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“To eat or not to be eaten?” Collective risk-monitoring in groups ☆

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Abstract

The importance of risk-monitoring has been increasing in many key aspects of our modern lives. This paper examines how individuals monitor such risks collectively by extending a behavioral ecological model of animal foraging to human groups. Just as animals must forage for food under predatory risk, humans must divide valuable material and psychological resources between foraging activity and risk-monitoring activity. We predicted that game-theoretic aspects of the group situation complicate such a trade-off decision in resource allocation, eventually yielding a mixed equilibrium in a group. When the equilibrium is reached, only a subset of members engage in the risk-monitoring activity while others free-ride, concentrating mainly on their own foraging activity. Laboratory groups engaging in foraging under moderate risk provided a support to this prediction. When the risk-level was set higher, however, “herding behavior” (conforming to the dominant behavior) interfered with the emergence of equilibrium. Implications for risk management are discussed.
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Keywords: Risk-monitoring; Foraging; Cooperation; Free-riding; Producer-scrounger game; Uncertainty; Information cascade; Behavioral ecology

Introduction

Most modern risks are collective in nature, affecting many people’s lives simultaneously. Fragile financial markets, moral hazards in international business, and pollution by toxic substances are all examples of risks that affect many people at the same time. Anecdotes abound that insufficient monitoring of these collective risks can cause serious, sometimes unrecoverable damages to a large human population (Reason, 1997; Slovic, 1987, 1999). On the other hand, despite the importance of the problem to modern societies, few psychological studies have addressed how such risks are monitored collectively. In this paper, we examine how people monitor collective risks in a group setting, focusing on the potential free-rider problem in risk-monitoring. Our theoretical perspective is adaptationist or game-theoretic (cf. Hastie & Kameda, 2005; Kameda & Hastie, 2004; Kameda, Takezawa, & Hastie, 2003, 2005). Specifically, we extend a behavioral ecological model of animal vigilance and foraging to human groups under risk, and test predictions derived from the game-theoretic model via an interactive, laboratory experiment.

Risk-monitoring as a key element in modern societies

Studies of risk in psychology have been developed on several major themes. One central theme concerns the elaboration of the notion of risk in judgment and decision-making (Kahneman & Tversky, 1979; see Dawes, 1998; Hastie, 2000 for reviews). Researchers in this field have formally refined the notion of risk, yielding important empirical results about its functioning in individual and group decision-making (e.g., Davis, Kameda, & Stasson, 1992;

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Kameda & Davis, 1990; Loewenstein, Weber, Hsee, & Welch, 2001). Another key theme is concerned with risk perception and communication (Fischhoff, Lichtenstein, Slovic, Derby, & Keeney, 1981; Slovic, 1987). Researchers have identified various factors affecting people's perception of risk, and have examined the ways to facilitate effective communication between experts and lay people about technological or policy issues involving risk (Fischhoff, 1995; Slovic, 1999).

Along with other applied work on health risks (cf. Adler, Kegeles, & Genevro, 1992), these developments have greatly contributed to our understanding of human behavior involving various risks. Yet, there seems to be one glaring omission in previous psychological research, despite its theoretical and practical significance—the study of risk-monitoring. An episode in international business may help to illustrate the increasing importance of risk-monitoring in modern societies. In February 1995, Britain's Barings bank, the oldest merchant bank in the country, collapsed due to the actions of a single trader based at a small office in Singapore. In just 3 years, the trader, Nick Leeson, caused a huge, irrevocable loss to the entire group, amounting to nearly 870,000,000 GBP through a series of unauthorized trades involving "error accounts." The most problematic aspect of this episode was that the trader's harmful actions were largely unmonitored. Even though some of the auditors at the Barings Group reported suspicious activity, concerns were largely unheeded at the head office in London, which was occupied with "other more urgent business"; they failed to systematically redirect their resources so as to monitor the potential risk at the Singapore branch (for details, see <http://www.riskglossary.com/articles/barings_debacle.htm/>, and Reason, 1997).

As illustrated in this example, insufficient risk-monitoring in a group can cause serious consequences, involving the demise of an entire group or population. Toward a better understanding of risk-monitoring behavior, we approach this issue from an adaptationist perspective (cf. Kameda & Hastie, 2004; Kameda & Tindale, 2004), exploring the applicability of a behavioral ecological model of animal vigilance to human groups.

Behavioral ecological models of animal vigilance

Although we tend to think of "risk" in humanistic terms, the notion applies to the entire animal kingdom. Recently, scholars have made attempts to link theories of risk developed in the social sciences (applied mostly to humans) to theories developed in behavioral ecology (Weber, Shafir, & Blais, 2004).

Behavioral ecology has yielded sophisticated models and empirical data concerning risk-monitoring in the animal kingdom (cf. Krebs & Davies, 1993, 1997). According to these models, the lives of many animal species are divided between foraging for food and avoiding predation by other animals. These two activities are often mutually exclusive—extra effort in one reduces the effort available to the other. Therefore, when an animal forages for food, it must divide its time and attention between feeding and being vigilant for predators. Notice that, as illustrated in the demise of the Barings Group, humans in modern, as well as in primordial societies, constantly face the same adaptive challenge, to strike a balance between foraging/intake activity and risk-monitoring.

The behavioral ecology literature suggests that many animals' behavior under such a trade-off may be approximated by a cost-benefit model (Lima, Valone, & Caraco, 1985; Milinski & Heller, 1978). Laboratory experiments and field observations of many species (some rodents and birds, for example) suggest that, if the animals live solitary lives, individual optimization models essentially approximate their allocation decisions. The times allotted for being vigilant and feeding yield approximately a maximum joint fitness to the individuals most of the time (see Houston, McNamara, & Hutchinson, 1993, for general results about the trade-off between gaining energy and avoiding predation).

On the other hand, game-theoretic aspects complicate allocation decisions for social species (Pulliam, Pyke, & Caraco, 1982). Often, animals that forage together can enjoy "aggregation economies", or benefits associated with grouping that are unavailable to solitary foragers. In a group, there are many more eyes to watch for predators, allowing each animal to devote a relatively greater proportion of their time to foraging for food. However, it is exactly these features that yield an incentive for free-riding—If there are already a sufficient number of watchers engaged, why should not one choose to forego vigilance and forage exclusively. Giraldeau and Caraco (2000) named such an interdependent structure (including the vigilance-foraging situation) a "producer-scrounger" game. In the producer-scrounger game, if there are many "producers" of public (or collective) goods that are beneficial to others as well as oneself (e.g., monitoring for predators), each individual is better off exploiting the efforts of others (e.g., eating 100% of the time). However, if there are too many "scroungers" on another's monitoring efforts, each individual is better off switching to producing. If no one serves as a watcher, the gain from one's own risk-monitoring exceeds its cost; under these circumstances, reducing the likelihood of predation is a better option than eating.

