

INCENTIVES, INNOVATION, AND IMITATION: SOCIAL LEARNING IN A NETWORKED
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Incentives, Innovation, and Imitation: Social Learning in a Networked Group

Humans' extraordinary talents for learning from their environments and from each other are the basis of cultural and technological development, but factors affecting the use of these skills such as time, information differences, group size, and material incentives are not yet completely understood. We used a series of laboratory experiments to investigate the causes, consequences, and dynamics of social learning strategies employed by groups of people in complex search environments, and how individual imitation and innovation behaviors affect results at the group level. In these experiments, participants played a simple computer-based puzzle game with others, in which guesses were composed of sets of discrete units that had both linear and interactive effects on score, and each player could view and imitate entire guesses or parts of guesses from others in the group. Players received round-based score feedback about the quality of their own guesses, and in some cases, others' guesses. Our results showed that participants used several social learning strategies previously studied in other species, as well as strategies studied in the context of innovation diffusion, such as imitation biases toward solutions similar to one's own, and toward increasingly popular solutions. We found that the risk of exploring in a large and complex problem space caused participants to take a conservative approach, with small amounts of innovation and imitation used to acquire good solutions and make incremental changes in the search for better ones.

Finally, we found that imitation, rather than merely being used to copy others and avoid exploration, was often used by group members to improve on each others' guesses. Contextual factors that disrupted or discouraged imitation generally resulted in poorer outcomes for the entire group, because of a reduced capacity for participants to create such cumulative improvements. These results are discussed in the context of knowledge as a commons, with implications for the promotion of innovations and intellectual property policy.

Table of Contents

1. (A)social Learning.....	1
2. Experiment 1 – Picture Game.....	24
3. Experiment 2 – Creature Game A.....	50
4. Exploration as a Social Dilemma.....	88
5. Experiment 3 – Creature Game B (score visibility).....	101
6. Knowledge as Property.....	130
7. Experiment 4 – Creature Game C (payment and protection).....	147
8. General Discussion.....	193
References.....	201

1. (A)social Learning

1.1. Introduction

Penguins are thought to be warm-blooded animals like other birds, but an often-told tale suggests otherwise. As the story goes, a group of penguins will often hesitate before leaving the ice to forage for krill, because a leopard seal may be waiting in the water to forage for *them*. Each penguin would prefer to find krill as soon as possible and never meet a leopard seal, but the only way to be sure the water is fine is for at least one of them to jump in. The penguins' simple solution to this dilemma is to push one of their fellows over the edge and observe it for signs of being devoured (Dawson, 1974).

Thankfully, human societies have developed in such a way that going out to find food does not typically require nudging our neighbors into the jaws of a hungry predator. But we do depend heavily on information about the experiences of others that we expect to share in some form. In fact, there are few activities that humans participate in that do not depend in some way on knowledge obtained from others. This is evident upon casual reflection about how people gather information and make choices about things like restaurants or movies, candidates for a job or political office, a new city to live in or a large household purchase. Such "social learning" allows people to obtain information about available options without undertaking the costly process of directly evaluating each one, though without the increased accuracy that such evaluation might provide. This prompts the question of how decisions are made between the options of learning about the environment directly through experience, or indirectly via information provided by others.

Learning directly from the environment often carries a cost for the learner in terms of risk or resources, so when possible, people will often prefer to obtain information indirectly through others without individually bearing the cost of learning on one's own. If too many people avoid the costs of direct individual learning but continue to make use of the information available through indirect social learning, an undesired stagnation or reduced adaptation to complexity and change in the environment may result.

On the other hand, when learners are in competition for resources, each learner may have an incentive to prevent imitation by others of their costly, individually-obtained information. A different problem may result from this avoidance of information sharing, because learners are prevented from building upon and improving others' solutions, which can lead to repeated "reinvention of the wheel," another kind of stagnation. If an individual can prevent other individuals from imitating their solutions, then the collective benefits of their innovations will be underutilized.

These tradeoffs between short-term self-interest and group interest can be treated as an example of the well-studied class of phenomena known as social dilemmas. Such dilemmas apply to use of natural resources such as fisheries (Acheson, Wilson, & Steneck, 1998) as well as artificial resources such as irrigation systems (Siy, 1982). A large literature of theory, field research and laboratory experimentation has been built around the study of social dilemmas, and the environmental and institutional factors that can contribute to their solutions (Ostrom, 1990). Recently, the methods and frameworks used to analyze social

dilemmas of physical resources have been productively brought to bear on the question of knowledge as a resource (Hess & Ostrom, 2007).

Though not always formally treated as such, the social dilemmas of social learning are addressed in the political economy of knowledge as a tradable commodity, in the form of intellectual property (IP). In theory, IP law and policy attempt to balance the interests of knowledge creators and users in order to further the progress of knowledge, given their environments and incentives. However, the distinction between knowledge creators and users is not always clear, because knowledge can be used as a foundation or scaffolding for creating further knowledge. So restrictive property rights granted to incentivize knowledge creators can actually have the effect of impeding the process of creation, reducing benefits for all. Thus a dilemma arises in the conflict between the private interests of individuals and the collective interests of their groups in the use of current knowledge and the creation of future knowledge.

The complexity of real-world learning and decision making makes it difficult to tease apart the effects of factors such as individual differences, group influence, and environmental characteristics, as well as changes in learning and interactions over time. The series of experiments reported in this dissertation will attempt to bridge the individual and group perspectives, by exploring the dynamic interrelationships of actions, incentives, and institutions involved in the exchange of ideas, and their consequences for both individuals and groups, through a series of controlled laboratory experiments on humans.

1.2. (A)social learning: Definitions and background

Boyd and Richerson (2005) defined "social learning" as "the acquisition of behavior by observation or teaching from other conspecifics." Social learning has been studied extensively in humans (e.g. Hurley & Chater, 2005), as well as non-human animals, including foraging choices in starlings (Templeton & Giraldeau, 1996), food preferences in various rodent species (Galef & Giraldeau, 2001), and mate choices in black grouse (Höglund, Alatalo, Gibson, & Lundberg, 1995). "Asocial learning" can be defined conversely as the acquisition of behavior by individual innovation or exploration of the environment, without recourse to information from others.

Later in this paper, "asocial learning" and "innovation" will be used interchangeably, as will "social learning" and "imitation." However, a great deal of research has gone into attempting to define and disambiguate the varieties of learning that organisms exhibit. Before we go on, we will survey some of this research and clarify which areas we will be exploring in detail, and what we will be neglecting in order to achieve this focus.

1.2.1. Social learning / imitation

Galef (1988) reviewed many studies of social learning in various species in an attempt to clarify the definitions and explanations that have been used for these phenomena. Galef noted in his review the futility of using the word "imitation" in a general and unambiguous way, because of the overabundance of uses and definitions it has acquired over the years. Galef discusses this abundance beginning

in the modern era with Romanes (1884), Morgan (1900), and Thorndike (1911), whose differences were rooted in differing views about the evolution of humans, and the evidence of precursors of human abilities in other animals.

Similarly to Boyd and Richerson (2005), Box (1984) suggested "social learning" as a generic descriptive term, to distinguish socially-influenced learning from learning that is not influenced by others, though Galef (1988) notes that this distinction is not necessarily clear, since "it is always the individual who learns;" behaviors may be initially acquired from others but subsequently maintained by individual learning of favorable consequences. We do not intend to attempt to resolve this ambiguity; it must remain in the background to help explain learning behaviors in any particular context as a mixture of influences.

It is important to distinguish between two major descriptive terms for social influence: (1) "social enhancement," in which others influence the performance of behaviors already established in an individual's repertoire (Galef, 1988); and (2) "social transmission," in which social interaction increases the likelihood that an individual will come to independently perform a behavior initially in the repertoire of another, such that there is an "increased homogeneity of behavior of interactants that extends beyond the period of their interaction" (Galef, 1976). For example, in the mid-20th century when it was common for milk to be delivered and left outside of homes, it was noticed that increasing numbers of birds were learning to open milk bottles to drink the cream from the top (Fisher & Hinde, 1949). This was found to be a case of social enhancement rather than social transmission: later experiments showed that for the purposes of learning how to open containers,

allowing naïve individuals to feed from containers opened by others was just as effective as allowing them to observe a conspecific opening a container. So conspecifics' activities focused others' subsequent foraging on similar containers, whose tops were vulnerable to existing feeding behaviors such as pecking (Sherry & Galef, 1984, 1990).

The phenomena that this paper will examine generally fall under the description of "social transmission" rather than "social enhancement;" we are interested in the spread of locally novel information via peer observation, rather than the influence of social interaction on use of information possessed by all group members.

A large variety of explanatory terminology has developed to refer to theorized behavioral mechanisms that could underlie the above descriptive terms. This collection of terminology, according to Galef (1988), is "extensive, contradictory, and vague", and though it has not proved adequate for exhaustively classifying or effectively explaining social learning behavior, it has been helpful in suggesting approaches for experimental analysis of the myriad ways in which social interaction influences behavior. Following are several of the more widely-used terms in this area.

"Stimulus enhancement" (Spence, 1937) and "local enhancement" (Thorpe, 1963) refer to situations in which observation of a demonstrator's actions, or evidence thereof in the environment, cause the observer to direct a greater proportion of its behavior toward the location or object of the demonstrator's activity. "Social facilitation" refers to situations in which the presence of others

"energizes all responses made salient by the stimulus situation confronting the individual at the moment" (Zajonc, 1965). "Contagious behavior" is used for situations in which "the performance of a more or less instinctive pattern of behavior by one will tend to act as a releaser for the same behavior in others and so initiate the same line of action in the whole group," such as yawning in humans (Thorpe, 1963). "Copying" refers to situations in which an observer is sensitive to the degree of similarity between its own behavior and its model's, and its responses are reinforced positively with greater similarity and negatively with dissimilarity (Miller & Dollard, 1941; Thorndike, 1911).

"True" or "reflective" imitation, also known as "observational learning," requires that the performance of an act is sufficiently instigated simply by observing it, and involves purposeful, goal-directed copying (Galef, 1988). Bandura (1965) called humans' rare talent for such imitation "no-trial learning," because it is even faster than the one-trial learning observed in animals with a strong built-in tendency to form certain associations (e.g. between the taste of a food and a subsequent stomach ache). Evidence for "true" imitation in other animals has so far been unconvincing (Davis, 1973; Hall, 1963) because of the difficulty of controlling for all of the alternative social learning processes (Galef, 1988; Heyes, 1993).

This dissertation is concerned mainly with phenomena that fall under the description of "social transmission," so of the above explanatory terms, we will be looking mainly to "true" imitation. The experiments described herein will be designed such that participants are given sufficient information, ability, and

opportunity to purposefully observe and imitate others. These aspects will be explained in more detail in later sections.

1.2.2. Asocial learning / innovation

As mentioned above, our use of the term "asocial learning" is essentially defined negatively as the process of obtaining or generating information from sources other than one's fellow learners. The term "innovation" is used as a shorthand out of the need for a concise and familiar descriptor for the implied individual introduction of information that is locally novel (given a very large space of options to explore) among a group of learners, as opposed to the transmission of existing information between learners. Using "innovation" in this way involves some risk of confusion, however, because this term is also used heavily in the broader study of creativity and its instantiation in scientific, industrial, and artistic practice. (See Sternberg (1999), Kounios and Beeman (2009), Paletz and Schunn (2010), Dunbar (1999), and Garcia and Calantone (2002) for hints as to the breadth of this field.)

In the interest of brevity, the complexity and specificity of analysis in this literature will be omitted. We will try to retain some clarity by limiting our definition of innovation to the use of locally novel solution elements by individual sampling from the environment in a problem-solving context, as opposed to obtaining locally known solution elements through observation of others.

1.3. Learning strategies and tradeoffs

Gabriel Tarde, one of the forefathers of social psychology, considered innovation and imitation to be "the fundamental social acts" (Tarde 1903/1969). Innovation (generating locally novel approaches to solving problems) produces a diversity of solutions, though often at a cost in resources (such as time or energy) or risk (in giving up the opportunity to exploit more reliable solutions in favor of something new or unknown). Imitation allows a decision maker to employ solutions discovered and passed on by others without having to develop them independently using costly trial-and-error learning. When a decision maker acquires information from others about possible solutions to a problem, the resources not expended in information gathering can be used for other aspects of problem solving, thus improving performance overall.

Of course, domination of a community by either innovation or imitation can be problematic. Excessive innovation is unhelpful because good ideas are not propagated and extended by others. Excessive imitation is maladaptive because good but suboptimal solutions are spread to the exclusion of better alternatives that are left unexplored. A common assumption is that the collective costs of excessive imitation within a group are particularly detrimental – there are typically strong incentives for individuals to pursue largely imitative strategies to avoid risk, which may lead to a dearth of good new solutions that would benefit everyone in the group. So the group may be better off if imitation is not universally chosen, but each individual is better off by choosing imitation. This idea has strong parallels in the large body of research on social dilemmas, in which individuals' self-interests are in conflict with the shared interests of themselves and others facing the same problem.

Research on social dilemmas has consistently shown that when such interactions are repeated over time, and participants are able to recognize the dilemma they share with others, they are often able to adapt their behavior to ameliorate or avoid social dilemmas (Ostrom, 1990).

Laland (2004) reviewed studies of animal (including human) social learning strategies, and their interactions with asocial learning in various food foraging behaviors, as well as mate choice, food preferences, and other important decisions. In general, it was found that the default strategy (that is, the preferred option whenever available) is the simplest possible behavior: exploitation of an existing solution or known resource continues until it is no longer productive, at which point either innovation or imitation can be used to acquire a new solution. Most of the strategies studied for making such decisions can be divided into “when” and “who” strategies; that is, heuristics that dictate under what circumstances social learning is favored over asocial learning, and, when it is favored, those that determine from which others an individual will learn.

1.3.1. When to imitate: Costly information

Deciding when to use social learning often depends on a relative assessment of asocial learning as an alternative. Often, there is greater reliance on social learning when acquiring information through asocial learning is costly (Boyd & Richerson, 1985). These costs can be in the form of the resources required to carry out asocial learning, the risk of acquiring information that will not be reliable in the

future, and the risk associated with learning about hazards directly (e.g. predators). As might be expected, social learning about predators has evolved in a wide variety of animals (Mineka & Cook, 1988). Returning to the Adelie penguins mentioned at the beginning of Chapter 1, it is difficult to prove that they intentionally push one another into the water to test for leopard seals (rather than accidentally jostling one another off the edge), but they do avoid the water temporarily when one of their fellows is eaten (Dawson, 1974). It has also been shown that they are sensitive to the effects of predators on group size: they are less likely to enter the water if a group returning from a foraging run is unusually small, indicating that it has been attacked and dispersed by a leopard seal (Müller-Schwarze, 1984). Perhaps more surprising is the fact that predator avoidance learning has evolved in some cases between different species vulnerable to the same predators (Mathis, Chivers, & Smith, 1996). This strategy is beneficial because it allows minimal individual contact with hazards, though if one individual learns the “wrong” hazards, imitation by others may be inefficient or dangerous.

A related strategy is to rely on social learning when a task is difficult to learn asocially. Such a strategy has been observed in the processing of foods with physical and chemical defenses by gorillas (Byrne & Russon, 1998) and in an experimental visual identification task in humans (Baron, Vandello, & Brunsman, 1996). Again, this strategy can save valuable risk and effort for imitators, but if the examples they learn from are flawed, inefficient or harmful behaviors can spread in a group.

1.3.2. When to imitate: Resolving uncertainty

Another "when" strategy is to copy others when one is uncertain about the relative value of available options. For instance, Beck and Galef (1989) showed that when presented with two novel foods, rats showed a bias for the one that had been consumed by conspecifics, as evidenced by the odor on their breath; when the foods were familiar, this bias was much weaker. Such strategies are especially useful when, as above, information is costly to gather asocially – sampling foods without regard to others' decisions can result in insufficient nutrition or even poisoning.

An early study of social influence in humans found that in a simple perceptual task, the less certain an individual was of his own judgment, the more likely he was to be susceptible to the influence of others (Deutsch & Gerard, 1955). Likewise, when an individual is uncertain about the appropriate response in a particular situation (because of either a lack of information or the failure of previous responses), it is more likely that the individual will resort to imitation (Thelen, Dollinger, & Kirkland, 1979). While randomly trying out social behaviors is not usually poisonous, social mistakes (violations of norms) can result in ostracism, which has been shown to cause neurological responses similar to those of physical pain (Eisenberger & Lieberman, 2004). This is thought to be due to the evolutionary necessity of group inclusion for survival (MacDonald & Leary, 2005). However, if norms are harmful, their costs may outweigh the benefits of inclusion in the group.

1.3.3. Benefits of imitation depend on selectivity

It may be that once a decision is made to imitate others via one of the strategies above, individuals do not mind who they copy, as long as they avoid the

costs of asocial learning. However, a simulation by Rogers (1988) of agents in a nonstationary environment showed that if avoidance of learning costs is the only benefit of imitation, then the addition of agents who persistently imitate (and choose targets of imitation randomly) to a population of individual learners does not improve the average fitness of the population. This is because over time, the costs avoided through imitation will be balanced by costs resulting from the use of information that is no longer accurate. Thus at equilibrium, a mixed population of social and asocial learners has the same average fitness as an asocial-only population. (A similar conclusion was reached in a theoretical analysis of foraging behavior by Giraldeau, Valone, & Templeton (2002).)

Boyd and Richerson (1995) and Kameda and Nakanishi (2002) confirmed these results, but also extended them to show that when social learners can imitate selectively (e.g. imitating when individual exploration is relatively unreliable and thus more costly), the overall fitness of the population can increase, because both individual and social learning can become more accurate.

1.3.4. Who to imitate: Frequency-biased strategies

Frequency-dependent imitation takes into account the relative prevalence of behaviors when deciding which to imitate. This often entails conformity to the behavior common to the greatest number of observed models. Such behavior has been observed in many species, including guppies (Lachlan, Crooks, & Laland 1998), rats (Beck & Galef, 1989), and humans (Hurley & Chater, 2005). Granovetter's (1978) theory of innovation diffusion is based on a "threshold" proportion of group

members necessary for an individual to adopt an innovation. Such conformity can result from a goal of obtaining information about the utility of a solution from its apparent popularity (informational conformity), or avoiding the appearance of deviance from a group and its norms (normative conformity).

1.3.5. Who to imitate: Payoff-biased strategies

Many selective strategies involve observing the success of models in order to determine which to imitate. Such "payoff-biased" strategies can use any of several criteria, depending on the information about others' success that is available. An individual can simply imitate any "successful" individual (which requires only some minimal threshold or criteria for success), as has been shown in unsuccessful bats' tendency to follow previously successful bats to feeding sites (Wilkinson, 1992). Adding a bit of complexity, one might compare the payoffs of all individuals and copy the most successful, as assumed in many theoretical models of human decision making (Schlag, 1998). An individual may also imitate any demonstrator more successful than itself (which requires evaluation of, and comparison between, the individual's own performance and the demonstrator's).

While such strategies may allow an imitator greater certainty in the payoff of a particular choice, they may also require great effort in information-gathering and calculation, and these requirements may grow exponentially with the size of a social group and their responsiveness to each other. The feasibility of such strategies is questioned in theories of bounded rationality, which posit "fast and frugal" heuristics that allow decision makers to prosper with limited information and

computational resources (Gigerenzer & Goldstein, 1996). In practice, such limitations may substantially change the cost-benefit calculation for complicated strategies, and lead decision makers to fall back on simpler strategies or face reduced performance in the face of excess information processing requirements. Heise and Miller (1951) showed that in a difficult communication task, the removal of some participant communication capacity led to increased performance. The broader phenomenon of reduced performance in the presence of large amounts of information has become known as "cognitive overload" (Sweller, 1988).

Though many models suggest that copying successful individuals can be an effective strategy, the behavior responsible for success may not be apparent, and thus unproductive or maladaptive behaviors may accompany successful ones (Boyd & Richerson, 1985). Even if accurate information about a good solution is available, its use or exploitation by too many users may reduce the benefits available to each. Thus simple payoff-biased strategies may have costs in the form of crowding and overuse, which are not remediable in the long run without more complex contingent strategies that recognize the effects that other users have on the payoff of some solutions.

1.4. Conformity and culture

Research on human social learning is fairly widely dispersed across a variety of focal behaviors and methodologies, which is understandable given the myriad possible functions for socially-mediated information in such a socially complex organism. Below is a focused summary of some of this research.

1.4.1. Innovation diffusion

In his studies of the diffusion of innovations across populations, Rogers (2003) posits several features of an innovation that can affect its adoption, among them the relative advantage obtained by replacing a previous solution with the adopted innovation, and the compatibility of the innovation with previous solutions. The former is a clear analog to the simple payoff-biased imitation strategies mentioned above, but the latter deals with more complex costs of adoption. "Backward compatibility" with a previous solution may be desired to minimize the costs of adaptation by the adopter, such as learning how to use it, or replacing items used complementarily with it. Compatibility may also be desired to maintain continued interactions with others who have not adopted the innovation yet. This minimizes social costs, and may allow the preservation of "network effects," benefits of an innovation which scale according to the number of users (Katz & Shapiro, 1985). Examples of backward compatibility in innovation include the ability to play games from an older video game system with a newer one, or the ability of users of newer technologies such as cellular telephones and voice-over-IP to connect to users of land-line telephones. When these compatibilities are not available, adoption of new technologies will presumably proceed more slowly.

1.4.2. Conformity as an adaptive bias

Imitation in human social activities brings to mind "conformity," which has negative connotations in both common usage and in much of the social psychology

literature. Some of these negative connotations can be traced back to Asch's (1951) classic studies of conformity involved measuring the effect of a group of unanimous confederates on the visual judgments of naïve individual participants. However, the early emphasis on the prevalence of undesirable behaviors in the results of experiments such as Asch's has been moderated in recent re-evaluations of the data (Hodges, 2004), and calls for a more balanced examination of the complexity of the environmental moderators and motives of biases like conformity (Krueger & Funder, 2004). For instance, a recent meta-analysis of 125 studies using tasks similar to Asch's experiment showed that the effect of the size of the confederate majority group depended on whether responses were given publicly and face-to-face or privately and indirectly, which is thought to determine the type of conformity process (normative or informational, respectively) that dominates the situation (Bond, 2005).

Modeling has shown that the tendency to imitate others rather than innovate ("conformity bias") can be adaptive in uncertain environments (Boyd & Richerson, 1985; Kameda & Nakanishi, 2002). Similarly, socially-influenced "informational herding" behavior has been proposed as an explanation for phenomena such as fads and financial panics (Bikhchandani, Hirshleifer, & Welch, 1992; Eguíluz & Zimmerman, 2000), but it has been argued that such behavior is the result of otherwise adaptively rational Bayesian reasoning in uncertain conditions (Anderson & Holt, 1997; Banerjee, 1992; Bikhchandani et al., 1992).

Kameda and Tindale (2006) argue that conformity bias has evolved in humans and several other taxa because of its tendency to promote a net average

benefit for individuals rather than error-free performance. Cultural conventions are thought to be a form of large-scale conformity to behaviors that evolve along with their associated populations, subject to accompanying adaptive pressures (Boyd & Richerson, 2005). Often the group-level or population-level outcomes associated with decisions that are individually rational are not immediately apparent or predictable. Much like the social learning strategies studied by Laland (2004), many complex cultural mechanisms have evolved to deal with this dilemma. When the interaction of a group of individuals in a certain environment is fairly stable over time, traditions can develop which dictate expectations for "sensible" behavior in that environment, and discourage innovation. Traditions may be related to interactions with the environment such as hunting or farming, or interactions with other individuals such as marriage customs or dominance hierarchies. Such traditions can be reinforced through punishment of those who violate them, rewards for those who follow them, or both. Traditions can also be stabilized through simple conformity, the tendency to imitate behaviors that are common in a group. When members of a group imitate, adaptive solutions to problems can be effectively preserved within a culture.

1.5. Studying innovation and imitation in a laboratory setting

1.5.1. Previous work

How can we project the infinite space of human ingenuity and social complexity onto the circumscribed stage of a controlled experiment? Aside from flaws in the interpretation of Asch's (1951) studies of confederate influence on the

judgments of naive individuals (Krueger & Funder, 2004; Friend, Raferty, & Bramel, 1990), a larger problem with this kind of experiment is in its treatment of conformity as a static influence rather than part of a dynamic, interactive process. Changes in culture and technology involve large numbers of agents interacting over long time scales, and the generation and exchange of information between people cannot realistically be treated as a series of isolated events. While ignoring socially mediated information in a laboratory setting may yield a clear study of important cognitive processes of individual problem solving and choice, in many situations it represents an unrealistic constraint, and may limit the relevance or applicability of the conclusions. Asch, and the vast majority of the subsequent research inspired by his studies of conformity, made the methodological choice of creating judgment situations with a single human subject surrounded by accomplices of the experimenter who were scripted to give specific judgments. This method is justified from the perspective of creating a well-controlled experimental environment for exploring factors affecting isolated individual choices to imitate. However, the costs of this method are roughly twofold. First, constraining the judgments of all but one participant in a group means that mutual influences in innovation and imitation cannot be revealed. Second, limiting the opportunities for response to a single trial for each judgment means that changes in these mutual influences are difficult to study. The impact of individual innovation and imitation choices on the group's performance can best be revealed by allowing all participants in a decision making task to be naturally, spontaneously, and repeatedly influenced by one another. Understanding the group dynamics of imitation and innovation is one of the main

goals of our study, and so we allow all group members' the opportunity to influence, and be influenced by, each other over time.

The extensive literature on “group dynamics” (e.g. Hare, 1976; Forsyth, 2006) provides insight into many interesting processes of interaction in groups, but much of it is focused on interpersonal variables and specific settings such as classroom discussion, jury deliberation, or workplace collaboration. While these are certainly fascinating and worthwhile topics, they often prioritize realism and application to these settings at the expense of control and generalizability, and thus for our purposes they remain an indirect influence. A more direct inspiration is derived from studies of the “emergence” of collective behavior from relatively simple interaction of individuals (Holland, 1999). Mason, Jones, and Goldstone's (2008) study of group exploration of a one-dimensional space serves as a foundation for our study in a more complex domain, and we will use it for comparison to our results later.

1.5.2. Experimental design and goals

Conceptually, we can distinguish between the options (behaviors, tools, foods, etc.) available to be explored, and the learning strategies (individual or social learning of various types) used to explore and exploit those options. We can also think of changes in such strategies over time as a form of learning at a higher level. In the context of an experiment, we would like to be able to clearly design and manipulate the options and strategies available to participants, without excessively constraining behavior.

Many learning tasks can be seen as combinatorial puzzles -- choosing a combination of more or less well-known parts or subtasks to create a more complex behavior. Such combinatorial problems are analogous to exploration of a large space of possible combinations. If participants have the ability to sample options from the environment through asocial learning strategies, or adopt them from others through social learning strategies, we can observe several important phenomena: varying combinations of elements in participants' tentative solutions, varying mixtures of learning strategies in participants' choices, and varying proportions of participant strategies in groups attempting to solve problems simultaneously. These variations can be observed within groups over time, or between groups (e.g. those with different numbers of members, or having access to different amounts or kinds of information).

With this in mind, we constructed two experimental paradigms with recognizable parallels in real-life exploratory and learning activities, in which participants can sample and share combinations of elements from a large (but finite, well-defined, and stably related) set, such that all choices can be evaluated according to an objective function, while allowing for a large degree of flexibility and variation in choices and learning strategies over time and across individuals and groups.

In contrast to several previous studies (e.g. Rogers, 1988; Boyd & Richerson, 1995; Kameda & Nakanishi, 2002), we used a task environment that does not change over time, and enabled provision of regular, reliable score feedback about participants' own solutions, as well as those of their peers. These features could be

expected to discourage exploration of the problem space, in that there is no penalty for perpetual exploitation of existing solutions or repeated imitation of others' solutions. In addition, the problem space was designed to be larger and more complex than in those models, in order to provide greater realism in the form of a larger number of options for exploration, as well as substantial uncertainty about optimal solutions and strategies.

However, by implementing the above changes and explicitly instructing participants to focus on a goal of maximization of cumulative performance, we hoped to simplify the task while mimicking characteristics of real-world problem-solving environments. In our task, solution information cannot become outdated in the sense of inaccuracy, but its performance can become relatively less satisfactory given continuing opportunities to find better solutions. This is analogous to practical technological progress, in that older technologies often still function adequately for their designed purpose, but newer technologies can provide improvements such as extra features or more reliable performance. If the goal is to maximize cumulative performance, some risk may be rationally justified to enable greater future rewards.

This approach is of course not ideally suited for answering all questions relating to human social learning, but it allows us to approach a variety of issues which might otherwise be too abstract, varied, and subtle to reasonably approach in a controlled laboratory experiment, such as the role of imitation in conformity, the effect of individual differences in risk tolerance or incentive responsiveness in the discovery of innovations, and the characteristics of learning as a complex, dynamic, social endeavor.

1.5.3. General predictions

Based on the social learning strategies and tradeoffs discussed earlier, we can discuss some preliminary predictions about participants' behavior and performance. First, given that every participant was subject to the same choice possibilities and payoff structure, and the payoff structure was fixed for a given game, we expected that imitation would be more common than innovation, because the former offers immediate risk-free returns, while the latter offers more risky and variable returns. Imitation would be biased primarily toward higher-scoring solutions (according to payoff-biased strategies), and secondarily toward relatively similar solutions to the imitator's own (due to compatibility strategies). As for outcomes, an intuitive prediction based on the above behavioral expectations is that the high rates of imitation and small amounts of innovation would lead to stagnant group learning processes, and a lack of substantial improvements in performance over time. This prediction is in line with a negative view of imitation as static, idle informational conformity, but at odds with the potential for groups to solve collective action problems given sufficient information and incentives (Ostrom, 1990). These predictions will be revisited and elaborated upon later in this dissertation.

2. Experiment 1 – Picture Game

2.1. Experiment 1 overview

In order to explore the dynamics of innovation and imitation in groups, and to attempt to arbitrate between the competing predictions regarding individual incentives and group consequences, we designed an experiment in which networked groups of people explored a high dimensional problem space over a series of time-limited rounds. Participants received score feedback about their guesses after each round, and passively shared information about their guesses and scores with others. Participants could observe and copy the most recent guesses of their neighbors as they formed their own guesses.

The difficulty of the problem was manipulated across conditions by changing the size of the problem space. A range of group sizes was tested to investigate the effects of the amount of social information on individual performance and strategies. The in-game interaction between players was limited to the simple passive exchange of guess information only, so as to allow examination of imitation and innovation behavior unencumbered by more complex social interactions, such as direct communication among players.

2.1.1. Predictions

Performance was predicted to improve over rounds within each game, and across games within an experiment session, due to score feedback and simple learning effects. Conversely, solution turnover (the amount of change in a solution

between rounds), and the diversity of solutions within a group, were expected to decrease over time as participants found more parts of the correct solution, narrowed their search to smaller areas of the board, and refined their search strategies.

Imitation was expected to be more common of peer guesses with higher scores, because utilities of guesses are explicit and thus imitators can maximize their expected utilities by choosing the highest scoring guesses. Imitation was also expected to be focused on guesses that were more similar to the imitator's own previous guess, as noted above. Participants who imitated most often were expected to obtain better score performance (relative to those who imitated less often), because they would presumably imitate good solutions while taking fewer risks. The average scores of participants in large groups (greater than 4 participants) were expected to be greater than those in small groups, because the larger groups would produce a greater diversity of solutions, and thus be able to search the problem space more efficiently, contingent on the ability of participants to make use of this increased diversity through selective imitation.

2.2. Experiment 1 Methods

145 participants were recruited from the Indiana University Psychological and Brain Science Department undergraduate subject pool, and were given course credit for taking part in the study. Participants populated each session by signing up at will for scheduled experiments with a maximum capacity of 9 persons, and were distributed across 39 sessions as shown in Table 2.1.

Table 2.1: Distribution of Participants Across Group Sizes

Group size	1	2	3	4	5	6	7	8	9
# Sessions	8	6	9	3	3	5	1	2	2
# Participants	8	12	27	12	15	30	7	16	18

We implemented the experiment using custom software run in a web browser, and each participant used a mouse to interact with the experimental game. All participants' computers communicated with a game server, which recorded data and updated scores and team information for participants at the end of each round. The task was a round-based picture-matching puzzle game with score feedback given after each round. The goal picture that participants attempted to match was a randomly generated spline quantized to a grid of square pixels. The squares making up the spline were colored black, and the remaining squares colored white (see Fig. 1 for examples).

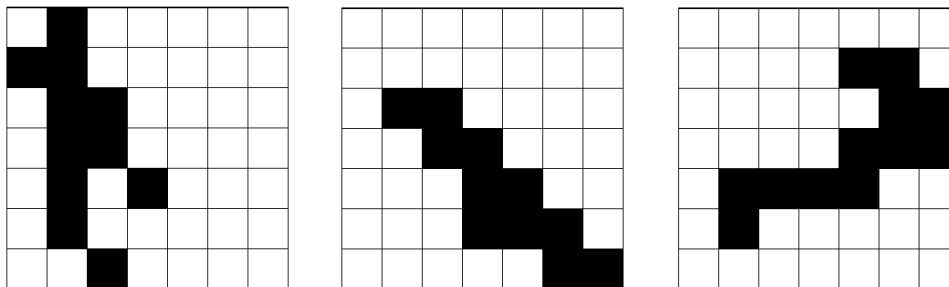


Figure 2.1: Examples of randomly generated goal pictures in Experiment 1.

The participant's game board was a grid of the same dimensions as the goal picture, with each square initially colored white. The color of each square on the game board could be toggled between black and white by clicking it with the mouse. Each participant's display included their own game board and most recent score (given as the number of squares, both black and white, marked correctly out of the total number of squares on the board), their neighbors' game boards and scores, and indications of the current round in the game and the amount of time remaining in the current round (see Fig. 2). Players could copy a neighbor's most recent solution to their own at any time during the game by clicking the chosen neighbor's board with the mouse. Each game consisted of 24 rounds of 10 seconds each¹. After the last round in each game, participants were shown their guesses and scores for each round, along with the goal picture, and a button to click when they were ready to begin the next condition. When all participants had clicked this button, the next condition began.

¹ In a pilot study, we found that using a game structure with half this number of rounds and twice the time per round yielded fairly low average and final performance measures, and a great deal of observed participant idleness toward the end of each round, which prompted the change to providing more frequent feedback in the current game structure.

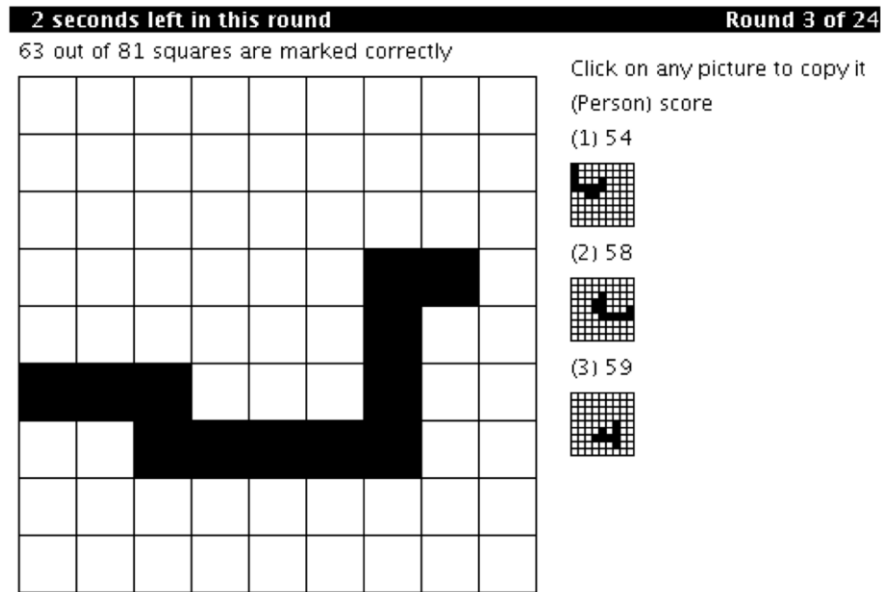


Figure 2.2: Example of a participant's display.

