Cost-Benefit Analysis of Social/Cultural Learning in a Non-Stationary Uncertain Environment: An Evolutionary Simulation and an Experiment with Human Subjects

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Abstract

Social/cultural learning is an effective way to reduce uncertainty about the environment, helping individuals adopt an adaptive behavior cheaply. Although this is evident for learning about temporally stable targets, such as acquisition of an avoidance of toxic foods, the utility of social/cultural learning in a temporally unstable environment is less clear, since knowledge acquired by social learning may be outdated. This paper addresses the adaptive value of social/cultural learning in a non-stationary environment both theoretically and empirically. We first conducted an evolutionary computer simulation that extended Henrich & Boyd's (1998) model of cultural transmission, with the following results. When individual learning about the non-stationary environment is costly, a mixed equilibrium emerges in the population, where members who engage in costly individual learning and members who skip the information search and free-ride on other members' search efforts coexist at a stable ratio. Such a "producer-scrounger" structure qualifies effectiveness of social/cultural learning severely, especially "conformity bias" when using social information. We then tested these propositions by an experiment implementing a non-stationary uncertain environment in a laboratory. The results supported our thesis. Implications of these findings and some future directions are discussed.

Key Words: social learning, cultural transmission, conformity, non-stationary environment, producer-scrounger equilibrium

1. Introduction

Uncertainty reduction is a central adaptive problem for many species. Some group-living species have evolved effective *social* mechanisms for reducing uncertainties in their environments. A prime example is a system of reciprocal exchange (e.g., Axelrod 1984; Trivers 1971; Wilkinson 1984) and sharing of resources such as food (e.g., Flack & de Waal 2000; Kaplan & Hill 1985; Kameda, Takezawa & Hastie, in press; Kameda, Takezawa, Tindale & Smith 2002). These social mechanisms secure a stable supply of resources by collectively buffering uncertainties associated with their acquisition. In this paper, we extend the uncertainty-reduction view beyond the domain of exchange and sharing, and reconsider adaptive functions of social learning from this perspective. As argued by various theorists (Boyd & Richerson 1985, 1996; Cavalli-Sforza & Feldman 1981; Durham 1991; Heyes & Galef 1996; Tomassello, Kruger & Ratner 1993), social or cultural learning is another important way, besides genetic transmission, to transmit information across generations. We first explore uncertainty reduction via social learning with an evolutionary computer simulation that extends Henrich & Boyd's (1998) recent model of cultural transmission. We then test theoretical propositions derived from the simulation, by an experiment with human subjects. Finally, we discuss how evolutionary game modeling of cultural learning, coupled with experimentation, provides useful insights into various social psychological phenomena in modern societies, as well as into the evolutionary forces that have shaped our social minds.

1.1. Uncertainty reduction by social/cultural learning

To prepare the ground for our theoretical development, let us start with a simple example. Suppose that you have found a clump of mushrooms while walking in a forest. Although the mushrooms look tasty, you are uncertain if they are indeed edible. Individual learning by trial and error may be fatal in this case, so a cheap and reliable way to cope with this uncertainty is to ask an expert's or elder's opinion, or simply observe their behaviors. Indeed, as illustrated by this example, the previous literature suggests that acquisition of food preferences is heavily influenced by cultural transmission (Katz & Schall 1979; Rozin 1989; see also Galef & Whiskin 2001, for social acquisition of food preferences in rats). Boyd & Richerson (1985) showed formally that social or cultural learning is effective in these cases, and in particular, that *conformity bias*, a propensity to preferentially adopt the cultural traits that are most frequent in the population, is adaptive in these uncertain situations. (See Festinger 1950, 1954, for a related argument.)

Although the "mushroom problem" illustrates the adaptive value of social learning, it may illuminate its limitations as well. Notice that culturally transmitted knowledge about the mushroom holds true across generations: if someone in your tribe died from the mushroom centuries ago, the incident still conveys valuable information to the current generation. Social or cultural learning about such a *temporally stable* target should therefore function as a highly effective mechanism to reduce uncertainty, but a far more challenging case is provided by a *temporally unstable* environment where a behavior that was adaptive in previous generations may no longer be so. This sort of environmental instability was actually quite common in our evolutionary history; for example, recent studies on ice cores and ocean sediments suggest that the Pleistocene EEA was an environment with frequent climate fluctuations on sub-millennial time scales (cf. Boyd & Richerson 2000; Potts 1996). Is social or cultural learning still adaptive in such a temporally unstable environment? Specifically, is conformity bias in social learning, as observed in acquisition of food preferences, functional?

1.2. Effectiveness of "conformity bias" in social/cultural learning in a non-stationary environment: Henrich & Boyd's (1998) simulation model

Henrich & Boyd (1998) addressed this question theoretically by an evolutionary computer simulation. Since we extend the Henrich & Boyd (1998) simulation in this paper, let us review their model first in some detail. An outline of their simulation algorithm is shown in Figure 1.

Insert Figure 1 about here.

To model a temporally fluctuating environment, Henrich & Boyd (1998) assumed that the environment can change between two states, A and B, with a small probability in any two consecutive generations. Behavior A is more fit (i.e., provides a better chance of surviving) if the environment is in state A, whereas behavior B is more fit in environment B. Thus, natural selection favors learning mechanisms that make individuals more likely to adopt the behavior that is adaptive in the current environment (see Figure 1 bottom).

As shown in the figure, two information sources are available for individuals to make behavioral choices in the current environment, viz., opportunities for *social* (*cultural*) *learning* and *individual learning*. The social learning opportunity provides information about the choices of several cultural parents in the *preceding* generation, and learning from several predecessors leads to a statistically reliable estimate about the environment in many cases (law of large numbers), but the information is outdated if an environmental change has occurred. By contrast, the individual learning opportunity provides updated information about the *current* environment, but because of random noise in environmental information, as a single observation, individual learning is statistically less reliable.

Each agent then combines the two kinds of information to decide how to behave in the current environment. Two “genes” are pertinent to this combination. One is a gene affecting variations in *propensity to use social information over individually-learned information*. As stated earlier, environmental information acquired by individual learning contains random noise, so that even if the signal suggests that the current environment is in state A, it may actually be in state B. As in signal detection theory (Green & Swets 1966), Henrich & Boyd (1998) assumed that each agent has a decision threshold and if the signal value exceeds it, he or she makes a choice based on the individually learned information (e.g., adopting behavior A). However, if the signal is insufficiently diagnostic, the agent disregards the individual information and relies solely on social information. Individual variations about the threshold were represented as effects of a gene in the simulation (the higher one’s threshold, the more likely one is to rely on social information).

The other gene regulates variations in *conformity bias when using social information*. Suppose that the environmental signal is insufficiently diagnostic, so the individual must rely on social information, and that 3 of 5 cultural parents sampled from the previous generation chose behavior A, while 2 chose behavior B. Henrich & Boyd (1998) conceptualized the degree of conformity bias when using social information as a likelihood of preferentially adopting the most frequent behavior among the cultural parents (behavior A in the above example). That is, individuals with *no* conformity bias adopt behavior A only proportionally (with a 60% chance in this case), having no tendency to focus preferentially on the most common behavior among the cultural parents. Individuals with a *full* conformity bias adopt behavior A with a 100% chance, *always* following the majority view. Combining individual and social information as determined by these two genes, each individual makes a behavioral choice.

