for a defender of type D_L only when the defender invests $d \leq \tilde{d}$. However, as argued above, the distortion in the defense effort is sufficient to exhaust all benefits from mimicking for defender D_H . Consequently, the defender D_H chooses d_H^O , which completely eliminates type uncertainty for attackers. In turn, attackers know that any defender who chooses to conceal effort will be of type D_L .

Lemma 4 *Assume that defender type D_L (D_H) makes defense efforts unobservable (observable) and that aggressors hold the beliefs specified in (25). Then, defender type D_L selects d_L^U , faces a_L^U , and earns π_L^U . Defender type D_H selects d_H^O , faces a_H^O , and earns π_H^O .*

This timing combination implies that the defender D_L is worse off relative to the complete-information case, because his efforts have been made unobservable. In contrast, defender type D_H is just as well off as in the scenario with complete information.

3.3 Incomplete information: Equilibrium including observability choice

The analysis up to this point has yielded that, for exogenous combinations of defense effort observability, defenders of type D_L (D_H) choose \tilde{d} (d_H^O) when they decide to make their effort investments observable. When a defender conceals defense efforts, they use the common knowledge of first-stage behavior to assess whether d_j^U or d_j^{22} is called for. These issues are incorporated in Table 1, in which the first (second) entry shows the expected payoffs for defenders of type D_L (type D_H).

$D_L \setminus D_H$	<i>Efforts observable</i>	<i>Efforts unobservable</i>
<i>Efforts observable</i>	$\tilde{\pi}_{D_L}, \pi_H^O$	$\tilde{\pi}_{D_L}, \pi_H^U$
<i>Efforts unobservable</i>	π_L^U, π_H^O	π_L^{22}, π_H^{22}

Table 1: Expected payoffs based on the observability of defense efforts.

In the following analysis, we delineate which of these different combinations could actually arise in equilibrium. In principle, both defender types prefer making efforts observable, as this allows them to choose an effort combination on the aggressor's best response function (as described in Section 3.1). However, informational aspects – which are of key importance to the present analysis – may change the preferences of defender types. In our analysis, we maintain the beliefs of the aggressor $\mu(d)$ as specified in (25), in combination with $\mu = q$ for the case in which both defender types make efforts unobservable. Should no defender choose observable defense efforts, the aggressor will expect a distribution of defender types that each chooses the privately optimal response to a given aggressor effort. A defender who opts for observable defense effort will be perceived as a defender D_L only when the level of the defense effort is low enough to allow signaling.

To obtain Combination (1,1) (i.e., the scenario in which both defender types choose

observable effort investments) as an equilibrium, the following conditions are necessary:

$$\tilde{\pi}_{D_L} \geq \pi_L^U \quad (31)$$

$$\pi_H^O \geq \pi_H^U. \quad (32)$$

The second condition is always fulfilled, since defenders of type D_H prefer to choose a point on the aggressor's reaction function (i.e., playing Stackelberg game) when their type is revealed. However, this does not automatically follow for a defender of type D_L , due to the necessary distortion in effort when effort is made observable. The first condition can be reduced to

$$\lambda \leq \frac{4(1-\rho)^2}{4(1-2\rho) + 3\rho^2}. \quad (33)$$

Finding an upper boundary for the level of λ while trying to ensure that $\tilde{\pi}_{D_L} \geq \pi_L^U$ is very intuitive. The distortion of \tilde{d} away from what the defender D_L would choose in the case of complete information is increasing in the level of λ (to discourage enhanced mimicking incentives for defenders of type D_H). This naturally diminishes the attractiveness of Combination (1,1) from defender D_L 's perspective. At the same time, the alternative payoff, π_L^U , is not influenced by the level of λ , since defender type is completely revealed to attackers. The threshold for λ is increasing in the level of asymmetry between defenders and attackers (i.e., the level of ρ). This results because the first-mover advantage is more significant in more asymmetric strategic interactions. The threshold value of λ is continuously increasing from 1 (when $\rho \rightarrow 0$) to 4/3 (when $\rho \rightarrow 1/2$). It should also be noted that condition (33) is not influenced by the share of defenders of type D_L , since neither payoff in (31) is affected by q (because there type revelation in each scenario).