Participants were instructed to maximize their scores over all rounds by matching the hidden goal picture as closely as possible. They were also informed that the picture they were supposed to match in each game was randomly generated and not representative of any particular object, shape, or symbol, and was generally not symmetrical; that the black squares were all connected to each other vertically, horizontally, or diagonally; and that the number of black squares was small relative to the size of the grid. Following the instructions, the participants were given the first condition, after which the experimenter confirmed that each of the participants understood the mechanics of the game, and answered any questions that arose. The participants then played the remainder of the conditions, in an order that was randomized within each session. At the end of each game, participants were shown the goal picture, along with their guesses and scores in each round.

A participant's *score* in each round was defined as a cell-by-cell comparison (overlap) between the participant's guess for that round and the hidden goal picture (i.e. the number of cells which the two pictures had in common), divided by the total number of squares in the goal picture, to give a percentage which could be compared between conditions of varying grid size (see Fig. 3). An *improvement* was defined as an instance of a participant obtaining a score higher than all prior scores of all players within a particular condition. Each participant's *normalized improvement share* was defined as their individually achieved proportion of the total improvements achieved by all participants in a session, multiplied by the number of participants in the session. A value of 1 indicated a "fair" share, e.g. a participant achieved one third of the improvements in a three-person session. A participant's *score rank* in a particular round was defined as the rank of their score (one being the best) among all scores in the group in that round; individuals with the same score had the same rank. *Turnover* for each round (after the first) was a measure of the amount of change between a participant's guesses over successive rounds. It was defined conversely to similarity, except that the two pictures compared were the participant's guesses from the current round and the previous round.

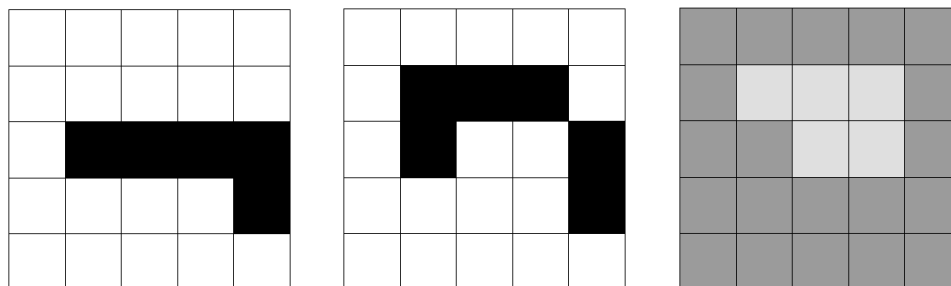


Figure 2.3: Score / overlap calculation: the first two pictures have 20 out of 25 squares in common (shown in dark grey on the right), so they have an overlap of 80%.

Imitation (a measure of whether a participant copied a neighbor's guess in a particular round) was defined as follows:

$$I_{pr} = \begin{cases} 1 : \max_i(\text{overlap}(G_{p,r}, G_{i,r-1})) > \text{overlap}(G_{p,r}, G_{p,r-1}) \\ 0 : \max_i(\text{overlap}(G_{p,r}, G_{i,r-1})) \leq \text{overlap}(G_{p,r}, G_{p,r-1}) \end{cases}; p \neq i$$

Where $G_{p,r}$ is the guess of Participant p for Round r , $G_{i,r-1}$ is the guess of Neighbor i for the Round prior to Round r , and *overlap* is the comparison described above for the score calculation. In other words, a participant has imitated in a particular round ($I_{pr}=1$) if the participant's guess is closer to the most similar neighbor's previous guess than to the participant's own previous guess.

Diversity (a measure of the spread of group members' guesses over the problem space within a particular round) was defined as follows:

$$D_r = 1 - \frac{\sum_s \sum_p \text{majority}(G_{spr})}{S_{tot} P_{tot}}$$

Where G_{spr} is the binary value (black or white) of square s in the guess of participant p in round r , S_{tot} is the total number of squares in the game board, P_{tot} is

the total number of participants in the group, and *majority* is a binary function that conveys whether the value of G_{spr} is in agreement with the majority of participants in the group for that square in that round (0 = not in majority, 1 = in majority).

Diversity as defined above is constrained to be within the 0 to 1 range, and higher values of diversity indicate more deviation of individuals' guesses from the majority guesses.

The number of squares in the game board was manipulated across two conditions: in the small board size condition, the game board was 7 squares on each side for a total of 49 squares, and in the large board size condition, the game board was 9 squares on each side for a total of 81 squares. The larger board was hypothesized to be more difficult to fully search. There were 4 repetitions of each condition, for a total of 8 games in each session. The probability distribution of scores among all possible game board states in each of the *board size* conditions described above is shown in Fig. 4. The size of the group participating in each session was treated as a covariate; *group size* ranged between 1 and 9. Another factor considered was the (randomized) position of each condition in an experiment session; this was called the *game order*.

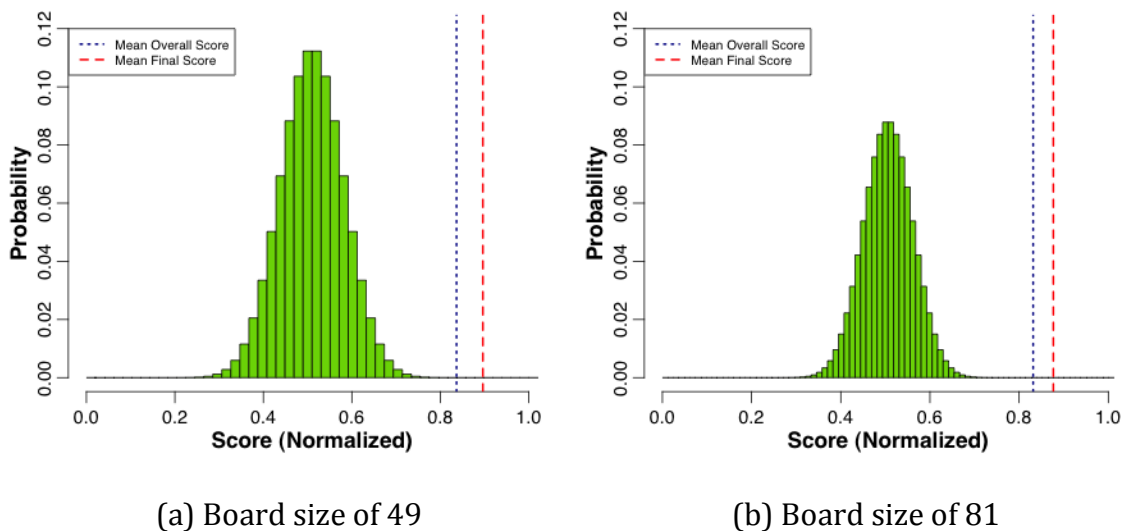


Figure 2.4: Distribution of scores for all possible game board states in each board size condition. Note that due to the number of possible game board states in each condition (approximately 5.6×10^{14} and 2.4×10^{24} , respectively) the mean overall and final scores appear to fall outside of the distributions, but in fact are just very rare scores in the upper tails.

2.3. Experiment 1 Results

For most analyses, dependent variables were averaged across all participants within a group to give measures for the group's aggregate activity. In this manner, the fundamental level of analysis was the group, not the individual, and dependencies between individuals within a group do not lead to elevated Type I statistical errors.

2.3.1. Board size / difficulty

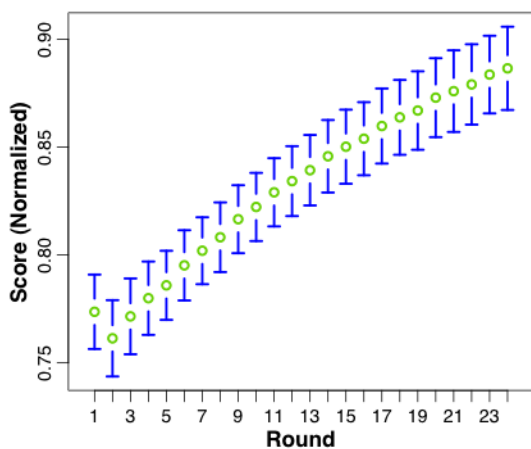
In the aggregate, participants achieved final scores of .893 (i.e. 89.3% of the way from the worst score to the best score), and average scores (over all rounds) of .833. Mean final scores were slightly but significantly (about 2 percentage points) lower in the larger board size condition ($t(38)=-2.88, p=.006$; see Fig. 2.4). The average guess turnover rate per round was 7.3% of the game board, and participants engaged in imitation on 25.8% of guesses. There were no significant differences in turnover or imitation rate between the two board size conditions.

2.3.2. Rounds

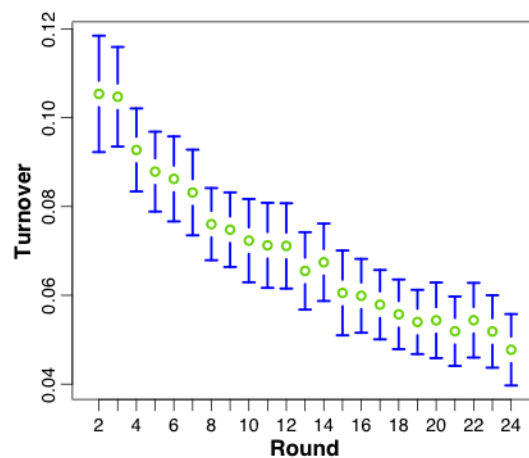
The data were averaged across all participants and all conditions in each group to give dependent variable measures for each group within each round. Linear mixed-effects models were used to examine trends across rounds for each dependent variable, with a random effect of group membership on the slope over rounds. A preliminary examination of guess content confirmed experimenter observations that participants' first round guesses often (approximately 18.5% of the time) consisted of all white squares, because the resulting score would reveal how many squares were correctly marked as white, and thus how many black squares were in the solution. This was a clever and useful tactic for participants, but tended to skew trends across rounds. For this reason, the first round was excluded from analysis.

Analysis of score versus round showed a strongly significant positive trend ($F(1,857)=139.91, p<.0001, B=0.577$; see Fig. 2.5a). Similarly, a strongly significant negative trend was observed for turnover versus round ($F(1,857)=169.06, p<.0001,$

$B=-0.527$; see Fig. 2.5b). A significant negative trend was also found for imitation rate versus round: participants tended to imitate each other less often as each game progressed ($F(1,713)=14.37$, $p=.0002$, $B=-0.182$; see Fig. 2.5c). Guess diversity was subjected to a similar analysis after normalizing it for participant group size, which was accomplished by dividing all values by the mean diversity value in the second round for the appropriate group size, which was generally at or near the maximum due to the first-round blank-board phenomenon noted above. The analysis showed that the diversity of guesses in a group decreased significantly over the course of a game ($F(1,713)=33.38$, $p<.0001$, $B=-0.415$; see Fig. 2.5d).



(a)



(b)

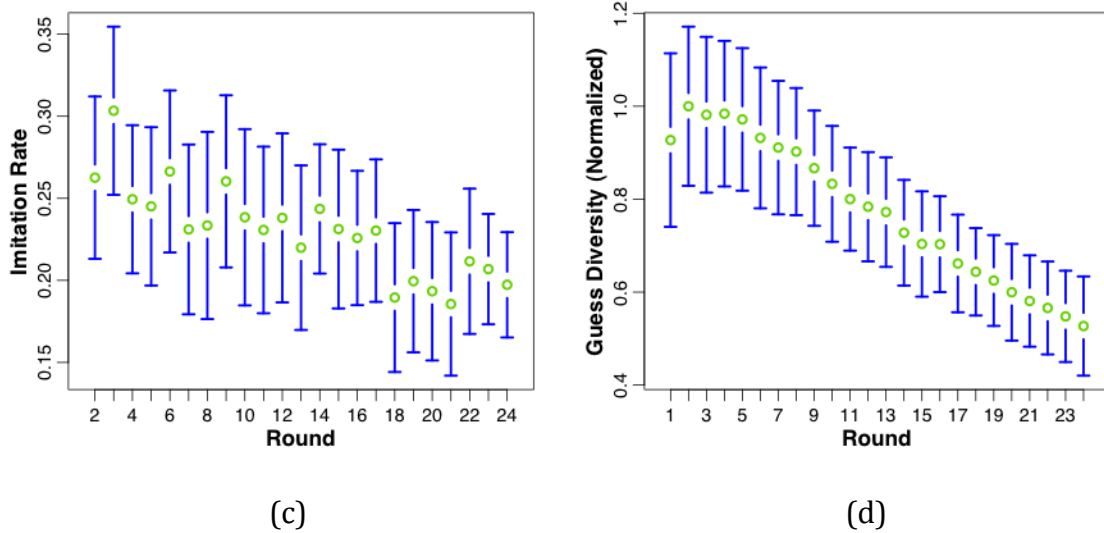


Figure 2.5: (a) Mean score increased, while (b) turnover, (c) imitation rate, and (d) guess diversity decreased as more rounds were played within a game.

2.3.3. Game order

Similar linear mixed-effects models were used to examine trends for dependent variables across game order within sessions, averaged across all participants and all rounds in each game. Once again, participant group was used as a random effect in each model. Analysis of score versus game order showed a significant positive trend ($F(1,272)=52.69$, $p<.0001$, $B=0.437$; see Fig. 2.6a), while a similar analysis of turnover showed a significant negative trend ($F(1,272)=23.08$, $p<.0001$, $B=-0.305$; see Fig. 2.6b). Imitation increased significantly across game order ($F(1,246)=11.86$, $p=.0007$, $B=0.214$; see Fig. 2.6c), while guess diversity decreased significantly across game order ($F(1,111)=7.27$, $p=.0081$, $B=-0.282$; see Fig. 2.6d).

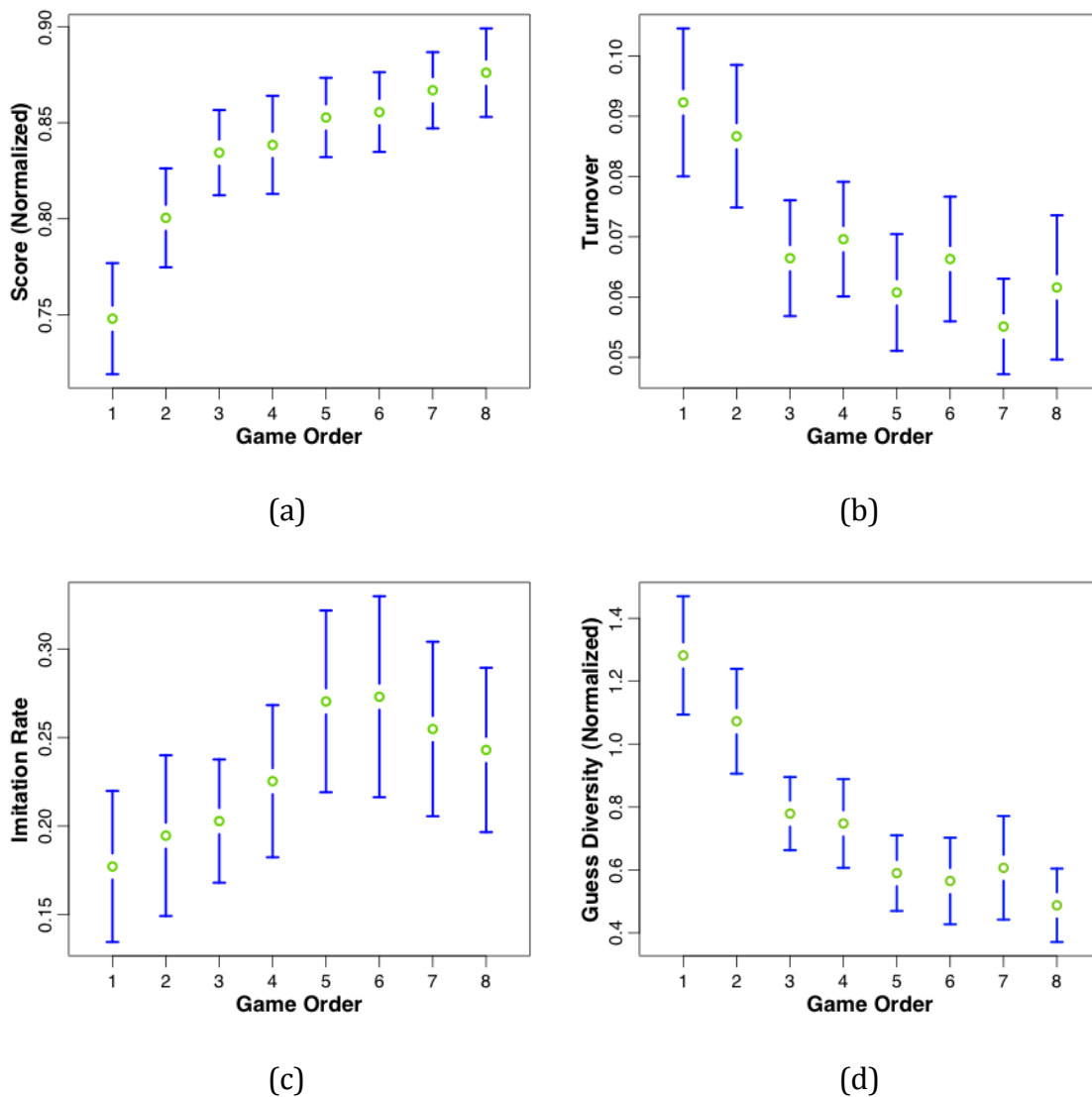
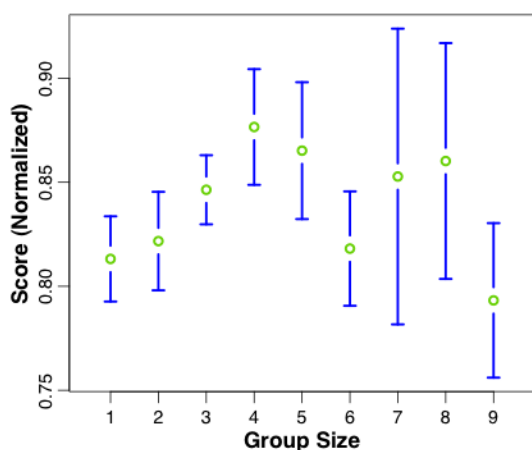


Figure 2.6: (a) Mean score and (c) imitation rate increased, while (b) turnover and (d) guess diversity decreased as more games were played within an experimental session.

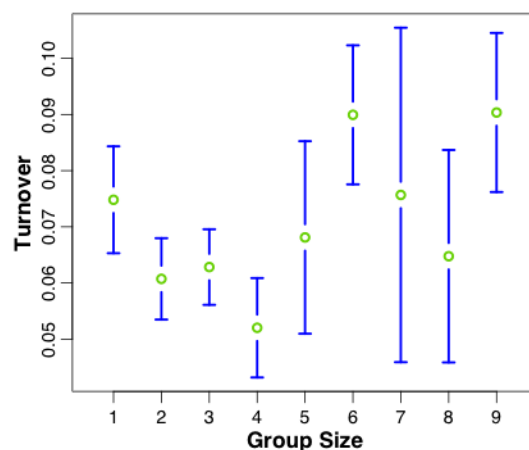
2.3.4. Group size

A mild upward linear trend was observed for score versus participant group size ($F(2,36)=4.56, p=.0395$), as well as a marginal quadratic trend which peaked at

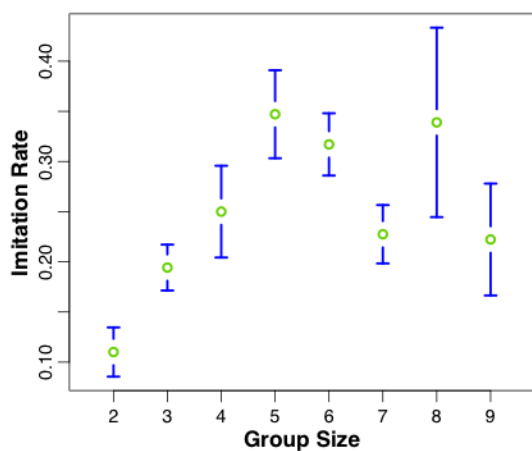
a group size of 4 ($F(2,36)=4.33$, $p=.0446$; see Fig. 2.7a). Similar, stronger upward linear ($F(2,28)=24.07$, $p<.0001$) and quadratic ($F(2,28)=16.94$, $p=.0003$; see Fig. 2.7c) trends were also found for imitation rate versus group size. No significant trends were found for turnover or guess diversity across group size, although both displayed substantial variance across group sizes, and both seemed to be generally inversely associated with score (see Fig. 2.7b & 2.7d).



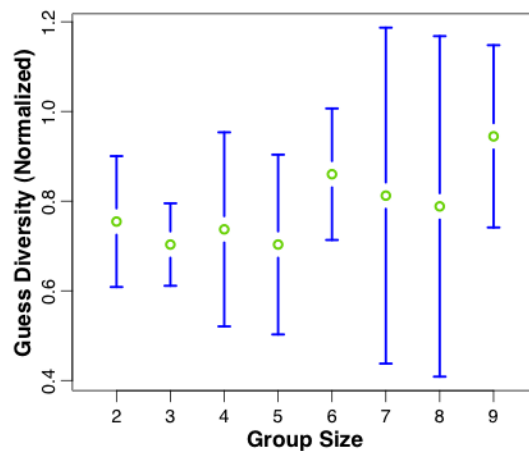
(a)



(b)



(c)



(d)

Figure 2.7: (a) Mean score and (c) imitation rate showed significant quadratic trends across participant group sizes, while (b) turnover (d) guess diversity showed no significant trends.

2.3.5. Score difference and rank in imitation

Analyses of the targets of imitation showed that nearly all instances of imitation were of those with higher scores than the imitator's (see Fig. 2.8a), implying that imitation behavior was generally purposeful and not random. However, there was a strong bias for imitating the top-scoring solution in smaller groups that weakened substantially (indicating that it was more difficult) in larger groups (see Fig. 2.8b).

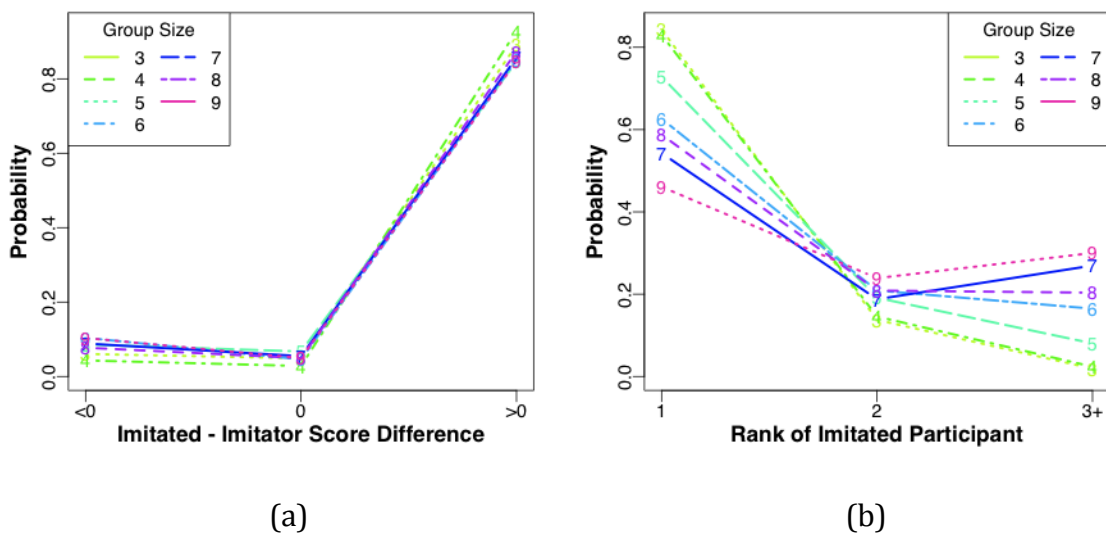


Figure 2.8: (a) Nearly all imitation was of guesses with higher scores than the imitator's, and (b) there was a strong bias toward imitating top-scoring participants, which weakened in larger groups.

2.3.6. Learning strategy

To further investigate the relationship between strategy and performance, we performed regression analyses of score versus mean rates of imitation and turnover for individuals and groups. Noting the peaking trends for score and imitation across group size in section 2.3.4, and the difference in imitation targets across group size in section 2.3.5, we split group sizes approximately in the middle of the range covered in the experiment, into those with 4 or fewer participants, and those with 5 or more. A linear regression of mean individual score versus mean individual imitation rate showed a significant positive relationship for those in group sizes of 4 or less ($F(1,49)=7.69$, $p=.008$, $B=0.368$), but none in groups of 5 or larger (see Fig. 2.9a). Likewise, a significant positive relationship was found between mean group score and mean group imitation rate in groups of 4 or smaller ($F(1,16)=9.92$, $p=.006$, $B=0.619$) but none in groups of 5 or larger (see Fig. 2.9b). Across all group sizes, there was a significant positive relationship between an individual's score and the mean imitation rate of all other group members, excluding the individual ($F(1,135)=11.68$, $p<.001$, $B=.282$; see Fig. 2.9c); that is, regardless of what an individual did, she/he was likely to have a higher score if the others in her/his group imitated more often. Similar analyses of score versus mean turnover showed strong negative relationships for all group sizes, at all levels: for individual score versus individual turnover ($F(1,143)=198.9$, $p<.0001$, $B=-0.763$; see Fig. 2.10a), group mean score versus group mean turnover ($F(1,29)=34.59$, $p<.0001$, $B=-0.738$; see Fig. 2.10b), and individual score versus group others' mean turnover

($F(1,135)=40.0, p<.0001, B=-0.478$; see Fig. 2.10c). In addition, for imitative guesses, we estimated a value for “innovation” by calculating the proportion of an imitative guess that was different from both the imitator’s previous guess and the guess that was imitated. The correlation of scores with this value were nearly identical to those found for turnover above.

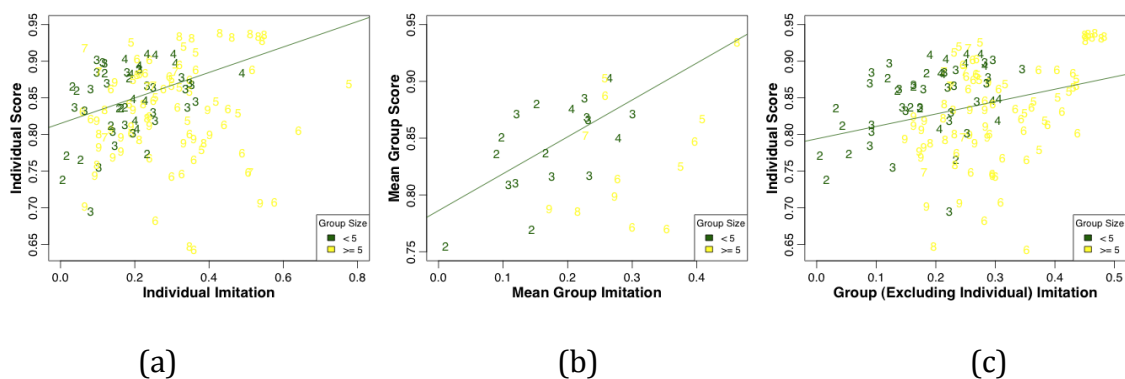


Figure 2.9: For smaller groups (< 5 participants), higher scores were associated with higher imitation rates for both (a) individuals and (b) groups; however, these relationships did not hold for larger groups. (c) For all group sizes, regardless of a particular individual’s imitation rate, the individual’s score tended to increase as the imitation rate of others in the group increased.

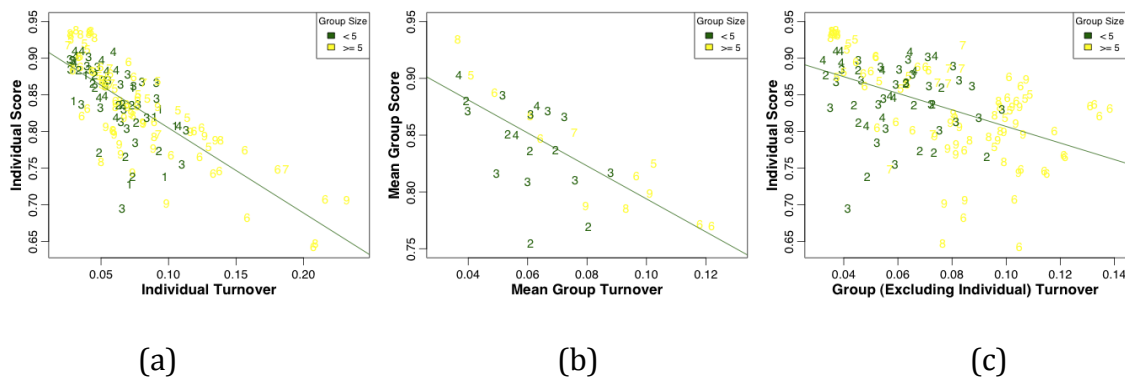


Figure 2.10 Higher scores were associated with lower turnover rates for (a) individuals and (b) groups, as well as for (c) individuals relative to the turnover rates of others in the group (regardless of the individual's turnover rate).

2.3.7. Improvements

An examination of participants' normalized improvement share showed a distribution with an unequal skew; approximately 57.7% of all participants achieved less than a "fair" improvement share of 1, while a small minority achieved much higher shares (see Fig. 2.11). In order to compare the distributions of improvement sums with an outcome generated from a random process, we constructed a Poisson distribution of improvement sums for each participant group with lambda (mean value) equal to the mean improvement sum for that group, and found the range of values which contained 50% of the density in this artificial Poisson distribution. In over 80% of groups with more than one participant, the 50% density range from the associated Poisson distribution contained less than 50% of the density of the actual individual improvement sums, indicating that they had a greater skew than would be expected by chance.

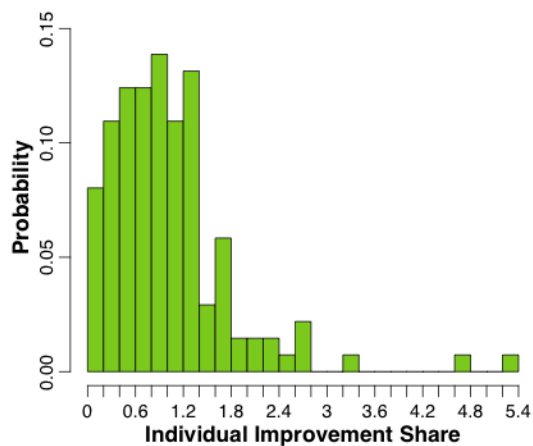


Figure 2.11: Histogram showing the unequal distribution of improvements across the participants within groups. (A value of 1 indicates an even share, e.g. an individual achieved one-third of the total improvements in a three-person group.)

Mean overall score showed a strong positive correlation with improvement share ($F(1,105)=46.89$, $p<.0001$, $B=0.350$) The mean turnover rate for guesses that resulted in improvements was significantly smaller than that of non-improvements (0.055 for improvements vs. 0.074 for non-improvements; $t(2040)=12.11$, $p<.0001$). No significant difference was found for mean imitation rate.

2.3.8. Guess similarity

A comparison between the similarity of imitators' most recent guesses to those which they imitated, and to those which they did not imitate, revealed that there was significantly greater similarity to imitated guesses than to non-imitated guesses (.777 for imitated vs. .723 for non-imitated; $t(4914)=-18.23$, $p<.0001$; see Fig. 2.12a). In other words, imitation tended to be biased toward guesses that were

more similar to the imitator's own prior guess. This difference held over all rounds within a game (see Fig. 2.11b), even though mean guess diversity decreased over rounds such that solutions generally converged (see Fig. 2.5d). No significant trends were observed in linear regressions of similarity versus imitated score rank, or the score difference between imitator and imitated participants.

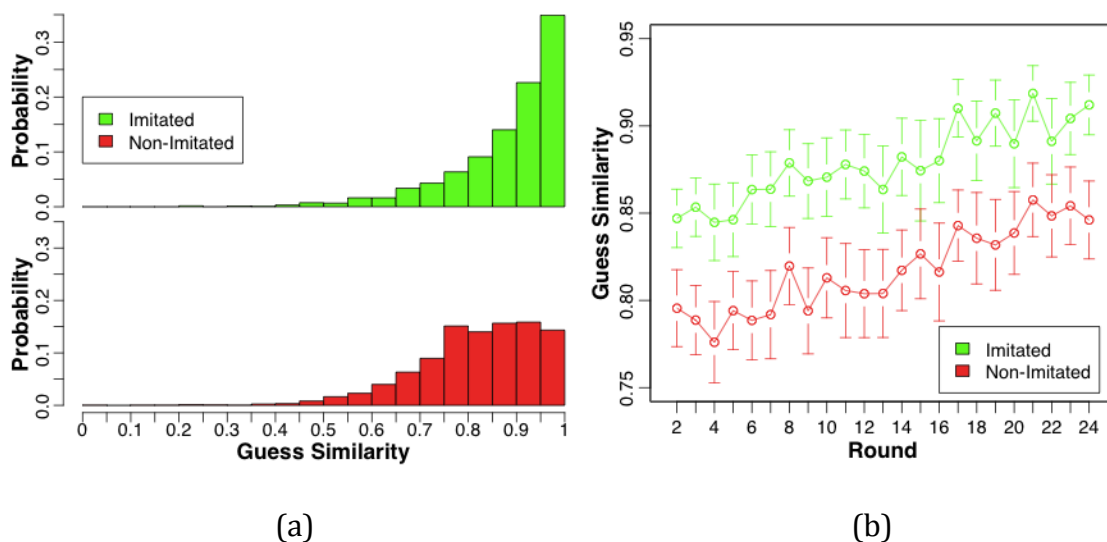


Figure 2.12: Similarity bias for imitation. (a) Imitators' previous guesses showed greater similarity to the guesses they imitated than to those they did not imitate. (b) The bias toward imitating more similar guesses was consistent across all rounds in a game.

2.4. Experiment 1 Discussion

2.4.1. Dynamics and strategies

The larger board size had a significant negative effect on final scores, which confirmed its use as a proxy for problem difficulty, but this change in difficulty had no significant effect on the other dependent variables. However, we observed revealing patterns in participants' behavior that gave some clues about their strategies.

Increasing mean scores across rounds and game order showed that participants in groups learned the task and their drawings converged upon the computer's "secret" picture over rounds of one game and over the course of the entire session. Participants accomplished their improvements through the use of fairly conservative strategies, as evidenced by the low mean turnover rate. Furthermore, the dynamics of these strategies caused solutions to become increasingly entrenched over the course of the game. This happened in two ways (which may have been mutually reinforcing): participants' rates of imitation and general turnover decreased across rounds, and the imitation that did occur was biased toward more similar solutions. This entrenchment carried over to the group level as well, shown by the decreasing group solution diversity across rounds. Of course, this result is likely partially due to participants converging toward the goal picture, but the average final score of approximately 89% of the maximum suggests that group members' solutions often converged before finding the optimal solution.

The problem space used in this task is quite large (on the order of 5×10^{14} possible solutions for the smaller board size), and any change to a solution by more than one pixel can easily result in a situation where score-decreasing changes cancel out score-increasing changes, which makes score feedback difficult to interpret. In

addition, the nature of the problem is purely linear – each correct square adds the same amount to the total score, and there are no interactions that make the search problem more complex, or incentivized large changes over small ones. Thus it makes sense that high scores were consistently associated with low turnover, and that mean turnover was significantly lower for guesses that resulted in improvements. Rather than large, revolutionary changes, participants made small, incremental improvements by changing only a few cells, typically just one. These small changes allowed participants to make accurate inferences about their effects on score.

The unequally skewed distribution of improvements within each group showed that not all participants were skilled at finding good new solutions, though imitation allowed some participants to take advantage of other participants' innovations and maintain high mean scores. The fact that average turnover was higher for non-improvement guesses shows, however, that non-improvers were not just idly waiting to imitate others' improvements.

2.4.2. Benefits of imitation

Imitation was biased toward higher-scoring and more-similar guesses, as expected. The latter allowed participants a way to take advantage of others' good solutions while maintaining low turnover and higher continuity with their own previous guesses, preserving the value of their existing knowledge of the problem space.