Notice that, in contrast to the social dilemma game (Dawes, 1980), defection is *not* a dominant strategy in the producer-scrounger game. The net benefit of one strategy is not fixed (i.e., neither strategy is dominant), but depends on the frequency of the alternative strategy within the group; too many players opting for one strategy simultaneously reduces its profitability while increasing that of its alternative, providing an incentive for individuals to switch. Since the two strategies are mutually constrained in terms of profitability, we can expect a mixed Nash equilibrium to eventually emerge (Gintis, 2000; Maynard Smith, 1982). At equilibrium, the group reaches a stable state in which producers and scroungers coexist. In a context of foraging under risk, the group is composed of two types of individuals in a stable manner, those who engage mainly in risk-monitoring at the expense of foraging, and those who exploit the monitoring-efforts of others and primarily concentrate on foraging.

Applicability of the behavioral ecological model to collective risk-monitoring in humans

Although the topic of risk-monitoring is conceptually important to the social sciences (see Reason, 1997, for a detailed analysis of organizational accidents accruing from insufficient risk-monitoring), there has been almost no attempt to apply behavioral ecological models to collective vigilance in humans. Possible exceptions we are aware of include field studies by Wirtz and Wawra (1986), Wawra (1988), Dunbar, Cornah, Daly, and Bowyear (2002). These behavioral ecologists studied people's vigilance in contemporary city environments including a large refectory-style cafeteria and an open park. Although interesting and innovative, these studies do not provide data pertaining to human risk-monitoring specifically. Instead, their treatment of vigilance consisted of individuals' "looking-around" in general and was not limited to risk avoidance as we conceive of it—for instance, both mate searching and guarding were included in vigilant behavior. (See also Treves, 2000, for a review of vigilance behavior, viz., looking-around, by non-human primates.)

Given the novelty of the adaptationist approach in social psychology (cf. Kameda & Hastie, 2004; Kameda & Tindale, 2004), some considerations may be in order about its applicability to human groups. More specifically, how relevant are the notions of behavioral ecology to explain human behavior? Of course, this is ultimately an empirical question that can only be answered by programmatic research. However, we should emphasize that the adaptationist perspective, as well as sophisticated formal models derived from this approach (e.g., evolutionary games: Gintis, 2000; Maynard Smith, 1982), have been vitally important to synthesize an understanding of animal behavior across multiple taxa (Alcock, 2001). Although still few in social psychology, recent attempts have successfully extended its scope to human social behavior (e.g., Barkow, Cosmides, & Tooby, 1992; Buss, 1989; Daly & Wilson, 1988), including our own work on the development of social norms under uncertainty (Kameda et al., 2003, Kameda, Takezawa, & Hastie, 2005), "fast and frugal" decision heuristics in groups (Hastie & Kameda, 2005), and the function of social/cultural learning in a non-stationary, uncertain environment (Kameda & Nakanishi, 2002, 2003).

Our hypotheses

Extending these developments, this paper explores collective risk-monitoring in humans from the adaptationist perspective. For this purpose, we created a laboratory test-bed approximating the foraging-vigilance trade-off. In the laboratory, participants engaged in a "foraging" task (earning money through a simple calculation task) in groups of six under a common potential danger. While performing the task, participants could observe how others were allocating their time between foraging and monitoring of the common risk. If the simulation is an adequate approximation of the producer-scrounger game (Giraldeau & Caraco, 2000), and assuming that participants respond to the game structure rationally, we expected a mixed equilibrium to emerge over time in the group. Thus, our first hypothesis is as follows:

Hypothesis 1. Over time, collective risk-monitoring in a group will approach a stable mixed equilibrium in which a subset of members will engage in vigilant behavior (monitoring for the common risk) and the remaining group members will behave as scroungers (free-riders), concentrating only on the foraging activity.

Notice that this game-theoretic prediction assumes rational actors, unaffected by "irrational" psychological forces. However, social psychological factors may interfere with the emergence of equilibrium. Most notably, if conformity (Asch, 1956; Boyd & Richerson, 1985; Kameda, Tindale, & Davis, 2003) operates under uncertainty, then members may tend to follow the behavior of others. If everyone follows another's move, we would expect homogeneous groups consisting entirely of either watchers or foragers to be a frequent occurrence, instead of the mixed groups. Interestingly, economists started to model and empirically examine such herding behavior under uncertainty (Anderson & Holt, 1997; Banerjee, 1992; Bikhchandani, Hirshleifer, & Welch, 1992). Rational calculation, they argue, should lead to "information cascades" whereby people subsequently conform their behavior while simultaneously neglecting their own perception of the environment.

For example, Hung and Plott (2001) created information cascades in a Bayesian judgment task. In this study, the experimenter picked up one of two urns (e.g., one with 70 white and 30 red balls; the other with 30 white and 70 red balls) and then provided each participant an opportunity to draw *privately* one random sample from the chosen urn with replacement. Participants were selected in sequence and asked to announce *publicly* as to their judgment of the source urn from which the sample had been drawn. When early respondents in a sequential judgment task favored one urn, subsequent respondents were more likely to ignore the information gained by their private sample and to conform to the preceding publicly-declared decisions. Ironically, a Bayesian analysis shows that this is exactly what people should do—ignore their own private information and conform to the prior members' opinions. Thus, their task has the insidious property of producing rational (but erroneous) information cascades when leading members have drawn misleading samples, a condition that occurs on approximately one-quarter of the trials in Hung and Plott's experiment.