To obtain Combination (2,2) (i.e., the scenario in which both defender types choose unobservable defense efforts) as an equilibrium, the following conditions are necessary:

$$\pi_L^{22} \geq \tilde{\pi}_{D_L} \quad (34)$$

$$\pi_H^{22} \geq \pi_H^O. \quad (35)$$

Defender D_L could make defense efforts observable and thereby ensure an expected private payoff of $\tilde{\pi}_{D_L}$ instead of being pooled with defenders of type D_H . However, the restriction regarding defender D_H will often be the stricter one, because the alternative of making defense efforts observable promises the relatively high payoff from the sequential contest with complete information. Condition (35) holds when

$$\lambda > \frac{4q^2(1-\rho)^3}{(2q(1-\rho)^{3/2} + 2(\sqrt{1-\rho} - 1) + \rho)^2}. \quad (36)$$

Since condition (34) cannot be reduced as easily as (31) and (35), we will consider an example below.

In the previous section, we detailed the effort levels that result when defender D_L chooses observable defense effort and defender D_H chooses unobservable defense effort, that is, Combination (1,2). With regard to defender D_H , it is clear that making defense efforts observable when defender D_L does so is preferable, because $\pi_H^O > \pi_H^U$. This rules out Combination (1,2) as a possible pure-strategy equilibrium.

To obtain Combination (2,1) (i.e., defender type D_H (D_L) chooses to make defense effort (un-)observable) as an equilibrium, the following conditions are necessary:

$$\pi_L^U \geq \tilde{\pi}_{D_L} \quad (37)$$

$$\pi_H^O \geq \pi_H^{22}. \quad (38)$$

The first condition is obviously fulfilled when (31) does not hold, that is, when the asymmetry between defenders is sufficiently large (such that (33) is violated). Defenders of type D_L would rather forfeit the first-mover advantage than distort effort markedly downwards. The more pronounced the difference between defender types, and the smaller the difference between defenders and attackers with respect to the valuation of the contest prize, the more likely this is to be the case. For defenders of type D_H , condition (38) requires the advantage of pooling with type D_L defenders to be insufficient to compensate for the first-mover

advantage gained by making effort observable.

We now formally summarize the above analysis:

Proposition 1 *With aggressors' beliefs specified as in (25) when a defender type chooses observable effort and by $\mu = q$ otherwise, we obtain:*

(i) *When (31) holds: Defender type D_L selects observable effort amounting to \tilde{d} and faces attacker effort \tilde{a} . Defender type D_H chooses observable effort amounting to d_H^O and faces attacker effort a_H^O .*

(ii) *When (34) and (35) hold simultaneously: Defender type D_L selects unobservable effort amounting to d_L^{22} and faces attacker effort a^{22} . Defender type D_H selects unobservable effort amounting to d_H^{22} and faces attacker effort a^{22} .*

(iii) *When neither (31) nor (35) is fulfilled: Defender type D_L selects unobservable effort amounting to d_L^U and faces attacker effort a_L^U . Defender type D_H selects observable effort amounting to d_H^O and faces attacker effort a_H^O .*

Up to this point, we have considered the requirements for the respective combinations as pure-strategy equilibria. Next, we will discuss the possibility of obtaining equilibria in mixed strategies in which all defenders of a given type make the same decision. More concretely, this implies that the mixing probabilities are the same for all defenders of type D_j , and that all defenders of type D_j apply the same strategy after the randomness is resolved. To obtain a mixed-strategy equilibrium, it is necessary to guarantee that (37), (35), and

$$\tilde{\pi}_{D_L} \geq \pi_L^{22} \tag{39}$$

hold. This last condition is fulfilled when (34) does not hold. The additional requirement for the defender D_H , $\pi_H^O > \pi_H^U$, is always true. Denoting the probability that defenders of type D_L will make their efforts observable and choose \tilde{d} by $(1 - \alpha)$ and that defenders D_H will make their efforts observable and choose d_H^O by $(1 - \beta)$, the expected payoffs in a

mixed-strategy equilibrium are given by

$$E\pi_L = \alpha^* (\beta^* \pi_L^{22} + (1 - \beta^*) \pi_L^U) + (1 - \alpha^*) \tilde{\pi}_{D_L} \quad (40)$$

$$E\pi_H = \beta^* (\alpha^* \pi_H^{22} + (1 - \alpha^*) \pi_H^U) + (1 - \beta^*) \pi_H^O, \quad (41)$$

where in equilibrium

$$\alpha^* = \frac{\pi_H^O - \pi_H^U}{\pi_H^{22} - \pi_H^U} \quad (42)$$

$$\beta^* = \frac{\pi_L^U - \tilde{\pi}_{D_L}}{\pi_L^U - \pi_L^{22}}. \quad (43)$$

When the specified conditions hold as inequalities, we obtain mixing probabilities $\alpha^* \in (0, 1)$ and $\beta^* \in (0, 1)$.