The association of higher scores with greater imitation rates at both the individual and group levels in smaller groups (who were better able to distinguish the top-scoring guess when imitating) shows that imitation is not necessarily harmful to innovation and performance improvements. In addition, the association of high individual scores with high imitation rates by others in the group (regardless of the individual's behavior) indicates a systemic benefit for imitation that does not accord with a view of imitation as a purely self-benefiting act. It may be that, regardless of the intentions of individuals, imitation benefits the group by acting as a filter for propagating and preserving the better solutions available in a group at a given time, as was found in a recent competition of social learning strategies in a simulated environment (Rendell et al., 2010). Though it was reasonable to expect improvements to be associated with a lower imitation rate (because those who only imitate others cannot do better than those they imitate), we found that the rate of imitation was about the same among improvements and non-improvements, which means that imitators were often building on the guesses they imitated to create improvements. Improvements were often achieved by imitating a relatively successful participant's solution and then slightly tweaking this solution. Once tweaked, the improved solution was then available to other participants, including the individual who was originally imitated.

2.4.3. Imitation information overload?

There was an unexpectedly lower benefit for imitation in larger groups, as shown by the lack of association between imitation and score in larger groups,

which was present for smaller groups. Larger groups can be thought to provide more information about the distribution of solutions to their members, because there are more models for each group member to observe. This can allow each of them to make more informed decisions about whom to imitate and what changes to make to their guesses. However, it may have been that for larger group sizes, the amount of information provided was more difficult to search and compare, which led to more random imitation decisions (as indicated by the weaker bias toward imitating the top-scoring guess) and thus poorer convergence on good solutions. It is unlikely that this was purely a statistical artifact of random choice among more options, because there was a universal tendency (across all group sizes) to imitate better-scoring peers than oneself, a relatively easier thing to accomplish than finding the best score, but decidedly non-random. So, though score information was readily available, it may have been subject to cognitive load effects (Sweller, 1988). Larger groups would be expected to show a greater variance in solution quality by chance, but an increasing inability to properly distinguish good solutions would cancel out this benefit.

2.5. Conclusions

Though our assumptions about participants' imitation strategies (favoring higher-scoring and similar guesses) were empirically supported, the related predictions of poor performance were not borne out. There was a consistent benefit for individuals to be in high-imitation groups regardless of their own behavior, and

imitation was also associated with better individual and group performance when it could be done selectively and accurately.

In short, the theoretical imitation-related social dilemma did not cause a tragic outcome, which is consistent with the benefit for "conformity bias" found in previous models and experiments of social learning (Boyd & Richerson, 1985; Kameda & Nakanishi, 2002), and with the literature on social dilemmas with repeated interactions and recognition of a collective action problems (Ostrom, 1990). In fact, the degraded performance of larger groups was likely due to an impediment to imitation.

2.5.1. Modifications and motivations

The first-game discontinuity for trends in score, turnover, and imitation indicated that the first game in each session might have functioned as a practice game, during which participants were still learning the mechanics of the experiment. This suggested that explicit practice should be included in future experiments before data gathering begins, in order to obtain more consistent data. In addition to the first-round blank board strategy noted above, participants were occasionally observed attempting to create images on the grid corresponding to patterns, symbols, and alphanumeric characters, despite instructions to the contrary. This is an understandable response given natural human creativity, the presumably low visual or conceptual interest in the goal pictures, and potential suspicion about experimenter deception. These behaviors added some noise to the data. The linear nature of the problem and lack of interactive effects between

solution elements may have resulted in a lack of variation from the slow and incremental strategies we observed in this experiment.

These issues suggest several modifications for subsequent experiments: (a) a more engaging task, with (b) less possibility for performing the task in a way that departs from its intended purpose, (c) a clearer and more intuitive interface and instructions, (d) more explicit recording of participant choices for imitation, innovation, etc., and (e) a smaller, more discrete problem space (to improve both participant comprehension and tractability of analyses) with (f) interactive effects between some solution elements (to observe possible variations in exploration strategies from those in this experiment).

In this study we found that the behavior of isolated individuals attempting to solve a complex problem differs markedly from that of people connected in groups, and that differences in the size of a group can have significant effects on behavior. Overall, there are strong implications in these data for testing the predictions of past work in the area of group problem-solving behavior, and potential applications to many real-world problems. The results present several intriguing areas for further study, which we decided to explore using a task modified according to the guidelines above.

3. Experiment 2 – Creature Game A

3.1. Experiment 2 Overview

In order to address some of the issues in Experiment 1 noted above, we designed a new task that incorporated thematic elements of popular games such as virtual pets and fantasy sports leagues (though the parameters of the task were limited to make it much simpler than either of these). The paradigm involves participants trying to maximize the score of a chosen subset of individual units from a larger set over a series of rounds. Participants can see the selections of others in each round and imitate them in whole or in part, and the units that participants choose from are assigned individual as well as pairwise interaction point values. The size and complexity of the problem space (and thus the task difficulty, as in Experiment 1) were manipulated via the sizes of the set of selectable units and the subset that could be chosen and evaluated at one time, as well as the number of pairwise interactions. We included thorough written and oral instructions to participants, as well as opportunities for hands-on practice with the task before data collection began. We changed the interface to make score feedback clearer (providing emphasis on the size and direction of score changes after each round). We also unambiguously defined and determined (rather than having to estimate) instances of imitation, innovation, and so forth, by recording the source of each player's selections in the interface.

3.1.1. Predictions

The new task also allowed us to gather additional explicit data about the proportions of the sources of participants' solution element choices, including Innovation (the introduction of solution elements without prior associated score feedback), and Retrieval (the reinstatement of previously used solution elements after changing them), which were not available as separate classifications in Experiment 1, as well as Imitation and Retention (roughly the inverse of turnover from Experiment 1).

Imitation was expected to be greater in greater difficulty conditions (reflecting the greater risk in a larger and more complex problem space), and Innovation was expected to decrease. In general, Innovation was expected to be relatively rare compared to Imitation, due to its relatively higher risk. Retention and Retrieval were expected to increase over rounds (and thus Innovation and Imitation were expected to decrease), as participants narrowed their search to smaller areas of the problem space. We expected decreases in Innovation and Retrieval and an increase in Imitation in larger participant group sizes, because participants would be able to rely on a larger pool of good peer solutions to imitate, which would reduce the need to explore or rely on their own previous solutions.

The new task was generally intended to maintain the same overall character of the task in Experiment 1, while correcting a few issues. Therefore we expected that the results would show the same general patterns observed in Experiment 1, with the exception of (1) smoother trends of dependent variables across game order (as opposed to the discontinuity in the first condition in Experiment 1) due to better instruction and hands-on demonstrations; and (2) roughly monotonic trends across

group size (as opposed to the peaked quadratic trends in Experiment 1), due to interface improvements allowing participants to search and compare peer solution and score information more efficiently.

3.2. Experiment 2 Methods

201 participants were recruited from the Indiana University Psychology Department undergraduate subject pool, and were given course credit for taking part in the study. Participants populated each session by signing up at will for scheduled experiments with a maximum capacity of 9 persons. 49 sessions were run, and 10 sessions (containing a total of 48 participants) were discarded due to network or software problems. The remaining 153 participants were distributed across 39 sessions as shown in Table 3.1.

Table 3.1: Distribution of participants across group sizes in Experiment 2

Group size	1	2	3	4	5	6	7	8	9
# Sessions	8	6	5	5	5	2	4	3	1
# Participants	8	12	15	20	25	12	28	24	9

We implemented the experiment using custom software run in a web browser, and each participant used a mouse to interact with the experimental game. All participants' computers communicated with a game server, which recorded data and updated scores and team information for participants at the end of each round. In the game itself, participants attempted to maximize the number of points earned

by their chosen subsets (“teams”) from a set (“league”) of creature icons over 24 rounds. The display included an area for the participant’s own current team, another area that could be toggled to show the participant’s previous round team or their best-scoring team so far in the game (along with the associated score), a league area which showed all of the icons (potential team members) that were available for selection, and indications of the current round in the game and the amount of time remaining in the current round.

If a session included more than one participant, each participant’s display also showed the team and associated score for all other participants in the previous round. Icons could be copied from any part of the display to a participant’s current team by dragging and dropping them with the mouse, except for those already on the participant’s current team, which were faded in the display and non-clickable. The current team could be replaced entirely by another team by selecting the score box above the latter as a “handle” and dragging it to the current team area. The ordering of peers’ teams in each participant’s display was not kept constant across conditions, to avoid imitation based on past behavior. A screenshot of the participant interface is shown in Fig. 3.1.

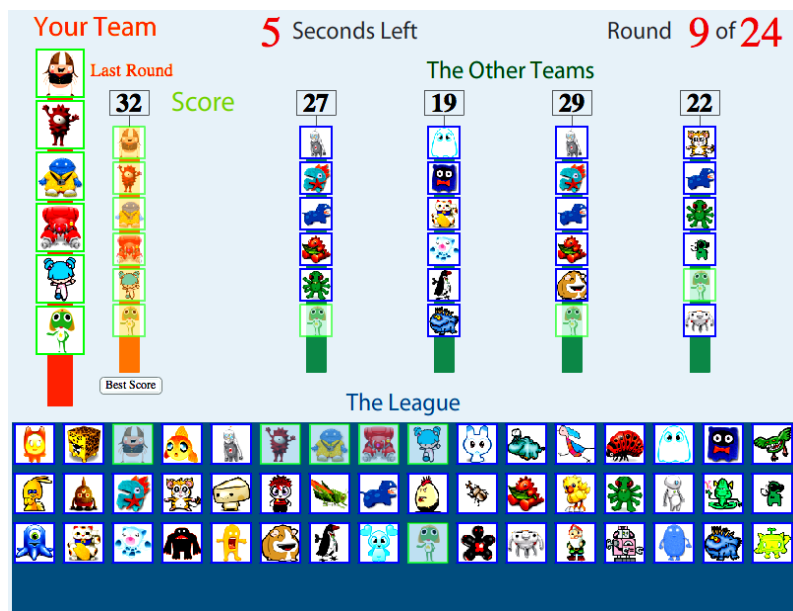


Figure 3.1: Example of experiment interface in Experiment 2.

At the beginning of each session, players were given a hands-on demo of the game (including the various ways to move creatures to one's current team), and further informed about the mechanics of the game and what to expect in the remainder of the experiment session, including the following information. Each game consisted of 24 rounds, and each round was 10 seconds long, as in Experiment 1. Score feedback was given after each round: if the participant's score had improved from the previous round, the numerical score display counted up to the new score and turned green, and if it had worsened, the display counted down to the new score and turned red. At the end of each game, the display showed the player's final score, along with a table of the scores of each player in each round of the game, which was sorted by average score. The player's own scores were

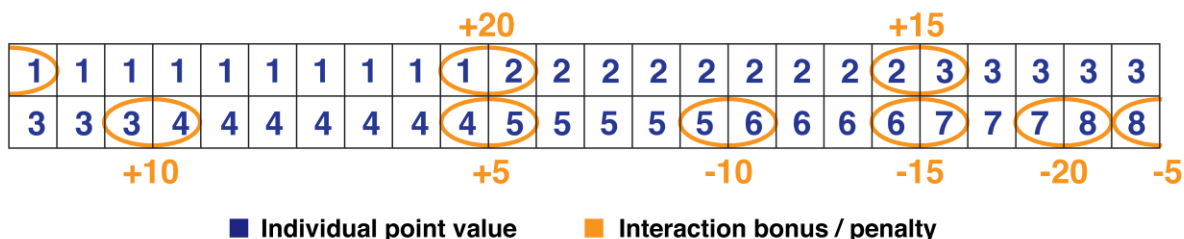
highlighted to show their relative performance without placing competitive emphasis on it. Players were instructed to do their best to maximize their teams' scores over all 24 rounds. At the beginning of each game, each player's team was a random selection of creature icons from the league.

Each group played 8 games, of which half had a large league and team size (48 and 6, respectively), and half were smaller (24 and 5). These two parameter settings were intended to vary the level of difficulty of the game, with the former being more difficult. This was because although the score distribution and combinatorics made higher numerical scores possible, it also made high-scoring teams rarer than in the latter case: for the smaller league size, about 4% of all possible teams had scores greater than 70% of the maximum, while for the larger league size this figure was 0.4% (see Fig. 3.3). That is, with the larger league and team size, it was harder to find good solutions because of the relatively large number of poorer solutions.

In each game, each icon was associated with a certain positive number of points, and several special pairs of icons were associated with separate score bonuses or penalties that captured interactions between icons. The score for a team was computed by summing the individual point values for each icon, and then adding or subtracting the value of any special pairs present. The pairs did not overlap, and the distribution was designed to be challenging: pairs which gave large positive bonuses were distributed among icons with small individual point values, and pairs which gave large negative penalties were generally found among icons with large individual point values (see Fig. 3.2).



(a) League size of 24



(b) League size of 48

Figure 3.2: Point distribution for individual icons (boxes) and interaction bonuses and penalties (ovals), for league sizes of (a) 24 and (b) 48.

Individual point values per icon ranged from 1 to 8 points, and pair interaction values ranged from -20 to 20 points, so that the possible score ranges for the large and small league and team size combinations were [-6,60] and [-6,51], respectively. For ease of comparison and analysis, all scores were normalized to the range [0,1] according to the range of scores possible with the associated league and team size combination. The combinations of such individual and pair values resulted in the probability distribution of scores among all possible teams for each league size shown in Fig. 3.3.

Participants were not given information about the maximum score, the score distribution, or the position of the interaction terms, though they could potentially have been deduced during play. The icons' display position and associations with the point distribution were shuffled randomly for each game, so that their appearance and placement in the display did not give clues as to their point values during the course of an experiment session.

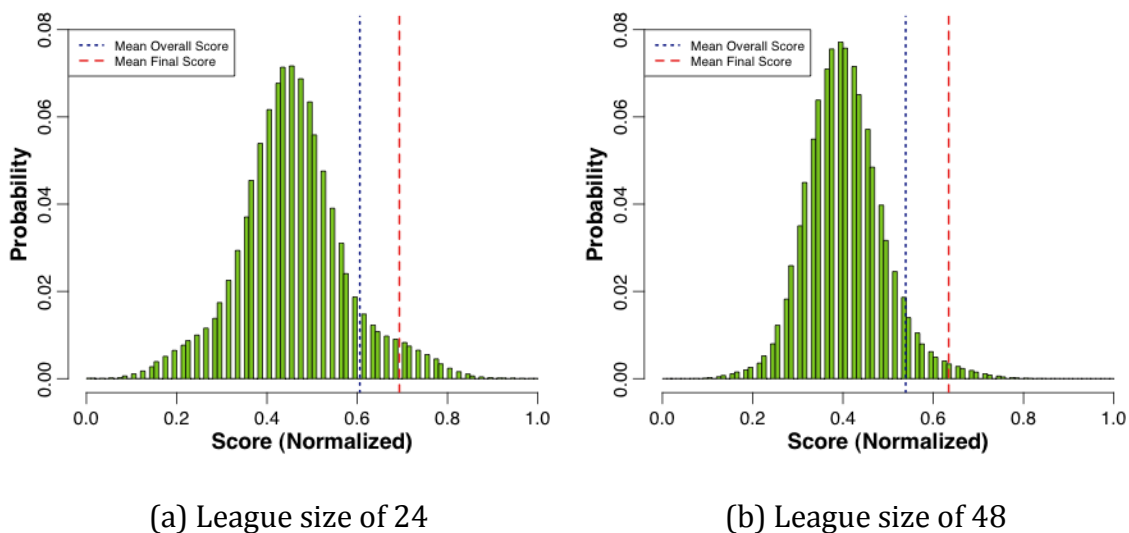


Figure 3.3: Distribution of scores for all possible teams in each difficulty (league size) condition.

In each round, the following data were automatically recorded for each player: the icons on the current team at the end of the round (or *choices*), the *source* of each icon, and the resulting *score*. The source information indicated whether each icon was unchanged from the previous round (*Retained*), copied from the player's own previous round team after initially being removed from the team (*Returned*),

copied from the player's own best-scoring team so far (*Retrieved*), chosen from the league display (*Innovated*), or copied from another player's team (*Imitated*). When Imitation was chosen, the persistent identifier of the copied player was recorded to allow further analyses of imitation decisions.

In the case of a player replacing the entire team with Imitated icons, all choices were recorded as Imitated, even if one or more of them were already on the player's previous round team. (The same was true of replacing an entire team with Retrieved icons, or removing an icon and then putting it back on the team via a League choice.) However, a comparison with the player's previous round team allows the determination of a *corrected* choice source for each icon, effectively revealing a potential increase in the Retain choice source, and a potential decrease for all other choice sources except the Return choice source. In essence, the original uncorrected choice sources reveal the literal actions of players, while the corrected choice sources reveal their effects. *Score improvements* and *score ranks* were defined identically to those in Experiment 1.

Similar to Experiment 1, *guess diversity* for a particular round was defined as the proportion of icons in the league represented on one or more participants' teams during a given round. This value was normalized by the average expected value of this proportion for each participant group size, generated by a Monte Carlo simulation assuming independent random teams. (It should be noted that this calculation and the associated solution spaces in Experiments 1 and 2 are of different types and sizes due to the nature of the task in each.)

3.3. Experiment 2 Results

Participants achieved a mean overall score of .596 (i.e. about 60% of the way from the worst score to the best score), and a mean final score of .690. The average guess choice source proportions (original and corrected) are shown in Table 3.2.

The very low Return rate suggested that an average turnover rate defined equivalently to that in Experiment 1 could be approximated as one minus the mean Retention proportion, or 26.1%. (All further analyses of choice source refer to the corrected versions, except where noted.)

Table 3.2: Average Original and Corrected choice source proportions

Choice Source	Imitation	Innovation	Retention	Retrieval	Return
Original	20.6%	14.0%	59.5%	6.5%	0.5%
Corrected	9.8%	13.7%	73.9%	2.6%	n/a
Difference	-10.2%	-0.3%	+14.4%	-3.9%	n/a

For the initial analysis, dependent variables were averaged across all participants and all rounds to give measures for the group's aggregate activity in each game. These data were analyzed using a repeated-measures ANOVA, treating each group as a single subject, with difficulty (league size) as a within-groups factor, the group size used as a covariate, and the participant group (session identifier) included as a random effect in the model for each dependent variable. Data from the first round of each game was excluded from analyses of choice source, because several choice sources (Imitated, Retrieved, Retained, and Returned) are only

defined relative to a previous round. The above analyses revealed significant main effects of difficulty and group size on score and several choice sources, and a significant main effect of group size on guess diversity, as well as a significant interaction effect between difficulty and group size on guess diversity. These results, as well as dependent variable trends over rounds, game order, choice source use, score performance, and guess similarity are described in detail below.

3.3.1 League size / difficulty

Participants achieved mean overall scores (averaged across all rounds) and mean final scores for each League Size as shown in Table 3.3 and Fig. 3.3. Scores were normalized as described above, and percentiles were defined as the percentage of all possible teams with lower scores than the associated mean score.

Table 3.3. Mean score, guess diversity, and choice source proportions in each condition.

League Size	Mean Overall Score (Percentile)	Mean Final Score (Percentile)	Mean Guess Diversity	Mean Imitation	Mean Innovation	Mean Retention	Mean Retrieval
24	.606 (90.1%)	.693 (95.7%)	67.6%	6.8%	16.8%	69.5%	6.3%
48	.539 (93.7%)	.634 (98.5%)	63.4%	7.1%	14.9%	72.1%	5.3%
Diff.	-.067*	-.059*	-4.2%*	+0.3%	-1.9%*	+2.6%*	-1.0%

*** significant differences**

A two-sample t-test was used to examine the main effect of difficulty on each dependent variable. It was found that relative to the lower difficulty condition, the higher difficulty condition resulted in significantly lower Innovation ($t(306.8)=2.71$, $p=0.007$), and significantly greater Retention ($t(307.5)=-2.02$, $p=.0445$), but no significant differences were found for Imitation or Retrieval between difficulty conditions, and trends for all were unchanged for uncorrected choice sources. The higher difficulty condition resulted in significantly lower guess diversity ($t(233.8)=2.16$, $p=.0320$), and significantly lower scores ($t(305.8)=7.55$, $p<.0001$; see Fig. 3.3). The score percentiles achieved are actually higher for the larger League Size, but this is most likely due to the difference in the shapes of the two score distributions used.

3.3.2. Rounds

Linear mixed-effects regression models were used to examine trends across rounds for each dependent variable, with a random effect of group on the slope. Analysis of score vs. round showed a strong positive trend ($F(1,919)=897.05$, $p<.0001$, $B=0.717$; see Fig. 3.4). The average improvement in score across rounds within a game was 23.7%, and trends in scores over rounds were positive for all group sizes. Guess diversity showed a significant decrease across rounds ($F(1,735)=188.62$, $p<.0001$, $B=-0.404$; see Fig. 3.4), and such trends over rounds were more strongly negative for increasing group size.

As for choice sources, Imitation showed a significant decrease over rounds ($F(1,681)=126$, $p<.0001$, $B=-0.453$), as did Innovation ($F(1,857)=70.78$, $p<.0001$,

$B=-0.277$). The overall incidence rate of imitation decreased similarly. Retention increased significantly across rounds ($F(1,857)=21.43$, $p<.0001$, $B=0.214$), as did Retrieval ($F(1,857)=9.67$, $p=.0019$, $B=0.128$; see Fig. 3.5). Using uncorrected choice sources revealed no significant changes to these trends, except for slight differences in slope.

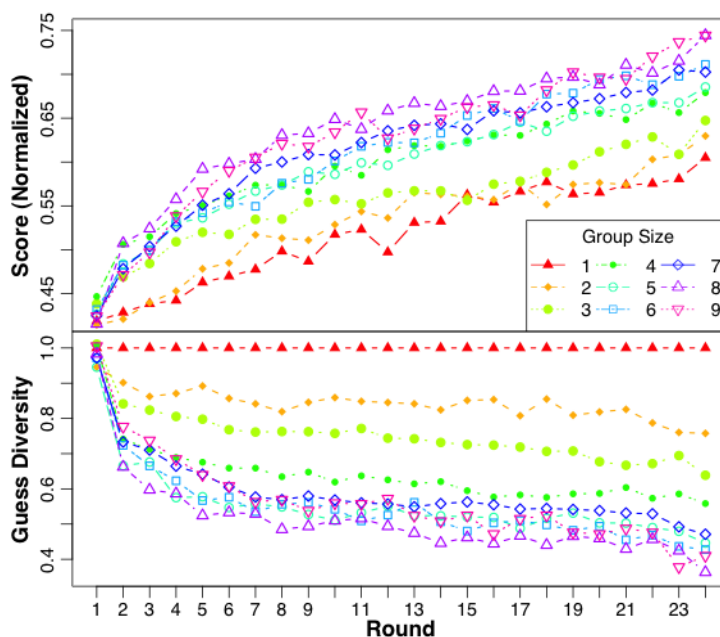


Figure 3.4: Mean score increased and mean guess diversity decreased as more rounds were played within a game; stronger effects were observed for larger participant group sizes.

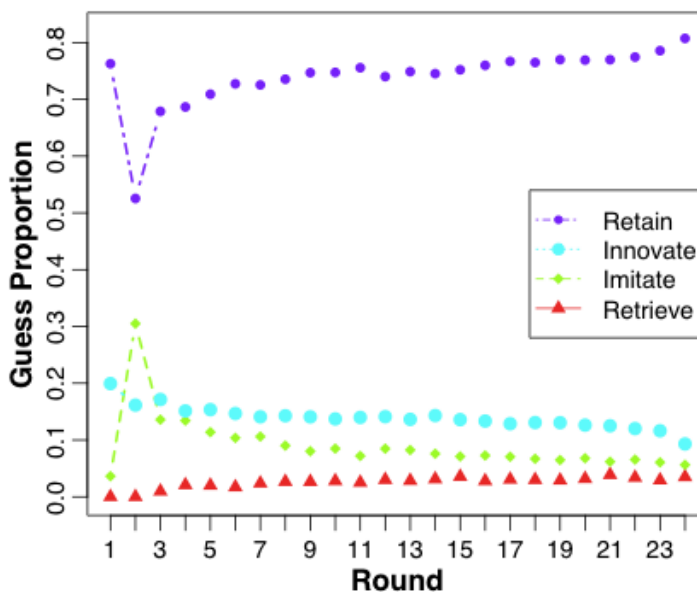


Figure 3.5: Mean proportions of Retention and Retrieval increased and Imitation and Innovation decreased as more rounds were played within a game.

3.3.3. Game order

Similar linear mixed-effects models were used to examine trends across game order within sessions for each dependent variable. Score displayed a significant upward trend across game order ($F(1,272)=14.69$, $p=.0002$, $B=0.186$; see Fig. 3.6a). The average improvement in score across game order within a session was .056. Guess diversity displayed a corresponding downward trend ($F(1,216)=20.02$, $p<.0001$, $B=-0.180$; see Fig. 3.6b). No significant trends were found for original or corrected choice source proportions over game order.

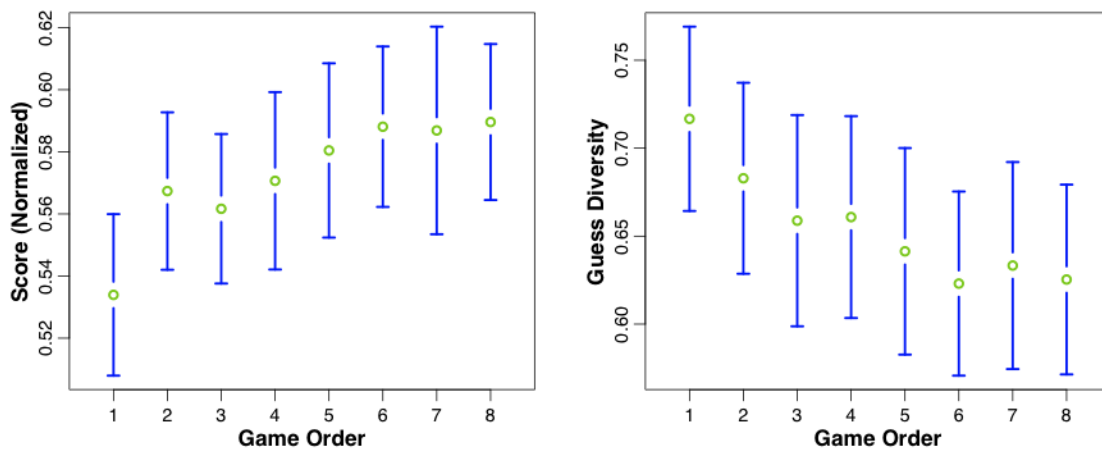


Figure 3.6: As more games were played within an experimental session, (a) Mean score increased, and (b) the diversity of guesses decreased.

3.3.4. Group size

Trends across participant group size for each dependent variable were examined using linear mixed-effects models, with the group (session identifier) used as a random effect on the intercept. Score showed a significant upward trend across group size, with an average score difference of 11% between isolated participants and those in the largest group size of 9 ($F(1,37)=73.62$, $p<.0001$, $B=0.466$; see Fig. 3.7a). Guess diversity decreased significantly for larger groups ($F(1,29)=38.25$, $p<.0001$, $B=-0.663$; see Fig. 3.7b).

As for choice sources, Imitation increased significantly for larger groups ($F(1,29)=22.35$, $p=.0001$, $B=0.565$), and Retention increased as well ($F(1,37)=12.09$, $p=.0013$, $B=0.433$), while Innovation decreased ($F(1,37)=28.95$, $p<.0001$, $B=-0.563$), and Retrieval decreased as well ($F(1,37)=12.46$, $p=.0011$, $B=-0.464$; see Fig. 3.8). Original (uncorrected) choice sources showed no trend for

Retention across group size, but otherwise maintained the same pattern of results noted above, with slight differences in slope.

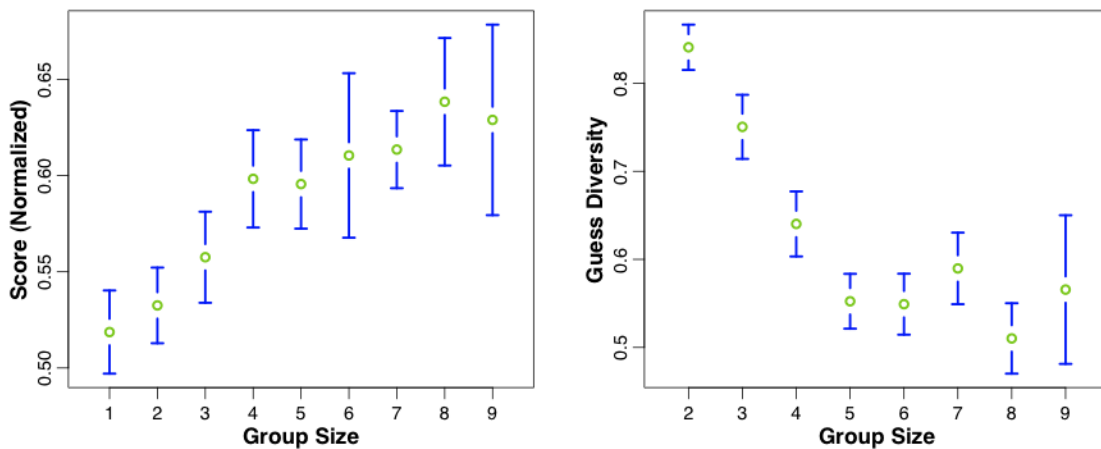


Figure 3.7: (a) As participant group size increased, mean scores in a group increased, and (b) the diversity of offered solutions decreased.

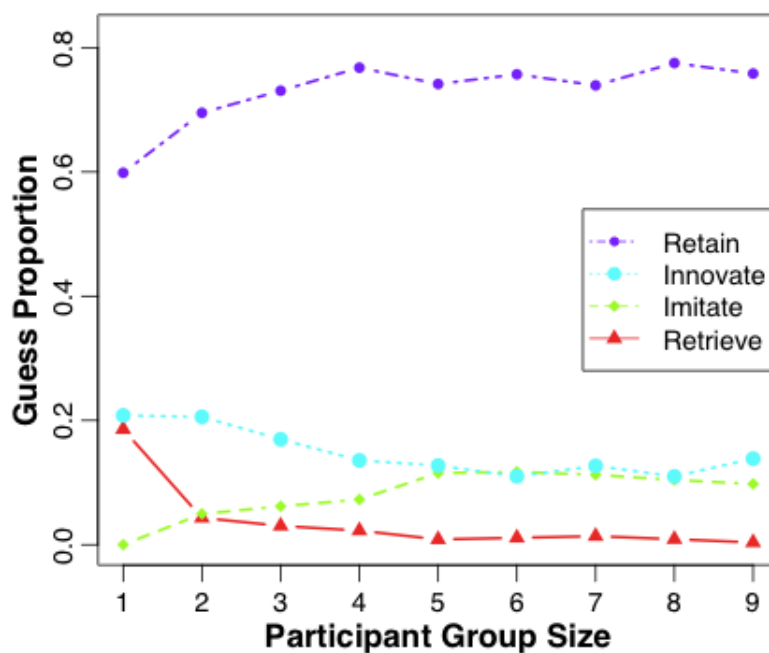


Figure 3.8: As participant group size increased, mean proportions of Retention and Imitation increased, and Innovation and Retrieval decreased.

Given the results for Imitation above, it is important to determine whether the score advantage for larger groups was simply an artifact of the greater chance of observing a better score than one's own given the larger number of guesses being made, leading to more imitation and thus higher scores. In order to determine whether this was the case, we calculated the score difference variance (SDV): the variance of the differences between the top-ranked participant and all other participants within each round, averaged within each game. Using a linear mixed-effects model like the others used for group size analyses above, we confirmed a slight but significant upward trend of SDV across group size ($F(1,29)=11.37$, $p=.0021$, $B=0.262$). However, a similar analysis of Imitation proportion vs. SDV did not reveal any significant trend, and controlling for SDV in the Imitation proportion vs. group size model above did not alter it significantly. In other words, the greater Imitation in larger groups did not appear to be due to increased score variance.

3.3.5. Score difference and rank in imitation

The analyses in this section refer to original uncorrected choice sources, because their intent is to capture participants' awareness of other players' scores, not the content of their guesses. Of all guesses with greater than zero Imitation proportion, 94.3% imitated only one other participant, 5.1% imitated two participants, and 0.6% imitated more than two participants. Of all instances of single-participant imitation, 82.4% involved imitation of participants whose score rank was 1 (the top score in the group), 10.7% whose score rank was 2, and 7%

whose score rank was 3 or below (see Fig. 3.9a). At the time of such single-source imitations, the score of the imitated participant was greater than that of the imitator in 89.6% of cases, equal to it in 2.6% of cases, and less than that of the imitator in 7.8% of cases (see Fig. 3.9b). No significant differences across group size, round, etc. were observed in these values.

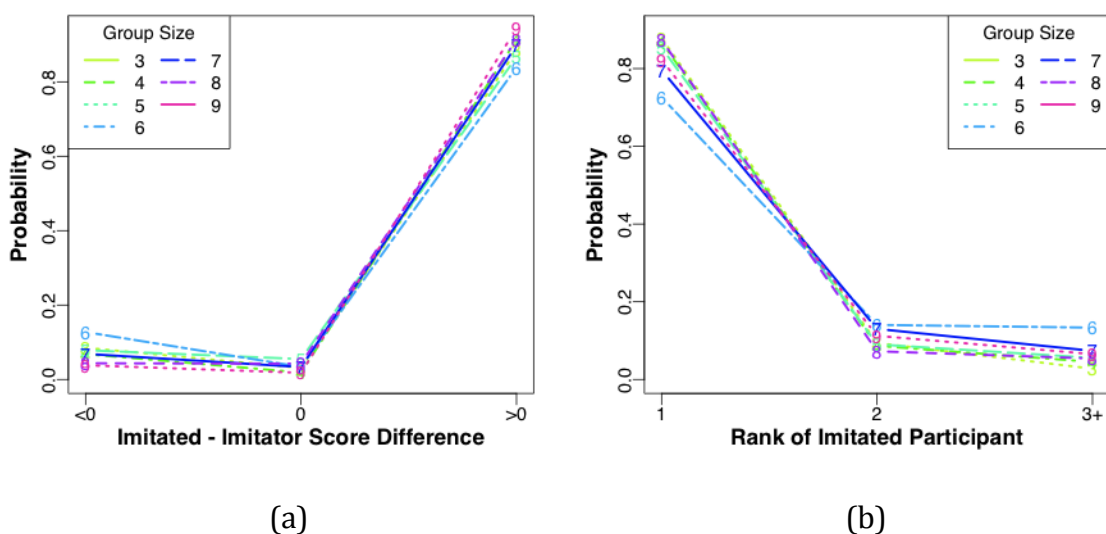


Figure 3.9: There were biases toward imitating (a) better-scoring participants than oneself, and (b) the best-scoring participant, and these biases were unaffected by group size.

3.3.6. Choice source strategy

The choice sources of each non-isolated participant over the entire session were analyzed, and each participant's choice source strategy was categorized according to their proportion of each source. Participants whose choices contained one source in an average proportion greater than the global average for that source

plus one standard deviation, were labeled with that strategy. For example, a player whose guesses over the course of a session consisted of a greater proportion of Imitate choices than the average for all other participants in the experiment, plus one standard deviation, were labeled as having an overall strategy of “Imitate.” Those who fit the above criteria for more than one choice source, or none, were labeled as having a “Mixed” strategy. The score distribution for players in each strategy category is shown in Fig. 3.10(a), with the Retain strategy scoring the best, followed by Mixed, Imitate, and Retrieve, with Innovate scoring the worst. Analysis of original uncorrected choice source strategies showed a similar pattern, except that the Imitate and Retain strategies switched places (see Fig. 3.10(b)).