Then, natural selection operates: those who behave adaptively gain a slight survival advantage, and with the relevant genes transmitted in a haploid, asexual fashion, the genes and resultant learning mechanisms that generate adaptive behavior in the current environment increase in the population gradually. The simulation repeats this process for many generations until an equilibrium state emerges in the population.[1]

Henrich & Boyd (1998) examined the adaptive value of conformity bias in social learning by systematically varying key parameters, such as the rate of environmental fluctuation and the average accuracy of environmental information. The result of primary relevance for our purposes was that a conformity bias was favored under a wide range of model parameters. Even when environmental change was rather frequent (e.g., the probability of environmental change between generations is 0.3), almost a full conformity bias emerged as a stable equilibrium.

1.3. Cost-benefit analysis of social learning

1.3.1. Free-rider problem

Henrich & Boyd (1998) established that conformity bias in social/cultural learning can serve as an effective uncertainty-reduction mechanism even in a non-stationary environment, but one critical factor seems to be missing from their model: *asymmetry of learning cost between individual and social/cultural learning*. The simulation assumed that the costs of individual and social/cultural learning were identical and that everyone engaged in both learning modes fully. However, in many actual situations, individual learning may be costlier than social learning in energy, time, or risk, and such an asymmetry creates the possibility that if many others engage in costly individual learning, it may be better for some to skip the individual information search completely and “free-ride” on others' search efforts, whereas if too many others just rely on social information, it may be better to engage in individual learning. In other words, a *free-rider problem* exists with respect to costly individual information search, and this may qualify the evolvability of conformity bias in social/cultural learning.

1.3.2. A “producer-scrounger” structure

This problem is conceptually parallel to the "producer-scrounger" issue in social foragers (Barnard & Sibly 1981; Giraldeau & Caraco 2000; Krebs & Inman 1992; Vickery, Giraldeau, Templeton, Kramer, & Chapman 1991). If there are many producers in a group, it is better for an individual to scrounge food discovered/captured by others, but if many others cease foraging, then it is better to forage. As a result, producers and scroungers often coexist in the group, constituting a mixed strategy Nash equilibrium.

Similarly, in the case of social/cultural learning, there may be equilibria in which individual learners (“information producers”) and social learners (“information scroungers”) coexist, and such a producer-scrounger relation may substantially limit the effectiveness of a conformity bias in social/cultural learning. Specifically, when the extra cost of individual learning is high, the proliferation of “information scroungers” in the population may degrade the average quality of collective knowledge under a non-stationary environment, reducing the adaptive value of conformity bias.

1.4. An extended simulation

To test these ideas, we conducted simulations that extended Henrich & Boyd’s model by adding a third gene controlling variations in *individual propensity to engage in costly individual learning*. Haploid agents with the “on” allele at this locus are information "producers" who pay an extra cost for updated information about the current environment; those with the “off” allele are information "scroungers" who skip the individual learning opportunity. Thus, an individual learning opportunity is not the default, but is *optional* in our algorithm. All else, including the fact that the social learning opportunity was provided free to all individuals, remained as in Henrich & Boyd's original simulation.

1.4.1. Results

Since the purpose of this simulation was to illustrate the logic of free-riding in social/cultural learning, we do not provide a full report of the simulation results here. Instead, we focus on the key parameter in our argument – extra cost required for individual learning. (Readers who are interested in other features of the simulation may write to the authors for details.) Figure 2 illustrates changes in the prevalence of information producers over generations. Individual learning was 4 times as costly in the "high cost" case as in the "low cost" case.[2] We conducted 10 simulation runs separately for each case, and the figure shows the average proportions.

Insert Figure 2 about here.

As shown in Figure 2, a mixed strategy equilibrium emerged over generations, whereby agents who engaged in costly individual learning and agents who relied solely on social information coexisted. The equilibrium proportions depended on the cost of individual learning. Figure 3 displays equilibrium proportions of information producers in the population as a function of this extra cost, which was varied systematically while keeping the other simulation parameters unchanged (see footnote 2). The equilibrium proportion of information producers decreased monotonically with an increase in individual learning cost; the population was dominated rapidly by free-riding information scroungers.

Insert Figure 3 about here.

The evolvability of conformity bias was also affected by the individual learning cost.

Figure 4 displays equilibrium levels of conformity bias among information producers and information scroungers respectively. (Simulation parameters other than individual learning cost were unchanged; see footnote 2.) Recall that full conformity bias (= 1) means that individuals always choose the most frequent behavior among sampled cultural parents, while no conformity bias (= 0) means a proportional imitation. As is shown in Figure 4, conformity bias evolved when individual learning cost was negligible, as in Henrich & Boyd (1998), but with an increase in this cost, evolvability of full conformity bias was hindered for both information producers and scroungers.

Insert Figure 4 about here.

1.4.2. Discussion

The results of the extended simulation confirmed our reasoning that the free-rider problem substantially affects adaptive values of social/cultural learning. As in the producer-scrounger dilemma, the asymmetry in learning cost between individual and social learning leads to a mixed strategy Nash equilibrium in the population, with those who engage in costly individual learning and those who free-ride on others' search efforts in stable coexistence (cf. Rogers 1988). Such a structure also qualifies the adaptive value of conformity bias in social/cultural learning. If individual learning is too costly, the equilibrium proportion of information producers is quite small. Given the non-stationary nature of the environment, this prevents fresh environmental information from flowing into the "cultural knowledge pool." Thus, with an increase in individual learning cost, the average quality of the knowledge pool is degraded, and natural selection favors a *decrease* in reliance on this flawed cultural knowledge and hence on conformity.

2. Experiment

We now submit these theoretical notions to empirical test in an experiment featuring a non-stationary uncertain environment in a laboratory setting. Here, we focus on *adaptive learning of learning strategies* rather than genetic evolution. That is, we examine whether participants may adjust their learning strategies adaptively (i.e., in the manner suggested by the theoretical analysis) through their experiences in a laboratory group. Our experimental hypotheses are as follows:

Hypothesis 1-a: In a temporally fluctuating uncertain environment, a mixed strategy equilibrium will emerge over time, with information producers who engage in costly individual learning and free-riding scroungers coexisting.

Hypothesis 1-b: The equilibrium proportion will depend on the cost of individual learning, with fewer producers in a group when the information search cost is higher.

Hypothesis 2: Participants will adjust their degree of conformity according to the individual learning cost, showing less conformity when the information search cost is higher.

2.1. Method

2.1.1. Participants

Participants were 246 (157 male and 89 female) undergraduate students enrolled in introductory psychology classes at Hokkaido University, Japan.

2.1.2. Experimental task

We implemented a fluctuating uncertain environment by means of a computer game called “where is the rabbit?”. In this game, participants judged in which of two nests a rabbit was currently located based on stochastic information. Participants played the game for a total of 60 rounds. To operationalize the fluctuating environment, we instructed participants that the rabbit (= environment) had a tendency to stay in the same nest over time but this tendency was not perfect. The rabbit might change its location between any two consecutive rounds with a small probability. Thus, the location of the rabbit in a given round corresponds to the current state of the fluctuating environment, conceptually. All participants experienced the same randomly determined fluctuation pattern.