We now formally summarize the above analysis:

Proposition 2 *With aggressors' beliefs specified as in (25) when a defender type chooses observable effort and by $\mu = q$ otherwise, we obtain:*

When neither (31) nor (34) is fulfilled, but (35) holds: Defender type D_L selects unobservable effort amounting to d_L^U with probability $\alpha^(1 - \beta^*)$ (against a_L^U), unobservable effort amounting to d_L^{22} with probability $\alpha^*\beta^*$ (against a^{22}), and observable effort amounting to \tilde{d} with probability $(1 - \alpha^*)$ (against \tilde{a}). Defender type D_H selects unobservable effort amounting to d_H^U with probability $(1 - \alpha^*)\beta^*$ (against a_H^U), unobservable effort amounting to d_H^{22} with probability $\alpha^*\beta^*$ (against a^{22}), and observable effort amounting to d_H^O with probability $(1 - \beta^*)$ (against a_H^O).*

Note that there is a unique equilibrium independent of the parameter values. The enumeration of conditions is such that the fulfillment of one set of conditions precludes another set of conditions from holding at the same time (see Table 2).

The above analysis establishes that the presence of incomplete information may induce Cournot-Nash play. This stands in sharp contrast to the result obtained under complete

Payoffs L	Payoffs H	Equilibrium
$\tilde{\pi}_{D_L} \geq \pi_L^U \geq \pi_L^{22}$	$\pi_H^O \geq \pi_H^{22} \geq \pi_H^U$	(1,1)
$\tilde{\pi}_{D_L} \geq \pi_L^U \geq \pi_L^{22}$	$\pi_H^{22} \geq \pi_H^O \geq \pi_H^U$	(1,1)
$\pi_L^U \geq \tilde{\pi}_{D_L} \geq \pi_L^{22}$	$\pi_H^O \geq \pi_H^{22} \geq \pi_H^U$	(2,1)
$\pi_L^U \geq \tilde{\pi}_{D_L} \geq \pi_L^{22}$	$\pi_H^{22} \geq \pi_H^O \geq \pi_H^U$	mixed, mixed
$\pi_L^U \geq \pi_L^{22} \geq \tilde{\pi}_{D_L}$	$\pi_H^O \geq \pi_H^{22} \geq \pi_H^U$	(2,1)
$\pi_L^U \geq \pi_L^{22} \geq \tilde{\pi}_{D_L}$	$\pi_H^{22} \geq \pi_H^O \geq \pi_H^U$	(2,2)

Table 2: Possible equilibria for different payoff rankings.

information. In addition, we also demonstrate the possibility of an asymmetric outcome in which only defenders of type D_H choose observable defense effort. The intuition is that defender D_L must distort defense efforts downwards when type information should be signaled to the attacker. The kind of equilibrium that results is critically determined by the distribution of defender types (summarized by q), the magnitude of the difference between defender types (summarized by λ), and the asymmetry between defender and offender with regard to the valuation of the objects being protected (summarized by ρ). This dependence stems from the influence of these factors on the conditions detailed in Proposition 1. We illustrate this dependence and the respective equilibria in Figure 1 for the case in which the population of defenders is equally split into types D_L and D_H (i.e., for $q = 1/2$) and $L = 1$.

Combination (1,1) is possible when the asymmetry between defender types is not too large. Otherwise, defender D_L prefers not to choose the distorted effort \tilde{d} associated with making effort observable to the attacker. Higher levels of the asymmetry between the defender and the attacker regarding the valuation (i.e., levels of ρ) create more opportunities to obtain Combination (1,1) because they enhance the first-mover advantage obtained from making effort observable. In contrast, Combination (2,2) cannot arise when the level of ρ is high, precisely because of the importance of the first-mover advantage. In Combination (2,1), defender D_H makes effort observable and enjoys the first-mover advantage, while defender D_L prefers to be the only defender type with unobservable defense effort (since making efforts