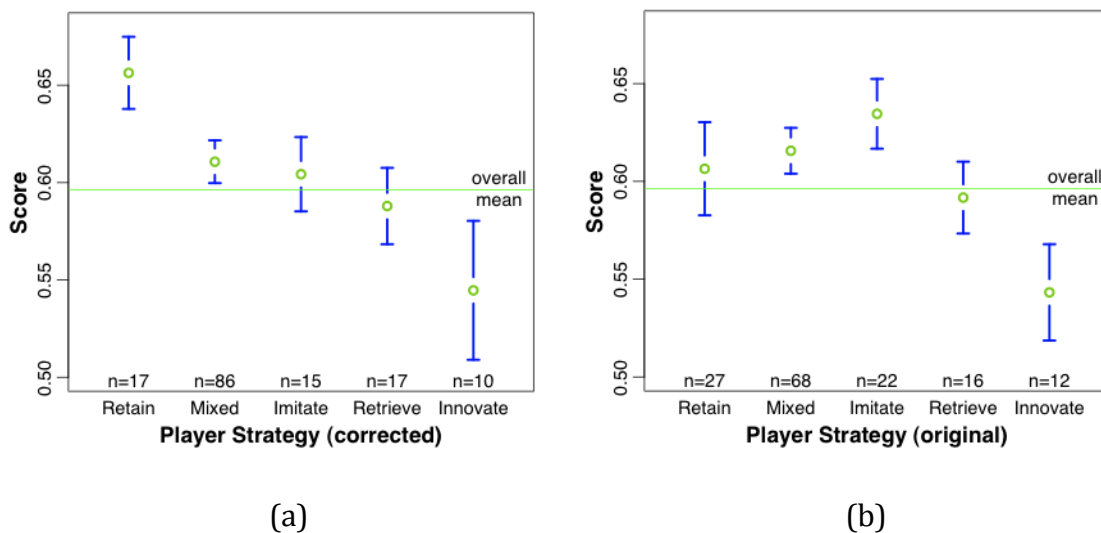


Figure 3.10: Score vs. (a) corrected choice source strategy and (b) uncorrected choice source strategy, showing that a conservative and imitative strategy resulted in the best performance.

The above-mentioned figures summarize the results of simple regression analyses performed for score vs. individual and group use of each choice source. A linear regression of mean individual score vs. mean individual Imitation guess proportion showed a significant positive trend – the greater a participant’s average proportion of Imitation, the better the participant’s score ($F(1,143)=8.64$, $p=.0038$, $B=0.239$; see Fig. 3.11a). A similar positive trend held for Retention ($F(1,143)=55.72$, $p<.0001$, $B=0.530$; see Fig. 3.12a). The opposite was true for individual score vs. Innovation, which displayed a significant negative trend ($F(1,143)=119.8$, $p<.0001$, $B=-0.675$; see Fig. 3.13a), as did Retrieval ($F(1,143)=10.93$, $p=.0012$, $B=-0.267$; see Fig. 3.14a). Analyses of score vs. original uncorrected choice sources showed similar trends for Imitation and Innovation, but none for Retention or Retrieval.

A very similar pattern of results was shown in analyses of mean group score vs. mean group guess proportion for each choice source, with upward trends for Imitation (i.e. the higher a group’s mean Imitation, the higher its mean score) and Retention, and downward trends for Innovation and Retrieval (all $p<0.001$; see Figs. 3.11b-3.14b). The only difference for analyses of uncorrected mean group choice sources was the lack of a trend for Retention. Likewise, a very similar pattern of results was found for analyses of mean individual score vs. mean group (excluding the individual) guess proportion for each choice source. There was a positive trend for Imitation (i.e. the more an individual’s fellow group members imitated, the higher the individual’s score), as well as Retention, and negative trends for Innovation and Retrieval (see Figs. 3.11c-3.14c). Once again, the only difference for

analyses of uncorrected mean group choice sources was the lack of a trend for Retention. All trends noted above were generally monotonic; that is, there were no thresholds or inflection points beyond which the relationships changed.

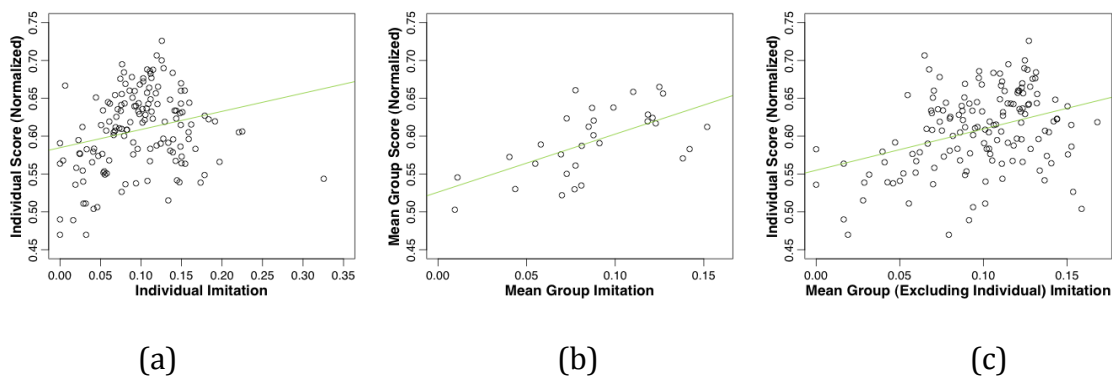


Figure 3.11: Higher scores were associated with higher imitation rates for (a) individuals and (b) groups, as well as for (c) individuals relative to the imitation rates of others in the group (regardless of the individual's imitation rate).

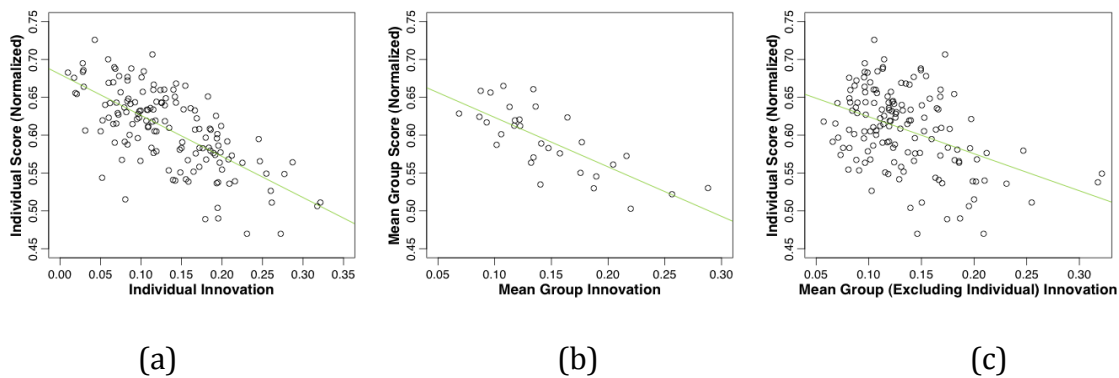


Figure 3.12: Higher scores were associated with lower innovation rates for (a) individuals and (b) groups, as well as for (c) individuals relative to the innovation rates of others in the group (regardless of the individual's innovation rate).

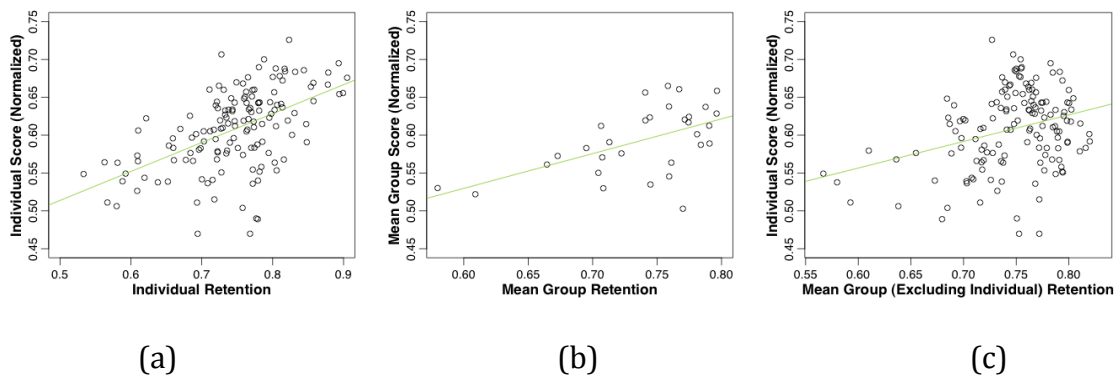


Figure 3.13: Higher scores were associated with higher retention rates for (a) individuals and (b) groups, as well as for (c) individuals relative to the retention rates of others in the group (regardless of the individual's retention rate).

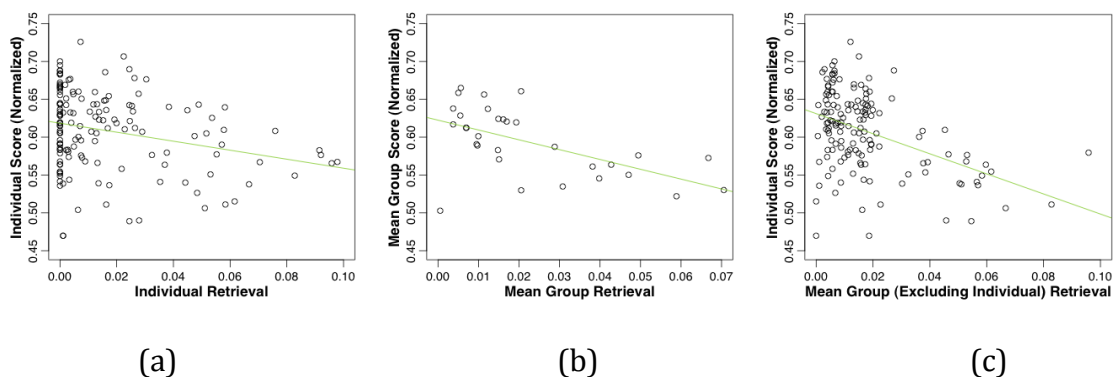


Figure 3.14: Higher scores were associated with lower retrieval rates for (a) individuals and (b) groups, as well as for (c) individuals relative to the retrieval rates of others in the group (regardless of the individual's retrieval rate).

3.3.7. Improvements

As in Experiment 1, improvements were tallied for each participant in each session. A histogram of normalized improvement share showed that just over half

(54.5%) of participants achieved less than the “fair” share of 1; however, the distribution was peaked strongly around 1, and there were no participants who obtained zero improvements (see Fig. 3.9). Just as in Experiment 1, in order to compare the distributions of improvement sums with an outcome generated from a random process, we constructed a Poisson distribution of improvement sums for each participant group with lambda (mean value) equal to the mean improvement sum for that group, and found the range of values which contained 50% of the density in this artificial Poisson distribution. In just over 60% of groups with more than one participant, the 50% density range from the associated Poisson distribution contained less than 50% of the density of the actual individual improvement sums, indicating that they generally had only a slightly greater skew than would be expected by chance.

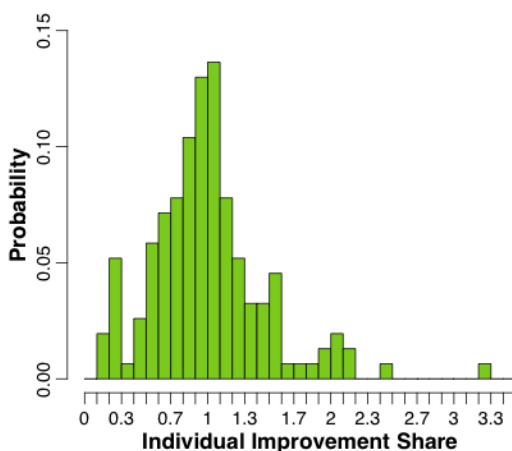


Figure 3.15: Histogram showing relatively equal achievement of improvements within groups. (A value of 1 indicates an even share, e.g. an individual achieved one-third of the total improvements in a three-person group.)

The mean choice source proportions for guesses that resulted in score improvements and those that did not are shown in Table 3.6.

Table 3.6. Mean choice source proportions for improvement and non-improvement guesses.

Choice Source	Imitation	Innovation	Retention	Retrieval
Proportion in non-improvement guesses	9.9%	12.9%	74.9%	1.7%
Proportion in improvement guesses	8.0%	20.2%	70.0%	1.4%
Difference	-1.9%*	+7.3%*	-4.9%*	-0.3%

*** significant differences**

3.3.8. Guess similarity

A comparison between the mean similarity of participants' most recent guesses to those whom they imitated, and to those whom they did not imitate, revealed a slight but significant difference: .550 for imitated vs. .503 for non-imitated ($t(5029)=-7.10$, $p<.0001$; see Fig. 3.20). In other words, prior to imitation, the average imitators' guess was more similar to that of the imitated participant(s) than to those of others. In addition, the difference between mean similarity for imitated and non-imitated participants remained over rounds (see Fig. 3.21). No significant trends were observed in linear regressions of guess similarity vs. imitated score rank, or similarity vs. the score difference between imitator and imitated participants.

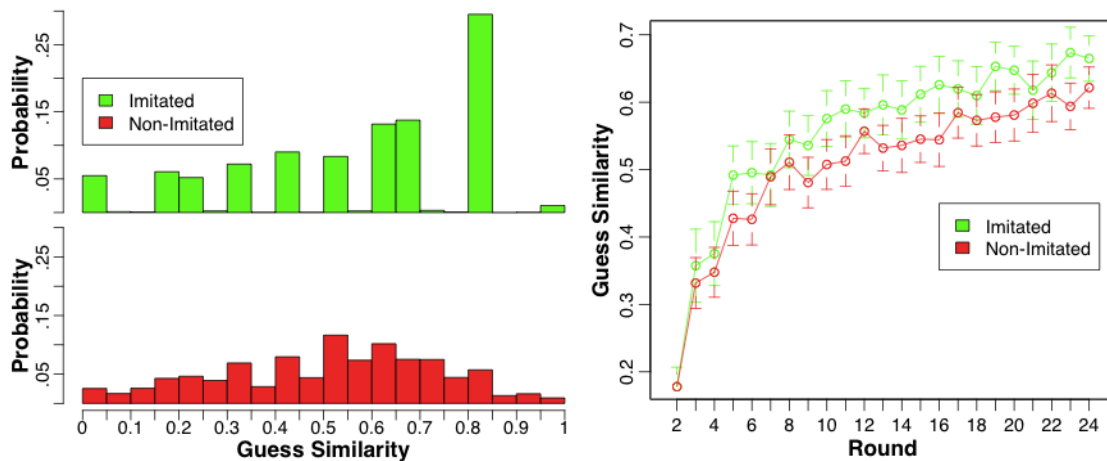
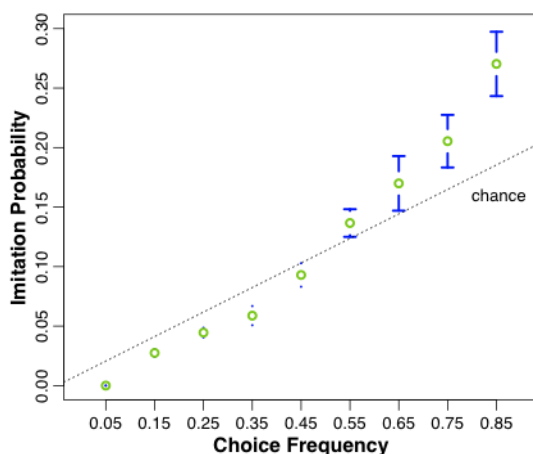


Figure 3.16: Similarity bias for imitation. (a) Imitators' previous guesses showed greater similarity to the guesses they imitated than to those they did not imitate. (b) The bias toward imitating more similar guesses was consistent across rounds in a game.

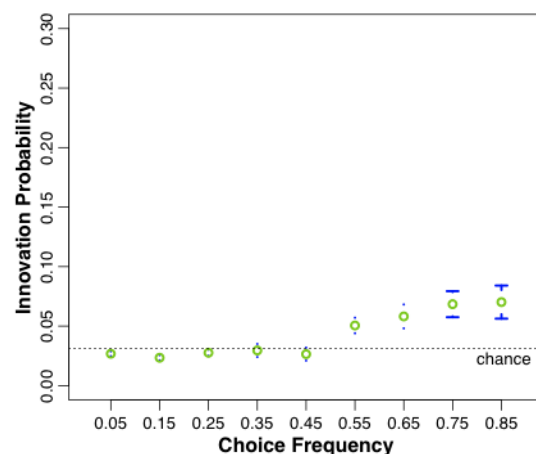
3.3.9 Frequency and momentum bias

In order to measure the bias of participants to choose an icon according to its frequency in neighbors' choices, we tallied the number of players in the group whose teams included each icon in the previous round (N_{R-1}), as well as the number of the remaining players who added it to their team in the current round via Imitation or Innovation. To convert these figures to normalized frequencies, the first number was divided by the participant group size (N), and the second number was divided by the number of participants who did not possess the icon in the previous round ($N - N_{R-1}$). In this way we were able to measure the mean probability of Imitation and Innovation for any icon not already included on a player's team, based on the frequency of its appearance on neighbors' teams in the player's display.

The chance probability of imitation (resulting from choosing an icon at random from among all neighbors' teams) scales with the choice frequency of an icon relative to the team size. The chance level of innovation (resulting from choosing an icon at random from the league display) is a constant at one divided by the league size. Since league and team size conditions were balanced in all sessions, we used the average value of each to calculate the chance baselines. A linear mixed-effects analysis of imitation probability versus choice frequency showed a positive frequency-dependent Imitation bias that was significantly greater than chance ($F(1,1128)=1648$, $p<.0001$, $B=.300$; see Fig. 3.17a), as well as a similar but much smaller frequency-dependent Innovation bias ($F(1,1128)=268.7$, $p<.0001$, $B=.062$; see Fig. 3.17b). Interestingly, the probabilities of Imitation and Innovation only rose above chance when the majority of a participant's neighbors possessed an icon (i.e. when Choice Frequency was greater than 0.5).



(a)



(b)

Figure 3.17: There were biases toward choosing elements that were more frequently represented on other teams in (a) Imitation and (b) Innovation decisions, showing a *copy the majority* strategy.

In a similar analysis of “choice momentum,” we tallied the change in the number of players whose teams included the icon in the previous two rounds ($N_{R-1} - N_{R-2}$), as well as the number of the remaining players who added it to their team in the current round via Imitation or Innovation. To convert these figures to normalized frequencies, the first number was divided by the participant group size (N), and the second number was divided by the number of participants who did not possess the icon in either of the previous two rounds ($N - \max(N_{R-1}, N_{R-2})$). In this way we were able to measure the mean probability of Imitation and Innovation for any icon not already included on a player’s team, based on the change in frequency of its appearance on neighbors’ teams in the player’s display over the previous two rounds.

The distribution of frequency changes for all icons was very nearly symmetrical around zero, such that an equivalent number of positive and negative proportion changes occurred, with small absolute changes more common than large ones. After log-transforming the Imitation probability data to achieve a normal distribution, a t-test of Imitation probability for negative and positive changes in choice frequency showed a significant positive momentum bias ($t(1236)=18$, $p<.0001$; see Fig. 3.18a), and a small but non-significant momentum bias for Innovation (see Fig. 3.18b). There was also a significant diminishing of the positive

momentum-biased Imitation effect across rounds, but no change across game order or participant group size.

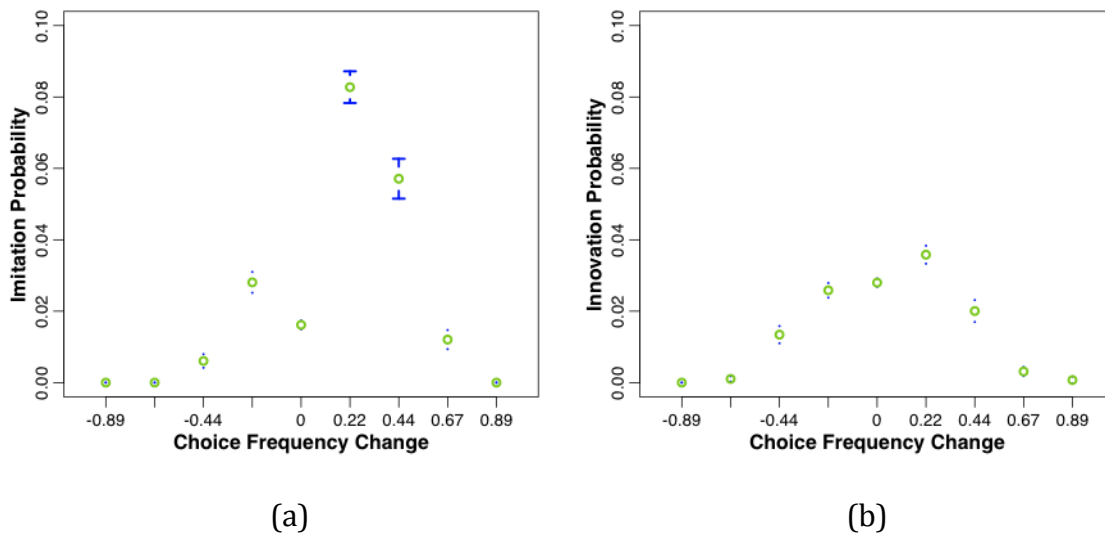


Figure 3.18: There were biases toward choosing elements whose representation on other teams was increasing in (a) Imitation and (b) Innovation decisions.

3.4. Experiment 2 Discussion

3.4.1. Dynamics and strategies

As in Experiment 1, participants' increasing mean scores across rounds and game order assured us that they learned the task and were not guessing randomly. The overall character of their strategies shared the conservative pattern of those in Experiment 1, as evidenced by the high mean proportion of Retention (which increased across rounds); this cautious approach was accentuated in the higher difficulty condition. Likewise, the corrected choice source results showed that many guess elements that were initially classified as Imitation or Retrieval were actually composed of largely Retained elements.

Our prediction of a higher mean proportion of Imitation relative to Innovation was borne out in participants' intentions (as recorded in their uncorrected choice sources), but contradicted in their effects (corrected choice sources) – the actual proportion of solution elements devoted to Innovation was higher than Imitation. As predicted, we did find significantly lower Innovation in the higher difficulty condition, but as in Experiment 1, there was no significant difference in Imitation between conditions.

Individual guesses became increasingly entrenched over time, as evidenced by the decreasing proportions of Innovation and Imitation, and increasing proportions of Retention and Retrieval, across rounds. This behavior is consistent with the *copy when uncertain* strategy in that more imitation occurred early on in each game when participants had less experience with the current problem. Guesses became entrenched at the group level across rounds as well (as shown by decreasing group solution diversity) despite decreasing amounts of imitation, because the remaining imitation was increasingly driven by convergent biases toward greater guess similarity, higher choice frequency, and positive choice momentum. These biases also help explain the decrease in guess diversity in the greater difficulty condition without an accompanying increase in the incidence of imitation. Whereas Baron, Vandello, and Brunzman (1996) found that increasing task difficulty increased the incidence of imitation, in this experiment it appears to have instead changed the focus of the imitation that occurred to favor increased group solution homogeneity.

The fact that average final scores are less than 70% of the maximum possible score implies that, especially in larger groups, participants are settling on good but suboptimal solutions due to insufficient search of the multimodal, “rugged” problem space. This result agrees with the findings of Mason, Jones, and Goldstone (2008), that fully-connected groups (like the ones in this experiment) performed relatively poorly on a multimodal problem space, whereas more sparsely-connected groups (lattices and small-world networks) found optimal solutions more reliably, though more slowly.

The lack of significant changes in choice source proportions across game order within sessions implies that learning in the combined context of the problem space and the group occurred anew for each game, without major adaptations of the members of the group to each other over the course of experiment. This may have been due to the lack of communication available for discussing or coordinating actions within the group during the session (Ostrom, Gardner, & Walker, 1994). However, guess diversity decreased across game order, suggesting (as with the decrease across difficulty conditions noted above) mechanisms of convergence that may have operated through the above biases in imitation.

3.4.2. Group size effects (and lack thereof)

The predicted increase in Imitation with larger group size (after accounting for artifactual score variance explanations), along with decreased Innovation and Retrieval indicate a bias toward social learning that scales with the number of model solutions to compare, choose from, and integrate, and the accompanying increase in

score indicates that this was a beneficial strategy for this task. Conversely, the reduction in Retrieval with increasing group size indicates a greater dependence by isolated individuals and those in smaller groups on the built-in “memory” of the Best Score option in the game as a source of reliably good solutions on which to build. The combination of these results implies that in larger groups, this function of memory may be “outsourced” to others who imitate and thus propagate and preserve good solutions within the group. This phenomenon has been explored previously as a “division of cognitive labor” in the theory of “transactive memory” in group cognition (Theiner, 2009; Wegner, 1986). A different approach to the *copy when uncertain* strategy is shown here: Imitation is favored when the payoff for innovation is relatively uncertain, compared to the abundant information available about the content and utility of neighbors’ guesses.

We confirmed the intuitive predictions (and the general pattern from Experiment 1) that most imitation events were of the top-ranked neighbor (confirming the use of the *copy successful individuals* strategy), and of neighbors with higher scores (confirming the use of the *copy if better* strategy). The actions of imitators who chose non-top-ranked or even lower-scoring neighbors to imitate were not explained by similarity between their guesses, and may have been due to random errors. The lack of influence of participant group size on this result (as well as the roughly monotonic increases in score and Imitation across group size, and the more equitable distribution of improvement shares) indicates that the task modifications we implemented in this experiment seemed to have the intended effect of clarifying the comparison of peer solutions and scores.

3.4.3. Choice strategies and cumulative innovation

The relationship evident between performance and choice strategy, in which above-average Retention and Imitation produce higher scores, while above-average Innovation and Retrieval produce lower scores, reinforces the evidence from Experiment 1 that the overall conservative (but not regressive) approach noted above is beneficial for this task. However, a counterpoint for this seemingly simple result is provided by the comparison of choice source proportions between solutions which generated improvements and those that did not, which showed that a replacement of significant amounts of Imitation and Retention with Innovation was required to create new and improved solutions. The fact that substantial amounts of each of the above three choice sources were present in such improved solutions shows that improvements were cumulative, relying on individuals' own past solutions as well as borrowing from others. This, in turn, implies that the adaptive value of Imitation in this context is due to its facilitation of selective learning and the generation of cumulative improvements with less risky Innovation (Boyd & Richerson, 1995; Kameda & Nakanishi, 2003).

3.4.4. Improvements, free-riding, and an absence of tragedy

The results regarding improvements and their distribution within groups indicate that participants shared the task of finding better solutions more equitably than if most participants were pursuing a pure social loafing strategy. However, the decrease in Innovation and increase in Retention in larger groups, suggest

adaptations by group members to limit risky Innovation to what was required to achieve “good enough” results given the efforts of others. In fact, it may be that the lower end of the distribution of Innovation that actually occurred was nearly optimal for the very thin-tailed distribution of scores in the space of possible solutions (see Figure 23). Only 4.3% and 1.6% of possible solutions have higher scores than the participants’ average final score in the lower and higher difficulty conditions, respectively. Thus, although the results showing inequality in individual improvement shares indicate a substantial amount of free-riding in this experiment, there was no associated “tragedy of the commons” for Innovations (Hardin, 1968; Ostrom, 1990). This also offers a plausible explanation for the increased Innovation and corresponding lower performance of participants in smaller groups -- having fewer fellow players to copy from also provides fewer clues as to the distribution of possible scores, which prompts further risky exploration at a higher cost in average performance.

3.5. Experiments 1 and 2 – General Discussion

3.5.1. Factors that influence imitation – when and whom to imitate

Participants in both Experiments 1 and 2 displayed fairly conservative strategies, typically preserving a large proportion of each guess from round to round (through low turnover and high retention, respectively). The entrenchment dynamics seen in both experiments showed this characteristic intensifying over time, as increasing proportions of guesses were preserved in later rounds. As for the changes that were made, Laland (2004) describes several strategies that are

observed across a wide range of species. The *copy when uncertain* strategy seemed to be the default at the beginning of both experiments, but for those who learned the risks of innovation firsthand, the *copy when asocial learning is costly* strategy was a very likely next resort. Participants almost universally employed the *copy when better* and *copy the best* strategies as well, and a strategy of frequency-dependent imitation that closely resembled *copy the majority* was prevalent in Experiment 2. Participants also showed a positive “momentum bias” toward imitation of solution elements that were increasing in overall frequency in the group rather than decreasing. This phenomenon has also been shown to occur in an examination of baby-naming decisions by parents as revealed by 130 years of social security data (Gureckis & Goldstone, 2009).

Characteristics of the problem space and the information environment played a substantial role in the dynamics of these strategies and their consequences. The participant group size-dependent patterns of imitation and its effects in Experiment 1 (and the lack thereof in Experiment 2) showed the importance of clear and sharable solution information.

It is useful to note that the task design in both experiments allowed participants to pursue hybrid strategies within a single round, in which they retained some parts of a solution while changing others using both social and asocial learning. One particularly interesting way this was accomplished was through similarity-biased imitation. This allowed the imitator to make use of social information while keeping a solution partially compatible with previous solutions and existing knowledge of the problem space, a phenomenon discussed at length in

relation to innovation propagation by Rogers (2003). A bias toward borrowing from similar rather than dissimilar solutions has also been incorporated into general machine learning algorithms featuring multiple agents simultaneously searching for solutions (Goldberg, 1989). When agents borrow solution elements from other agents pursuing substantially different solutions, there is a strong risk that the resulting blend of solutions will be a sub-optimal hybrid not well adapted to the niche of either of the original solutions. By analogy, two solutions to predation for a small mammal might be evolve large claws for climb trees effectively or to develop large wings for flying. However, a half-breed that combines both solutions might well enact neither solution effectively. Likewise, given the complex problem search landscapes used in the experiments, participants may have been biased to copy solution elements from similar rather than dissimilar solutions to ensure greater solution compatibility.

3.5.2 Group-level effects of imitation and innovation

The results of Experiment 1 suggest that imitation can be individually counterproductive when social information cannot be readily compared, integrated, and adapted to create new solutions. This situation may arise for several reasons: (1) evaluative information is either actually unavailable, or presented in such a way that cognitive load effects hinder its use; (2) the problem space is too large or

complex for parts of different solutions to be easily analyzed and combined; or (3) the problem space is too large for substantial changes to be effectively evaluated.

The results of Experiment 2 show that when the above-mentioned problems can be avoided or ameliorated, imitation can be productive for individuals as well as groups, because it enables the preservation of good tentative solutions in “group memory” and their further improvement through cumulative innovation. These results also showed that the risks of innovation can outweigh the benefits for both individuals and groups, and thus become counterproductive when used too much. Obviously, a complete lack of innovation will result in a lack of improvements (because strategies that combine imitated elements from different models will often lose beneficial interactions), but this experiment suggests that in a large and complex problem space, at both the individual and group levels, innovation is best used sparingly, along with the retention of previous good solutions and imitation of others, to improve overall outcomes while maintaining high average performance.

These two results taken together with the reductions in diversity over time imply a view that is at odds with those predicted from a simple Tragedy of the Commons (Hardin, 1968) or producer-scrourger dilemma (Kameda & Nakanishi, 2002) interpretation of social learning. Much like “conformist,” being a “scrourger” often carries a negative connotation or denotation, such as “social loafing” (Latané, Williams, & Harkins, 1979). However, such behavior may be appropriate when not all group members’ full efforts are required to produce sufficient benefit. In a complex but relatively stable environment, the best outcome for the group may result from most group members converging on a “good enough” solution quickly to

achieve high mean performance, and then introducing productive innovations when possible. Thus, in some circumstances a tragic (or at least distinctly suboptimal) outcome can result from too much innovation and not enough imitation, rather than the other way around, because innovation is risky and possibly redundant (and thus wasteful of resources), and imitation helps to concentrate efforts and improve the thoroughness of search in the proximity of known good solutions. Given some baseline inclination to a minimum amount of individual exploration, the limiting factor in improving search performance may be the amount of information sharing and coordination among searchers, which allow them to pool both the benefits and the risks of asocial learning (Hess & Ostrom, 2007).

Of course, the results obtained here are likely to be highly dependent on the problem space and the information environment in use. Though the benefits of social learning in a temporally stable environment are often assumed to be evident (e.g. Kameda & Nakanishi, 2002), this study illuminates some details about the dynamic individual and group-level mechanisms by which these benefits can accrue (or not, in some circumstances). Given imperfect individual memory, the “cultural knowledge pool” (Kameda & Nakanishi, 2003) requires not only provision of information by asocial learning, but also its amplification and preservation through mechanisms like frequency-biased adoption, or “conformist transmission” (Boyd & Richerson, 1985). Our task, in which solutions have multiple components with epistatic relationships, also allowed us to examine how such solutions are built cumulatively using selectively varying proportions of different information sources.

This adds realistic complexity beyond that provided by models and experimental settings with simpler problem structures or less flexible learning strategies.

4. Exploration as a Social Dilemma

4.1 Dilemmas of knowledge

So far we have found evidence for several important learning strategies discussed in previous models and animal research. We have also explored the idea that collective search problems like the ones in our experimental tasks are potentially susceptible to social dilemmas (though we have not observed evidence for such a dilemma). However, we have not sufficiently elaborated upon the characteristics of the "resource" involved, how it is created and maintained, or how it might be degraded or destroyed. At this point it will be useful to return to the literature on social dilemmas to pursue this further.

4.1.1. Stories and assumptions

Social dilemmas can be said to occur "whenever individuals in interdependent situations face choices in which the maximization of short-term self-interest yields outcomes leaving all participants worse off than feasible alternatives" (Ostrom, 1998). Contemporary examples of large-scale social dilemmas include the failure to limit the production of atmospheric pollutants, and the overharvesting of ocean fish stocks. But such dilemmas can arise in many everyday situations, from traffic jams at rush hour to fibbing at tax time. Social dilemmas have often been framed in terms of three metaphorical stories: the Prisoner's Dilemma (Poundstone, 1992), the Tragedy of the Commons (Hardin, 1968), and the Logic of Collective Action (Olson, 1965).

The Prisoner's Dilemma is based on a hypothetical situation in which two individuals accused of committing a crime together are questioned separately and offered two choices: confess to the crime or keep silent. If both keep silent, the authorities can only convict them on minor charges and the penalty for both is mild. If both confess, they are convicted for the crime and receive substantial jail sentences. If only one confesses, he goes free while the other receives a harsh sentence. This set of possibilities is such that whatever the other does, the rational (or dominant) option for each individual is to confess. However, if both individuals follow this reasoning, the best option for both (keeping silent) is unavailable. (It may be that we do not want criminals to be able to escape such a dilemma, but this situation can be re-framed in any number of other ways, e.g. an arms race between countries, steroid use among competitive athletes, etc.) The actions of the two agents are interdependent such that either can independently increase his own payoff at the expense of the other, but the best outcome can only be obtained if both have some way to trust the other and jointly increase their payoffs.

The Tragedy of the Commons (Hardin, 1968) is another hypothetical situation, in which a pasture (or commons) is available for use by many individuals to graze their animals. Each additional animal added to the commons increases its owner's payoff in the short term, but reduces the amount of fodder available for all of the other animals. In the long term, overgrazing can lead to the ruination of the pasture, so that no fodder is available. The marginal benefit of adding another animal is obtained by one individual, but the short-term cost is spread across all individuals using the commons (a negative externality). This means that the short-

term benefits outweigh the costs for each individual; if all individuals follow this reasoning symmetrically, the long-term benefits (continued grazing capacity) are unavailable. Again, this model is not only important for cattle farmers in agrarian villages, as it can be re-framed to fit many other situations more relevant to modern society (e.g. using lawn sprinklers supplied by a common reservoir during a drought). Once again, the important point is that the actions of multiple agents are interdependent such that each can increase his or her own short-term payoff at the expense of others, but the best long-term outcome can only be obtained if all find some way to cooperate.

The Logic of Collective Action (Olson, 1965) portrays the conflict inherent between the self-interests of a large number of firms selling the same good. The market for this good is presumed to be perfectly competitive, but in a "disequilibrium" state, so that price exceeds marginal cost for all firms. Each would like to maximize profits by selling as much of the good as they can produce at the highest price possible. However, (under certain assumptions such as high barriers to market entry, inelastic demand, and so forth), firms that increase production will sell more but also increase the overall supply, which will eventually lower prices. Any firm that attempts to unilaterally restrict its own output in order to lower supply will simply reduce its revenues, given that no firm has enough market power individually to affect prices. All of the firms have a common interest in higher prices, but each would rationally prefer that the others bear the cost of lowered production in order to get it. (Once again, if one has trouble feeling empathy for the firms depicted here, the framing can be changed to that of workers who cannot all earn a

sufficient wage if each offers his full capacity to exploitative employers.) In Olson's formulation, the only way to keep prices high is through some external intervention, such as government price supports, tariffs, or cartel agreements, the creation of which requires costly lobbying or organization. Assuming that the firms somehow foresee the problem and band together to collectively create the price-supporting intervention (a slight departure from the previous two models), a problem remains. Because the market for the good is indivisible, each firm once again has the rational incentive to enjoy the benefits of such intervention without contributing to create or maintain it, if such contributions (lobbying firm fees or union membership dues) are voluntary. Thus the first-order dilemma (agreeing to organize to control prices) is at least temporarily solved, but the second-order dilemma (maintaining the costly organization) is vulnerable to a "free-riding" problem.