2.1.3. Procedure

For each hourly session, six participants came together to the laboratory. These six-person groups were randomly assigned to one of the two experimental cost conditions: 21 groups to the high-cost condition and 20 groups to the low-cost condition.

Upon arrival, each participant was seated in a private booth and received further instructions *individually* via computer. "Where is the rabbit?" was explained, and the players were told that their rewards would be contingent upon their performances in this game. Participants were instructed that they would play this game for many rounds (unspecified) and would gain 30 yen for each round in which they guessed the location of the rabbit correctly.

Two information sources were available for making judgments about the rabbit's location: opportunities for *social learning* and *individual learning*. The social learning opportunity was available to all participants as a default. That is, except for the first round, judgments of 3 participants in the *preceding* round, who were randomly sampled from the 5 group members other than self, were provided to each participant for *free*. As discussed earlier, social learning in a fluctuating uncertain environment provides statistically reliable (i.e., aggregated) information cheaply, but this information may be *outdated* due to the possibility of environmental change (the rabbit's move).

In addition to this social learning opportunity, participants could use individual learning, but at a cost: in each round, participants could choose to use a "rabbit-search-machine" by paying a certain amount: 15 yen in the high-cost condition and 5 yen in the low-cost condition. Since the monetary reward for making a correct judgment was 30 yen, those participants who used the machine (i.e. individual learning) to get the correct answer in a given round had to defray 50% (high-cost condition) or 16.7% (low-cost condition) of the reward to cover the individual information search cost. The "rabbit-search-machine" provided stochastic information about the location of the rabbit. By a series of pilot tests, we set the accuracy of the search machine so that the using this individual learning opportunity alone (i.e. without using social information) yielded 67% correct judgments on average. In a practice session before the main experiment, participants were given opportunities to familiarize themselves with the search machine and its accuracy. In the first round only, when no social information was possible, all participants received information via the search machine for free.

After every five rounds, participants received feedback about their relative performances in the group. That is, a summary table of all six members' cumulative rewards up to that point (e.g., 30 yen x the-number-of-rounds-where-a-participant-made-correct-judgments – 15 yen x the-number-of-rounds-where-the-participant-used-the-search-machine, in the high-cost condition) was displayed on the computer screen after every five rounds. This feedback provided an opportunity for participants to learn the effectiveness of their learning strategies, permitting *adaptive learning of learning strategies* for participants in a way conceptually parallel to the selection phase in the evolutionary simulation. It should also be noted that *no* direct feedback about the exact location of the rabbit was provided at any point in the experiment; thus direct learning of the rabbit's exact location was impossible throughout the experiment.

After completing 60 rounds, participants answered a brief post-session manipulation check questionnaire, and were then paid and dismissed.

2.2. Results and discussion

2.2.1. Emergence of a producer-scrounger equilibrium over time

We hypothesized that, in a temporally fluctuating uncertain environment, a stable mixed strategy equilibrium should emerge over time, with information producers who engage in costly individual learning and free-riding scroungers coexisting (hypothesis 1-a).

We also predicted that the equilibrium proportion would depend on the cost of individual learning, with fewer information producers when the information search cost was higher (hypothesis 1-b). Figure 5 displays *mean proportions of information producers* in 6-person groups over 60 experimental rounds, in the high-cost and low-cost conditions, respectively, and shows that both predictions were upheld. Dividing the 60 experimental rounds into 3 blocks, a 2 (high cost vs. low cost) x 3 (block) repeated-measures Analysis of Variance (ANOVA) yielded a significant cost x block interaction effect, $\underline{F}(2, 38)=5.12$, $\underline{p}<.02$.

Insert Figure 5 about here.

If this pattern indicates that the proportion of information producers in a group is approaching equilibrium over time (as predicted by hypothesis 1-a), *variances* associated with the proportion should decrease over time. There are two ways to assess this possibility. One way is to focus on *between-group variances*. That is, if the proportion of information producers is approaching equilibrium, between-group variability in this proportion should decrease over rounds. To test this, we conducted a multiple regression analysis on the between-group variances, with experimental round and condition as predictors, and as expected, the round was a significant predictor ($\underline{ß}=-.21$, $\underline{t}(115)=2.64$, $\underline{p}<.01$). Although the between-group variance was generally smaller in the high-cost than in the low cost condition ($\underline{t}(115)=5.59$, $\underline{p}<.001$), the regression line collapsed across the two conditions had a *negative* slope ($\underline{ß}=-.21$), indicating that variability among the groups in the information-producer proportion decreased monotonically as play progressed.

The other way to check the emergence of equilibrium is to focus on *within-group variances*: if the proportion of information producers is approaching equilibrium, fluctuations in the proportion *within each group* should become smaller with successive play. Thus, for each group we calculated variances in the proportion of information producers across the first block of 20 rounds, the middle block, and the last block. Mean within-group variances (collapsed over the two experimental conditions) were 0.040 for the first block, 0.032 for the middle block, and 0.030 for the last block. As expected, a 2 (cost) x 3 (block) repeated-measures ANOVA yielded a significant main effect for the block, $F(2, 78)=5.73$, $p<.01$. Although the within-group variance was smaller in the high-cost condition than in the low-cost condition ($F(1, 39)=5.14$, $p<.05$), as was the case with the between-group variance, it also decreased monotonically as play progressed.

Taken together, these results provide clear support for hypothesis 1-a about the emergence of a producer-scrounger equilibrium over time.

2.2.2. Monomorphism or polymorphism?

Given this demonstration of an equilibrium, the next question is how it was realized. The mixed strategy Nash equilibrium could be a *monomorphic* equilibrium where all members play the identical mixed strategy; in our case, this corresponds to a state where each player behaves as an information producer stochastically in each round, with a probability of around .2 in the high-cost condition and around .5 in the low-cost condition (see Figure 5). Alternatively, it could be a *polymorphic* equilibrium, with about 20% of players in the high-cost condition and about 50% in the low-cost condition always behaving as information producers -- a situation where “division of roles” exists. (More precisely, there can be intermediate states between these two extreme cases, with the aggregated proportion corresponding to the equilibrium rate; cf. Gintis 2000).

To shed some light on this question, we first checked how frequently each participant engaged in costly individual learning during each of the 3 blocks. Since each block is composed of 20 rounds, the frequency of individual information search during a block could range from 0 (pure scrounging) to 20 (pure producing). Figure 6 displays distributions of the information-search-frequency for each block in the low-cost (top) and high-cost (bottom) conditions, respectively, and shows that the relatively symmetric distribution pattern in the first block disappeared over time. In the low-cost condition, pure scroungers (0) and pure producers (20) increased in the later blocks, while pure scroungers (0) dominated groups rapidly in the high-cost condition.

Insert Figure 6 about here.