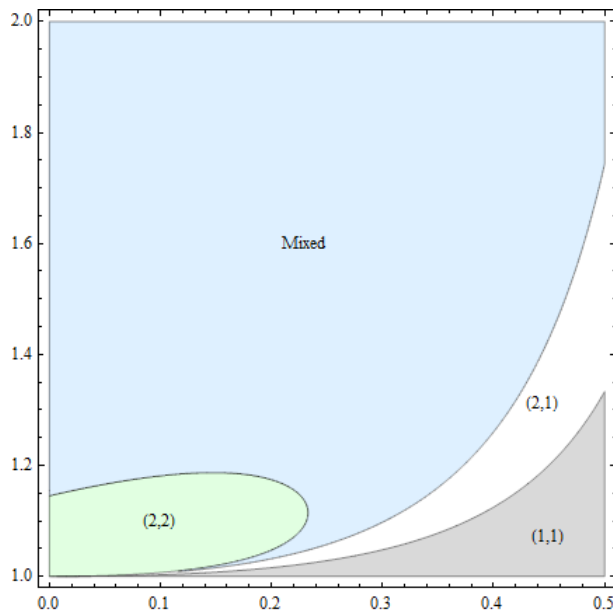


Figure 1: Equilibria for $\rho \in (0, 1/2)$, $\lambda \in (1, 2)$, and $q = 1/2$.

observable is associated with the distorted level of defense effort). The scenario in which the asymmetry between defender types is considerable yields a mixed-strategy equilibrium. High levels of λ make choosing observable effort \tilde{d} relatively unattractive when the alternative of being the only defender type with unobservable defense effort is available. However, when defender D_H conceals effort, Combination (2,2) is similarly unattractive, because the attacker will play relatively aggressively for high levels of λ . Defender D_H , on the other hand, very much prefers Combination (2,2) to the option of making her own effort known with d_H^O , because the attacker's aggression will be somewhat more moderate in the former case. Overall, this implies that there is only an equilibrium in mixed strategies for large levels of λ .

As argued above, the range of parameters allowing Combination (1,1) is not dependent on the share of defenders of type L in the population of defenders. In contrast, the other conditions are influenced by the level of q . This fact is illustrated in Figure 2, in which

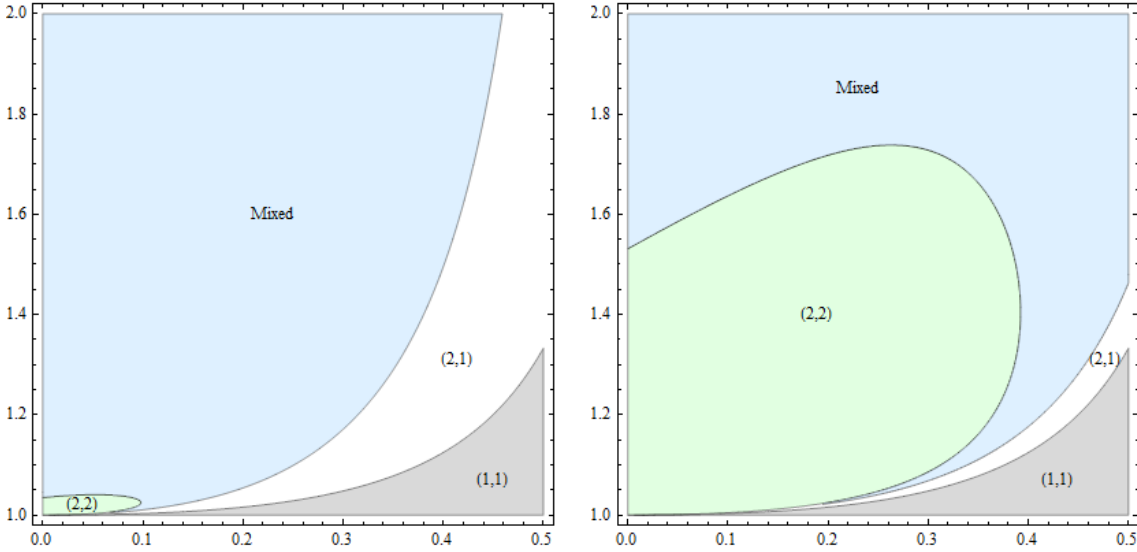


Figure 2: Equilibria for $\rho \in (0, 1/2)$, $\lambda \in (1, 2)$, and $q = 3/10$ ($q = 7/10$) in the left (right) panel.

we depict respective equilibria when q is either higher ($q = 7/10$) or lower ($q = 3/10$). The outcome in which both defender types choose unobservable defense effort is much more likely to result when the level of q is high. This is a very intuitive finding, since the attractiveness of attackers pooling the two types is higher from the defenders' standpoint when the share of low values is high. The same reasoning explains why Combination (2,1) is less likely when the level of q is high. In this arrangement, defender D_H must prefer making defense efforts known to the attackers, thereby losing the benefits from pooling. The opposite holds for a lower level of q ; see the left panel of Figure 2.