Each of the above three models illustrates an important point about social dilemmas, and the nontriviality of their solutions. Though they can each be adapted to resemble familiar situations, problems arise when these models are taken to be realistic representations of human behavior. Without denying that social dilemmas can have tragic outcomes, it must be noted that the stories above (and the theories they represent) involve several overly simplistic assumptions about social dilemmas: (1) resource users are strictly selfish maximizers of short-term gains, who will not cooperate to overcome a social dilemma, (2) it is a relatively simple analytical task to change the incentives of resource users by designing new rules, and (3) centralized direction and coercion is required to successfully overcome social dilemmas (Ostrom, 1999). In general, the three assumptions above have not

been borne out by data gathered on human responses to social dilemmas, in the laboratory or in the field. People can in fact recognize the dilemmas they face, and change rules and incentives to avoid them (Ostrom, 1990). However, doing so can be quite a complex and uncertain process, involving much trial and error, and may not always be successful (Sandberg, 2001). Finally, centralized solutions have generally not been as successful as those designed using the knowledge and participation of local resource users (Sneath, 1998).

4.1.2. Types of goods

Social dilemmas deal with potential conflicts between agents over a valuable resource or good. Two pertinent dimensions over which goods can vary are subtractability (whether the use of some portion of the good by one individual precludes its use by others), and excludability (the extent to which potential users can be prevented from using the resource). Subtractability is generally a binary characteristic, and subtractable goods are also known as rivalrous goods, because potential users are necessarily rivals when any portion of a good can only be used by one of them, but is desired by all. When a subtractable good is scarce and no measures are in place to prioritize its use among individuals (such as property rights or other rules), the expected result is increased scarcity and conflict. However, the characteristic of subtractability can be used to monitor the use of a good, which can help in encouraging or enforcing cooperation in a dilemma. Excludability is a more continuous characteristic, and need not be absolute in order to be effective. Physical and technological means play a role, but legal, social, and

cultural norms are important as well; concepts of fairness, justice, and tradition can all affect the excludability of a good.

"Private goods" are those that are both subtractable and excludable, such as a tool or a loaf of bread. "Club goods" are those that are excludable but not subtractable, such as access to copyrighted works, or a scenic view from fenced land. Private and club goods are generally presumed not to entail serious dilemmas, because their owners or providers can exclude potential users, and users can avoid those which are inefficiently provided.

Goods which are subtractable but for which exclusion is imperfect or costly are known as "common goods" or "common pool resources" (CPRs). Instances of these include fisheries, forests, and the canonical example of pasture lands. Common-pool resources are typically self-renewing at some finite rate, but a dilemma may obtain if individual incentives do not sustain appropriation of the resource and avoid overuse or destruction. They have typically been thought of according to the Tragedy of the Commons model as described above.

Goods that are imperfectly excludable and non-subtractable are known as "public goods." Instances of these include generally intangible or indivisible items such as television broadcasts and the light from lighthouses, respectively. The primary potential dilemma for public goods is the "free-riding" problem: how such goods can be sufficiently provided and maintained, since they can be used by individuals who don't contribute to their provision (free riders). A connected problem is how to assure those who wish to contribute (but don't want to waste their contribution) that others will do so as well, instead of free-riding (the

assurance problem). This dilemma is often modeled using the Logic of Collective Action paradigm described above.

Public Goods and Common Pool Resources are conceptually and naturally related, in that a CPR often requires an initial or continuing investment in the provision of institutions and infrastructure related to appropriation. This investment allows current and future users to participate in the appropriation of the resource; that is, the inputs that create the benefit of the institution's continued existence are rivalrous even if the resource itself is not. The more general classes of provision and appropriation problems are typically modeled and treated separately in order to elucidate useful characteristics in alleviating each type of problem (Ostrom, Gardner, & Walker, 1994).

4.1.3. Knowledge as a commons

The task of understanding knowledge as a good according to the above taxonomy can be a bit tricky, because knowledge can take various forms that are subject to different uses and norms. Hess and Ostrom's (2007) treatment of "Knowledge as a Commons" begins by defining "knowledge" as "all types of understanding gained through experience or study" (p. 8). In this intangible form, knowledge appears to be a pure public good. Firstly, it is quite difficult to exclude potential users: as discussed in previous chapters, humans have a prodigious talent and inclination for gaining knowledge from each other, and once a particular idea has been understood, it is difficult to un-understand (or "derstand" (Currie, 2010)) it by any reliable means, voluntary or coercive. Secondly, one person's

understanding of an idea does not preclude or subtract from any other person's; if anything, the sharing of understanding can reinforce and preserve it.

Of course, people have found ways to encode and record this intangible understanding in various physical forms (e.g. painted tomb walls, incised clay tablets, handwritten paper scrolls, printed books, pressed phonograph records, celluloid film, and documents and databases in any number of digital media) in order to archive it and pass it on to new potential understanders. The varying degrees to which these tools for instantiation of knowledge are subject to physical and legal constraint is what complicates the governance of knowledge as a resource.

As physical objects, printed matter and audiovisual recordings can be privately owned by an individual and made inaccessible to others, or held by a public library collection for full and free use by one person at a time, or kept in a museum's display case where they are observable but not fully usable. Images, text, and sound can be encoded digitally and copied more or less effortlessly (though they must always be stored in some physical form).

Despite the non-rivalrous nature of intangible knowledge (and as transmission and storage become cheaper, perhaps any digitizable knowledge) as a public good, some resources required to create it (money, tools, etc.) are certainly rivalrous. To the extent that knowledge depends on more than one person for its provision, the classical assurance problem of collective action obtains. To the extent that the creation of new knowledge depends on the use of previously existing knowledge and (1) the physical infrastructure of knowledge storage and access requires resources for maintenance, or (2) knowledge can be appropriated and

access prevented, dilemmas of underprovision and overappropriation become possible.

Finally, if a "commons" is defined simply as a "a shared resource that is vulnerable to social dilemmas" (Hess & Ostrom, 2007, p. 13), it is easy to see "knowledge as a commons." For Hess and Ostrom (2007), analysis of any commons requires examinations of equity ("issues of just or equal appropriation from, and contribution to, the maintenance of a resource"), efficiency ("optimal production, management, and use of the resource"), and sustainability ("outcomes over the long term"). We will return to these three criteria to judge the results of our subsequent experiments and those of other studies.

4.2. Influence of information environment on social learning strategies

So far we have not found evidence for a "tragic" outcome in underprovision of individual exploration in our participants' collective search behavior over time, extreme inequity in provision, or unsustainability in longer-term results. Though participants were rather conservative in their strategies, innovation was more common on average than imitation, implying a relative lack of harmful "free riding." Improvement share was fairly equitably distributed within groups, and final scores were quite high in terms of percentiles in the distribution of possible outcomes. However, participants generally did not reach optimal solutions, so there could be possibilities for improving efficiency and absolute performance through changes in participants' incentives and information environment. There may also be important

factors that could harm participants' ability to contribute to the production and sharing of innovations.

4.2.1. Inefficiency and information

Previous work has shown that making social learning processes less efficient can actually improve the long-term performance of groups attempting to search a complex problem space, both in laboratory experiments (Mason, Jones, & Goldstone, 2008) and agent-based models (Lazer & Friedman, 1997). The reduction in efficiency was implemented in these studies by changing the distribution of links in the social network connecting participants. This had the effect of slowing the spread of information via social learning, encouraging greater exploration, and maintaining greater solution diversity among group members, thus avoiding premature settling of the group's search on good but suboptimal regions of the problem space. Having observed some general dynamics and learning strategies of collective search in the experiments described so far, we wished to see whether this seemingly paradoxical effect would occur with conceptually similar changes to our experimental paradigm.

Our previous experiments have also shown that the social learning strategies that participants pursue depend on the information available to each participant, specifically in terms of the number of other participants sharing information about their tentative solutions. Presumably, this is because larger numbers of peers sharing information increase the overall reliability of the information available to each. As previously discussed, this can be interpreted as an instance of the *copy when uncertain* social learning strategy (Laland, 2004), because greater certainty

about the validity of social information increases the relative uncertainty of asocial learning. Other work on diffusion of innovations has shown that the use and influence of social information depend on the relative ambiguity of the benefit of adopting a particular solution (Granovetter, 1978; DiMaggio & Powell, 1983; Abrahamson & Rosenkopf, 1997; Gibbons, 2004). In a model of social foraging behavior in a changing environment, Krebs and Inman (1992) showed that if there is a delay in an observer's recognition of the foraging success of a demonstrator, there is a corresponding reduction in the information (and thus the benefit) provided by the social information provided by the demonstrator; with a long enough delay, the observer is better off ignoring the demonstrator and foraging asocially. Another result from modeling is that if personal (asocial) and social information cannot be gathered simultaneously, there may be no benefit to using social information, because they cannot be effectively combined; furthermore, when others' actions are available to be observed, but not the resulting success-related cues, social information should be minimized to avoid information cascades (Giraldeau, Valone, & Templeton, 2002; Bikhchandani, Hirshleifer, & Welsh, 1992).

4.2.2. Motivation and conceptual description of changes in Experiment 3

Having shown in previous experiments that participants can use a variety of learning strategies to solve a collective search problem, we wanted to see how these strategies would shift in response to changes in the information environment. Rather than changing the structure of the social network connecting our participants (as in the work cited just above), we decided to simply remove access

to score information about others' solutions. Participants would still be able to observe and copy their peers, but would have to wait for their own feedback to learn the value of imitated choices; information about others' solutions was entirely ambiguous, while information about their own solutions was entirely unambiguous. This is similar to contexts in which individual animals can observe the behavior of others, but not the cues or outcomes that motivate those actions, or situations in which private firms can withhold information about revenues (i.e. the success of their actions) from competitors.

We wished to use this relatively small modification to ask questions about how the elimination of information supporting one kind of social learning would cause participants to change their learning strategies, and how such changes would affect performance. As the work above on improved collective search performance through reduced communication efficiency indicates, impeding social learning may increase asocial learning among most participants. Such an outcome would presumably reduce free-riding (improving equity of provision); but would this change cause participants to actually find better solutions, or would the reduced efficiency of access to previous knowledge (and the inability to use it simultaneously with asocial information) reduce the efficiency of knowledge production? Presuming that social learning is not displaced entirely by asocial learning, how would its prevalence and use change, and what information would be used to direct remaining imitation choices? Finally, would these adaptations in behavior improve overall individual and collective outcomes and improvements over time (sustainability)?

In order to avoid ceiling effects on performance and presumably make it easier to distinguish the performance of successful social and asocial learning, we changed the problem space slightly from the previous experiment to shift some of the mass of the score distribution to a longer and fatter upper tail (increasing the proportion of solutions with higher scores). This allowed the parallel discovery of higher-scoring solutions among participants without requiring as much convergence of solution content; performance could be increased without necessarily constraining solution diversity.

5. Experiment 3 – Creature Game B (score visibility)

5.1. Experiment 3 Overview

The task used in this experiment was the same as the “Creature Game” of Experiment 2, with two major changes: (1) the scores associated with peers’ solutions were shown in half the games in each experiment session, and hidden in the other half; (2) the problem space was changed by adding more positive-scoring bonus interactions between solution elements, which had the effect of making the upper tail of the score distribution longer and fatter, so that there were relatively more solutions with high scores. Modification (1) allowed for the examination of differences in strategies and performance associated with differences in the available social information. Modification (2), though it made direct comparisons with Experiment 2 slightly more tenuous, allowed participants to achieve high scores without necessarily converging in their solutions.

5.1.1. Predictions

Because of the small changes we made to the task, we expected that results would be quite similar to those of Experiment 2 when peers’ scores were shown. When evaluative information about peer solutions was unavailable, participants would be unable to be sufficiently selective in imitation, and thus participants employing highly imitative strategies would have relatively lower scores than those with less imitation-heavy strategies, participants would employ less imitation and more innovation, and solution diversity would increase. Similarity-biased and frequency-biased imitation strategies would be stronger when peer scores were

invisible, in order to compensate for the lack of direct evaluative information. Overall, rather than improving exploration behavior, the impedance of social learning by making peer scores invisible would result in lower mean scores (including those of relatively successful asocial learners) because they would be unable to easily take advantage of good solutions found by others through selective imitation and further improve upon them.

5.2. Experiment 3 Methods

234 participants were recruited from the Indiana University Psychology Department undergraduate subject pool, and were given course credit for taking part in the study. Participants populated each session by signing up at will for scheduled experiments with a maximum capacity of 9 persons, and were distributed across 65 sessions as shown in Table 5.1.

Table 5.1: Distribution of participants across group sizes in Experiment 3

Group size	1	2	3	4	5	6	7	8	9
# Sessions	16	8	11	11	7	2	4	4	2
# Participants	16	16	33	44	35	12	28	32	18

The task used was nearly identical to that of Experiment 2, with the following changes. To more easily fit the session in the one-hour time limit required for experiments using our subject pool, there were six games per session instead of eight. In three of these games (the *invisible-scores* condition), the scores of other

participants were not shown along with their solutions from the previous round; in the other three games (the *visible-scores* condition), other participants' scores were shown. Of course, this distinction only mattered in sessions that included more than one participant.

The distribution of individual point values for the icons was the same as for the larger league size in Experiment 2, but seven new positive bonus interactions were added between icons, and several existing interaction values were shifted to different pairs of icons, as shown in Fig. 5.1 (compare to Fig. 3.2b). These changes had the effect of increasing the complexity of the problem space, as well as increasing the number of possible high-scoring teams. As a result, the possible score range changed to $[-6,88]$, but all scores were again normalized to the range $[0,1]$ for ease of analysis. (Note that due to this shift, normalized scores cannot be directly compared between Experiments 2 and 3.) The combinations of these individual and pair values resulted in the probability distribution of scores among all possible teams shown in Fig. 5.2 (compare to Fig. 3.3b).

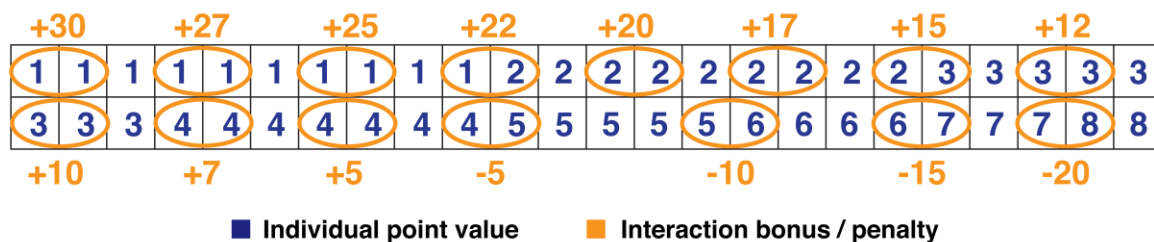


Figure 5.1: Point distribution for individual icons (boxes) and interaction bonuses and penalties (ovals).

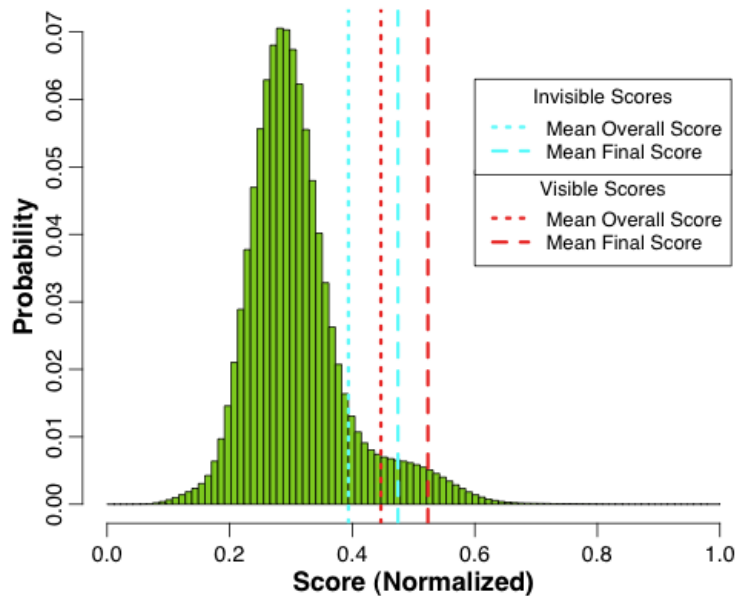


Figure 5.2: Distribution of scores for all possible teams.

5.3. Experiment 3 Results

5.3.1 Overall means

Mean dependent variables in each condition are shown in Table 5.2 (see also Fig. 5.2). Of all grouped participants, 81.7% had higher mean scores in the visible-scores condition than in the invisible-scores condition (see Figure 5.3). Isolated participants achieved mean overall and final scores of .356 and .395.

Table 5.2. Mean score, guess diversity, and choice source proportions by condition

Cond.	Overall Score (Percentile)	Final Score (Percentile)	Guess Diversity	Imitation	Innovation	Retention	Retrieval
Visible	.447* (92.6%)	.523* (97.5%)	62.2%*	9.1%	13.4%*	75.0%*	2.4%*
Invis.	.394* (89.1%)	.475* (94.6%)	79.0%*	8.4%	15.0%*	71.0%*	4.2%*
Isolated Partic.	.356 (81.4%)	.395 (89.1%)	--	--	29.2%	55.8%	13.7%

* significant differences between conditions

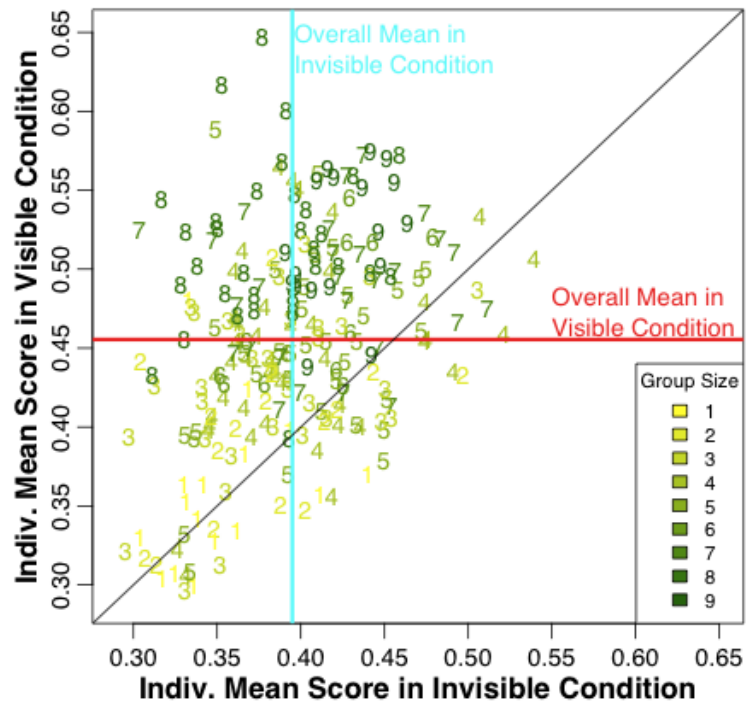


Figure 5.3: Scattergram of individuals' mean scores in each condition, labeled with their participant group size.

5.3.2. Rounds

Linear mixed-effects models were used to examine trends across rounds for score and guess diversity, with a random effect of participant group. Analysis of score versus round showed a strong positive trend for grouped participants in the visible-scores condition ($F(1,1126)=521.82$, $p<.0001$, $B=.656$, mean total increase=0.220), and a slightly shallower positive trend in the invisible-scores condition ($F(1,1126)=446.53$, $p<.0001$, $B=.727$, mean increase=0.172; see Fig. 5.4). Guess diversity showed a similarly strong decrease across rounds in the visible-scores condition ($F(1,1126)=304.78$, $p<.0001$, $B=-.443$, mean change=-0.468), and a weaker decrease in the invisible-scores condition ($F(1,1126)=97.31$, $p<.0001$, $B=-0.453$, mean change=-0.271; see Fig. 5.4). Isolated participants' scores increased much less (though significantly) across rounds ($F(1,751)=30.26$, $p<.0001$, $B=.348$, mean increase=0.075; see Fig. 5.4).

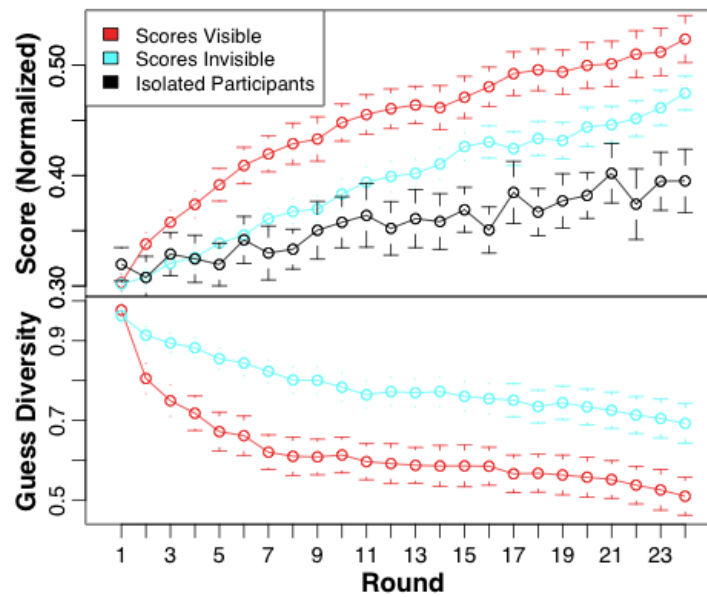


Figure 5.4: Scores increased and guess diversity decreased more across rounds in the scores-visible condition than in the scores-invisible condition.

Trends for choice sources across rounds showed very similar patterns to those in Experiment 2: Imitation and Innovation decreased significantly, and Retrieval and Retention increased significantly. There were no substantial differences in slopes between conditions, nor substantial differences with the slopes over rounds found in Experiment 2.

5.3.3. Game order

Similar linear mixed-effects models were used to examine trends across game order for each dependent variable within conditions. For this analysis, the game order value for each game was corrected to its order within the condition, i.e. Game 1, 2, or 3 in each condition. Score displayed a slight but significant increase

across game order in the visible-scores condition ($F(1,97)=16.57$, $p=.0001$, $B=0.264$, mean change= $+0.048$; see Fig. 5.5), and a small but non-significant increase in the invisible-scores condition. Guess diversity displayed a corresponding decrease across game order in the visible-scores condition ($F(1,97)=62.09$, $p<.0001$, $B=-0.263$, mean change= -0.103), as well as in the invisible-scores condition ($F(1,97)=70.79$, $p<.0001$, $B=-0.363$, mean change= -0.115 ; see Fig. 5.5).

As for choice sources, changes over game order within conditions were generally slight. Imitation decreased slightly but significantly over game order in the visible-scores condition ($F(1,97)=6.24$, $p=.0141$, $B=-0.121$, mean change= -0.011), while increasing significantly in the invisible-scores condition ($F(1,97)=32.97$, $p<.0001$, $B=0.289$, mean change= $+0.040$; see Fig. 5.6a). Innovation decreased significantly across game order within both the visible-scores ($F(1,97)=26.82$, $p<.0001$, $B=-0.173$, mean change= -0.028) and the invisible-scores ($F(1,97)=41.04$, $p<.0001$, $B=-0.226$, mean change= -0.036 ; see Fig. 5.6a) conditions. Retention increased significantly only in the visible-scores condition ($F(1,97)=29.97$, $p<.0001$, $B=0.252$, mean change= $+0.041$; see Fig. 5.6b), and Retrieval increased significantly only in the invisible-scores condition ($F(1,97)=14.42$, $p=.0004$, $B=0.228$, mean change= $+0.012$; see Fig. 5.6b).

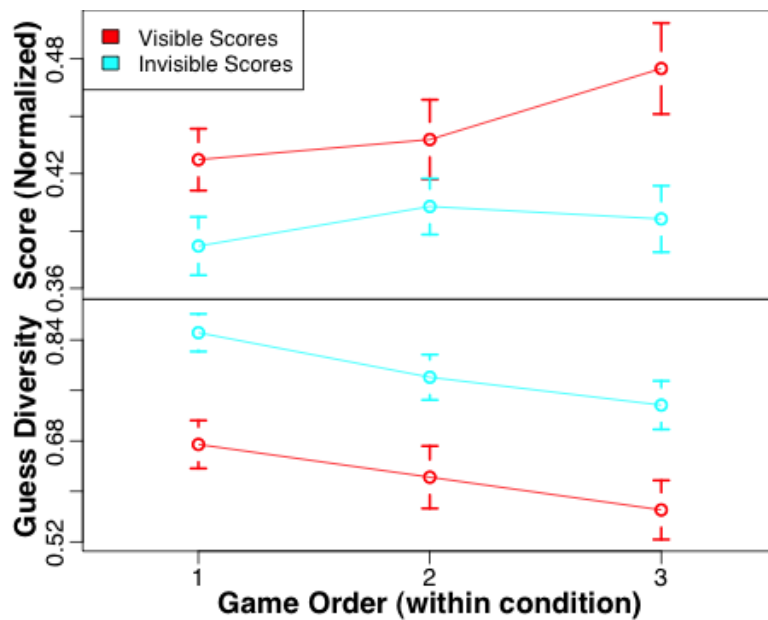


Figure 5.5: Score increased significantly only in the visible-scores condition, and guess diversity decreased in both conditions.

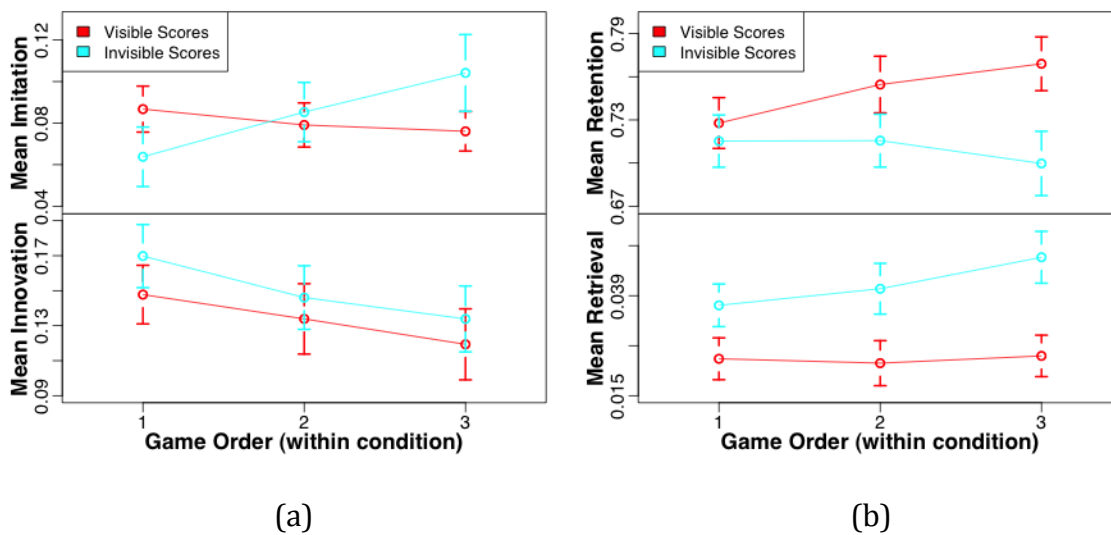


Figure 5.6: (a) Imitation and Innovation decreased significantly in the scores-visible condition, while Imitation increased and Innovation decreased in the scores-

invisible condition. (b) Retention increased significantly only in the visible-scores condition, and Retrieval increased significantly only in the invisible-scores condition

5.3.4. Group size

Trends across participant group size for each dependent variable within conditions were examined using linear mixed-effects models, with the participant group used as a random effect on the intercept. Score increased significantly with group size in the visible-scores condition ($F(1,63)=79.59$, $p<.0001$, $B=0.580$), as well as in the invisible-scores condition ($F(1,63)=15.45$, $p=.0002$, $B=0.309$; see Fig. 5.7), though the latter trend was not as strong. Guess diversity showed a corresponding decrease with increasing group size in the visible-scores condition ($F(1,47)=68.83$, $p<.0001$, $B=-0.699$), as well as a weaker trend in the invisible-scores condition ($F(1,47)=17.28$, $p=.0001$, $B=-0.430$; see Fig. 5.7).

As for choice sources, Imitation increased significantly for larger groups in both the scores-visible ($F(1,47)=41.47$, $p<.0001$, $B=0.597$) and scores-invisible ($F(1,47)=28.04$, $p<.0001$, $B=0.500$; see Fig. 5.8a) conditions, and Innovation decreased significantly for larger groups in both the scores-visible ($F(1,47)=18.42$, $p=.0001$, $B=-0.492$) and scores-invisible ($F(1,47)=14.04$, $p=.0005$, $B=-0.436$; see Fig. 5.8a) conditions. Retention increased for larger groups only in the scores-visible condition ($F(1,47)=5.91$, $p=.019$, $B=0.286$; see Fig. 5.8b), while Retrieval showed no significant trend across group size (see Fig. 5.8b).

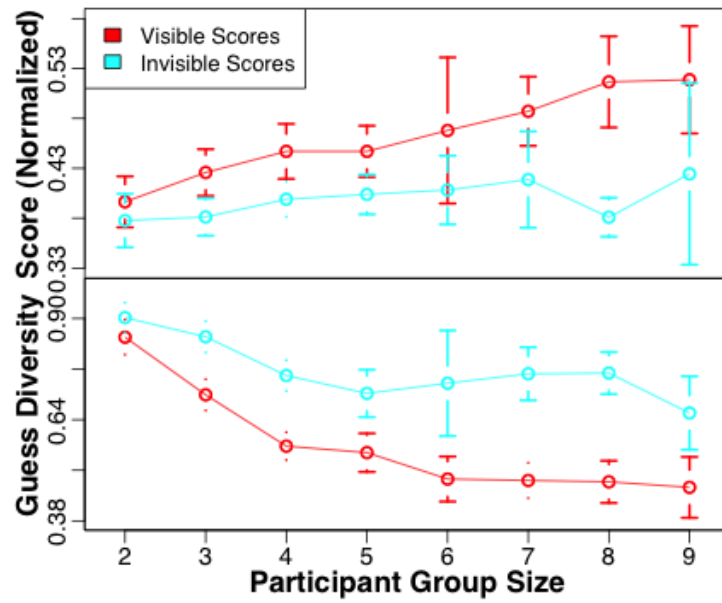


Figure 5.7: As participant group size increased, mean scores in a group increased, and the diversity of offered solutions decreased, with slightly weaker effects for both in the invisible-scores condition.

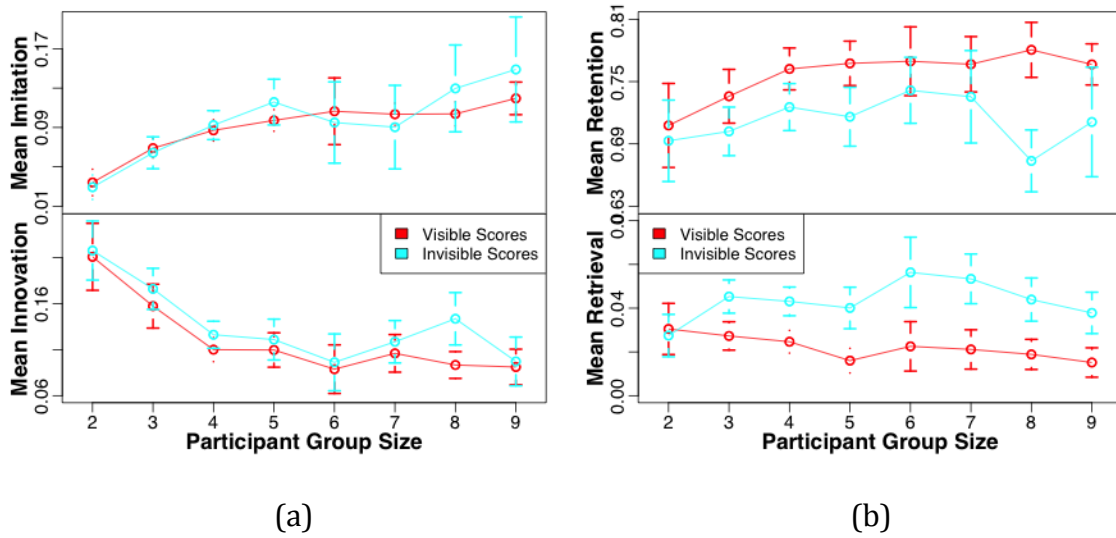


Figure 5.8: As participant group size increased, (a) mean proportions of Imitation increased and Innovation decreased in both conditions, and (b) Retention increased

only in the visible-scores condition, and Retrieval showed no significant change across group size.

5.3.5. Differences in imitation

Of all instances of single-participant imitation, the score of the imitated participant was greater than that of the imitator significantly more often in the visible-scores condition than in the invisible-scores condition ($t(74)=16.07$, $p<.0001$; see Fig. 5.9a); in the latter condition, the probability was about 54%, or approximately at chance. In addition, there was a significantly greater probability of imitating the top-scoring solution in the group in the visible-scores condition ($t(80)=20.08$, $p<.0001$; see Fig. 5.9b).

To examine separately how *often* and how *much* participants imitated one another, we measured the mean proportion of guesses in which there was greater than zero Imitation (*Imitation incidence*), as well as the mean Imitation proportion in such cases (*Imitation proportion*). Mean Imitation incidence was significantly higher in the visible-scores condition ($F(1,229)=31.17$, $p<.0001$), but the distribution of mean imitation proportions was weighted significantly more heavily toward higher values in the invisible-scores condition, as shown by a Kolmogorov-Smirnoff test of equality of distributions ($D=0.1893$, $p<.0001$; see Fig. 5.10). In other words, participants in the scores-invisible condition copied one another less frequently but in larger amounts at a time.

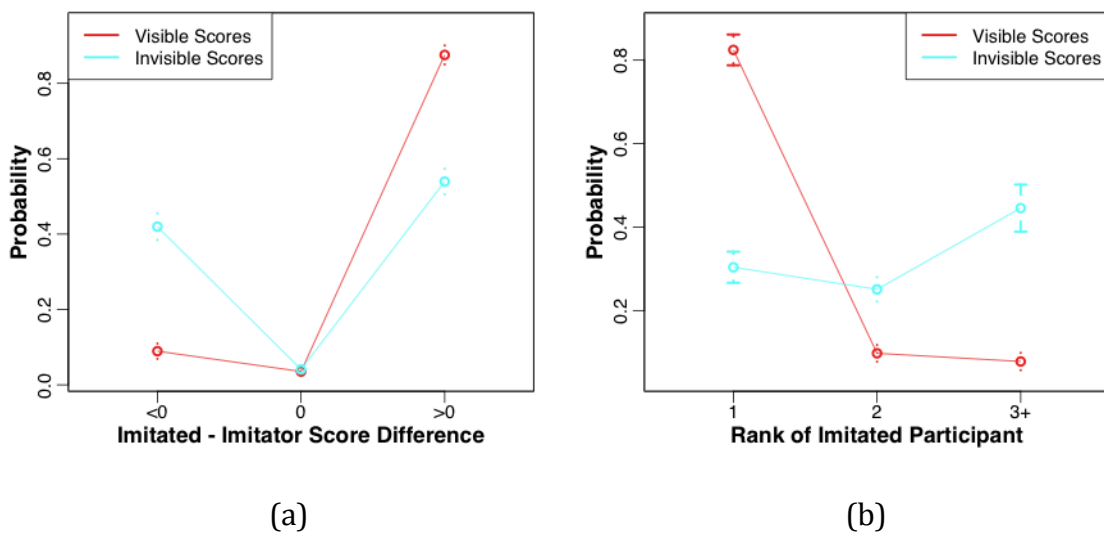


Figure 5.9: In the visible-scores condition there were strong biases toward imitating (a) better-scoring participants than oneself, and (b) the best-scoring participant, while imitation behavior in the invisible-scores condition appeared essentially random with respect to score difference and score rank.