To understand these changes in play more fully, we checked consistency in each participant’s information search strategy between two consecutive blocks, to see if someone who engaged in individual information search, say, 5 times in the *t*-th block would again do so 5 times in the *t+1*-th block? Figure 7 displays the proportions of participants who were consistent in this way, engaging in costly information search exactly the same number of times in the second block as in the first, or in the third block as in the second. Evidently, participants became more consistent in their individual information search strategies over time, showing greater consistency from the second block to the third than from the first to the second. A 2 (cost) x 2 (consecutive blocks: 1→2, 2→3) repeated-measures ANOVA yielded a significant main effect for the consecutive blocks, $F(1, 39)=12.58$, $p<.001$. The main effect for cost was also significant ($F(1, 39)=10.46$, $p<.003$), indicating that strategies were more consistent in the high-cost than in the low-cost condition.

Insert Figure 7 about here.

Taken together, these results indicate that the equilibrium observed in the experiment was closer to a polymorphic equilibrium than to a monomorphic equilibrium. “Division of roles” characterized the equilibrium, especially with some hardcore information-scroungers, who never engaged in individual information search and consistently free-rode on others’ costly search efforts, emerging in a group over time.

2.2.3. Adaptive adjustment of conformity bias

Besides the emergence of a producer-scrounger equilibrium, our evolutionary simulation indicated that the adaptive value of conformity bias, viz., behavioral tendency to preferentially adopt the most frequent behavior among cultural parents (Boyd & Richerson, 1985), decreased as individual learning cost increased. Given this result, we hypothesized that people would adjust the degree of conformity according to the individual learning cost, showing *less* conformity in the high-cost than in the low-cost condition (hypothesis 2).

To test this hypothesis, we calculated the proportions of times that each participant adopted (conformed to) a majority choice, when his/her choice was in disagreement with the majority choice. To illustrate, suppose that a participant chose “nest A” for the location of the rabbit in the *previous* round. Suppose also that, when making a choice in the *current* round, the participant received social information that all 3 other participants (“cultural parents”) chose “nest B” in the previous round. Although the participant could acquire additional information by individual information search, he/she somehow had to resolve the difference between own view and the majority view in the previous round. We calculated the proportions of times each participant conforming to the dissenting majority choice in such occasions, separately for cases where the participant behaved as an information producer or as a scrounger in the current round. Figure 8 displays mean proportions of participants' “conformity” choices in each condition.

Insert Figure 8 about here.

As expected, conformity was less common in the high-cost than the low-cost condition, regardless of whether participants engaged in costly individual learning in the current round. A 2 (cost) x 2 (producer vs. scrounger) repeated-measures ANOVA yielded an expected main effect for cost, $F(1, 160)=6.00$, $p<.02$. A main effect for producer vs. scrounger was also significant, $F(1, 160)=3.90$, $p<.05$, indicating that participants showed a greater conformity bias when behaving as information scroungers than when behaving as producers in the current round (cf. Figure 4). Furthermore, these results were significant for “consenting” cases as well, where a participant's choice in the previous round was in agreement with a majority choice. A 2 (cost) x 2 (producer vs. scrounger) repeated-measures

ANOVA yielded a significant main effect for cost, $F(1, 143)=9.44$, $p<.01$, again confirming *less* conformity bias in the high-cost than in the low-cost condition. A main effect for producer vs. scrounger was also significant, $F(1, 143)=94.45$, $p<.0001$.

Thus, hypothesis 2 was clearly supported; consistent with the evolutionary simulation results, participants adopted a majority view to a lesser extent with an increase in information search cost.

3. General discussion

This paper has examined adaptive values of social/cultural learning in a non-stationary uncertain environment, for although such learning can be a cheap but highly effective uncertainty-reduction mechanism about a temporally stable target, as illustrated by the mushroom problem, its efficacy for temporally *unstable* targets is intuitively less clear.

Both the computer simulation and the laboratory experiment supported our reasoning that a free-rider problem is essential in a non-stationary, uncertain environment. As shown by Henrich & Boyd (1998), social/cultural learning coupled with "conformity bias" when using social information (Boyd & Richerson 1985, 1995) is an effective mechanism, *if* an extra cost required for individual learning is negligible, but if this cost is not negligible, the free-rider problem produces a producer-scrounger equilibrium about information search. With an increase in individual learning cost, the equilibrium proportion of information producers decreases, reducing the flow of fresh environmental information into the population and degrading the average quality of the cultural knowledge pool under a non-stationary environment. Thus, conformity bias in social/cultural learning decreases with an increase in individual learning cost. The experiment provided evidence that such adjustments in learning strategies could also occur through one's own experiences: the adaptive learning of learning strategies.

3.1. Theoretical links to social psychology and innovation research

These results seem to have important implications across several disciplines. Besides the direct links to anthropology and animal learning that we have discussed in this paper (e.g., Boyd & Richerson 1985, 1996; Durham 1991; Giraldeau & Caraco 2000; Heyes & Galef 1996; Henrich & Boyd 1998; Laland, Richerson, & Boyd 1996; Rogers 1988; Tomassello et al. 1993), they have theoretical implications for social psychology and innovation research in particular.

3.1.1. Implications for social psychology

In a classical paper on attitude formation in social psychology, Festinger (1954) emphasized the role of social learning, proposing a notion of *social comparison*. Festinger postulated that there is a basic human drive to evaluate own beliefs, and that, if some "physical reality checks" are available to assess the validity of beliefs, one will try to use them, but if such checks are not available, one will engage in "social comparison", using others as points of reference. Elswhere, Festinger (1950) also proposed a notion of *consensual validation*: consensus with others provides confirming evidence of the validity of one's beliefs. (See Kameda, Ohtsubo, & Takezawa 1997; Kameda, Tindale, and Davis in press, for an extension of the notion of consensual validation at various psychological levels in interactive groups.)

Notice that Festinger's idea as sketched above has a remarkable similarity to the Henrich & Boyd model. As reviewed in section 1.2., Henrich & Boyd assumed that people facing uncertainty rely on personally learned information to make behavioral choices, if the environmental information is diagnostic enough – "if physical reality checks are available (or useful)" in the terminology of Festinger (1954) – but that when the environmental information is not diagnostic enough, people turn to social information (i.e., social comparison). Furthermore, Henrich & Boyd assumed that, when referring to social information, people are affected by conformity bias – "consensual validation" in the terminology of Festinger (1954).

These similarities suggest that it may be possible to recast Festinger's theory in a modern evolutionary perspective. Often, the availability of "physical reality checks" is a matter of choice or motivation rather than an external premise beyond an actor's control: if one decides to expend sufficient time or money, one can access the information to evaluate one's beliefs more or less fully. The analysis in this paper suggests that such a motivational feature necessarily leads to a producer-scrounger structure in the population, and that the effectiveness of social comparison as a validity check for one's beliefs is determined critically by this structure. In this sense, our contribution in this paper may be seen to have introduced the interdependent, motivational aspects of information-seeking behavior to Festinger's theory.

3.1.2. Implications for innovation research

Our results have implications for innovation research as well. On the basis of observations of the diffusion of new merchandise, agricultural and medical technologies, etc., Rogers (1983) pointed out that innovations often spread in such a way that the cumulative frequency of adopters of the novel knowledge follows a sigmoidal pattern over time. (“Epidemiological models” of cultural transmission predict this pattern mathematically: e.g., Cavali-Sforza & Feldman 1981; see also Boyd & Richerson 1985.)