The information cascade can be seen as "rational panic", derived from the basic fact that conformity often leads to statistically correct inferences under uncertainty (see Henrich & Boyd, 1998; Kameda & Nakanishi, 2002 for an evolutionary game analysis of conformity from this perspective). We conjecture that collective risk-monitoring under noisy environments may have some parallels with the Bayesian statistical-inference situation as described above. Since risk can only be estimated (with error) under uncertainty, escalation of vigilant behavior by one's neighbors may imply that danger is imminent, just as multiple sensors simultaneously reporting seismic activity suggest an impending volcanic eruption (cf. Hastie & Kameda, 2005). In other words, people may use the frequency of high vigilant behavior in the group as a statistical cue to infer the imminence of risk, which leads to herding behavior at the group level. Thus, we have the following alternative hypothesis:

Hypothesis 2. Herding behavior will characterize people's collective risk-monitoring under uncertainty. Rather than approaching a stable mixed equilibrium where only a subset of members engage in vigilance, the group will fluctuate frequently between all vigilance and no vigilance.

In the following, we report an interactive, group experiment designed to test these hypotheses. It is possible that the validity of each of the two proposed hypotheses depends on the level of risk present in the foraging environment, which may mediate the strategy used to monitor common risk. To explore boundary conditions for hypotheses one and two, we created two conditions differing in risk-level.

Methods

Participants

Participants were 180 undergraduate students (133 males and 47 females) enrolled in introductory psychology classes at Hokkaido University in Japan.

Overview

We composed random six-person groups and implemented a foraging-under-risk situation in a laboratory connected through a local area network (LAN). As a laboratory foraging task, each participant was asked to solve individually as many simple calculation problems as possible during each trial. Participants accumulated 10 yen (about 10 cents) towards their experimental reward for each correct solution. While performing the calculation task, a common danger could arise in each trial. If an individual failed to avoid the danger, 30 yen (low-risk condition) or 50 yen (high-risk condition) was subtracted from his/her accumulated reward. Given average trial length, a penalty of 30-yen was sufficient to wipe out all earnings in the current trial plus a portion of previous earnings; a penalty of 50-yen might wipe out all earnings from the previous two trials. An individual could increase the likelihood of avoiding the danger by elevating his/her vigilance level. Choosing to do so, however, meant that the individual must sacrifice his/her foraging activity. Hence, a tradeoff between the two survival activities of risk-monitoring and foraging was simulated in the laboratory. The potential danger was common in that it affected all six individuals simultaneously. If one or more group members detected the danger, their subsequent evasive behavior could alert remaining members who were initially unaware of its imminence, thus affording them the opportunity to escape as well, time permitting. Thus, acting as a watcher and maintaining a high level of vigilance could, on average, help other members who were concentrating on solving the problems for their own benefit. Hence, a free-rider problem was simulated in the laboratory with respect to monitoring the common danger. There were 60 trials in total.

Procedure

Six participants were randomly assigned to one of two experimental conditions (low- or high-risk), each lasting approximately one hour. There were 15 groups (90 participants) in each condition.

Upon arrival, each participant was seated in a private cubicle and received further instructions individually via computer. Foraging under risk was explained, and the participants were informed that their reward would be contingent upon their performance in the experiment. The foraging task was a series of simple calculations (addition of two three-digit numbers). Participants earned 10 yen by typing in a correct answer for each problem appearing on the computer screen. The duration of each trial was determined randomly ($M = 30$, $SD = 10$ s). Trials ended when either the time had elapsed or after the common danger arose.

Monitoring the danger

The probability of the common danger occurring during a trial was 0.3 (unspecified to the participants). Two sources of information regarding the current risk-level were available to participants during each trial: environmental and social. This information was given to help the participant adjust his/her vigilance level against the danger (see Fig. 1).

The environmental information alluded to the imminence of the common danger and consisted of a regularly updated bar-chart displayed on the computer screen. The environmental information contained random noise (Brunswik, 1956); the cue value (i.e., height of the bar-chart) at any given moment reflected the sum of the true risk-level with a random parameter. We set the environmental cue so that participants were warned of the imminent danger (when it existed) with a 32% chance on average. At any time during a trial, participants could elevate their vigilance level to a high alert state, thereby gaining more precise environmental information (i.e., less noise), and increasing the average chance of detection to 64%. Higher vigilance, however, came with a price—partic-

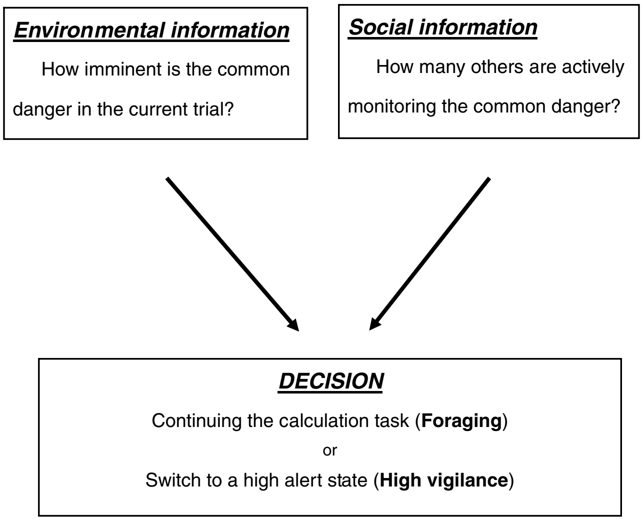

Fig. 1. Two sources of information, environmental, and social, were available for the participants to adjust their vigilance level while foraging.

ipants had to cease all foraging activity for the remainder of the trial.

Besides the environmental information, participants also had access to social information regarding other group members' collective risk-monitoring. Regular reports were provided throughout the trial informing each participant as to the number of group members who had switched to the high alert state. Combining the two types of information, participants were able to adjust their own vigilance level to defend against the common danger.

Escaping from the danger

To evade the approaching danger, participants had to click an escape button that became functional for a limited time once the common threat materialized. The allowable time for group members to escape was determined randomly from a uniform distribution ranging from 1- to 3-s. Fig. 2 summarizes the implementation of this process.