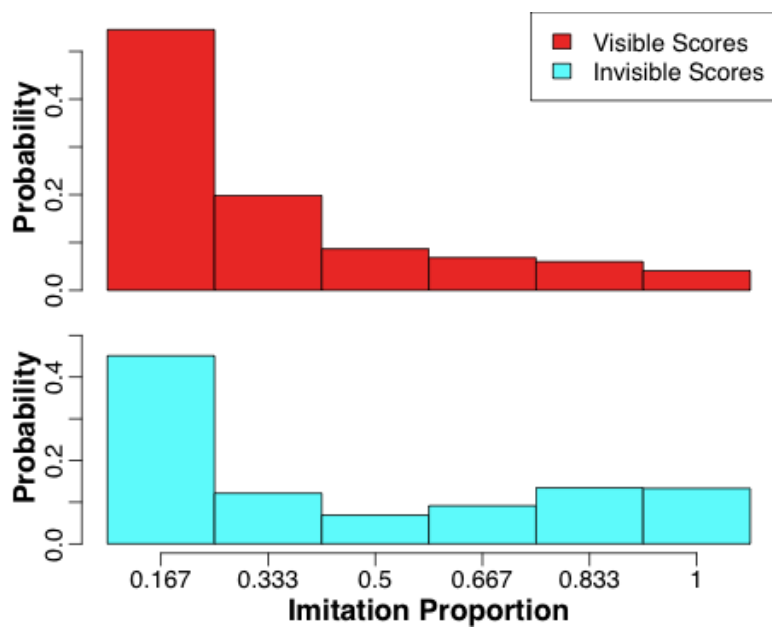
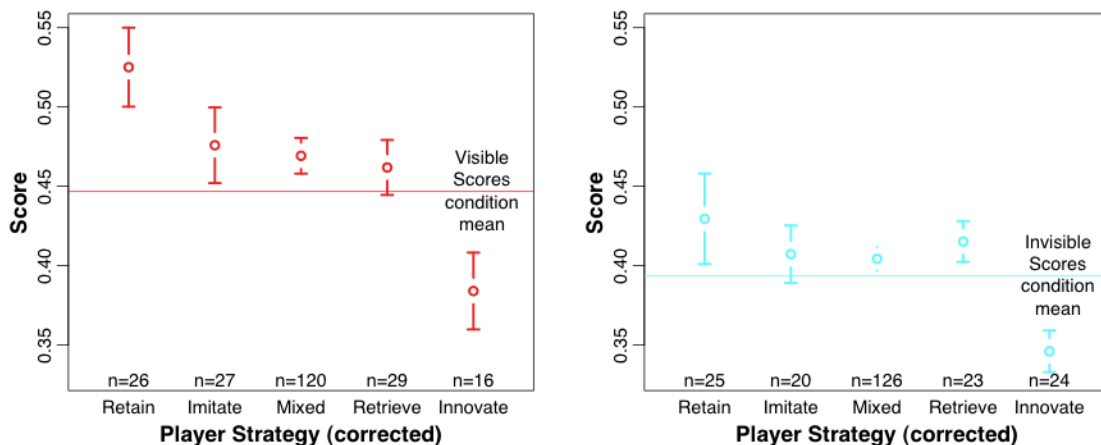


Figure 5.10: For guesses that included at least some Imitation, participants in the invisible-scores condition had higher proportions of Imitation in their guesses.

5.3.6. Choice source strategy

As in Experiment 2, the choice sources of each non-isolated participant over the entire session were analyzed, and each participant's choice source *strategy* was categorized according to their proportion of each source. Participants whose choices contained one source in an average proportion greater than the global average for that source plus one standard deviation, were labeled with that strategy. For example, a player whose guesses over the course of a condition consisted of a greater proportion of Imitate choices than the average for all other participants in that condition, plus one standard deviation, were labeled as having an overall strategy of "Imitate." Those who fit the above criteria for more than one choice source, or none, were labeled as having a "Mixed" strategy. The score distribution for each strategy category in each condition is shown in Fig. 5.11.



(a)

(b)

Figure 5.11: Score vs. choice source strategy in (a) visible-scores and (b) invisible-scores conditions, showing that a conservative high-Retention strategy resulted in the best performance, though a similarly conservative high-Retrieval strategy (returning often to a personal best-so-far) showed good relative performance in the invisible-scores condition.

The above-mentioned figures summarize the results of simple regression analyses performed for score vs. individual and group use of each choice source. A linear regression of mean individual score vs. mean individual Imitation guess proportion showed a significant positive relationship (that is, the greater a participant's average proportion of Imitation, the better the participant's score), but only in the visible-scores condition ($F(1,216)=8.12$, $p=.005$, $B=0.190$; see Fig. 5.12a); no significant relationship was found in the invisible-scores condition. The opposite was true for individual score vs. Innovation, which displayed a significant negative relationship in both the visible-scores ($F(1,216)=146.2$, $p<.0001$, $B=-0.635$; see Fig. 5.12b) and invisible-scores ($F(1,216)=67.88$, $p<.0001$, $B=-0.489$) conditions. A positive relationship held for Retention in both the visible-scores ($F(1,216)=64.6$, $p<.0001$, $B=0.480$; see Fig. 5.12c) and invisible-scores ($F(1,216)=13.81$, $p=.0003$, $B=0.245$) conditions. Finally, a positive relationship was found for Retrieval in only the invisible-scores condition (SI: $F(1,216)=12.73$, $p=.0005$, $B=0.236$; see Fig. 5.12d).

As in Experiment 2, analyses of mean group score vs. mean group guess proportion for each choice source showed similar relationships of the same significance and directions as those noted above, as well as analyses of mean

individual score vs. mean group (excluding the individual) guess proportion, with the exception of the absence of a relationship with Retrieval at both levels. All trends noted above were generally monotonic; that is, there were no thresholds or inflection points beyond which the relationships changed.

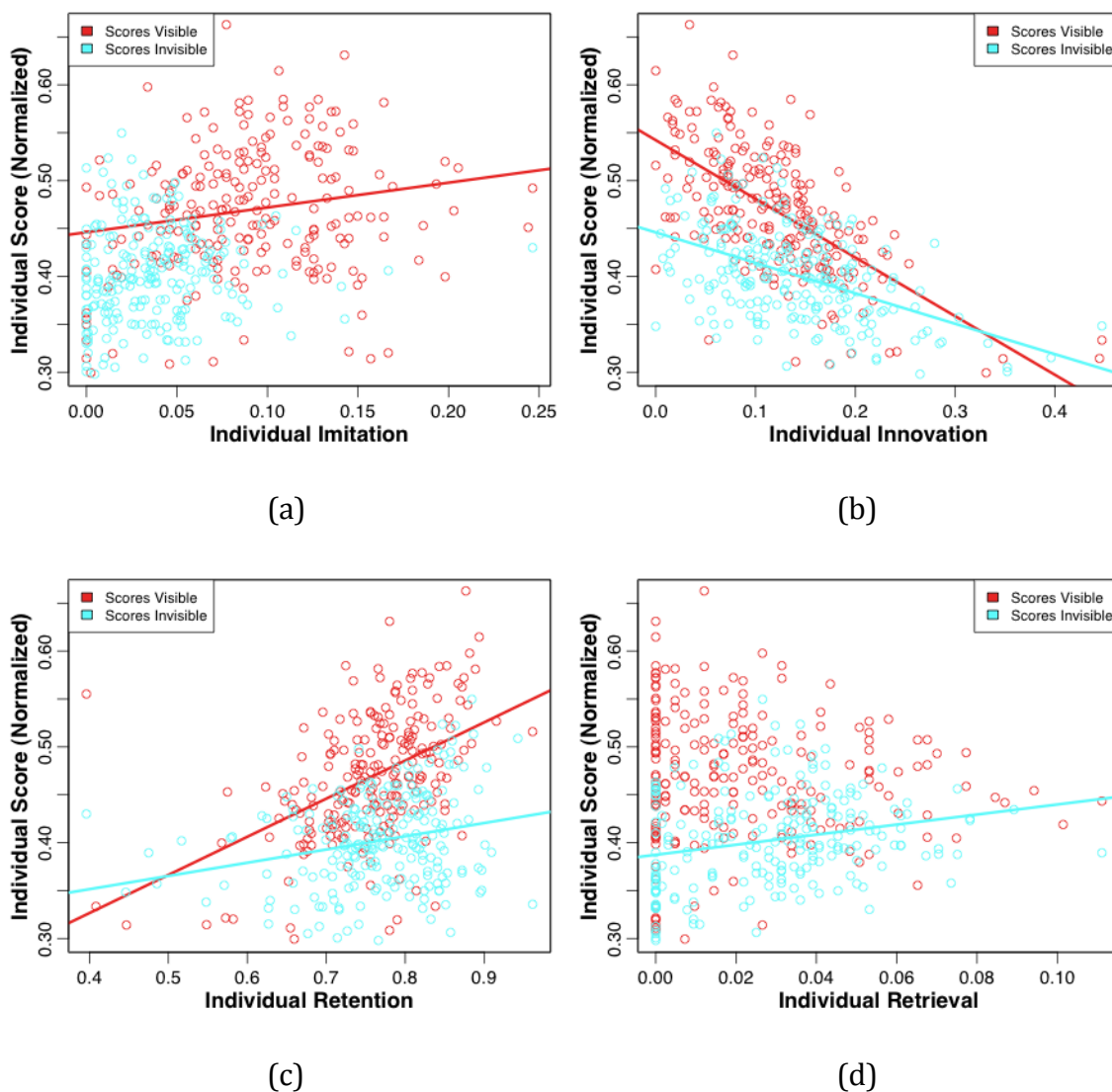


Figure 5.12: Higher individual scores were associated with (a) higher individual Imitation only in the visible-scores condition, (b) lower Innovation in both

conditions, (c) higher Retention in both conditions, while (d) higher individual Retrieval only in the invisible-scores condition. Best fitting linear regression lines are only shown when the linear relation was significant.

5.3.7. Improvements

As in Experiment 1, improvements were tallied for each participant in each session and condition. Histograms of normalized improvement share showed a relatively equitable distribution of improvements within groups in the visible-scores condition, with a distribution strongly peaked near a “fair share” of 1 (56% of participants were between 0.4 and 1.2), and only 6.4% of participants having zero improvements; in contrast, there was a strongly inequitably-skewed distribution in the invisible-scores condition, with only 36.2% of participants having improvement shares between 0.4 and 1.2, and 21.1% with zero improvements (see Fig. 5.13). A Kolmogorov-Smirnoff test of equality of distributions indicated that these distributions were significantly different ($D = 0.1789$, $p=0.002$). Mean overall score showed a strong positive correlation with improvement share in the invisible-scores condition ($F(1,168)=64.49$, $p<.0001$, $B=0.369$), but this relationship was not evident in the visible-scores condition.

The mean choice source proportions for guesses that resulted in score improvements and those that did not are shown in Table 5.3. In both conditions, the proportion of Innovation choices was higher for guesses that yielded improvements relative to non-improvements (invisible-scores: $t(733.20)=-14.03$, $p<.0001$; visible-

scores: $t(907.73)=-17.14, p<.0001$). In the invisible-scores condition, the proportion of Imitation choices was significantly lower for improvements than non-improvements ($t(916.77)=11.54, p<.0001$), while in the visible-scores condition, the proportion of Retention choices was significantly lower for improvements than non-improvements ($t(916.33)=9.34, p<.0001$). Of all improvements in the visible-scores condition, 24.2% resulted from guesses that included Imitation, versus 12.2% in the invisible-scores condition. In 52.3% of all improvements in the visible-scores condition, the focal player imitated at least one peer who had previously imitated the focal player, versus 41.5% in the invisible-scores condition. In other words, a player who was imitated by another player often later imitated that same player in the course of creating an improvement, but this happened substantially more often when scores were visible.

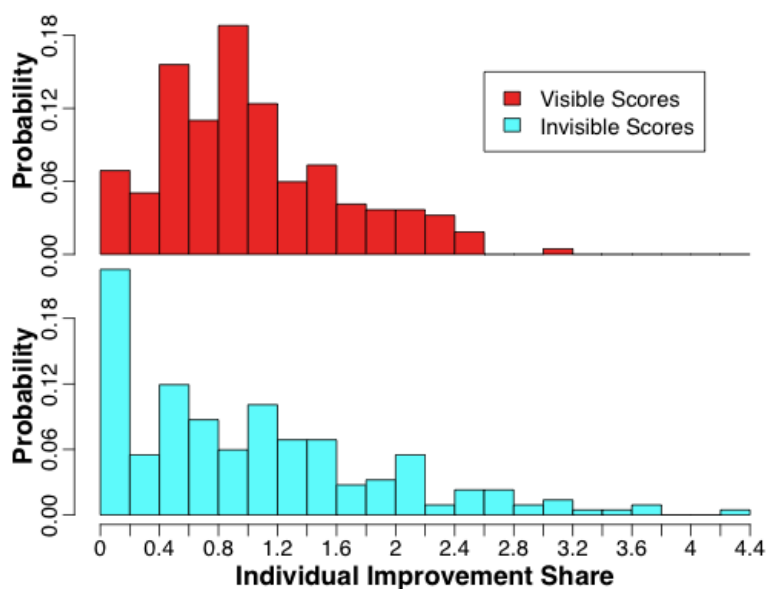


Figure 5.13: Histograms showing relatively equitable achievement of improvements within groups in the visible-scores condition, and an inequitable distribution in the invisible-scores condition.

Table 5.3: Mean choice source proportions for improvement and non-improvement guesses in each condition.

Condition	Improvement	% of guesses	Imitation	Innovation	Retention	Retrieval
Visible Scores	No	94.6%	9.1%	11.4%*	76.3%*	2.2%
	Yes	5.4%	8.2%	19.4%*	69.5%*	2.1%
Invisible Scores	No	95.6%	10%*	13.3%*	71.2%	4.4%
	Yes	4.4%	3.9%*	21.6%*	70.5%	3.5%

*** significant differences within condition**

5.3.8. Guess similarity

A comparison between the mean similarity of participants' most recent guesses to those whom they imitated, and to those whom they did not imitate, revealed slight but significant differences in both conditions, but in opposite directions. In the scores-visible condition, there were similarity values of .563 for imitated vs. .524 for non-imitated guesses ($t(5084)=-5.47$, $p<.0001$; see Fig. 5.14a). In the scores-invisible condition, there were similarity values of .316 for imitated vs. .346 for non-imitated guesses ($t(4267)=4.35$, $p<.0001$; see Fig. 5.14b). In other words, prior to imitation, the average imitators' guess was more similar to that of the imitated participant(s) than to those of others in the scores-visible condition, and less similar in the scores-invisible condition.

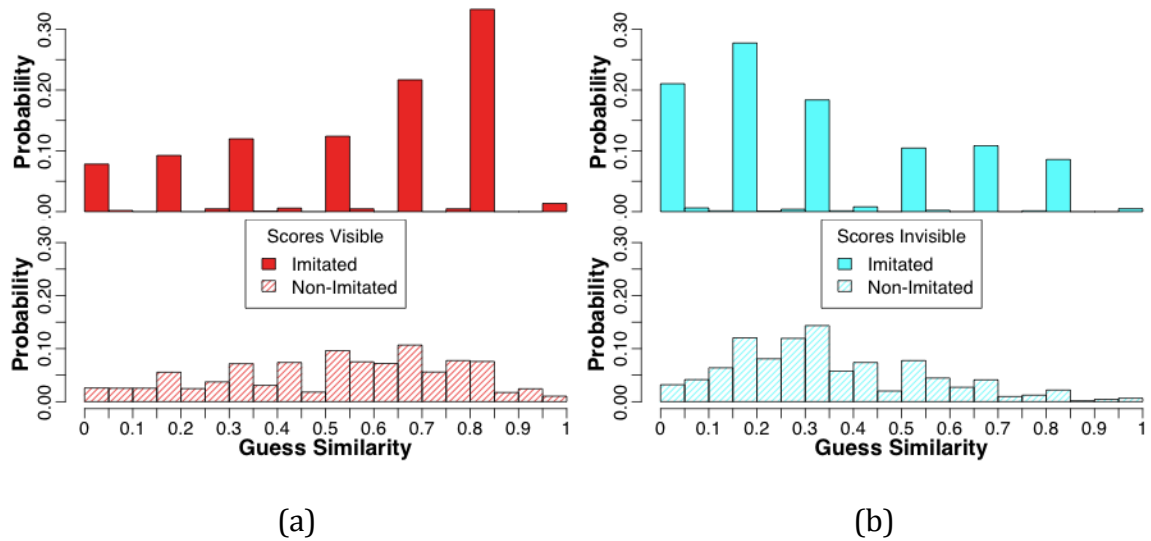


Figure 5.14: (a) In the scores-visible condition, imitators' previous guesses showed greater similarity to the guesses they imitated than to those they did not imitate, while (b) in the scores-invisible condition, the opposite effect was observed.

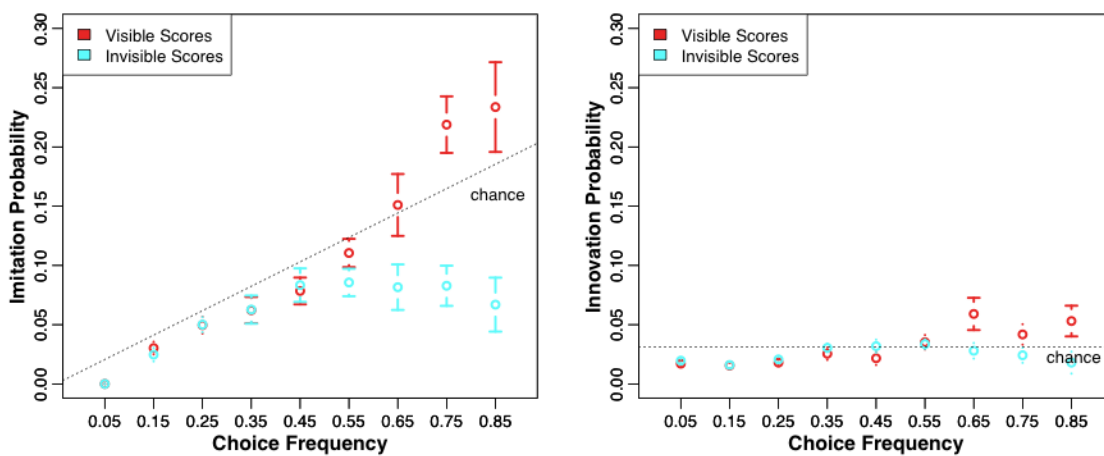
5.3.9. Frequency and momentum bias

As in Experiment 1, we measured the bias of participants to choose an icon according to its frequency in peers' choices. To reiterate briefly, we measured the mean probability of Imitation and Innovation for any icon not already included on a player's team, based on the frequency of its appearance on peers' teams in the player's display, and compared them to expected chance baselines.

Linear mixed-effects analysis of imitation probability versus choice frequency showed a positive frequency-dependent Imitation bias that was significantly greater than chance in the visible-scores condition ($F(1,604)=943.25$, $p<.0001$, $B=.741$), but significantly lower than chance in the invisible-scores condition ($F(1,604)=231.67$, $p<.0001$, $B=.470$; see Fig. 5.15a). There was a slight

positive frequency-dependent Innovation bias above chance in the visible-scores condition ($F(1,604)=181.20$, $p<.0001$, $B=.441$), and below chance in the invisible-scores condition ($F(1,604)=12.78$, $p=.0004$, $B=.131$; see Fig. 5.15b).

We also repeated the analysis of “choice momentum,” by tallying the change in the number of players whose teams included the icon in the previous two rounds, as well as the number of the remaining players who added it to their team in the current round via Imitation or Innovation, and normalizing for group size. After log-transforming the Imitation probability data to achieve a normal distribution, a t-test of Imitation probability for negative and positive changes in choice frequency showed a significant positive momentum bias in the visible-scores condition ($t(640)=-14.192$, $p<.0001$), and a smaller positive bias in the invisible-scores condition ($t(661)=-9.98$, $p<.0001$; see Fig. 5.16a). A slight positive momentum bias was found for Innovation in the visible-scores condition, but no corresponding significant bias was found in the invisible-scores condition (see Fig. 5.16b).



(a)

(b)

Figure 5.15: There were biases toward choosing elements that were more frequently represented on other teams in the visible-scores condition, and less frequently represented on other teams in the invisible-scores condition for (a) Imitation and (b) Innovation decisions.

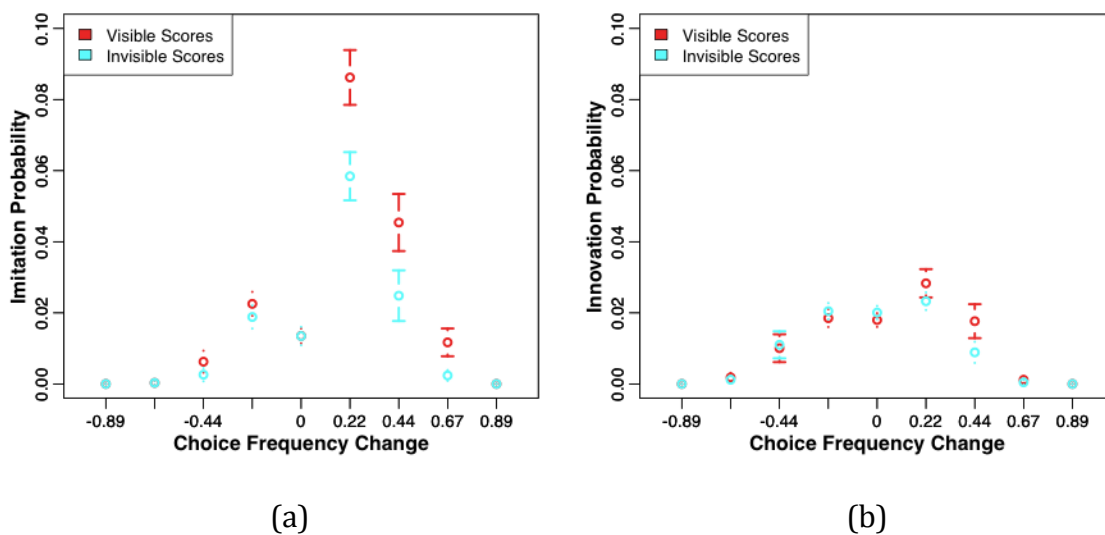


Figure 5.16: There were biases toward choosing elements whose representation on other teams was increasing in (a) both conditions for Imitation and (b) only the visible-scores condition for Innovation decisions.

5.4. Experiment 3 Discussion

As predicted, results in the scores-visible condition were quite similar to those in Experiment 2, while the results in the scores-invisible condition differed in some ways we did not predict.

5.4.1. Differences in performance

Having demonstrated benefits for Imitation in the previous experiments, the impediment to social learning introduced in the invisible-scores condition lowered performance as predicted. Thus, the reduction in the efficiency of social learning implemented by hiding peers' scores did lead to increased Innovation and solution diversity, but did not seem to improve collective search performance as in Mason, Jones, and Goldstone (2008) and Lazer & Friedman (1997). This difference from the studies cited above was likely due to the way that communication efficiency was reduced: whereas they decreased the connectivity of the social network through which information was exchanged, we left the network unchanged but eliminated an important part of the information that participants used to guide imitation decisions. Our results are substantially in accordance with the findings of Giraldeau, Valone, and Templeton (2002), who found that an inability to combine the use of social and asocial learning simultaneously would result in a lack of benefit for social learning; however, we did observe some benefit for social learning, in that participants in the invisible-scores condition still performed better than isolated participants.

5.4.2. Differences in strategy

Overall, the change in the availability of performance information seemed to shift participants' tactics from making small changes to their guesses, combining asocial and social learning (*incrementalist* strategies) in the visible-scores condition, to making larger jumps around the problem space and often jumping back to

previous known good solutions (*saltationist* strategies) in the invisible-scores condition. This difference was discernible in a number of results. First, when scores were invisible, proportions of Innovation and Retrieval were higher and Retention was lower, implying that on average participants were keeping smaller portions of their guesses from round to round and changing often between new and old solution elements. Though the overall mean proportion of Imitation was the same in both conditions, Imitation was used less often and for a larger proportion of the guess in the invisible-scores condition – participants were significantly more likely to copy most or all of a peer’s solution. The lower mean Retention in the invisible-scores condition implies that participants were often jumping to a peer’s guess and either keeping it if it increased their score, or jumping back to their Retrieved previous best guess if it did not.

The ability to make incremental changes, mixing elements from all sources, should allow participants to assess the effect of smaller changes and make better judgments about the quality of individual elements and pairs from other participants; thus there were substantial increases in score across rounds and associations of Retention and Imitation with high scores observed in the visible-scores condition. A reliance on large risky jumps around the problem space would likely pay off about half the time for the median participant, and those who jumped back to good previous solutions would lose less overall than those who continually jump around; thus there were shallower increases in score over rounds, and an association of higher scores with Retrieval but not Imitation in the invisible-scores condition. This saltationist strategy seems to have been more successful than not

using Imitation at all, however, as shown by the substantially lower performance of isolated participants.

The removal of score information also affected the use of other kinds of information in participants' imitation strategies; however, rather than strengthening socially-mediated information biases (as suggested by Abrahamson and Rosenkopf (1997) and Gibbons (2004)) such as frequency bias or similarity bias, participants actually showed weakened or opposite inclinations. The above interpretation in terms of changing the magnitude of movements in the problem space holds here as well. Copying a similar solution to your own is an inherently incrementalist strategy, so the presence of this bias in the visible-scores condition, and the presence of its opposite in the invisible-scores condition can also be explained in terms of an overall change from incrementalist to saltationist strategies. The unpopularity bias and reduced momentum bias we observed may have occurred because participants knew that imitation decisions were often not based on reliable performance information, and thus frequency-based biases should be avoided to keep from joining information herds (Banerjee, 1992), as suggested by Giraldeau, Valone, and Templeton (2002).

5.4.3. Learning?

Changes in strategy across game order can be thought of as learning or adaptation to the task over successive games. The changes we observed across game order imply that strategies in each condition were strengthened over the course of the session. In the visible-scores condition, the decreases in Innovation and

Imitation and increase in Retention show a more incrementalist approach, while in the invisible-scores condition, the increases in Imitation and Retrieval and decrease in Innovation displayed more solidly saltationist tendencies. It is fairly simple to see that an increasingly incrementalist strategy that included some Imitation would show an increasing payoff in terms of being able to distinguish good individual elements and pairs, and the improvement in score across game order in the visible-scores condition reflects this. An increasingly saltationist strategy, however, is not likely to show benefits unless the solutions of one's peers improve, and thus we saw no improvement in score across game order in the invisible-scores condition. There is no obvious better-performing strategy in this context, however, so participants seemingly doubled down on this one.

5.4.4. Convergent / locally efficient search

As seen in the increasing score and decreasing guess diversity trends across rounds, average performance increased via the convergence of group members on regions of the problem space that contained high-quality teams. This convergence combined with a small amount of individual exploration caused such regions to be explored more thoroughly and still better solutions to be found. However, in the invisible-scores condition, when imitation was not focused on a small group of better-performing neighbors (because performance information was not available), similar guesses, or popular solution elements, this convergence happened much more slowly, search was more diffuse and less efficient, and lower performance resulted. The weaker trends of increasing score and decreasing guess diversity

across group size in the invisible-scores condition showed that the lack of score information made searchers unable to effectively take advantage of the increasing numbers of their fellow searchers.

5.4.5. Cumulative mutual improvement

The significant correlation of improvement share with mean scores in the invisible-scores conditions shows that individuals who were relatively more skillful (or lucky) were rewarded with proportionately better overall scores compared to others; this was because their fellow players could not easily copy their improvements and achieve their scores, and because knowing that Imitation was unreliable made some participants more likely to seek out improvements on their own. In the visible-scores condition this correlation disappeared, but the more equitable distribution of improvements showed that more participants were contributing to their discovery, and mean scores increased significantly such that nearly all participants did better. In other words, when social learning was unimpeded in the visible-scores condition, high and low individual achievers had approximately the same payoffs, but absolute payoffs were higher for all compared to the invisible-scores condition, in which high-achievers got a bigger piece of a smaller pie. Thus impeding social learning led to relatively greater inequity and inefficiency, and presumably lower long-term performance (though we did not test this explicitly with longer games).

This advantage for more efficient social learning accrued because imitators were not merely scroungers; the substantial proportion of Imitation present in

improvements shows that imitated guesses were often the basis for further cumulative innovations. The cumulative innovation hypothesis is supported by the fact that a larger proportion of improvements were the result of mutual Imitation in the visible-scores condition, in which solution elements were passed between players via copying and built into better solutions in the process. This enabled a more active sharing of the “labor” of producing improvements, and increased performance from participants overall. In the invisible-scores condition, the necessity of adopting others’ guesses in order to obtain information about their performance allowed fewer opportunities to evaluate variations on them; it also prevented group members from performing the “filtering” function of copying and consistently retaining only solution elements associated with relatively high scores, so that others would have less chance of obtaining low-scoring solution elements when copying.

5.5. Conclusions

In Experiment 2, we noted the lack of a “tragic” outcome in the production and use of high-scoring solutions, despite the apparent incentive for individuals to under-produce innovations and free-ride on the innovations of others via self-interested imitation. In this experiment, we showed that it was possible to induce a tragic outcome by reducing the capacity of individuals to make self-interested imitation decisions, even while they increased their production of innovation.

It appears that lower performance in this task was not due to an underprovision of individual innovation, but a lack of evaluative filtering of solution

elements, which participants in the visible-scores condition did by choosing to imitate and retain solution elements associated with high scores, and which in the scores-invisible condition was made much more difficult. The consistent use of the better-performing solutions does not rely on altruistic or publicly-minded motives, but such filtering is important for supporting others' successful social learning, as was highlighted in a recent tournament of simulated social learning strategies (Rendell et. al 2010). In summary, we have shown through this experiment that when knowledge is cumulative, efficient and informed appropriation is an important step in further provision of the public good of knowledge.

6. Knowledge as Property

6.1. Promoting progress

In two parts of the social learning experiments described thus far (larger group sizes in Experiment 1, and the invisible-scores condition in Experiment 3), we have seen that despite apparently adequate provision of innovation, obstacles to accurate, strategic imitation of those innovations can lead to underperformance in further innovation. In this chapter we will explore some measures taken in the real world to (ostensibly) encourage efficient innovation and (eventual) imitation, and introduce several important concepts for understanding their implications on the related public and common goods of knowledge discussed in Chapter 4.

6.1.1. The Progress Clause

Practical research and development are costly activities in terms of money, effort, time, risk, and opportunity. These activities generally will not be undertaken unless their results have some expected value to justify their costs. The "Progress Clause" of the U.S. Constitution empowers the legislature "To promote the Progress of Science and useful Arts, by securing for limited Times to Authors and Inventors the exclusive Right to their respective Writings and Discoveries." Many other countries have enacted similar statutes and policies protecting "intellectual property" (IP), which generally allow the originators of certain innovations to control the dissemination or production (and thus the benefit) of the products of their innovations. (This clause covers the creation of both patents and copyrights; in this chapter and the next, we will be focusing on patents, though many of the same

arguments could apply to copyrights.) The owner of a patent granted by the U.S. Patent and Trademark Office is given the right to exclude others from "making, using, selling, offering to sell, or importing" the patented invention (35 U.S.C. § 271), and this right can be renewed until 20 years after the patent application was filed (35 U.S.C. § 154). In exchange, a patent applicant must describe the invention in enough detail so that a person who is skilled in the field would be able to make and use the invention (35 U.S.C. § 112).

The disclosure required for a patented invention can be considered a contribution to a knowledge commons, in that the information that enables one to "make and use" the invention can also be used to improve it, or to create other inventions. As Ghosh (2003) notes, the characterization of a good as rivalrous depends on the property rights that govern it. The exclusive control over an invention that IP statutes give to creators can make that invention usable by only one individual or firm, and so artificially transform practical knowledge into a subtractable resource. Thus the exercise of IP rights can be considered appropriation of resource units from the commons, which cannot be done in an unrestrained way without threatening the viability of the resource.

The balance of rights and responsibilities in these provisions implicitly acknowledges that individual innovation is encouraged for the purpose of the extending the collective benefits of the general progress of knowledge. The standard assumption about the intent of the "Progress Clause" is that it was motivated by the framers' view that "encouragement of individual effort by personal gain is the best way to advance public welfare" (Mazer v Stein, 1954). That is, public benefit is the

primary intended end, and the provision of a private incentive is the preferred means for achieving it. As discussed previously, however, privatization of a resource is not always the best way of ensuring its equitable, efficient, and sustainable use.

6.1.2. Measuring the promotion of progress

The progress of science depends on the incentives that inventors have to invest in research and development, as well as to disseminate their inventions to those who can productively adopt them in society at large. Thus, the success of patent statutes in the promotion of scientific progress can be usefully evaluated on the basis of the net effects of the IP system, both for those who directly advance the progress of science, and for the general populace. There are undoubtedly benefits that accrue to many patent holders as a result of their exchange of ideas for money, as there are plainly benefits to society in the form of patented modern technologies. The question is whether the rewards of the IP system outweigh its costs for all inventors (both those who are IP holders and those whose inventions are not protected by IP), and the society and economy in which they work. (The latter can be considered an extension of the former: as economies and societies grow, new technological needs arise and thus new opportunities for innovation.) Here we will take a short detour to examine previous attempts to answer this question empirically, as well as the theories underlying IP systems; these will help constrain and motivate our final experiment.

Though "rights" can seem rather abstract, proxies have been developed for studying the quantitative effects of various factors on overall economic growth in

cross-national econometric studies, including protections for property rights. Generally, traditional property rights (those governing e.g. objects or real estate) have a strong and unambiguous relationship with growth (Svejnar, 2002; Keefer & Knack, 1995, 1997). Park and Ginarte (1997) performed a regression using indices of "market freedom" (i.e. traditional property rights) as well as IP rights, and confirmed that the former had a strong relationship with growth, but not the latter. In a follow-up study, Ginarte and Park (1997) actually found evidence for a correlation between 5-year lagged R&D spending and the strength of IP rights protection, implying that investment in innovations led to the development of protections for them ("reverse causality"). In contrast to traditional property rights, IP rights appear to have only an indirect or weak relationship to economic growth; it may hold only for certain groups of countries or certain kinds of measures (Falvey, Foster, and Greenaway, 2006), and the causal direction is unclear.

Several lines of research have been pursued to address the question of whether IP rights are beneficial for inventors (and their employers and investors). Studies of innovation prior to and during the 19th century showed that many inventions made their inventors enormous profits and were judged to be highly innovative despite being unpatented or having their patents invalidated (Mokyr, 1999; Moser, 2002). Bessen and Meurer (2008) and Boldrin and Levine (2008) reviewed a broad range of "natural economic experiments" on discrete changes in the patent laws of various countries in the 20th century. They found that, overall, there is strong evidence that strengthening patent protection leads to more patenting (as in the "reverse causality" noted above), but weak or no evidence that it

increases innovation. In fact, in the realm of software patents, firms that acquired relatively more patents subsequently tended to reduce their R&D spending relative to sales (Bessen & Hunt, 2007). Boldrin and Levine (2008) describe increases in patenting activity as "navigating the patent thickets," in which firms that fear infringement lawsuits from as-yet-unknown patentees acquire patents strictly for the purpose of filing countersuits and achieving settlements without having to modify their business, that is, to avoid being forced to innovate further.

Bessen and Meurer (2008) examined patent renewal behavior in order to estimate the value of patents apart from their underlying technologies, and found that nearly 60% of U.S. patents filed in 1991 were not renewed to full term, which indicates that the majority of patents filed depreciate to a value less than the few thousand dollars of the average renewal fee. As one might expect, the distribution of patent values is skewed -- most patents are of relatively little value, while a small number are quite valuable. A variety of measures of patent and invention value adhere approximately to the 80-20 rule: 80 percent of the total value is contained in 20 percent of the inventions (Harhoff, Scherer, & Vopel, 2003). Bessen and Meurer (2005) found that generally, patents granted to small inventors (individuals, nonprofits and corporations with less than 500 employees) are much less valuable than those granted to larger entities, about 50% in the mean, and the difference between individuals and organizations overall is even greater. Furthermore, the ownership of this value is found to be rather lopsided: more than half of the value of worldwide patents accrues to a small number of large pharmaceutical companies,

and more than two-thirds to firms in the chemical and pharmaceutical industries generally.