This observation suggests what types of psychological or social mechanisms may be operating in the diffusion process, but Rogers's theory is silent about why such novel knowledge is produced occasionally in the society and why a certain number of innovators exist in the group in the first place; the presence of novel knowledge or innovators in the society is simply a premise. There are several possibilities here (Giraldeau, Caraco, & Valone 1994; Huffman 1996), but our results may provide one ultimate reason: the producer-scrounger dynamic assures that a certain number of innovators emerge or exist in the population as a stable equilibrium, at least in a changing environment. Of course, as suggested in this paper, the equilibrium proportion of such innovators will depend on the cost of innovation; if it is too costly, innovators should be rare. Thus, for expensive innovations to occur in a society at a desired frequency, some exclusive rights to the novel knowledge's perquisites (e.g., patents) or to other personal rewards (e.g., social prestige) may have to be guaranteed to the innovators.

3.2. Some future directions

In concluding, let us speculate about some future directions, two of which seem to us potentially fruitful.

3.2.1. Biased modeling in social/cultural learning

One limitation of the present paper may be in our operationalization of social/cultural learning. In both the simulation and the experiment, social/cultural models were selected in an unbiased manner, with members of the previous generation or round randomly sampled and designated “cultural parents” to an individual in the current generation. Although useful as a first approximation, this feature may be unrealistic. Do our results still hold when individuals are “biased” about choices of cultural parents?

We have addressed this question partially by extending our simulation in a “lattice-structured population” (Nakanishi & Kameda 2001). Effects of individual modeling bias associated with geographical locations were of major concern. We ran two conditions in the simulation: in one, individuals could acquire social information only about 8 neighbors located in adjacent cells, while the other was like the present simulation in that 8 members were chosen randomly for cultural reference. The results supported our thesis: both the producer-scrounger equilibrium and the decrement of conformity bias in response to individual learning cost emerged, whether social/cultural learning was “local” or “global”. Future research addressing effects of “biased modeling” (Boyd & Richerson 1985), with operationalizations of the bias not limited to the geographical bias as illustrated above, seems to be a fruitful endeavor (e.g., Henrich & Gil-White 2001).

3.2.2. Herd behavior in markets: effects of conformity in a frequency-dependent situation

Another interesting venue for future research may be to study “herd behavior” in financial markets (Eguíluz & Zimmermann 2000) – a prime example of a non-stationary uncertain environment in modern days. Izumi & Ueda (1999) observed that dealers in foreign exchange markets often value “consensus of the market” in making their trade decisions; consensus about future directions of the market among dealers affects own selling or buying in a substantial manner.

The economic literature has mathematically modeled herd behavior in various contexts (e.g., Banerjee 1992; Bikhchandani, Hirshleifer, & Welch 1998; Kirman 1993). What is particularly interesting about financial markets is that an adaptive behavioral choice there is *frequency-dependent*. Recall that this paper has focused on a situation where the adaptive value of a behavior was uniquely determined by the nature of the physical environment, regardless of others’ choices: the payoff for a correct decision was constant regardless of how many others made the same choice. However, this is not the case in financial markets where a dealer’s decision to buy or sell brings different returns to the dealer, depending on other dealers’ decisions. Notice that, in the market situation, two conceptually related but distinct types of frequency-dependence may affect individual fitness, one accruing from behavioral choice per se (e.g., buying or selling), the other from choice of learning strategies (e.g., behaving as an information producer or scrounger). Is conformity bias in such a "dually frequency-dependent" situation adaptive?

In this paper, we have combined evolutionary simulations inspired by anthropological work with an experiment to shed some light on adaptive values of social/cultural learning in a non-stationary uncertain environment. Our results provide useful insights into various social psychological phenomena in modern societies, as well as into the evolutionary forces that have shaped our social minds. Although early social psychologists were well aware of the critical relevance of anthropological theories to their work (cf. Jacobs & Campbell 1961; Jones & Gerard 1967), this link seems to have been largely lost in modern social psychology. We believe that the evolutionary framework may change this situation, providing a strong common thread to link both disciplines in a mutually fruitful manner.

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Footnotes

[1] This is a rough outline of the Henrich & Boyd (1998) simulation. The original simulation (see their appendix) also had a phase of migration between different populations. However, we ignore this feature here, since it is not critical for our theoretical development in this paper.

[2] The simulation parameters in Figure 2 were set as follows. Rate of environmental fluctuation = 0.01, Average accuracy of environmental information = 0.66, Individual learning cost = 0.0024 (high cost) and 0.0006 (low cost).

Figure Captions

Figure 1. An outline of Hernich & Boyd's (1998) simulation algorithm.

Figure 2. Mean proportions of information producers (members who engage in costly individual learning) in the population over time, when the individual learning cost was high or low (Simulation).

Figure 3. Equilibrium proportions of information producers in the population as a function of individual learning cost (Simulation).

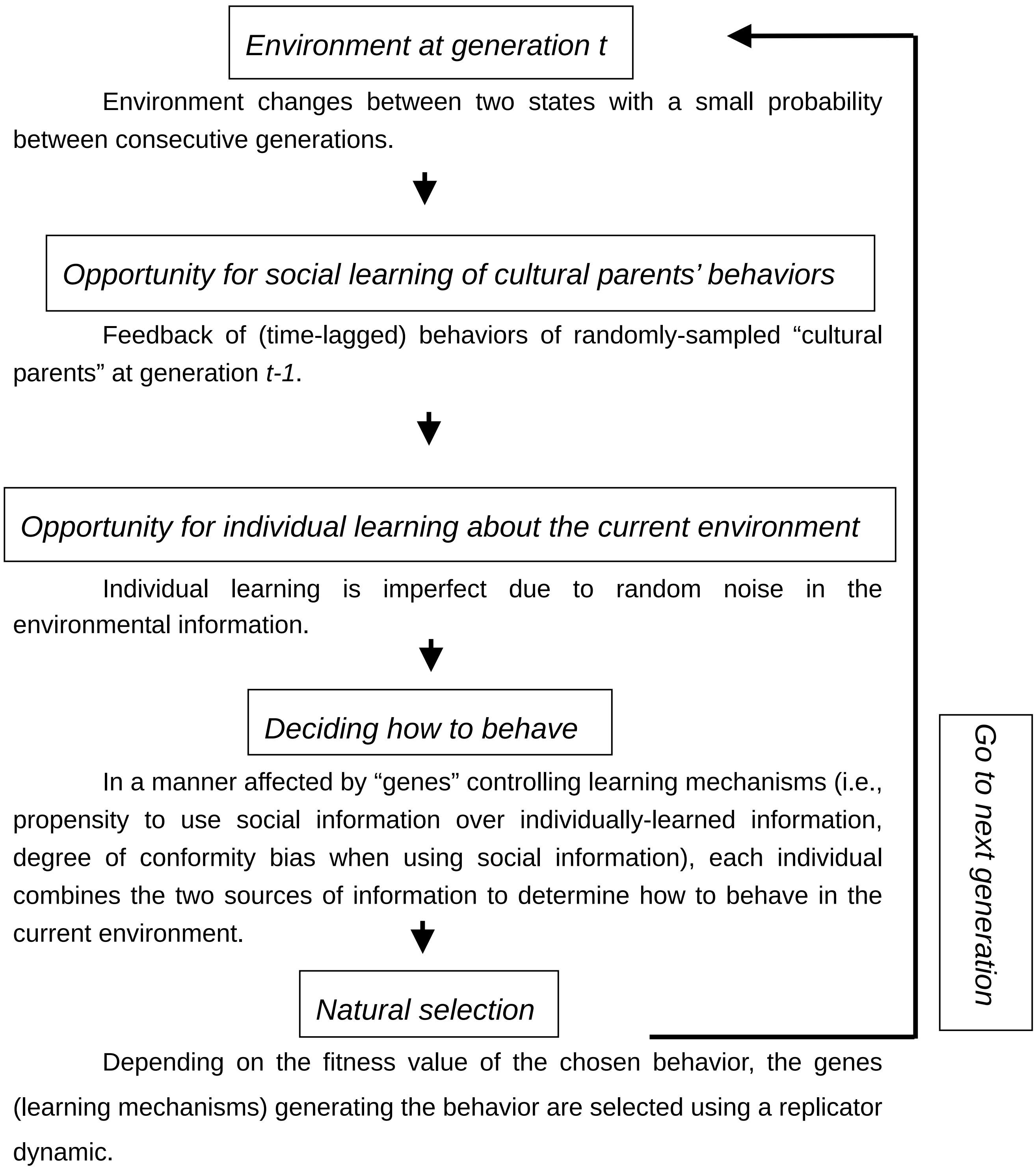
Figure 4. Equilibrium levels of conformity bias among information producers and information scroungers, as a function of individual learning cost (Simulation).