As mentioned earlier, individual detection (i.e., being warned) of the danger was probabilistic. If one or more group members detected the danger, their subsequent evasive behavior could alert remaining members who were initially unaware of its imminence. These members were still able to access the escape button, but only for the time that remained. Depending on the total length of the allowable time, and how quickly those who detected the danger had reacted, it was possible, though not certain, for any member to escape the danger simply by reacting to others in the group.[1]

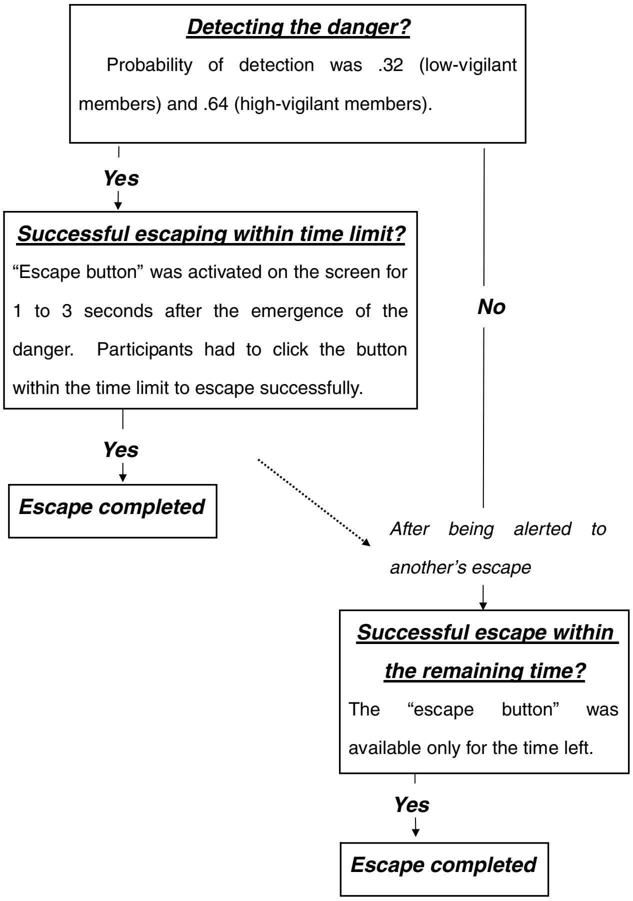

Fig. 2. Steps required for each individual to escape from the danger.

Performance feedback

After every five trials, participants received a summary table listing each member's cumulative reward, including their own. However, because the other members were unidentifiable in the table, it was impossible to associate an individual's alert history with his/her earnings. This feedback allowed participants to gauge the effectiveness of their strategy in terms of their relative performance within the group. The reward (in yen) for each participant was calculated as follows:

$$[10 * (\# \text{ Solutions})] - [\text{Penalty} * (\# \text{ failures to escape})].$$

Penalties in the low- and high-risk conditions were 30 and 50 yen respectively. There were 60 trials in total (18 of which the common danger arose). After completing the experiment, participants were paid and dismissed.

Results

On average, participants earned 1130 yen (about 11 US dollars) for a one-hour experiment ($SD = 499$ yen). This amount was about twice that of the average hourly wage undergraduate students typically earn working a part time job. Post-session interviews suggested that the participants were motivated to maximize their monetary rewards from the experiment. In the sections that follow, we first provide

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[1] The presence of high-vigilant members was beneficial to the group in two ways. First, high-vigilant members detected the common danger more effectively (.64 versus .32), thus increasing the overall probability of escape. Second, because it was impossible to forage in the high alert state, high vigilant members' reaction to the danger alert should have been relatively rapid, affording low vigilant members more time to reply with their own escape attempt. Therefore, with the provisioning of a public benefit comes the impetus for free-riding.

an overview on the participants' average vigilance rates and the mean amount of reward they received. We then report detailed statistical analyses testing whether those collective patterns better reflect an emergence of a stable mixed equilibrium (Hypothesis 1) or herding behavior under risk (Hypothesis 2).

Overview: Mean vigilance rates and rewards

Average vigilance-rates

For this analysis, we divided the 60 trials into three 20-trial-blocks. Fig. 3 presents the average proportion of participants in each group who switched to a high alert (vigilant) state.

Not surprisingly, participants were more vigilant in the high-risk condition than in the low-risk condition, elevating their risk-monitoring in proportion to penalty incurred for failure to avoid the common danger. When tested in a 2 (condition) × 3 (block) repeated-measures Analysis of variance (ANOVA), the main effect for condition was significant [$F(1,28) = 6.15$, $p < .05$]. There was also a main effect for block [$F(2,56) = 24.49$, $p < .001$], indicating that vigilant activity declined over time. Given that the risk level was held constant (at 0.3) across the 60 trials, results suggest that the participants adjusted their behavioral strategies of foraging and vigilance over time.

Average reward

To see the effects of such behavioral adjustments on our operationalization of fitness (monetary outcome), we examined the average reward earned by the participants across the three trial blocks and discovered that the mean reward increased over time. Collapsed across the low- and high-risk conditions, the mean reward was 340 yen in the first block, 357 yen in the second block, and 433 yen in the third block [$F(2,56) = 43.62$, $p < .001$]. This increase suggests that the participants came to balance the two key survival activities (foraging and vigilance) under risk more efficiently over time. Not surprisingly, there was also a main effect for condition [$F(1,28) = 22.11$, $p < .001$], indicating that the mean reward was higher when the penalty for failing to detect the common danger was lower—1327 yen in the low-risk condition compared to 933 yen in the high-risk condition.

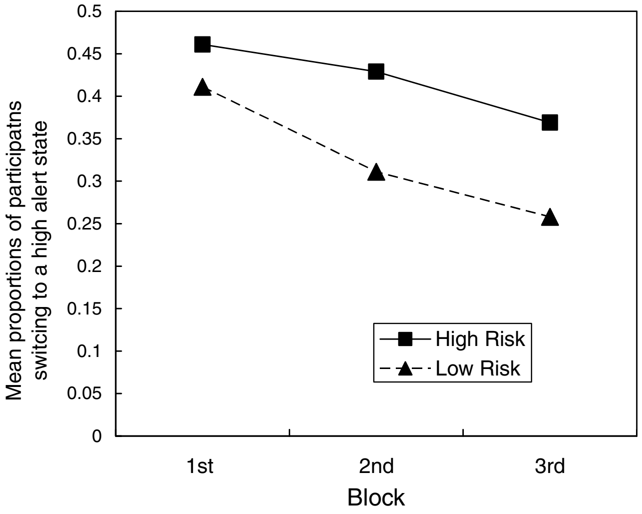

Fig. 3. Mean proportion of individuals in a group switching to the high vigilance state.