Turning explicitly to the application of our model in the context of private precautions against crime, our analysis contributes to an explanation of why some households prefer observable safety measures but others do not. Based on our analysis, we would expect households to rely on observable measures when the population of households is relatively homogenous and the protected valuables are not easily transformed into money by thieves

(i.e., in scenarios in which λ is low while ρ is high). In contrast, when households vary widely with respect to the value of the property inside, they will try to outsmart each other in terms of the observability of defense efforts, which will lead to a mixed-strategy equilibrium and permit all discussed combinations. The possibility that contradicts expectations that rely on the complete-information intuition – that is, all defenders choosing unobservable precautions – is particularly probable in areas in which only a few households have objects of considerable value (i.e., in scenarios in which q is high). For instance, when a top-earning household moves into a medium-earner neighborhood, it is unlikely that this household will opt for observable private precautions. This endogenous determination of the most preferable kind of private precaution for a given household represents a break from prior literature, in which the selection of such precautions has been treated as a given.

4 Welfare

In this section, we will briefly refer to the potential welfare implications of the presence of incomplete information in our contest. One measure that is often used in this regard is the sum of contest efforts, given that these can be considered waste (see, e.g., Konrad 2009). We will also discuss the repercussions of taking into account the expected loss in value due to the transfer of the valuable objects to the attacker when $\rho > 0$.

We can specify expected social costs for the case of complete information in which defenders always make defense efforts observable (i.e., they opt for Stackelberg play), indexed here by an ‘C’ for complete information, as follows:

$$C^C = q \left[\frac{a_L^O}{d_L^O + a_L^O} \eta \rho L + d_L^O + a_L^O \right] + (1 - q) \left[\frac{a_H^O}{d_H^O + a_H^O} \eta \rho H + d_H^O + a_H^O \right], \quad (44)$$

where η is an indicator variable that is equal to one (zero) when the expected loss of value is (not) counted. The general formulation of expected social costs for the scenario with

incomplete information, indexed by an ‘I’ for incomplete information, is given by

$$\begin{aligned}
C^I = & \alpha\beta \left(q \left[\frac{a^{22}}{d_L^{22} + a^{22}} \eta\rho L + d_L^{22} + a^{22} \right] + (1-q) \left[\frac{a^{22}}{d_H^{22} + a^{22}} \eta\rho H + d_H^{22} + a^{22} \right] \right) \\
& + (1-\alpha)\beta \left(q \left[\frac{\tilde{a}}{\tilde{d} + \tilde{a}} \eta\rho L + \tilde{d} + \tilde{a} \right] + (1-q) \left[\frac{a_H^U}{d_H^M + a_H^U} \eta\rho H + d_H^U + a_H^U \right] \right) \\
& + \alpha(1-\beta) \left(q \left[\frac{a_L^U}{d_L^U + a_L^U} \eta\rho L + d_L^U + a_L^U \right] + (1-q) \left[\frac{a_H^O}{d_H^O + a_H^O} \eta\rho H + d_H^O + a_H^O \right] \right) \\
& + (1-\alpha)(1-\beta) \left(q \left[\frac{\tilde{a}}{\tilde{d} + \tilde{a}} \eta\rho L + \tilde{d} + \tilde{a} \right] + (1-q) \left[\frac{a_H^O}{d_H^O + a_H^O} \eta\rho H + d_H^O + a_H^O \right] \right), \tag{45}
\end{aligned}$$

where α and β must be adjusted according to the decisions regarding effort observability that result for given parameter values. For example, $\alpha = 0$ and $\beta = 0$ represents the case in which both defender types make their defense efforts observable.