Figure 5. Mean proportions of information producers in the 6-person groups over time, in the high-cost and low-cost conditions (Experiment).

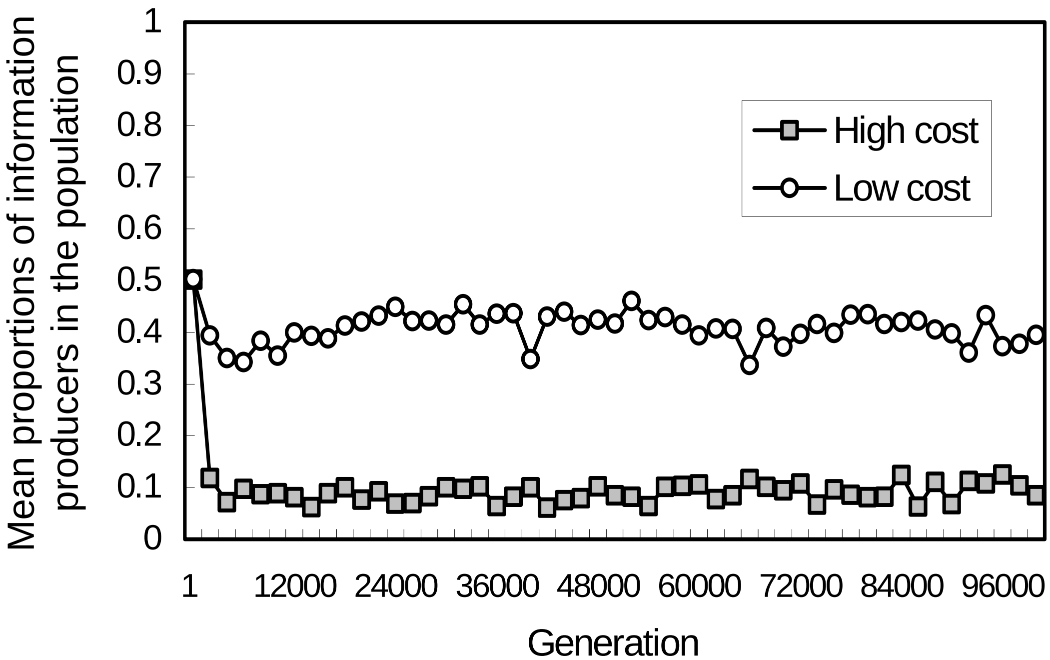
Figure 6. Distributions of information-search-frequency for each block in the low-cost and high-cost conditions (Experiment).

Figure 7. Mean proportions of members who were consistent in their information search frequencies between two consecutive blocks (Experiment).

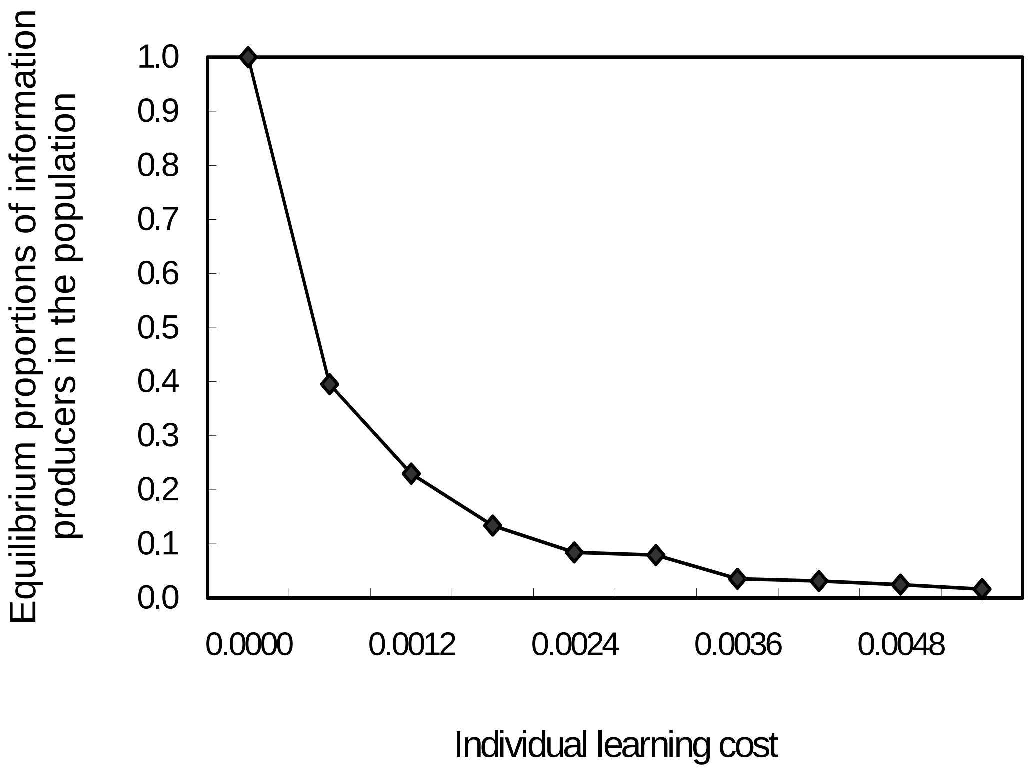
Figure 8. Mean proportions of participants' conformity choices toward dissenting majority in the high-cost and low-cost conditions (Experiment).