Overall, there is strong evidence that patents can deliver significant value to (some of) their owners, but the patent system also imposes costs on patent owners through disputes over the rights to their inventions, as well as on nonpatenting inventors through disputes related to inadvertent infringement of others' patents. The process of "clearing" rights (by either making sure no trespass occurs or obtaining a license) is not necessarily simple for many patents, because the boundaries of what an invention does, and by what process or method it is done, can be arcane and open to costly legal interpretation (Moore, 2005). Bessen and Meurer (2005), after controlling for a wide variety of variables, found that increased spending on R&D is actually correlated with an increased risk of being sued for infringement, which suggests that infringement is often not willful, and occurs due to difficulties in determining patent boundaries. A comparison of aggregate litigation losses incurred by a sample of defendant public firms during the years of 1984-1999 with the aggregate incremental profits derived by public firms during the same period showed that outside of the chemical and pharmaceutical industries, the costs of litigation clearly exceeded profits from patents (Bessen & Meurer, 2008). Thus overall, the patent system appears to constitute a net disincentive for innovation.

The results noted above suggest that in its present form, the patent system is not promoting the progress of technological advancement; that is, the equity, efficiency, and sustainability of the knowledge commons do not appear to be

improved by the patent system. This may simply be due to structural shortcomings of the system, remediable by adjustments to patent length or breadth (Gilbert & Shapiro, 1990). However, there may also be more subtle issues regarding the motivational principles and interdependencies of innovators that are not being adequately addressed by existing patent theory, law, and institutions.

6.2. Prospecting for progress

The monopoly granted by a patent is expected to cause "deadweight loss," a reduction in mutual value for producers and consumers that occurs when consumers who are willing to pay more than the marginal production cost of a good, but less than the patentee's monopoly price, are thus prevented from purchasing the good (Gilbert & Shapiro, 1990). Kitch (1977) introduced the "prospect theory" of patents to common legal usage, in which the cost to society of deadweight loss is explicitly justified and discounted by a perceived need to incentivize not just creation and disclosure of innovations, but also their efficient management. Kitch expounded upon this theory with an analogy to the exploitation of mineral resources in the American West, but he was responding to Barzel's (1968) call for a solution to a collective action problem among innovators. Barzel observed that firms who wanted to use the "free public good" of basic scientific knowledge to produce innovations for commercial use each had an incentive to introduce such innovations as soon as they were profitable. But he reasoned that innovators (and thus society at large) would collectively be better off if firms delayed the introduction of innovations until an "optimal" time, when marginal profit (relative to reliable

outside investments) could be maximized through the development of sufficient production capacity and demand. In the same year as Hardin's (1968) analysis of the Tragedy of the Commons, Barzel (1968) also recommended enclosure of the knowledge commons in the form of ownership of basic knowledge in order to prevent what he viewed as a tragic outcome in its use. But as with Hardin, the intellectual origins, analogies, and assumptions used to understand this complex situation must be closely examined for clues as to where proposed solutions may succeed or fail.

Barzel's analysis of this "optimal" use depends on a number of simplifying assumptions; for our purposes the most salient are that (a) innovations have a constant cost and thus can be introduced at any time (ignoring the dynamic and cumulative development of knowledge), (b) there is only one innovator associated with a given innovation (ignoring collaborative innovation processes), (c) there are no benefits of the innovation passed on to the consumer (ignoring the existence of externalities or "spillovers" (Frischmann & Lemley, 2007) uncapturable by the producer, such as "network effects" (Katz & Shapiro, 1985)), and (d) the parameters of the system are widely and accurately known (ignoring the complex and uncertain nature of innovation). Kitch (1977) argued, among other things, that the U.S. patent system was structurally predisposed to "prospect" uses, and that granting broad and long-term patent rights on the basis of the "prospect" for efficient introduction and management of an innovation (rather than on the basis of the previously-accepted "reward theory" of simply incentivizing production and disclosure of innovations) would result in a net positive for society.

Implicit in this approach are other assumptions about innovators and their motivations. Primarily, the above analyses treat innovation as an activity that is pursued only by firms who produce goods for the purpose of selling them to end users. The mining analogy used by Kitch (1977) implies that most practical inventions require a great deal of investment in the extraction and processing of the "ore" of basic knowledge, and thus that firms with exclusive claims will be the best informed and equipped to create and manage innovations. However, the history of technology should teach us that people are generally not skilled at anticipating the uses of new inventions or the needs of future users (Boyle, 2007); inventions such as mobile phones, DVD players, and financial database software have resulted in a variety of uses and a magnitude of economic and social benefits unimaginable and uncapturable by their creators (Baumol, 2002). Though prospect theory posits a decentralized, entrepreneurial implementation of innovation at large, it centralizes control of any particular innovation in one firm. In practice, holders of patents can delay or prevent future innovations by either refusing to license their patents to subsequent innovators, or charging sufficiently high licensing fees so that smaller innovators are prevented from entering the market (Merges & Nelson, 1990).

Previous inventions can aid in the creation of new innovations either as "research tools" that enable a further innovative stage, or as the basis for an improved product (or sequential innovation) on the "quality ladder" (Hall, 2007). It is not necessarily the case that either the original innovator or only those with deep-pocketed investors are best suited to improve upon or use a previous innovation to create another, but in some cases these may be the only agents who are able to do so

legally. Additionally, innovators may not have sufficient incentive to create or allow improvements on their original ideas, if they fear that a new use would compete with the old one (Scotchmer, 1991). When previous innovations necessary for the creation or development of a new invention are patented by multiple parties, a phenomenon called “the tragedy of the anticommons” can result (Heller & Eisenberg, 1998). In this situation, the tragedy results not from a lack of resource oversight, but from an excess of it; owners of technologies that are collectively necessary for a new innovation may fail to agree on licensing or revenue sharing terms, and thus any of them can veto further progress.

To summarize, we have seen that patent systems are intended to incentivize the creation and disclosure of innovations, as well as their efficient management (under certain interpretations). In practice, however, patents can also (a) incentivize non-innovative strategic or rent-seeking behavior, (b) reduce the incentives to create and disclose through the accompanying risk of costly patent litigation, and (c) reduce the incentive to optimally manage through patent holders' ability to delay or prevent (but not capture or profit from) many positive externalities of their patented innovations. The above factors also constitute disincentives to imitate and build sequential improvements from the innovations of others. Returning to the concept of a knowledge commons, these problems are signs of an institution that is failing to ensure contribution and prevent overappropriation from a resource (the overall pool of existing knowledge) by its community of users. In the long term, such flaws threaten the viability of the resource.

6.3. Balancing motivations

Another area of research in which the adequacy of exclusion in fostering innovation becomes suspect is the curious tendency of people to treat extrinsic incentives (such as monetary payment) and intrinsic or social motivations (such as personal satisfaction or social approbation) differently: as non-additive, mutually exclusive, or completely incommensurable. For example, given an activity that produces intrinsic rewards such as volunteer service or blood donation, the offer of monetary rewards may actually "crowd out" the motivation to pursue the activity and reduce its overall level. Thus, under certain circumstances the price mechanism for raising the supply of goods, one of the fundamental pillars of economics, may not hold. The study of this phenomenon has produced a large body of work in both economics (e.g. Titmuss, 1970; Frey & Jegen, 2001) and social psychology (e.g. Deci, 1971; Deci, Koestner & Ryan, 1999).

Heyman and Ariely (2004) posited that social and monetary rewards are mediated by separate "markets," and that they cannot be mixed. They performed experiments in which they measured the effort put forth in response to varying levels and types of rewards offered to participants for performance of a task. It was found that effort was consistently high when no reward was offered, as well as when token non-monetary rewards (e.g. candy) of varying value were offered. When cash was offered or the cash value of the non-monetary rewards was mentioned, effort was proportional to the value of the reward offered, and only approached the level reached by no rewards at high levels of monetary rewards.

Frey and Jegen (2001) reviewed studies related to the crowding-out effect of extrinsic rewards on intrinsic motivations and found that it was present for a variety of norm-related motivations and settings: work effort and reciprocity in supplying labor, altruism in service provision, civic duty and environmental care in managing a common-pool resource, and trust in legal systems. Deci, Koestner, and Ryan (1999) performed a meta-analysis of 128 studies on this effect and found that a wide variety of extrinsic rewards and reward criteria undermined intrinsic motivation and interest in effortful tasks.

The presence of social or intrinsic rewards for some creative and innovative activity is in a sense evident by definition, from the fact that such behaviors continue in a multitude of contexts without any external monetary reward, and even in the presence of substantial costs (e.g. various hobbyist pursuits, amateur blogging, Wikipedia contributions, etc.) Beyond this evidence, the intrinsic motivations that people have for creative work have also been studied in some detail and a variety of reasons are found for participating: curiosity, the enjoyment of challenge or novelty, personal expression of values, building or maintaining a positive reputation among peers, and so forth (Lakhani & Wolf, 2003).

To the extent that innovators understand the dependence of their work on that of previous innovators, and that spillovers can accrue to fellow innovators and to society at large as a result of their efforts, the motivations of reciprocity and public benefits may be included in this list of intrinsic motivations. In this case, the opportunity to exclude others from building upon one's work may be unattractive. To the extent that extrinsic rewards can undermine these motivations for certain

kinds of work, some innovative activity may simply not occur, or only at a greater relative cost.

6.4. Other models of innovation

These flaws prompt us to consider other models of innovation and its governance. The assumptions of the "reward" and "prospect" theories of innovation by producers exclude important classes of innovators: individuals or firms who create innovations for their own internal use, and those who produce innovations in open collaboration with others in order to share in the costs of their creation and the benefits of their use (Baldwin & von Hippel, 2009; Strandburg, 2009).

Innovations created by individuals or firms for their own internal use (rather than for selling to users at a profit) need only to provide enough benefit to cover the effort of producing them. This means that small, incremental, or specialized innovations that might not justify investment or production by a non-user firm can be created without the provision of external incentives. Studies in a wide variety of industries such as chemical products (Freeman, 1968), scientific instruments and semiconductors (Von Hippel, 1976, 1977), and sporting equipment (Shah, 2000) have shown that a large proportion of important and novel products and processes were developed by users, and that substantial proportions of users engage in developing or modifying products they use (Gault & von Hippel, 2009). Moreover, user innovators often "freely reveal" (relinquish exclusive rights and allow general access to) their innovations (Harhoff, Henkel, & von Hippel, 2003). They do this both to avoid the costs and difficulty of excluding others through IP rights (as discussed

above) or trade secrecy, and to take advantage of private benefits such as access to the sequential improvements of others, reputation enhancement, or positive network effects resulting from increased use of their innovation (Harhoff, Henkel, & von Hippel, 2003). However, user innovators can also maintain some IP rights and pursue other legal measures for the purpose of avoiding expropriation of their efforts (O'Mahony, 2003).

This concept can be taken to another level in open collaborative innovation, in which a group of users actively reveal and coordinate their creative contributions to each other for integration in a larger-scale project, effectively pooling their investments with assurances that all will share in the rewards. Such processes are in use most recently and visibly in open-source software development (Benkler, 2002), but this model of development has been used in other industries for many years (Allen, 1983). Open-source contributors do so because they want to include rather than exclude others from the use of their contributions, often for normative reasons related to the culture of open-source software, or for private benefits such as those mentioned above (Lerner, Tirole, & Pathak, 2006). Advances in computing power have enabled large reductions in design and development costs for user innovation, and related advances in networked communication and collaboration software have lowered barriers for the coordination of contributions in collaborative projects (Benkler, 2002). These developments, along with the incentives that such activities provide for both innovation and imitation (and related sequential innovations and other spillovers), make it increasingly attractive as a mode of scientific and general

academic practice (Boyle, 2007; Lougee, 2007), as well as more socially optimal governance of knowledge (Baldwin & von Hippel, 2009).

6.5. Testing models of incentives and progress

The complexity of IP systems as well as their large potential impact on economic, technological, and cultural outcomes in society makes them fertile breeding grounds for theories about underlying issues such as incentives, conformity, creativity, the optimal balancing of individual and common interests, the nature and structure of knowledge, and a host of other issues; these theories by necessity cross the disciplinary boundaries of law, political science, economics, psychology, and philosophy. The purpose of experiments in understanding "intellectual property" and the promotion of intellectual discovery, as in any other system, is to simplify the issues at hand in order to show more clearly how they operate and interact, and in so doing, to point out what is not well understood for further study.

The previous experimental tasks in this dissertation can be conceptually compared to open collaborative development, because every participant's candidate solutions and (except in one condition) information about their performance are available for use by others in the group, with no cost or hindrance (though participants did not have a choice in the matter). However, the rewards for good and bad performance are materially the same -- course credit was the only compensation given to all participants. We wished to test the effect of a change to the incentives in this context by paying participants a small cash reward based on

their performance, as well as implementing a very basic and limited patent-like system. In this system, each participant would be allowed, at a certain cost and for a limited time, to automatically charge others who copy their innovations. The previously existing incentives for innovation (the possibility of receiving the benefit of an improved solution) would be enhanced by the payments that successful innovators could get for their solutions; the previously existing incentives for imitation would be reduced by the payment to the imitated player.

This change would ostensibly increase the use of innovation, which could result in the discovery of better solutions, which could be copied by other users while rewarding originators. But we know from previous experiments that innovation is risky, and the gains of improvements can be canceled out by poorer-performing solutions discovered in the process. We also know from these experiments that cumulative improvements are important to the collective performance of groups -- if this change caused less efficient imitation or less use of imitation overall, the gains achieved by successful innovators could fail to propagate and bear fruit in sequential improvements. There is also the risk that competitive motivations among participants could lead to excessive patenting to intentionally keep others from imitation, without regard to potential innovator gains via transfers from imitators.

Previous laboratory experiments by others regarding the consequences of different systems for distributing and rewarding knowledge production do not give us reason for confidence in the performance of exclusionary patent systems. One such study compared "patent-like" (winner-take-all, according to first discovery of

the best solution elements) and "market-based" reward systems (in which participants can buy and sell shares in solution components, effectively making bets on the success of their solutions) for groups of individuals attempting to solve the Knapsack Problem (Martello & Toth, 1990), and showed substantially inferior performance for the patent-like system (Meloso, Copic, & Bossaerts, 2009). Another experiment using a multi-user invention game task showed that both "patent-only" and mixed "patent and commons" systems of cumulative invention underperformed a "commons-only" system on several measures, including innovation, productivity, and societal utility (Torrance & Tomlinson, 2009).

We will discuss these experiments further in the next chapter in comparison with our own results in Experiment 4. In this experiment, we have not attempted to approach the level of verisimilitude to real patent systems seen in the abovementioned studies, because we are interested in the effects of changing incentives on generalized search tasks, and not necessarily in all of the specific details of a particular potential patent system. We expect that the results of this experiment will have some relevance to patent systems, as well as other situations in which environmental or institutional factors change the incentives of those who explore. The goals for Experiment 4 are to continue our study of the basic mechanics and dynamics of social learning seen in the previous experiments, by examining how they are influenced by concrete and differential rewards for different search strategies, and how individual-level processes affect group-level results.

7. Experiment 4 – Creature Game C (payment and protection)

7.1. Experiment 4 Overview

The task used in this experiment was the same as in Experiment 3, with four major changes: (1) in half of the games in each experiment session, we allowed participants to forfeit a small number of points to “protect” their guesses so that others who used the same guess (or any very similar guess) were forced to pay a small number of points to the protector; (2) we lengthened the time of each round slightly, so that participants would have sufficient time to take note of whether their guess was protected by another player and change it if they wished, and the number of games in each experiment session was decreased, in order to fit the session in the allotted time; (3) participants received a small cash payment according to the number of points they earned in the game; (4) participants filled out a post-task survey about their perceptions of the task, and their own strategies and performance.

Modification (1) allowed for the examination of differences in strategies and performance associated with changing the incentives for asocial and social learning. It is important to note that this is a very simple change, and intentionally omits many other relevant mechanisms of real patent systems, such as determinations of patentability and prior art, infringement, licensing negotiations, patent pools, and so forth; this was done for two reasons. First, attempting to create a convincing facsimile of a real patent system in the laboratory would require a much larger and more complex experiment. Even if there were some broadly agreeable set of elements we could introduce that were sufficiently similar to equivalents “in the

wild” such that we could claim optimal realism, the validity of our results would still be questionable for any number of other reasons, such as using a subject pool of undergraduates rather than businesspeople or patent attorneys. We do not doubt that such experimental investigation is valuable and interesting, but it was not feasible for us. (For discussion of some recent and somewhat more “realistic” experiments of patent mechanisms on innovation, see section 7.5.2 at the end of this chapter.) Second, introducing changes of this kind and magnitude would represent a large discontinuity from the previous experiments in this dissertation; we preferred to take a more focused, incremental approach that would allow us the possibility of understanding new results in light of the established patterns of strategies and outcomes from the (largely similar) previous experiments.

Modification (2) was intended to avoid noise in the data associated with unintended or hurried choices. Modification (3) allowed for the examination of behavioral differences (from previous experiments) associated with extrinsic monetary rewards. Modification (4) offered further insight into the motivations and judgments of participants, which could be correlated with their behavior in the task.

7.1.1. Predictions

In the games where the “protection” feature was unavailable, we expected little change in behavior and only a small improvement in performance (compared to the visible-scores condition of Experiment 3) due to the small additional time per round and the expectation of cash rewards. When the protection feature was available, we expected differences in results compared to when it was not available.

The possibility of receiving additional points from imitators was predicted to cause participants to innovate more in order to find relatively high scoring solutions, and those with high scoring solutions would tend to protect them when possible.

Though the “fee” for using a protected solution was set quite low relative to the average score earned in a single round, we expected that participants would avoid imitating protected solutions, thus reducing imitation behavior overall, and directing a larger share of imitation to unprotected lower-scoring solutions. Similar to Experiment 3, this was expected to reduce or reverse social learning biases such as frequency and similarity bias. The combination of these two influences would slow convergence of solutions, and keep guess diversity relatively high. As for performance, we expected that the extra incentive to explore would result in higher maximum scores, but the large number of lower scores encountered in the process, as well as the disincentive to build upon the (protected) better solutions found through this increase in exploration would lower search efficiency, thus making mean performance the same or lower than when protection was unavailable.

7.2. Experiment 4 Methods

159 participants were recruited from the Indiana University Psychology Department undergraduate subject pool, and were offered course credit for taking part in the study, as well as a small cash payment according to their performance (mean payment was approximately three dollars). Participants populated each session by signing up at will for scheduled experiments with a maximum capacity of

9 persons, and were distributed across 45 sessions as shown in Table 7.1. One participant's data (from one of the 8-person sessions) was excluded due to extremely outlying performance.

Table 7.1: Distribution of participants across group sizes in Experiment 3

Group size	1	2	3	4	5	6	7	8	9
# Sessions	14	8	3	4	5	4	3	2	2
# Participants	14	16	9	16	25	24	21	16	18

The task used was nearly identical to that of the visible-scores condition in Experiment 3, with the following changes.

Protection availability: in half of the games in each session (the *protection available* or PA condition), participants were presented with a choice for seven seconds at the end of each round (just after learning the score associated with their solution) to forfeit four points (approximately .042 in terms of normalized score) to “protect” the solution (if they made no selection while the choice was available, the default was not to protect). For the next three rounds after a solution was protected, any other player who used (at the end of the round) a solution within one element difference of the protected solution would automatically transfer two points (approximately .021 in normalized score) to the protector. Solutions within one element difference of a protected solution could not be protected.

The *protection fee* and *use fee*, respectively, were intentionally set at fairly low values in order to ensure that the cost for these options would be visible but

would not unduly discourage participants from using them, or excessively warp incentives toward one option or the other. The wording of the options presented to participants at the end of each round is shown in Appendix 7.A. We ensured that participants understood these options with additional instructions and hands-on demonstrations before data gathering began. In order to ensure that participants were aware of the decisions they made concerning the use of protected teams during each round, any peers' teams that were currently protected were shown with their background highlighted in bright red. In addition, when a participant changed their team such that it was protected by another player, its background was also highlighted in bright red, and the message "Protected by another player" was shown above it (these notifications occurred as soon as the change was made, not at the end of the round). In each round, we recorded whether each participant *protected* his or her team or *used* another's protected team, and how many others (if any) used the player's protected team. In the other half of the games in each session (the *protection unavailable* or PU condition), the protection option was not available to participants, and games were played as they were in the Scores Visible condition from Experiment 3. Games were played in a random order in each session.

Longer rounds and fewer games: to give participants sufficient time to evaluate this choice and change their guesses if desired in the *protection available* condition, and to be able to properly compare behavior between conditions, we lengthened each round from 10 to 15 seconds in both conditions. Because of the longer rounds (including the additional seconds given to make the protection choice after each round), additional practice time for the new game features, and the post-

task survey (discussed below), we reduced the number of games in each experiment session from six to four to fit the session in the one-hour time limit required for experiments using our subject pool. Of course, the distinction between games in the *protection available* and *protection unavailable* conditions only mattered in sessions that included more than one participant, but rounds and sessions were identical in length for all participant group sizes.

Payment: participants were informed before each session that they would receive a small cash payment of “a few dollars” which would vary according to the total number of points they earned individually during the session. We set the payment per point (\$0.00086) according to the distribution of scores from Experiment 3, such that the mean payment would be approximately \$3.00.

Post-task survey: we devised a 10-item questionnaire for participants to complete after the final game in each session in order to gather self-report data on participants’ attitudes and judgments about the task and their strategies, which included 8 multiple-choice questions with response options on a Likert scale, and two free-response items. The full text of the survey is shown in Appendix 7.B.

The distribution of individual point values and interactions for the icons was the same as in Experiment 3, and scores were again normalized from [-6,88] to [0,1] for ease of analysis. Note that because the normalization did not include the increased range possible from the transfer of protection-related fees, it was possible for normalized scores to go beyond [0,1], but this did not occur. *Unadjusted score* refers to values which do not include the subtraction of protection or use fees paid or the addition of use fees received, corresponding to the plain value of the solution

according to its elements; *adjusted score* refers to the same values with the above fees added or subtracted (when present). All analyses of score will refer to unadjusted score except where noted; in general there were no differences between results for adjusted and unadjusted scores.

7.3. Experiment 4 Results

7.3.1 Overall means

Mean dependent variables in each condition are shown in Table 7.2 (see also Fig. 7.1). For grouped participants, mean overall and final scores in each condition were nearly identical to each other and to those observed in the visible-scores condition in Experiment 3. On average, minimum scores were lower and maximum scores were higher in the protection available condition, but neither difference was significant. Isolated participants achieved slightly higher mean overall and final scores than those in Experiment 3.

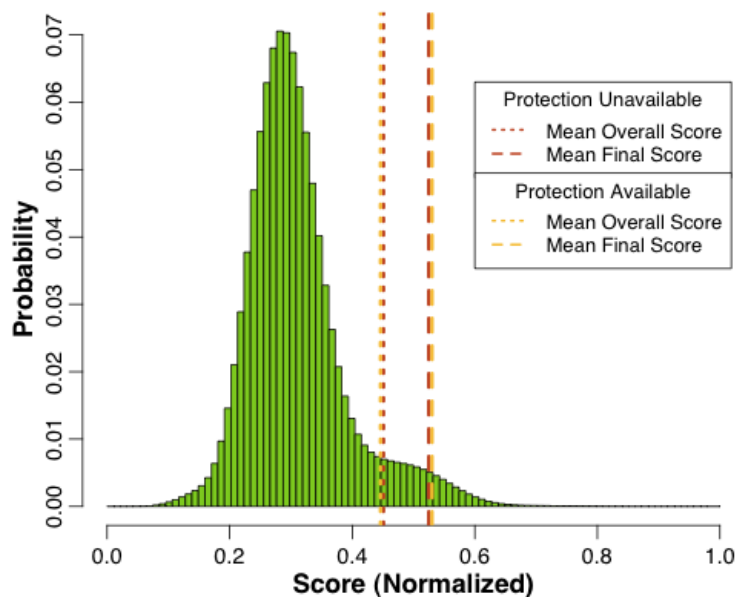


Figure 7.1: Distribution of scores for all possible teams.

Table 7.2: Mean score, guess diversity, and choice source proportions by condition

(PU: Protection Unavailable, PA: Protection Available)

Cond.	Overall Score (Percentile)	Final Score (Percentile)	Guess Diversity	Imitation	Innovation	Retention	Retrieval
PU	.451 (93.3%)	.525 (97.5%)	60.1%*	6.9%*	14.6%*	75.6%*	2.2%
PA	.446 (92.6%)	.530 (97.5%)	65.9%*	6.2%*	17.8%*	72.9%*	2.3%
Isolated Partic.	.376 (86.1%)	.466 (94.0%)	--	--	26.1%	61.0%	12.2%

* significant differences between conditions

7.3.2. Rounds

Linear mixed-effects models were used to examine trends across rounds for score and guess diversity, with a random effect of participant group. Analysis of score versus round showed very similar positive trends for grouped participants in each condition (PU: $F(1,712)=208.87$, $p<.0001$, $B=.627$; PA: $F(1,712)=283.72$, $p<.0001$, $B=.670$). Isolated participants' scores increased significantly across rounds as well, but significantly less so than for grouped participants ($F(1,657)=95.52$, $p<.0001$, $B=.498$, mean increase=0.150; see Fig. 7.2). Guess diversity showed corresponding decreases across rounds in both conditions (PU: $F(1,712)=169.33$, $p<.0001$, $B=-0.458$; PA: $F(1,712)=165.94$, $p<.0001$, $B=-.485$; see Fig. 7.2).

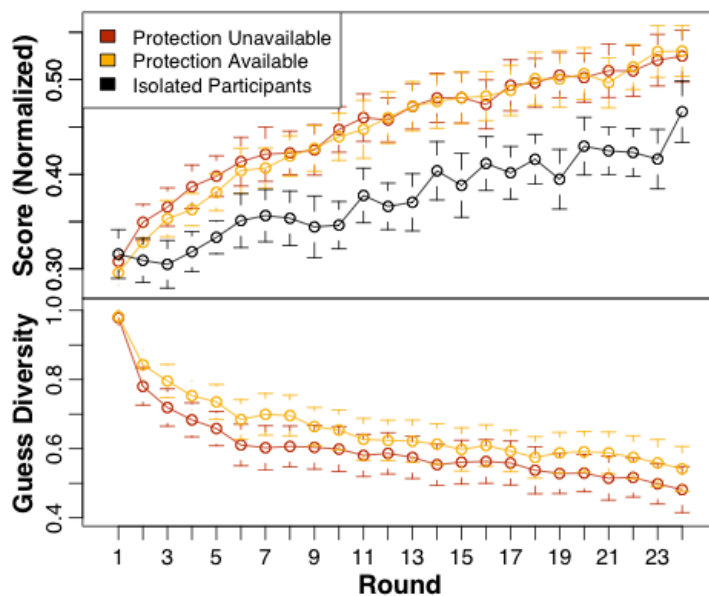


Figure 7.2: Scores increased and guess diversity decreased at about the same rate whether protection was available or unavailable.

Trends for choice sources across rounds showed very similar patterns to those in Experiments 2 and 3, with approximately the same magnitude and significance: Imitation and Innovation decreased significantly over rounds, and Retrieval and Retention increased significantly. There was no significant difference in slope for any choice source between conditions, nor a substantial difference in comparison to the slope over rounds for each choice source found in Experiment 3. Protection decreased across rounds ($F(1,712)=17.54$, $p<.0001$, $B=-0.170$), while use of protected teams increased ($F(1,712)=49.26$, $p<.0001$, $B=0.331$; see Fig. 7.3).

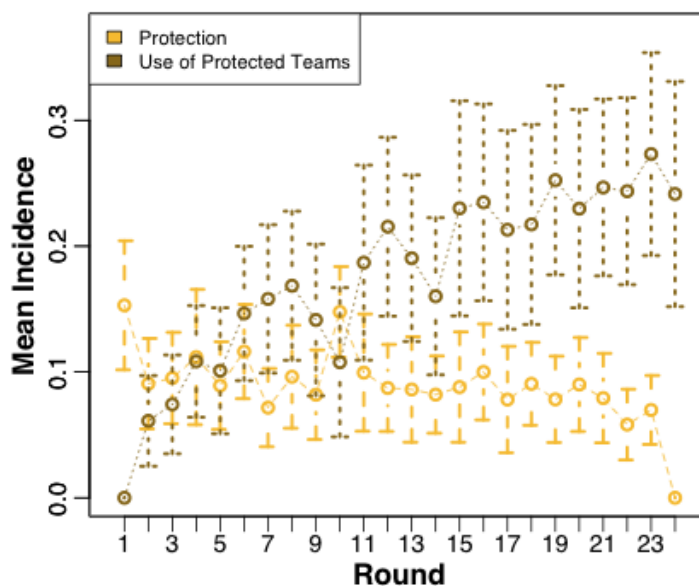


Figure 7.3: Protection decreased across rounds, while use of protected teams increased.

7.3.3. Game order

Similar linear mixed-effects models were used to examine trends across game order for each dependent variable within conditions. For this analysis, the game order value for each game was corrected to its order within the condition, i.e. Game 1 or 2 in each condition. Score showed no significant change across game order in either condition, and guess diversity displayed a decrease across game order in both conditions (PU: $F(1,30)=5.94$, $p=.021$; PA: $F(1,30)=4.76$, $p=.037$; see Fig. 7.5). There were no significant changes across game order for any choice source in either condition (see Fig. 7.5).

Within the protection available condition, protection decreased across game order ($F(1,26)=9.79$, $p=.0043$, $B=-0.217$, mean chg. $=-0.020$), but use of protected teams did not change significantly.

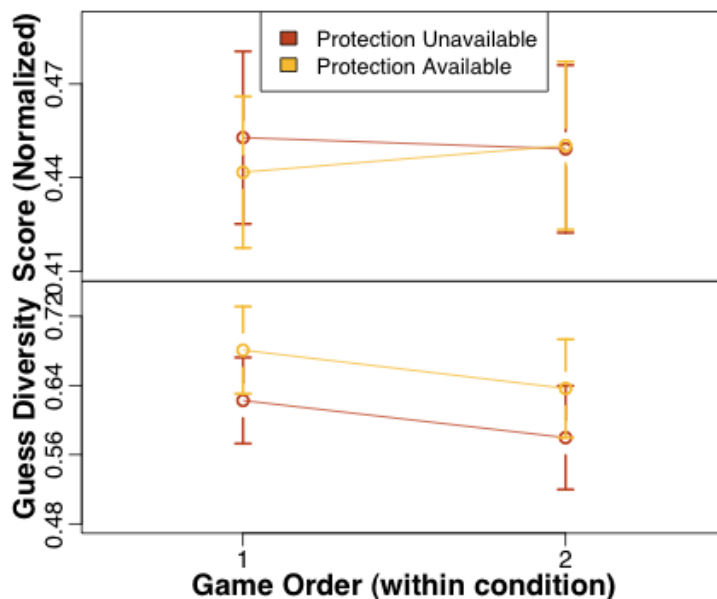


Figure 7.4: Score did not change significantly in either condition, and guess diversity decreased in both conditions.

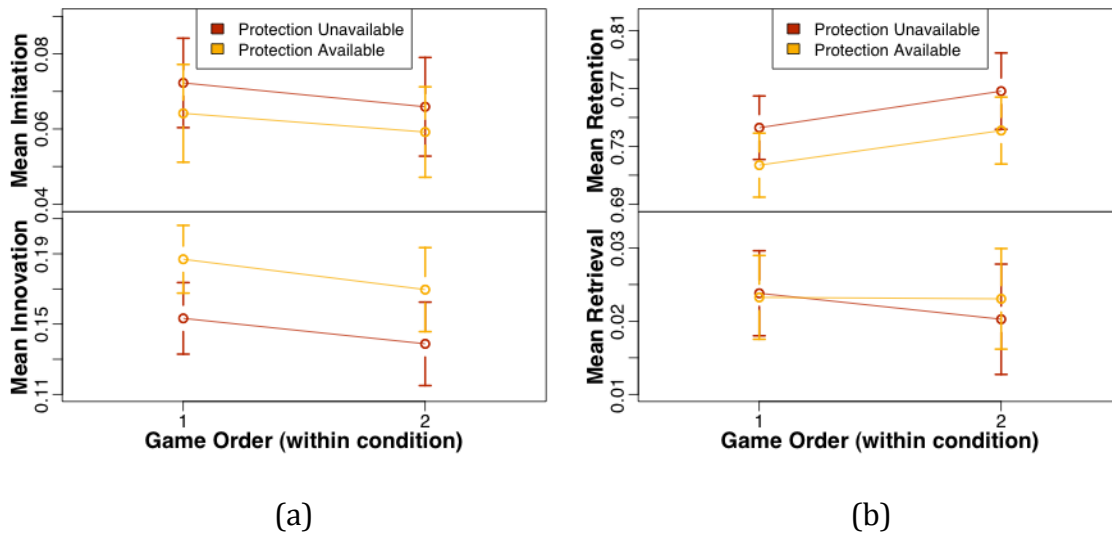


Figure 7.5: (a) Imitation and Innovation did not show significant changes across game order in either condition, nor did (b) Retention or Retrieval.

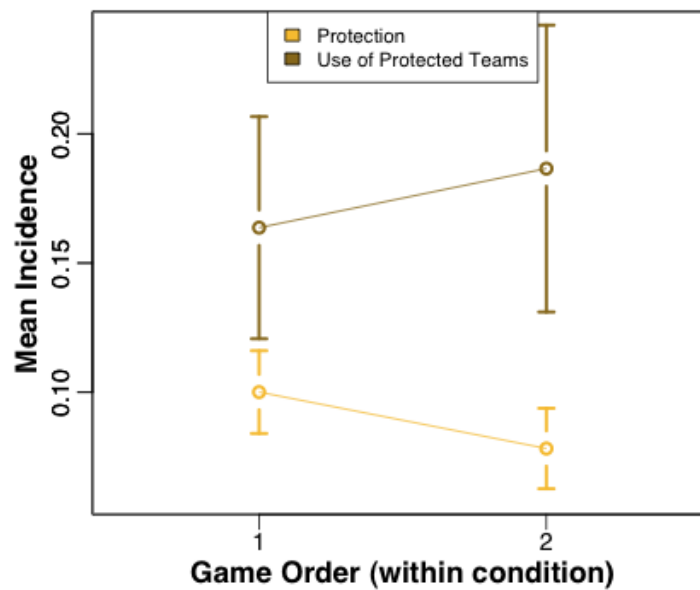


Figure 7.6: Protection decreased significantly across game order, while use of protected teams showed no significant change.

7.3.4. Group size

Trends across participant group size for each dependent variable within conditions were examined using linear mixed-effects models, with the participant group used as a random effect on the intercept. Slopes across group size did not show differences between conditions for any dependent variable, except where noted. Score increased significantly with group size in both conditions (PU: $F(1,43)=27.19, p<.0001, B=0.512$; PA: $F(1,43)=36.69, p<.0001, B=0.568$; see Fig. 7.7), and guess diversity showed a corresponding decrease in both conditions (PU: $F(1,29)=28.96, p<.0001, B=-0.661$; PA: $F(1,29)=34.48, p<.0001, B=-0.672$; see Fig. 7.7). As for choice sources, Imitation increased significantly for larger groups in both conditions (PU: $F(1,29)=37.72, p<.0001, B=0.680$; PA: $F(1,29)=37.20, p<.0001, B=0.699$; see Fig. 7.8a), while Innovation decreased significantly only in the protection available condition ($F(1,29)=8.94, p=.006, B=-0.437$; see Fig. 7.8a). Neither Retention nor Retrieval showed significant changes across group size (see Fig. 7.8b).

Protection did not show a significant trend across group size, while use of protected teams increased in larger groups ($F(1,29)=37.45, p<.0001, B=0.751$; see Fig. 7.9).