In our discussion, we first turn to the standard welfare measure, that is, the sum of contest efforts. When $\eta = 0$, the comparison of social costs is clearly in favor of incomplete information in Combination (1,1), in which defender D_L distorts defense efforts downwards (since the adjustment in the attacker’s effort is not dominating). In other words, we find that

$$\tilde{d} + \tilde{a} = \frac{L}{2} \sqrt{\lambda(2[\lambda - \sqrt{\lambda(\lambda - 1)}] - 1)} < \frac{L}{2} = d_L^O + a_L^O, \tag{46}$$

because the term $\sqrt{\lambda(2[\lambda - \sqrt{\lambda(\lambda - 1)}] - 1)}$ is less than one for $\lambda > 1$. There is no change in effort costs for defender D_H in Combination (1,1). In addition, this implies that the sum of effort costs under incomplete information is also lower than under complete information should Combination (1,2) or (2,1) arise (in comparison to Combination (1,1), which always results for complete information). In both Combinations (1,2) and (2,1), the defender’s type is revealed. The defender type that chooses unobservable defense efforts chooses d_j^U ; the attacker chooses a_j^U when playing against this defender type. As already established, in this case, the sum of contest efforts is lower than the sum of contest efforts in the event of complete information and observable effort choices. At the same time, also for the defender

type that chooses observable defense efforts, the sum of defender and attacker efforts is not higher than in the complete-information scenario.

In contrast, in Combination (2,2), both defenders make effort unobservable, and attackers choose effort against an *averaged* defender. In order to evaluate this outcome, we first consider the counterfactual scenario in which both contestants know the contest prize and choose their efforts simultaneously and independently. We find that the expected efforts of the attacker and the defender would amount to

$$Ea = q \frac{(1-\rho)^2}{(2-\rho)^2} L + (1-q) \frac{(1-\rho)^2}{(2-\rho)^2} H = \frac{(1-\rho)^2}{(2-\rho)^2} [qL + (1-q)H] \quad (47)$$

$$Ed = q \frac{(1-\rho)}{(2-\rho)^2} L + (1-q) \frac{(1-\rho)}{(2-\rho)^2} H = \frac{(1-\rho)}{(2-\rho)^2} [qL + (1-q)H]; \quad (48)$$

as, for example, the value will be L with probability q , in which case the attacker (defender) will choose $L \times (1-\rho)^2/(2-\rho)^2$ ($L \times (1-\rho)/(2-\rho)^2$). In the section analyzing the complete-information scenario, we established that the equilibrium outcome will in fact be a sequential contest with even higher expected efforts, such that comparing the outcome under incomplete information to this benchmark implies a bias against the repercussions of incomplete information. We now turn to the case in which the attacker is uninformed about the actual value and chooses effort at the same time as the defender. From the attacker's first-order condition,

$$(1-\rho) \left[q \frac{d_L}{(a+d_L)^2} L + (1-q) \frac{d_H}{(a+d_H)^2} H \right] - 1 = 0,$$

in combination with the best response of defender j , $d_j = \sqrt{aJ} - a$, we find that the attacker effort will be

$$Ea = \frac{(1-\rho)^2}{(2-\rho)^2} \left[q\sqrt{L} + (1-q)\sqrt{H} \right]^2. \quad (49)$$

This can be used to determine the expected defender effort, given that the defender L is represented with share q ; we obtain

$$Ed = \frac{(1-\rho)}{(2-\rho)^2} \left[q\sqrt{L} + (1-q)\sqrt{H} \right]^2. \quad (50)$$

The concavity of the root function yields the result that the sum of contest efforts under incomplete information will be lower than in the complete-information scenario (see (49)-(50) in comparison to (47)-(48)). This argumentation follows the analysis by Wärneryd (2003). Accordingly, the sum of effort will also be lower in the incomplete-information setup for every mixed-strategy equilibrium.