Environment at generation t
Environment changes between two states with a small probability between consecutive generations.
Opportunity for social learning of cultural parents' behaviors
Feedback of (time-lagged) behaviors of randomly-sampled "cultural parents" at generation t-1.
Opportunity for individual learning about the current environment
Individual learning is imperfect due to random noise in the environmental information.
Deciding how to behave
In a manner affected by "genes" controlling learning mechanisms (i.e., propensity to use social information over individually-learned information, degree of conformity bias when using social information), each individual combines the two sources of information to determine how to behave in the current environment.
Natural selection
Depending on the fitness value of the chosen behavior, the genes (learning mechanisms) generating the behavior are selected using a replicator dynamic.
Go to next generation

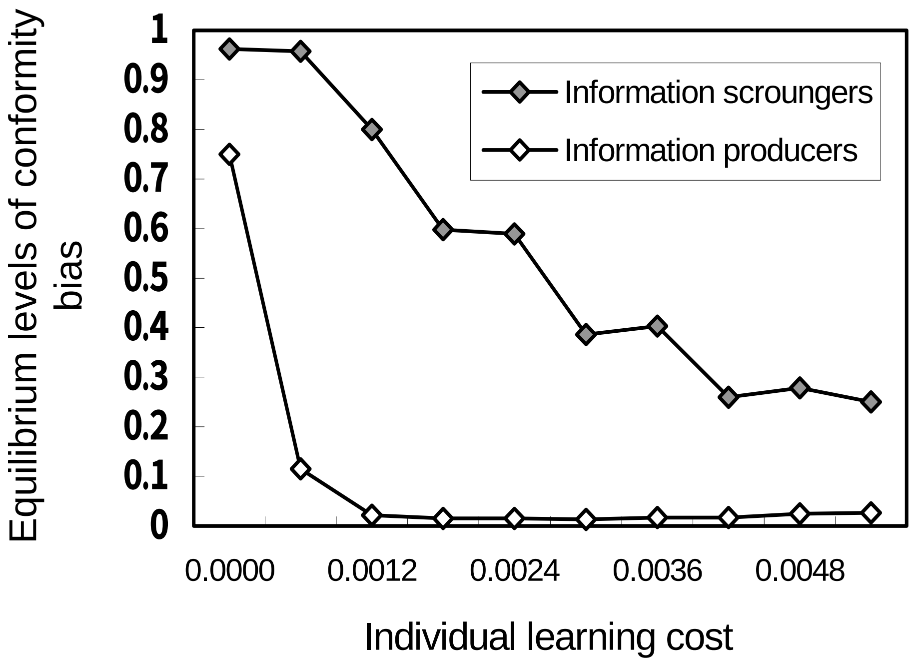
< *Figure 1* >


Mean proportions of information producers in the population
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
High cost
Low cost
1
12000
24000
36000
48000
60000
72000
84000
96000
Generation

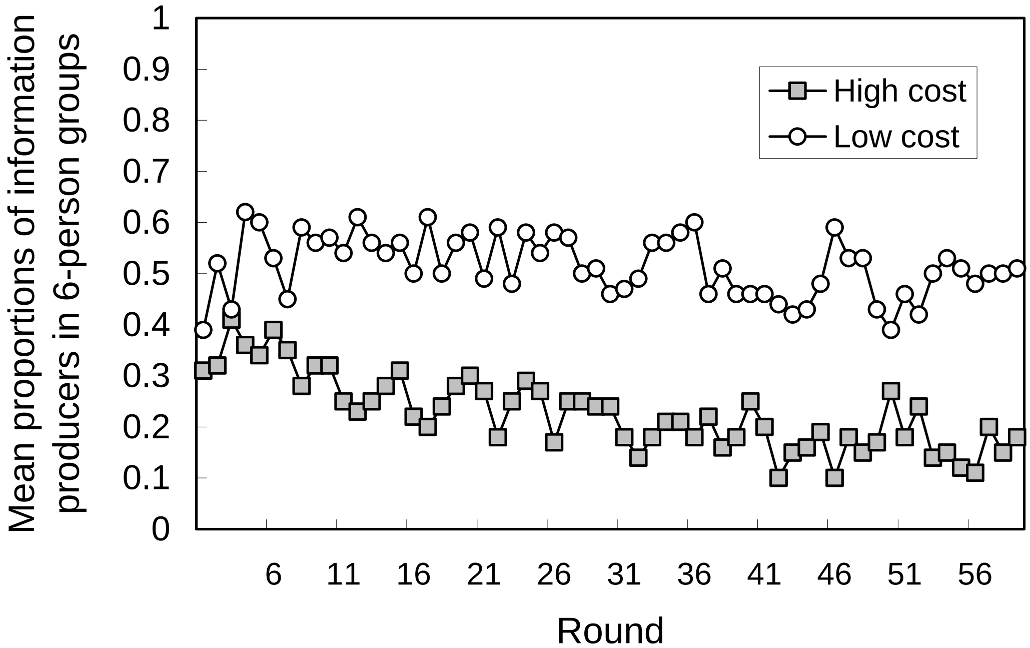
< Figure 2 >


Equilibrium proportions of information producers in the population
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0000
0.0012
0.0024
0.0036
0.0048
Individual learning cost