More important to our inquiry was whether the foraging under risk situation in this study indeed had the incentive structure of a producer-scrounger game (Giraldeau & Caraco, 2000). Recall that, in a producer-scrounger game, payoff to each strategy is not fixed, but instead depends on the frequency of the other strategy in the group. Individuals are better off exploiting the efforts of a sufficient number of producers, but should switch to producing public goods themselves if the number of producers is too few.

Is this condition adequately satisfied in the current experiment? Fig. 4 displays the average individual payoff to a watcher and a forager each trial, as a function of the number of *other* watchers engaged in high vigilance.[2]

As can be seen in Fig. 4, in both the low-risk and high-risk conditions, watching was more beneficial than foraging when there were too many foragers in a group (see the left side of the figure where the number of other watchers was small). Foraging was more beneficial, however, when many others were watching. Thus, our experimental setting seems consistent with a producer-scrounger situation. As expected, the net benefit of one strategy (watching or foraging) depended on the frequency of the other strategy in a group; if there were too many players with one strategy, each participant was better off switching to adopt the other strategy.

Emergence of a stable mixed equilibrium over time (test of Hypothesis 1)

As we saw in Fig. 3, the participants' use of vigilance became better adjusted over time in terms of the monetary outcome that was earned. The central question in the present study was to see whether these collective patterns reflect the emergence of a mixed equilibrium in the group

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[2] This was calculated as follows. For each trial, we examined occurrences of 7 possible group-compositions. A group composition could be (0,6), (1,5), (2,4), (3,3), (4,2), (5,1), or (6,0), where (*n*, 6-*n*) refers to a group composed of *n* watchers and 6-*n* foragers in a trial. Collapsing across all 15 groups in the low-risk and high-risk conditions, respectively, we then calculated the average reward that watchers and foragers earned in each of the 7 group compositions. The means depicted in Fig. 4 were taken from these calculations. For example, the mean payoff to a watcher when no other group member was engaging in high vigilance corresponds to the average reward for watchers in the trials with (***1***, 5) composition, and the mean payoff to a forager when no other group member was engaging in high vigilance corresponds to the average reward for foragers in the trials with (0, ***6***) composition; this comparison allowed us to see which strategy was more beneficial for an individual, to watch or to forage, when no other member was engaging in high vigilance in a trial.

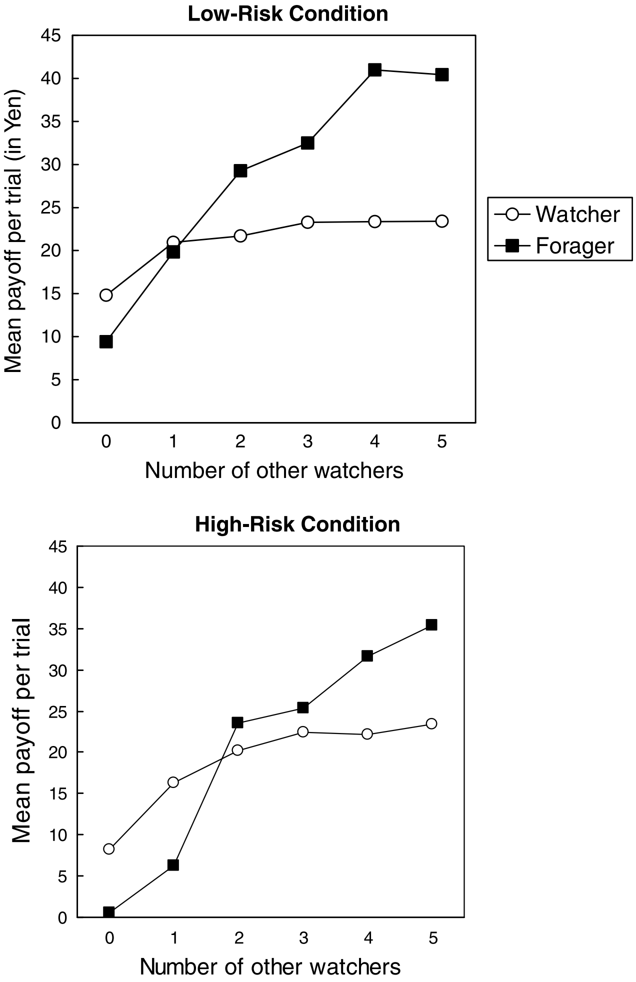

Fig. 4. Mean individual payoff to a watcher and a forager each trial, as a function of how many *others* were engaging in high vigilance during a trial.

(Hypothesis 1) or are governed by herding behavior (Hypothesis 2).

We have already confirmed that the foraging task had an incentive structure consistent with a producer-scrounger game (Giraldeau & Caraco, 2000). Furthermore, Fig. 4 also demonstrates that the payoff functions for watching and foraging intersect at the point 1.1 in the low-risk condition, and 1.8 in the high-risk condition. This means that an individual is better off switching to high vigilance if only one other member is watching in a group, but should continue foraging if two other members are watching. Thus, the game-theoretic equilibrium demands that approximately two members *in total* be monitoring risk during a given trial. The observed mean rates for watching in the third block (.26 in the low-risk condition and .37 in the high-risk condition) were close to the equilibrium proportion (.33 = 2/6) approximated from Fig. 4.

Although these results are in line with the notion of an equilibrium, closer examination is needed to test Hypothesis 1. Given the temporal nature of this hypothesis, we need to focus on changes in participants' behavior over time. Specifically, if the collective vigilance level approaches a stable mixed equilibrium over time, we might expect two things to happen: first, the proportion of watchers observed in each group should become less variable in later blocks; second, a division of roles may emerge consisting of hardcore free-riders who concentrate on foraging and altruistic watchers who commit to risk detection. We will examine these points in turn.

Variability of vigilance-rates in each group

Within-group variance associated with the proportion of watchers should decrease over time as the proportion itself approaches equilibrium. For instance, the proportion of vigilant individuals within each six-person group may be highly variable across early trials (e.g., 80% watchers in the first trial, 20% in the second trial, etc.), but should remain relatively consistent across later trials. To determine if this was true, we calculated the variance associated with the proportion of watchers for each group across the three successive blocks of 20 trials. Fig. 5 displays the means for the within-group variances of each condition.