In summary, we find:

Proposition 3 *In a contest setting in which one party can decide whether its defense efforts will be observable or unobservable, the presence of incomplete information lowers the sum of contest efforts.*

Proof. Follows from the preceding argumentation. ■

Turning to the case in which $\eta = 1$, we must take into account the possibility that incomplete information may result in a higher probability that the attacker will be successful and therefore that additional social losses will occur (due to the lower valuation of the object by the attacker in comparison to the defender). Starting with Combination (1,1), we assert that the downward distortion in the defense efforts of defender type D_L implies that the loss in value due to the transfer to the attacker will materialize more often. This increases the social costs of Combination (1,1) under incomplete information. The critical question is thus whether the advantage that stems from the difference in total contest effort dominates this disadvantage. This is indeed the case, as

$$\begin{aligned} & \frac{a_L^O}{d_L^O + a_L^O} \rho L + d_L^O + a_L^O - \left[\frac{\tilde{a}}{\tilde{d} + \tilde{a}} \rho L + \tilde{d} + \tilde{a} \right] \\ &= \frac{(1 - 2\rho)L}{2(1 - \rho)} \left(1 - \sqrt{\lambda(2[\lambda - \sqrt{\lambda(\lambda - 1)}] - 1)} \right) > 0. \end{aligned} \quad (51)$$

In Combination (2,1), the defender D_L chooses unobservable defense effort, thereby entering into a simultaneous-move contest. This again implies that the probability of society losing share ρ of the value of the object at stake will be higher when there is incomplete

information about the defender type. However, it once again holds that the effect stemming from the difference in contest effort dominates this adverse effect, since

$$\begin{aligned} & \frac{a_L^O}{d_L^O + a_L^O} \rho L + d_L^O + a_L^O - \left[\frac{a_L^U}{d_L^U + a_L^U} \rho L + d_L^U + a_L^U \right] \\ &= \frac{\rho(1 - 2\rho)L}{2(1 - \rho)(2 - \rho)} > 0. \end{aligned} \tag{52}$$

In Combination (1,2), the welfare-superiority of incomplete information can be established by reference to (51) for defenders of type D_L and to (52) for defenders of type D_H (where we substitute H for L in (52)). Finally, as established in the Appendix, it can be shown that the social costs are lower under asymmetric information in Combination (2,2) as well.

In summary, we find:

Proposition 4 *The presence of incomplete information lowers the sum of contest efforts and expected losses in value.*

Proof. The proof for Combinations (1,1), (2,1), and (1,2) follows from the above argumentation. The arguments for Combination (2,2) can be found in the Appendix. ■

5 Conclusion

In a struggle over resources akin to a contest, defenders often have both private information about the value of the resource and the possibility to decide whether or not to make their defense efforts observable. This paper analyzes such a scenario involving endogenous observability and the level of contest efforts in equilibrium. We find that widely varying arrangements may arise in equilibrium, including scenarios that are the diametric opposite of the outcome that results under complete information. For instance, defenders may choose unobservable defense effort, forfeiting their presumed first-mover advantage. The intuition

is that attackers rely on defender behavior when updating their beliefs about defender type (i.e., the value of the protected resources). For defenders, this means that making defense efforts known to aggressors may actually be detrimental. In addition to the positive analysis of this relevant setting, we show that the presence of incomplete information improves the outcome by softening the competition between defenders and attackers for resources and reducing wasteful effort expenditures.

The analysis presented here can be applied to the setting in which households determine their private precautions against crime. Whereas the literature has treated observable private precautions and unobservable safety measures as distinct cases, we allow households to choose between either observable or unobservable precautions against crime. Since the level of precaution signals information about the valuables present in the house, it may be the case that households will prefer to conceal their safety investments. Although incomplete information introduces a mimicking incentive that can harm less well-off households, it implies that less will be spent in total in the contest over households' property.

Appendix: Welfare considerations for Combination (2,2)

In order to establish that the level of social costs for Combination (2,2) in the setting of incomplete information falls below the level in the complete-information scenario, we first evaluate how the difference is affected by variations in the level of λ and then turn to the level of social costs at $\lambda = 1$. The derivative of the difference in social costs resulting from the outcome of Combination (2,2) and the outcome under complete information with respect to λ is given by

$$\frac{\partial(C^I - C^C)}{\partial\lambda} = -\frac{(1-q)\left((1-2\rho)\rho\sqrt{\lambda} + 2(1-\rho)^2(1+\rho)\left(\sqrt{\lambda}-1\right)q\right)L}{2(2-\rho)(1-\rho)\sqrt{\lambda}} < 0. \quad (53)$$

Furthermore, we know that the difference between social costs in Combination (2,2) and social costs under complete information evaluated at $\lambda = 1$ is

$$(C^I - C^C)|_{\lambda=1} = -\frac{\rho(1-2\rho)L}{2(2-\rho)(1-\rho)} < 0. \quad (54)$$

Accordingly, the cost difference $C^I - C^C$ is negative for all feasible levels of λ .

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