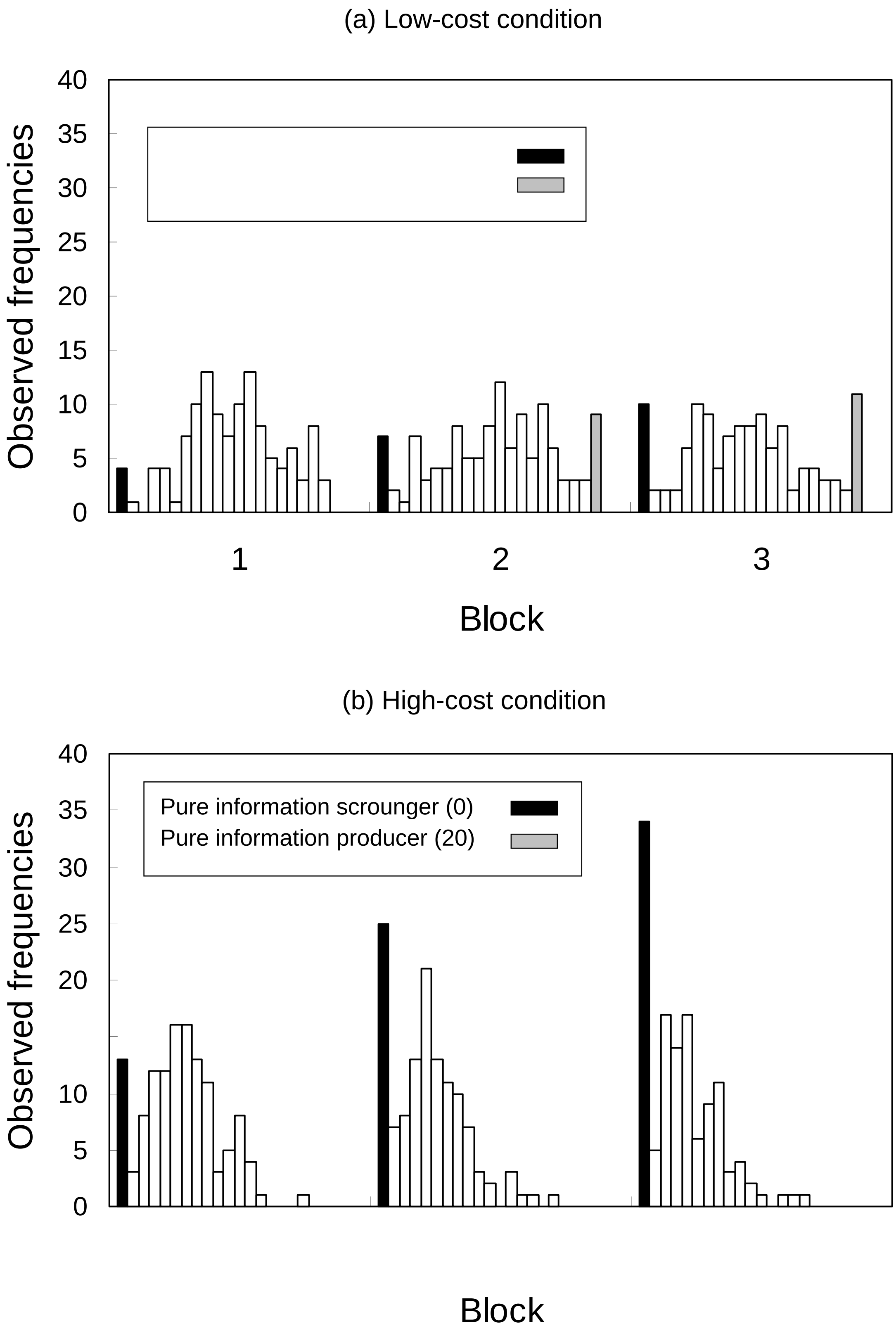
< Figure 3 >


Equilibrium levels of conformity bias
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Information scroungers
Information producers
0.0000
0.0012
0.0024
0.0036
0.0048
Individual learning cost

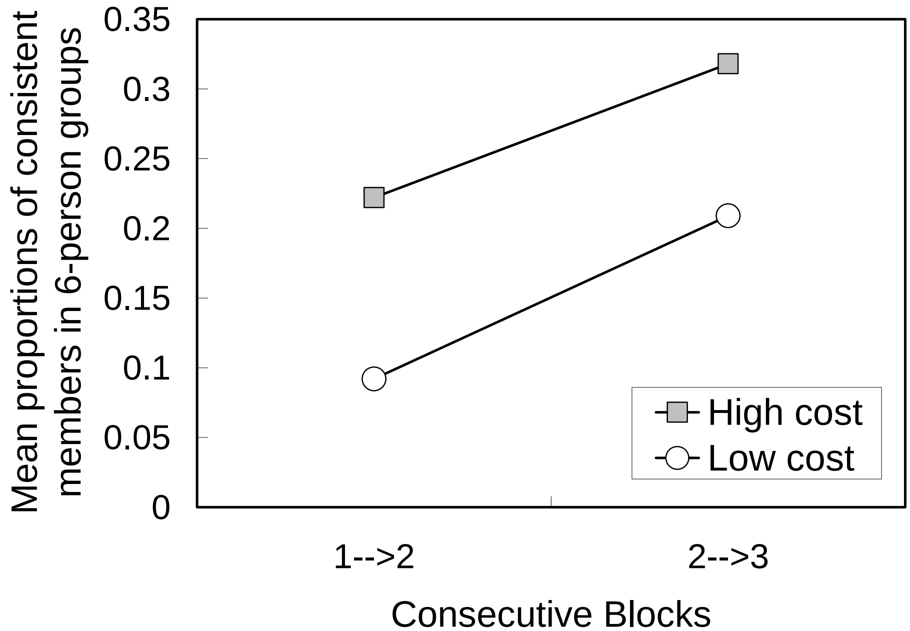
< Figure 4 >


Mean proportions of information producers in 6-person groups
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
High cost
Low cost
6
11
16
21
26
31
36
41
46
51
56
Round

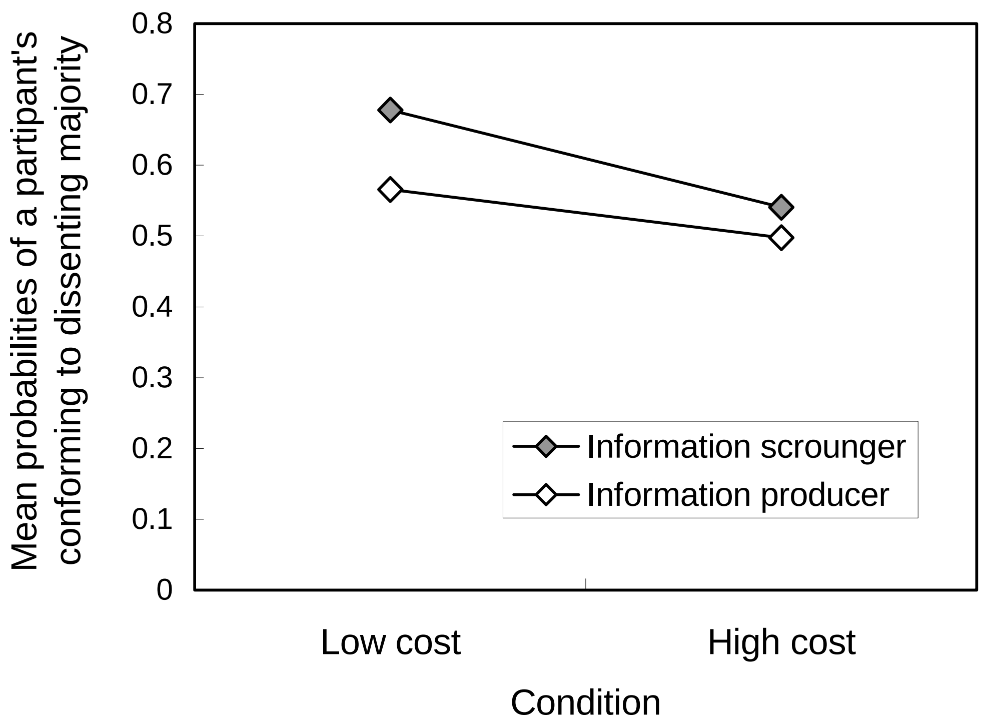
< Figure 5 >


(a) Low-cost condition
Observed frequencies
40
35
30
25
20
15
10
5
0
1
2
3
Block
(b) High-cost condition
Pure information scrounger (0)
Pure information producer (20)
Observed frequencies
40
35
30
25
20
10
5
0
Block

< ***Figure 6*** >


0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Mean proportions of consistent members in 6-person groups
High cost
Low cost
1-->2
2-->3
Consecutive Blocks

< Figure 7 >


Mean probabilities of a partipant's conforming to dissenting majority
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Information scrounger
Information producer
Low cost
High cost
Condition

< Figure 8 >