In line with Hypothesis 1, fluctuation of the watcher-rate in each group decreased over time. A 2 (condition) × 3 (block) repeated-measures ANOVA yielded a significant main effect for block [$F(2, 56) = 12.09$, $p < .01$], and a main effect for condition [$F(1, 28) = 5.78$, $p < .05$]. However, the interaction effect was also significant [$F(2, 56) = 4.71$, $p < .05$] indicating that the main effect for block depended on the risk level of the situation. We thus conducted a separate one-way ANOVA for each condition. Using the omnibus error term, the block factor was highly significant in the low-risk condition [$F(2, 56) = 15.64$, $p < .001$], but not in the high-risk condition [$F(2, 56) = 1.16$, *ns*]. Thus, consistent with the equilibrium hypothesis, the vigilance rate became more stabilized over time in the low-risk condition. Conversely, the corresponding decrease in the high-risk condition (from .14 in block one to .13 in block three) was statistically non-significant; the vigilance rate remained equally variable across the blocks.

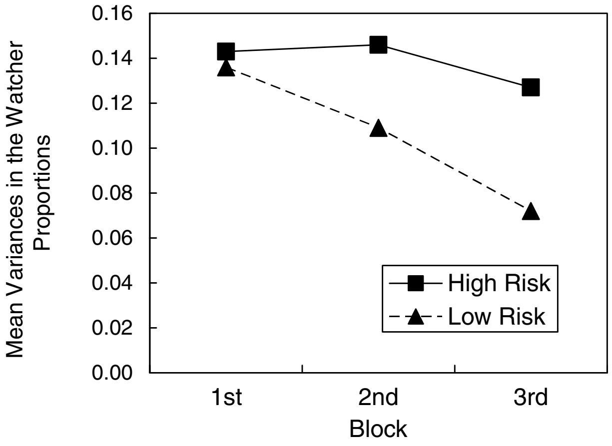

Fig. 5. Mean within-group variances in the proportion of vigilant individuals. If a producer-scrounger equilibrium is emerging, variances should become smaller over time.

Emergence of role-division over time

Theoretically, a mixed equilibrium can be monomorphic or polymorphic in nature, or (more likely) some intermediate state between the two with the aggregated proportion corresponding to the equilibrium rate (cf. Gintis, 2000; Maynard Smith, 1982). A *monomorphic* equilibrium occurs when all individuals play the identical mixed strategy. If we apply this notion to the low-risk condition, a monomorphic equilibrium corresponds to a state where each individual behaves as a watcher stochastically in each trial, with a probability of about .26 (see Fig. 3 for the third block in the low-risk condition). A *polymorphic* equilibrium occurs when a division of roles exists in a group, with around 26% of individuals always behaving as watchers and the remaining 74% always behaving as free-riding foragers in the present example.

To shed some light on this point, we examined how frequently each participant switched to a high vigilance state during each of the three blocks in the two conditions. Since each block was composed of 20 trials, the frequency of individual vigilance during a block could range from 0 (no vigilance) to 20 (full vigilance).

The top panel of Fig. 6 displays distributions of the vigilance-frequency for each block in the low-risk condition. Notice that the relatively symmetrical distribution in the first block disappeared over time; free-riders who never served as watchers (shown as black bars) increased rapidly in the later blocks. This implies the emergence of an equilibrium in the low-risk condition, as evidenced by the decreased variability in the vigilance rates over time (Fig. 5), was clearly not monomorphic (see Kameda & Nakanishi, 2002, 2003 for related findings). A Kolmogorov–Smirnov test revealed that the distribution in the third block was significantly different from the distribution predicted by a monomorphic equilibrium ($p < .001$), where all individuals behave as watchers with a probability of .26. On the other hand, the observed distributions were not purely polymorphic either, because there was a lack of committed producers in the third block. The overall patterns indicated that the hardcore free-riders did indeed emerge to become the majority in a group over time; the other group members were, however, more or less mixed as to their behavioral choices.

We also checked the consistency of each individual's vigilance-level between any two consecutive blocks. If role-division emerged within the group, each participant's vigilance behavior should have become increasingly more consistent over time; someone who engaged in high vigilance X times, in the t-th block, should have done so X times again in the $t+1$-th block. To test this, we examined the proportion of participants in each group who engaged in high vigilance for exactly the same number of trials between consecutive blocks (first and second block, second and third block), to determine the level of consistency over time. Results supported our reasoning; the mean proportion of consistent participants in the low-risk condition was only .12 between the first and second blocks, but this proportion increased to .30 between the second and third blocks (the increase was mainly caused by the emergence of the hardcore free-riders). This increase in the behavioral consistency over time was significant [$F(1,28) = 13.08$, $p < .01$].

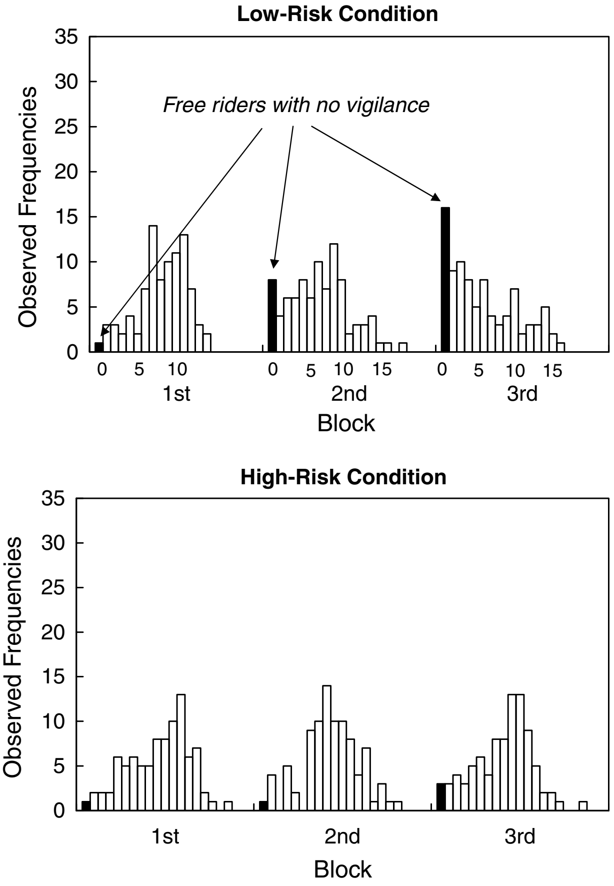

Fig. 6. Distribution of vigilance frequencies in each of the three blocks in the low-risk and high-risk conditions. The frequency could range from 0 (100% foragers) to 20 (100% watchers).

On the other hand, as shown in the bottom panel of Fig. 6 (see also Fig. 5), the pattern observed in the high-risk condition was inconsistent with the emergence of a division of roles; the symmetry of the distribution remained essentially unchanged and each participant's vigilance frequency remained variable across three blocks [$F(1,28) = 1.61$, *ns*].

Taken together, the overall results suggest that the equilibrium hypothesis (Hypothesis 1) was supported in the low-risk condition; within-group vigilance became more stabilized over time with determined free-riders eventually emerging as the majority in these groups. No corresponding pattern was observed in the high-risk condition, however.

Herding behavior under risk (test of Hypothesis 2)

As demonstrated above, the vigilance proportion in a group approached a mixed equilibrium in the low-risk condition, but not in the high-risk condition. Instead, the vigilance pattern remained equally variable, both within-group and within-individual, across the three experimental blocks in the high-risk condition (cf. Figs. 5 and 6). Next, let us address whether Hypothesis 2 might better characterize the data.

Hypothesis 2 predicted that the group would shift back and forth between two extreme situations (all vigilance or no vigilance) frequently, due to an individual's tendency to follow herd behavior (Hung & Plott, 2001). To see if this was the case, we examined the observed frequencies of 7 possible group-compositions in the experiment (cf. footnote 2). A group composition could be (0, 6), (1, 5), (2, 4), (3, 3), (4, 2), (5, 1), or (6, 0), where (*n*, 6-*n*) refers to a group composed of *n* watchers and 6-*n* foragers in a trial. Hypothesis 2 predicts that the two extreme combinations [(0, 6) and (6, 0)] should occur more frequently in the experiment than other group compositions.

Fig. 7 displays the mean observed frequencies of each group composition in the low- and high-risk conditions, again broken down into three 20-trial-blocks. The abscissa of each panel refers to the number of watchers in a group—*n* if using the above notation (*n*, 6-*n*).

As depicted in the figure, different patterns were observed between the low- and high-risk conditions. The U-shaped pattern for the high-risk condition is consistent with the prediction generated from Hypothesis 2, whereas the U-shaped pattern was less evident in the low-risk condition. A 2 (Condition) × 3 (Block) × 6 (Number-of-watchers) repeated-measures ANOVA revealed a significant Condition × Number-of-watchers interaction effect [$F(6,168) = 2.94$, $p < .01$]—the three-way interaction effect was not significant [$F(12,336) = .90$, *ns*]. Collapsed across block, the (6, 0) cases, in which all group members engaged in high vigilance, were more frequent in the high-risk condition ($M = 3.9$ out of 20) than in the low-risk condition ($M = 1.4$ out of 20), $t(28) = 9.45$, $p < .0001$. A regression analysis of the observed frequency in each condition with linear and quadratic terms also revealed that the quadratic coefficient was larger in the high-risk condition ($\beta = 1.21$) than in the low-risk condition ($\beta = 1.01$), ($t(208) = 9.94$, $p < .0001$), indicating that homogeneous groups of all watchers or all foragers were more characteristic of the high-risk condition.

Taken together, these results indicate that herding behavior (Hypothesis 2) was more relevant to the high-risk condition than to the low-risk condition. Participants who faced the high-risk situation conformed to others' behavior more frequently than those who faced the low-risk situation. Such herding behavior (Hung & Plott, 2001) could have interfered with the emergence of a strategic mixed equilibrium in the high-risk condition.

Discussion

Just as animals must forage under predatory risk, humans too must find an efficient trade-off in dividing their valuable resources—such as time, money, attention, and motivation—between foraging and risk-monitoring. If we were a solitary species, such a trade-off could be solved in terms of an individual optimization problem most of the time (Houston et al., 1993; Lima et al., 1985; Milinski & Heller, 1978). Yet, as a social species, a simple optimization solution does not apply to the human case.

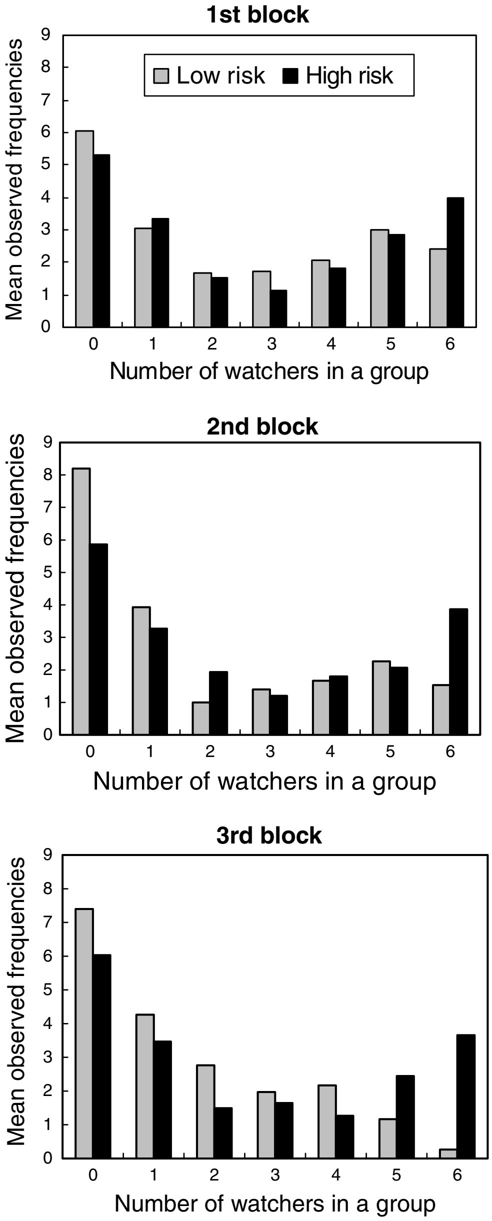

Fig. 7. Mean observed frequencies of 7 group-compositions in the low- and high-risk conditions. The abscissa of each graph refers to the number of watchers in a group.

Opposite social dynamics operating under risk

Group-living often provides "aggregation economies" (Giraldeau & Caraco, 2000; Kameda & Tindale, 2006). Within a context of risk-monitoring, this means there are many more pairs of eyes available to survey the landscape for common risks, which in turn allows individuals living in groups to divert supplementary time and effort to other key activities (such as foraging). Also, given that environmental cues almost always contain some noise (Brunswik, 1956), the behavior of others can often be used to provide valuable information regarding the imminence of a particular risk. If many others are on watch, it is likely that some risk is brewing, as implied by the law of large numbers in statistics. Using the behavior of conspecifics is an effective heuristic for reducing statistical uncertainty in perception and choosing an adaptive behavior in the environment, which is available only to social species (Hastie & Kameda, 2005; Kameda & Nakanishi, 2002, 2003).

However, the game theoretic model (Pulliam et al., 1982) suggests that the basis for just such an aggregation economy could provide an incentive for each individual to free-ride on the monitoring efforts of group members. Using Giraldeau and Caraco's (2000) terminology, the vigilance/foraging situation constitutes one instantiation of the producer-scrounger game, in which the efficacy of either behavior depends on the number of individuals already pursuing that strategy—if there are enough watchers, continue foraging; if there are too many foragers, switch to watching.

Notice from the above reasoning that the presence of watchers in the group can tempt the individual in *opposite* directions. From a statistical perspective (cf. Hung & Plott, 2001; Kameda, Ohtsubo, & Takezawa, 1997), if many others are watching, the risk is likely imminent, and individuals are better off switching to vigilance themselves. Conversely, from the game-theoretic perspective (cf. Giraldeau & Caraco, 2000), if many others are on watch, individuals are better off exploiting their risk-monitoring efforts to focus on foraging for themselves. Theoretically, opposite social dynamics may thus be triggered from the presence of other watchers in the group. We formulated these two social dynamics as the equilibrium hypothesis (Hypothesis 1), and as the herding hypothesis (Hypothesis 2). We then tested whether these two dynamics could characterize people's collective risk-monitoring behavior under different risk-levels.

Results suggested that the risk-level in the foraging environment may moderate these social dynamics. When the risk-level was low, participants' collective vigilance level became more stabilized (i.e., less variable) over time, as predicted by the equilibrium hypothesis (Hypothesis 1). Moreover, a division of roles emerged after a time in the low-risk condition; hardcore free-riders emerged to perpetually exploit high vigilance members' efforts. On the other hand, when the risk-level was high, such an equilibrium did not emerge. Instead, the groups shifted back and forth frequently between high vigilance and no vigilance across experimental trials (Hypothesis 2). In other words, participants in the high-risk condition seem to have used others' behavior as a statistical cue to infer the state of the environment (risky or safe), as observed in some experiments investigating information cascades (e.g., Hung & Plott, 2001).

From the adaptationist perspective, it seems highly reasonable to switch our behavioral strategies in response to the risk-level of the environment—using the presence of watchers as a cue to begin free-riding in low-risk environments, but as a statistical cue suggesting imminent danger in high-risk environments. Each of these strategies may be generally adaptive depending on the current level of risk in the environment. Along with formal modeling of people's collective risk-monitoring in general (cf. Kameda et al., 2003, 2003), future empirical work addressing this interaction of risk-level seems quite promising. Specifically, studies that manipulate risk-level by a different operationalization (e.g., differences in risk probability) from the one used here (differences in the amount of loss) will be informative.

Limitations and implications of the present study

Motivated by the importance of risk management in modern societies (Reason, 1997; Slovic, 1987, 1999), this experiment was a first step toward an integrative understanding of social psychological mechanisms about risk-monitoring. For this purpose, we have taken an adaptationist perspective (cf. Barkow et al., 1992); specifically, we have applied a behavioral ecological model of animal foraging and vigilance (Giraldeau & Caraco, 2000) to risk-monitoring in human groups. Behavioral ecological models of animal behavior (cf. Krebs & Davies, 1993, 1997) have many merits for social scientific research, including their heuristic value for formulating novel hypotheses of human behavior (see Kameda & Hastie, 2004; Kameda & Tindale, 2004, 2006, for fuller discussions of these merits). Yet, there are several limitations as well (cf. Gould & Lewontin, 1979). In the following, we will consider some of the limitations of the present study along with its implications for future research.

First, to understand the social dynamics underlying human collective risk-monitoring, the present experiment focused on *macro* behavioral-patterns, such as the emergence of a mixed equilibrium (Hypothesis 1) or herding behavior in groups (Hypothesis 2). Such macro-patterns are predicted to manifest as an accumulation of each individual's adaptive (rational) behavioral decisions under risk, and they have been a major focus in the behavioral ecological literature (cf. Giraldeau & Caraco, 2000). However, at this point, we do not have enough information on the *proximate* psychological mechanisms that enable each individual to conduct the necessary rational calculations and to use the adaptive heuristics involved in risk-monitoring. The moderating influence of risk-level that we have identified from the overall results of this experiment may serve as a useful guide to explore these mechanisms, including the proximate cues that trigger different behavioral strategies under risk. Future work addressing these psychological processes is essential for a fuller understanding of human collective risk-monitoring.

Second, the group used in this experiment was minimal in nature, a collection of unrelated individuals. There was no common group goal governing their behavior; participants essentially tried to maximize their individual outcomes while working within a group structure. However, in many "real" groups (teams, organizations), it is often the case that the groups have specific goals, and are structured accordingly with associated social norms (Moreland & Levine, 1982). In such cases, a division of roles often exists, including official roles designated to engage in risk-monitoring (e.g., auditors), as was the case in the Barlings Group. It is important to examine how the issue we raised in this paper applies to more structured organizations. Indeed, one way to interpret the stable mixed equilibrium, as observed in the low-risk condition, is that it may provide an infrastructure for official divisions of roles to emerge in risk-monitoring. It would be interesting to see how such formal social roles may emerge over time in a group where no such structure was built in initially (cf. Moreland & Levine, 1982).

Lastly, in this paper, we used a laboratory method to test two hypotheses of human collective risk-monitoring derived from behavioral ecology. Although the laboratory method is particularly suited for theory-testing with rigorous control, it may well be argued that it sometimes lacks ecological validity. This criticism is well taken in the present study, because we assumed that money was a valid currency (Krebs & Davies, 1993, 1997) for stimulating fitness-maximization and trade-offs between vigilance and foraging. However, there may be a more appropriate resource for tendering risk-monitoring in general, or which may in fact vary as a function of the risk itself. Together with laboratory experiments such as the present one, field observations in natural settings would provide valuable information to better understand human risk-monitoring in modern societies, both theoretically and empirically.

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