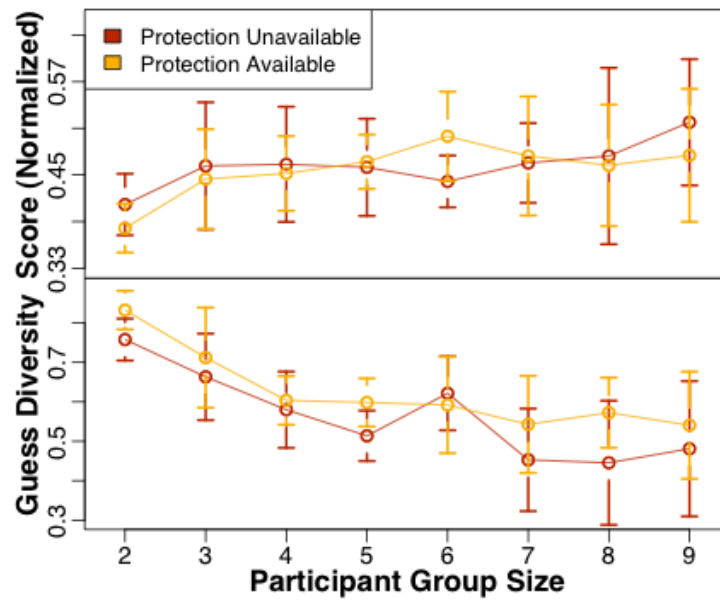
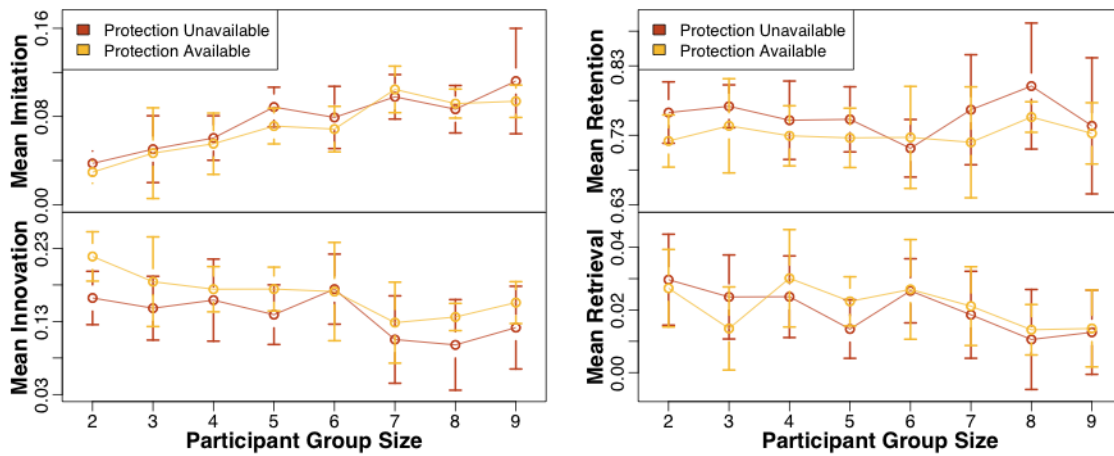


Figure 7.7: As participant group size increased, mean scores in a group increased, and the diversity of offered solutions decreased.



(a)

(b)

Figure 7.8: As participant group size increased, (a) mean proportions of Imitation increased in both conditions and Innovation decreased only in the protection available condition, and (b) Retention and Retrieval showed no significant change.

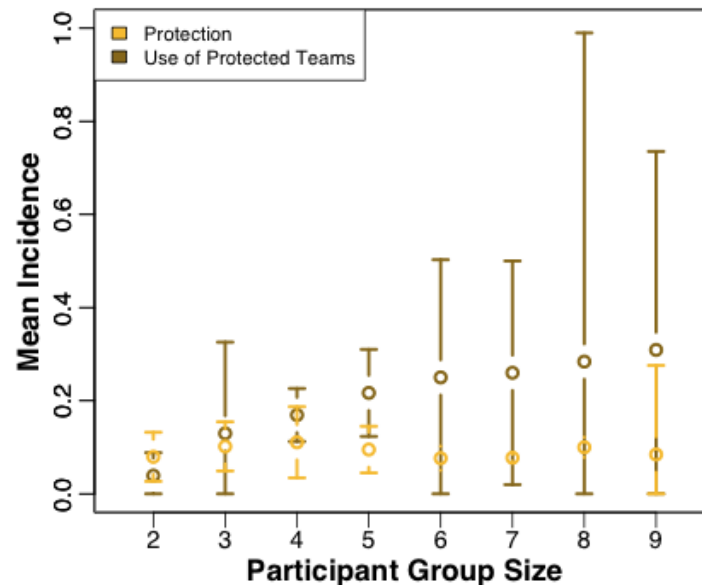


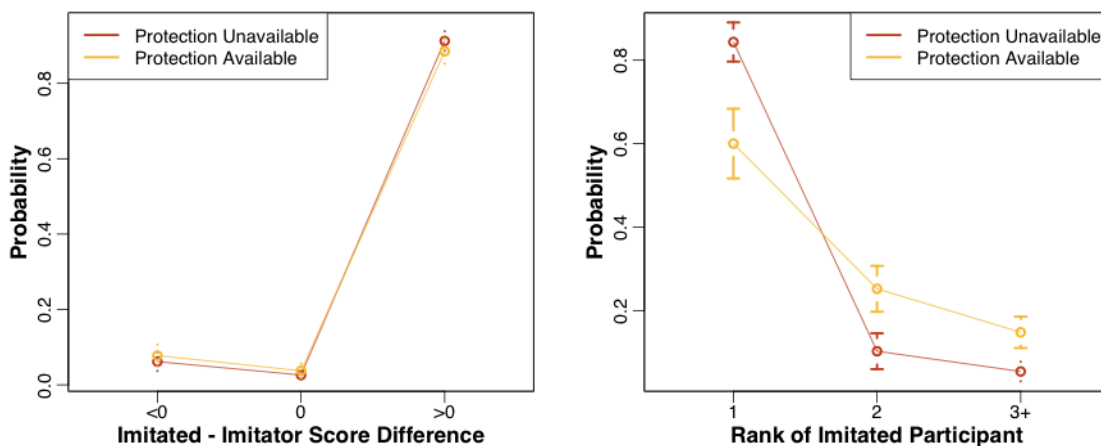
Fig. 7.9: As participant group size increased, protection did not change significantly, but use of protected teams increased.

7.3.5. Differences in imitation

Across both conditions, approximately 94.7% of all guesses including Imitation were of a single participant. At the time of such single-source imitations, the score of the imitated participant was greater than that of the imitator in approximately 90% of cases in both conditions (see Fig. 7.10a). Of all instances of single-participant imitation, the probability of imitating the top-scoring solution in the group was significantly higher in the protection unavailable condition than the

protection available condition ($t(34)=5.27, p<.0001$; see Fig. 7.10b). An analysis of the probability of protection across score rank showed that the best two solutions present in any given round were nearly always protected (see Fig. 7.10c).

To examine separately how *often* and how *much* participants imitated one another, we measured the mean incidence of guesses in which there was greater than zero Imitation (*Imitation incidence*), as well as the mean use of Imitation in those cases where it was greater than zero (*Imitation proportion*). Mean Imitation incidence was significantly higher in the protection unavailable condition (0.205 vs. 0.162; $F(1,92)=19.37, p<.0001$), but mean Imitation proportion was lower (0.341 vs. 0.390; $F(1,89)=7.28, p=.008$), and the distribution of mean imitation proportions was weighted slightly but significantly more heavily toward higher values in the protection available condition, as shown by a Kolmogorov-Smirnoff test of equality of distributions ($D = 0.1116, p<.0001$; see Fig. 7.11). In other words, participants in the protection available condition copied one another less frequently but in larger amounts at a time.



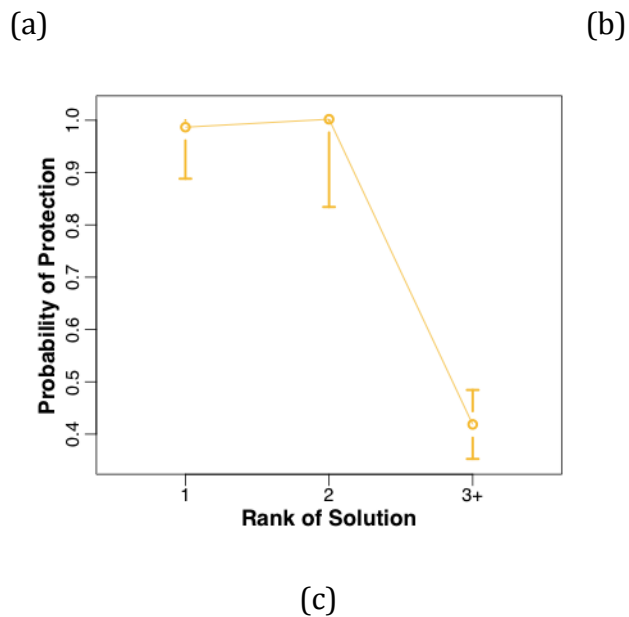


Figure 7.10: (a) There were strong biases toward imitating better-scoring participants than oneself in both conditions, and (b) a significantly stronger bias toward imitating the best-scoring participant in the protection unavailable condition than in the protection available condition; and (c) a related analysis showed that the best two solutions in any given round were highly likely to be protected.

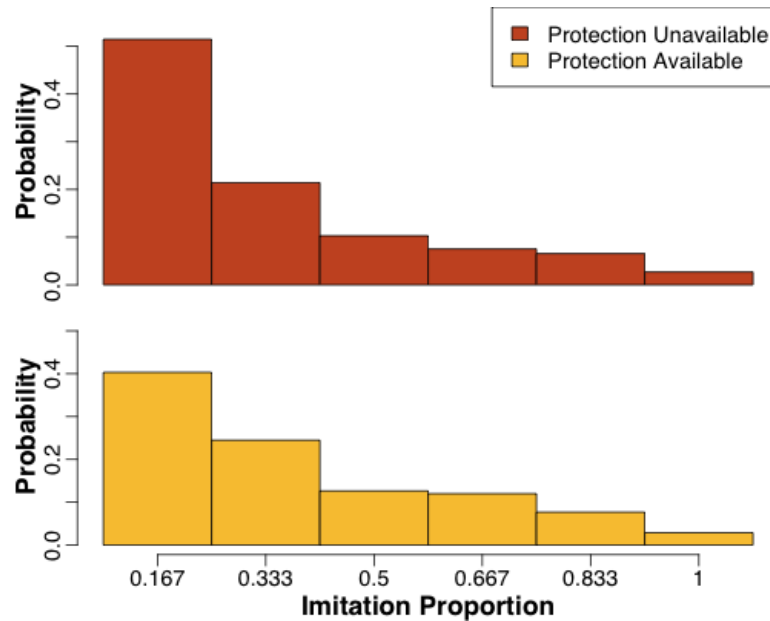


Figure 7.11: For guesses that included at least some Imitation, participants in the protection available condition had higher proportions of Imitation in their guesses.

7.3.6. Choice source strategy

As in Experiment 2, the choice sources of each non-isolated participant over the entire session were analyzed, and each participant's choice source *strategy* was categorized according to their proportion of each source. Participants whose choices contained one source in an average proportion greater than the global average for that source plus one standard deviation, were labeled with that strategy. For example, a player whose guesses over the course of a session consisted of a greater proportion of Imitate choices than the average for all other participants in the experiment, plus one standard deviation, were labeled as having an overall strategy of "Imitate." Those who fit the above criteria for more than one choice

source, or none, were labeled as having a “Mixed” strategy. The score distribution for each strategy category in each condition is shown in Fig. 7.12.

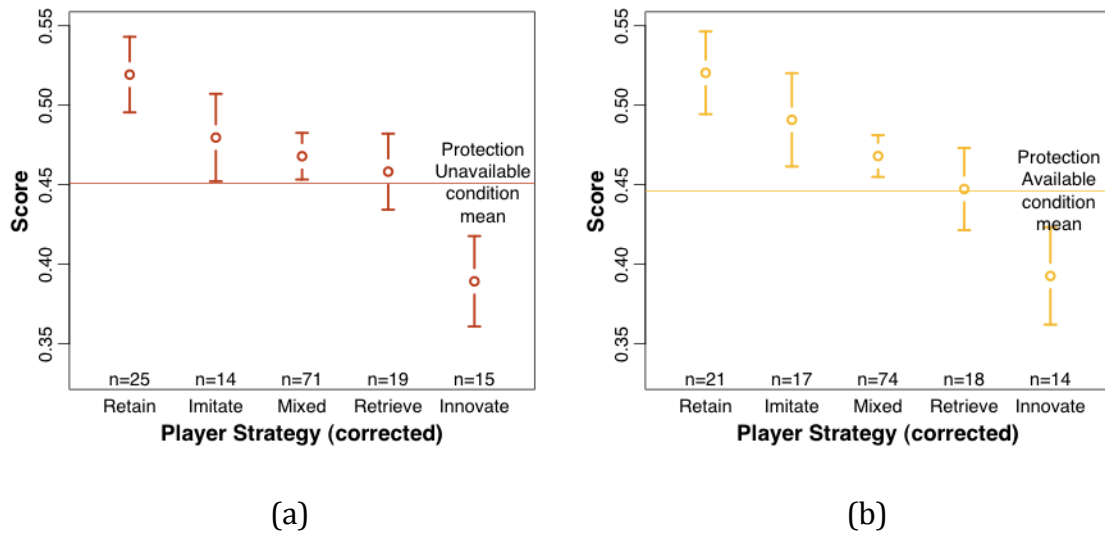


Figure 7.12: Score vs. choice source strategy in (a) protection unavailable and (b) protection available conditions, showing that a conservative high-Retention strategy resulted in the best performance in both conditions, though highly Imitative strategies also performed well.

A linear regression of mean individual score vs. mean individual Imitation guess proportion showed a significant positive relationship (that is, the greater a participant’s average proportion of Imitation, the better the participant’s score) in both conditions (PU: $F(1,142)=7.91$, $p=.006$, $B=0.230$; PA: $F(1,142)=3.96$, $p=.048$, $B=0.165$; see Fig. 7.13a). The opposite was true for individual score vs. Innovation, which displayed a significant negative relationship in both conditions (PU: $F(1,142)=120.30$, $p<.0001$, $B=-0.677$; PA: $F(1,142)=98.01$, $p<.0001$, $B=-0.639$; see

Fig. 7.13b). A positive relationship held for Retention in both conditions (PU: $F(1,142)=56.24, p<.0001, B=0.533$; PA: $F(1,142)=53.38, p<.0001, B=0.523$; see Fig. 7.13c). Finally, a negative relationship was found for Retrieval in both conditions (PU: $F(1,142)=4.88, p=.029, B=-0.182$; PA: $F(1,142)=7.15, p=.008, B=-0.219$; see Fig. 7.13d).

As in Experiment 2, analyses of mean group score vs. mean group guess proportion for each choice source showed similar relationships of the same significance and directions as those noted above. Analyses of mean individual score vs. mean group (excluding the individual) guess proportion showed similar relationships as well, with the exception of the absence of significant relationships for Retention or Retrieval. Plots of these are omitted for clarity. All trends noted above were generally monotonic; that is, there were no thresholds or inflection points beyond which the relationships changed.

Similar analyses of protection showed no significant relationship with score for individuals (see Fig. 7.14a), or at the other two levels discussed above (group and individual vs. group others), while score vs. use of protected teams showed a significant positive relationship for individuals ($F(1,142)=67.42, p<.0001, B=0.567$; see Fig. 7.14b), as well as for groups ($F(1,60)=72.99, p<.0001, B=0.740$), and for individual score versus protection by others in the group, excluding the individual ($F(1,142)=40.86, p<.0001, B=0.471$). All of the same relationships were found for both adjusted and unadjusted score. Plots of these are omitted for clarity.

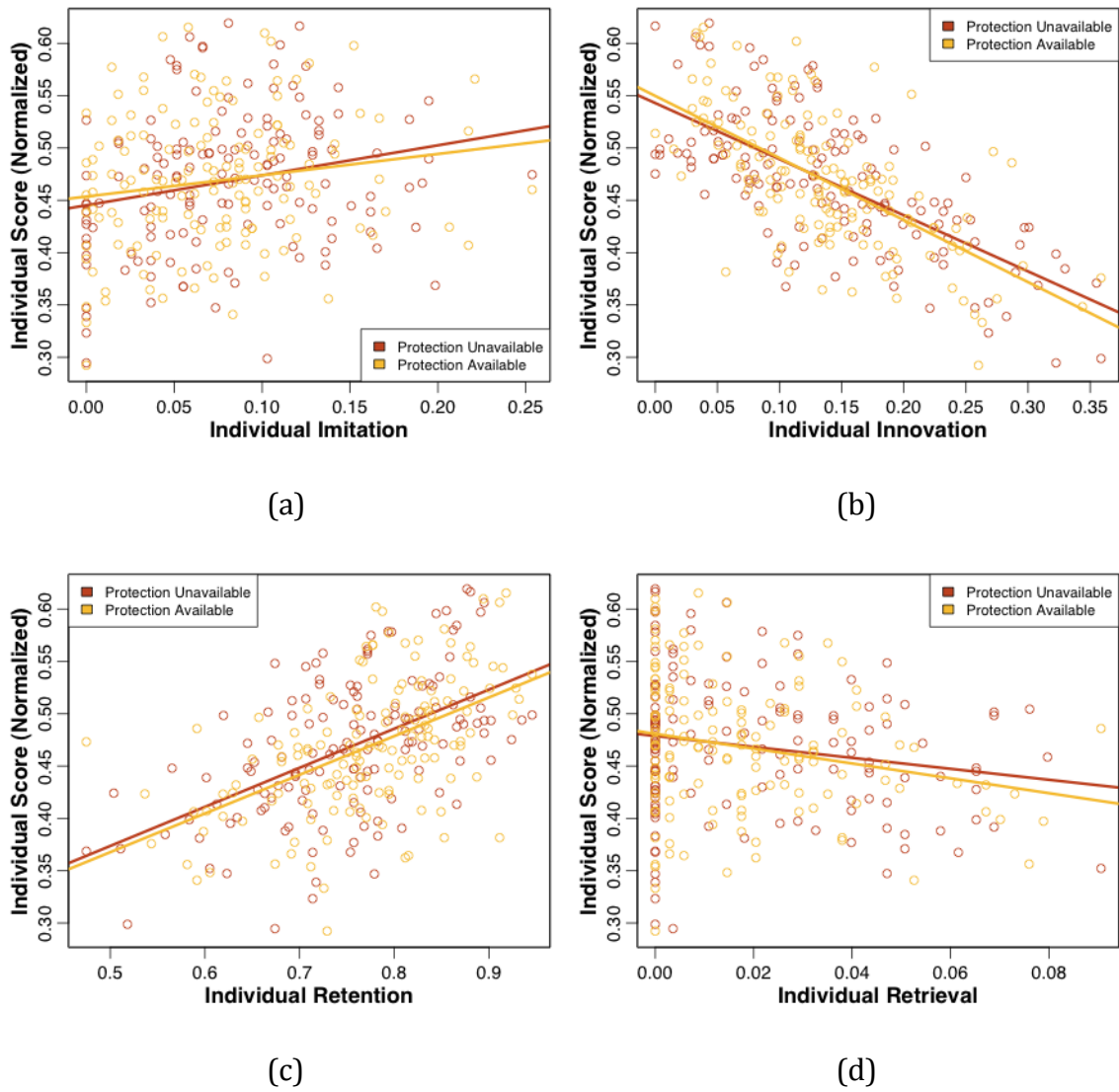


Figure 7.13: Higher individual scores were associated with (a) higher individual Imitation, (b) lower Innovation, (c) higher Retention, and (d) lower Retrieval.

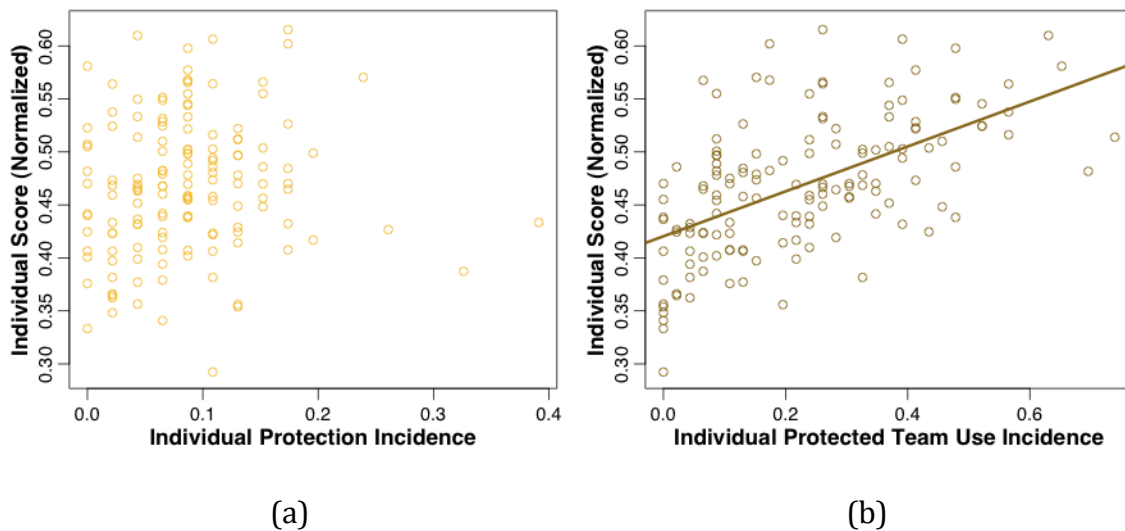


Figure 7.14: (a) Protection showed no significant relationship with score, while (b) higher use of protected teams was associated with higher scores.

7.3.7. Improvements

As in previous experiments, improvements were tallied for each participant in each session and condition. Histograms of normalized improvement share in both conditions showed a less equitable distribution of improvements within groups (more participants with zero improvements, and fewer with shares near 1) relative to the scores-visible condition in Experiment 3 (compare Figs. 7.15 and 5.13). A Kolmogorov-Smirnoff test of equality of distributions indicated that the distributions in each condition were not significantly different. However, the upper tail of the distribution was essentially shifted upwards (i.e. the highest improvement shares in the PU condition were replaced by even higher shares in the PA condition), though the highest achievers in each condition were entirely different sets of individuals. Mean overall score also showed a strong positive correlation with

improvement share in the PA condition ($F(1,112)=49.98, p<.0001, B=0.348$), but this relationship was not evident in the PU condition.

The mean choice source proportions for guesses that resulted in score improvements and those that did not are shown in Table 7.3. In the protection unavailable condition, guesses that yielded improvements had higher Innovation ($t(417)=-9.78, p<.0001$) and lower Retention ($t(395)=6.01, p<.0001$) relative to non-improvements. In the protection available condition, there was higher Imitation ($t(549)=-2.78, p=.006$), lower Innovation ($t(574)=2.86, p=.004$), and lower Retrieval ($t(682)=3.37, p=.0008$) for improvements than non-improvements. Of all improvements, about the same proportion in each condition resulted from guesses that included Imitation (PU: .252 vs. PA: .224).

In 51.2% of improvements in the protection unavailable condition and 43.9% in the protection available condition, the focal player imitated at least one peer who had previously imitated the focal player. In other words, a player who was imitated by another player often later imitated that same player in the course of creating an improvement, and this happened more often when protection was unavailable.

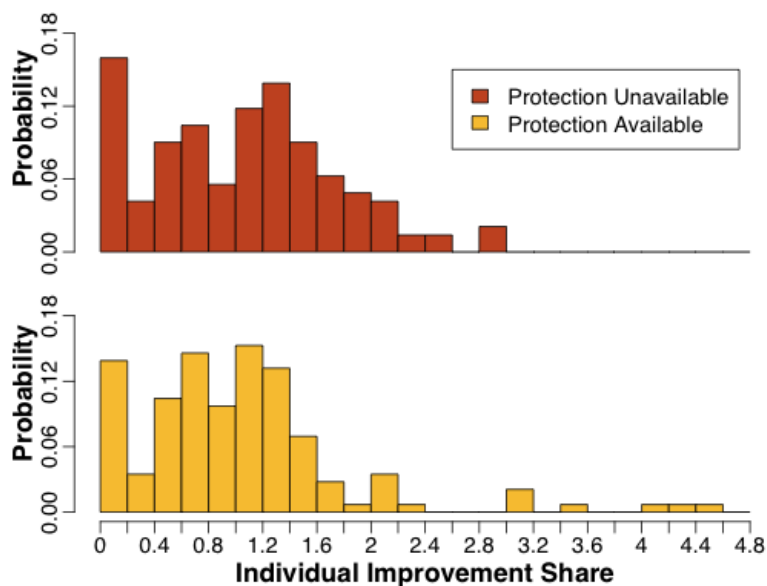


Figure 7.15: Histograms showing distributions of improvements within groups in each condition.

Table 7.3: Mean choice source proportions for improvement and non-improvement guesses in each condition.

Condition	Improvement	% of guesses	Imitation	Innovation	Retention	Retrieval
PU	No	94.7%	7.9%	13.6%*	75.7%*	2.0%
	Yes	5.3%	9.1%	20.1%*	69.0%*	1.7%
PA	No	92.5%	7.0%*	16.8%*	73.0%	2.3%
	Yes	7.5%	10.0%*	14.4%*	73.9%	1.3%

*** significant differences between improvements and non-improvements**

within condition

7.3.8. Guess similarity

A comparison between the mean similarity of participants' most recent guesses to those whom they imitated, and to those whom they did not imitate, revealed slight but significant differences in both conditions. In the protection

unavailable condition, there were similarity values of .576 for imitated vs. .545 for non-imitated guesses ($t(2511)=-2.90$, $p=.0037$; see Fig. 7.16a). In the scores-invisible condition, there were similarity values of .491 for imitated vs. .457 for non-imitated guesses ($t(2051)=-3.18$, $p=.0014$; see Fig. 7.16b). In other words, prior to imitation, the average imitators' guess was more similar to that of the imitated participant(s) than to those of others in the protection unavailable condition, and this relation was found but was slightly less prominent in the protection available condition.

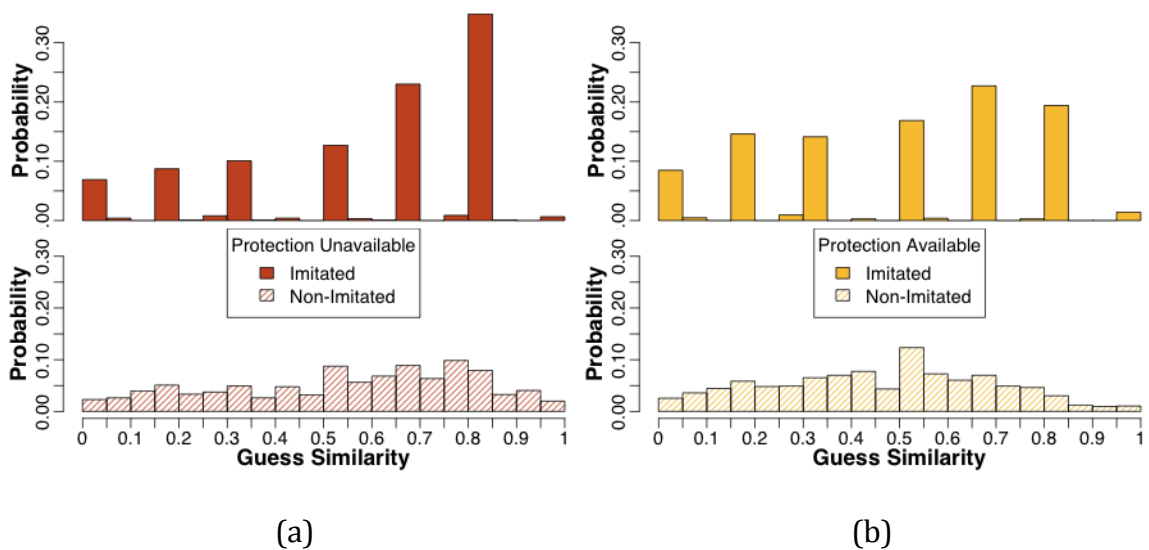


Figure 7.16: (a) In the protection unavailable condition, imitators' previous guesses showed greater similarity to the guesses they imitated than to those they did not imitate, while (b) in the scores-invisible condition, a similar but weaker effect was observed.

7.3.9 Frequency and momentum bias

As in Experiment 1, we measured the bias of participants to choose an icon according to its frequency in peers' choices. To reiterate briefly, we measured the mean probability of Imitation and Innovation for any icon not already included on a player's team, based on the frequency of its appearance on peers' teams in the player's display, and compared them to expected chance baselines.

Linear mixed-effects analysis of imitation probability versus choice frequency showed a positive frequency-dependent Imitation bias that was significantly greater than chance in the protection unavailable condition ($F(1,258)=355.39, p<.0001, B=.722$), but significantly lower than chance in the protection available condition ($F(1,258)=387.81, p<.0001, B=.714$; see Fig. 7.17a); both became apparent at higher values of choice frequency than in Experiment 3. There were similar positive frequency-dependent Innovation biases above chance in both conditions (PU: $F(1,258)=133.15, p<.0001, B=.517$; PA: $F(1,258)=192.79, p<.0001, B=.601$; see Fig. 7.17b).

We also repeated the analysis of "choice momentum," by tallying the change in the number of players whose teams included the icon in the previous two rounds, as well as the number of the remaining players who added it to their team in the current round via Imitation or Innovation, and normalizing for group size. After log-transforming the Imitation probability data to achieve a normal distribution, t-tests of Imitation probability for negative and positive changes in choice frequency showed similar significant positive momentum biases in both conditions (PU: $t(304)=-8.66, p<.0001$; PA: $t(299)=7.76, p<.0001$; see Fig. 7.18a). Slight positive

momentum biases were also found for Innovation in both conditions (PU: $t(385)=-3.40$, $p=.0007$; PA: $t(346)=-5.54$, $p<.0001$; see Fig. 7.18b).

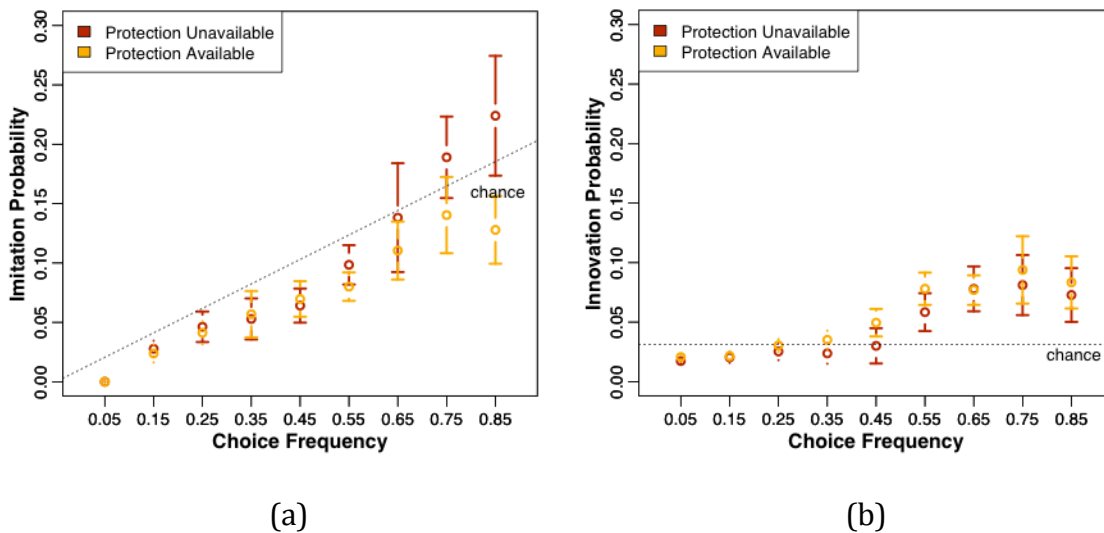


Figure 7.17: (a) There were biases toward choosing elements that were more frequently represented on other teams in the protection unavailable condition, and less frequently represented on other teams in the protection available condition for Imitation and (b) biases toward more frequent elements for Innovation decisions in both conditions.

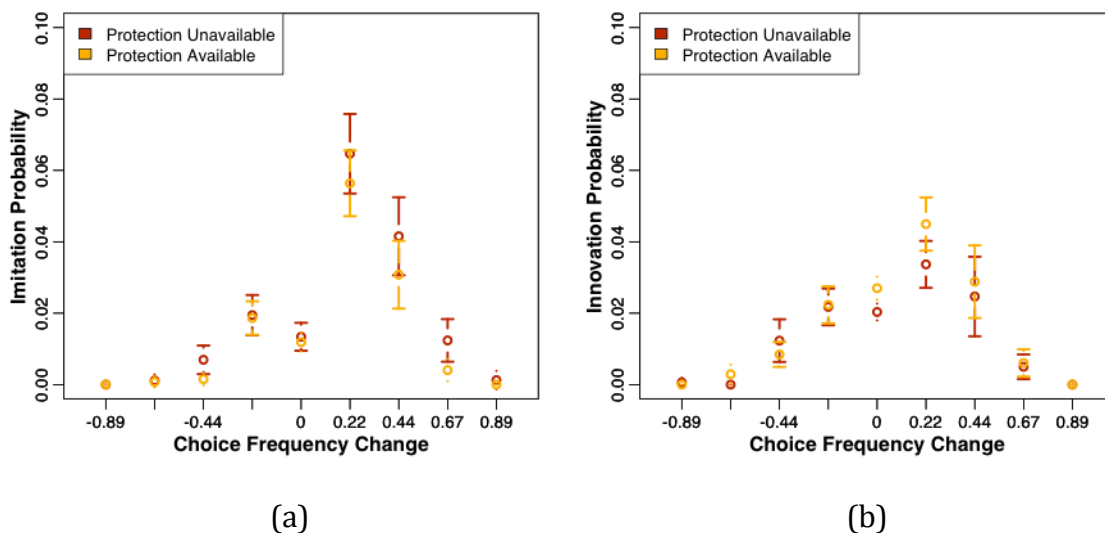


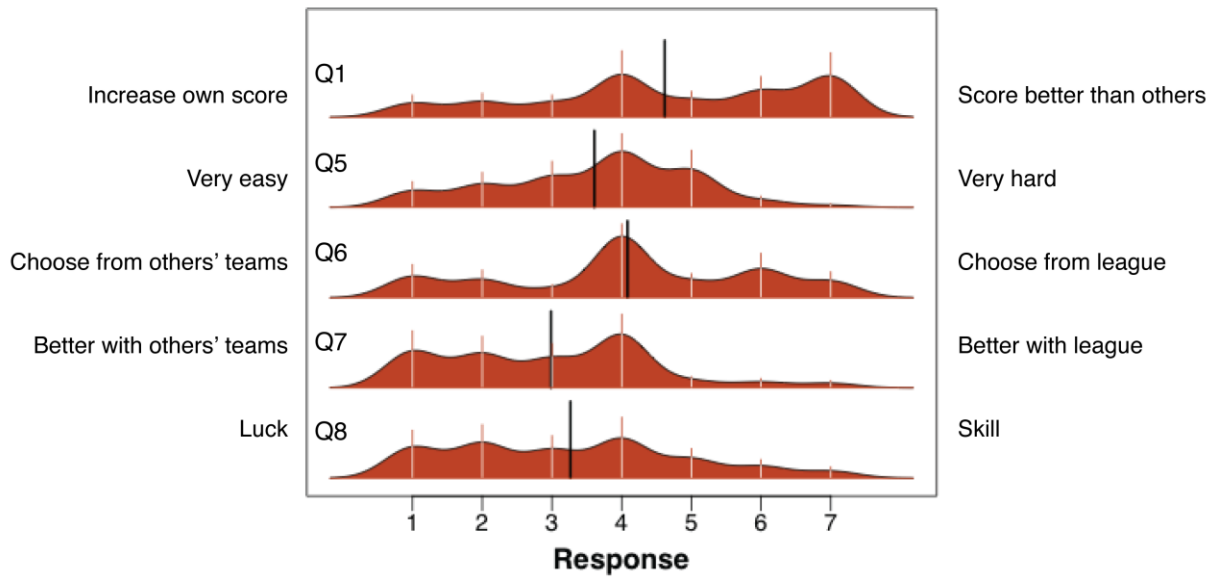
Figure 7.18: There were biases toward choosing elements whose representation on other teams was increasing in both conditions for (a) Imitation and (b) Innovation decisions.

7.3.10. Survey responses

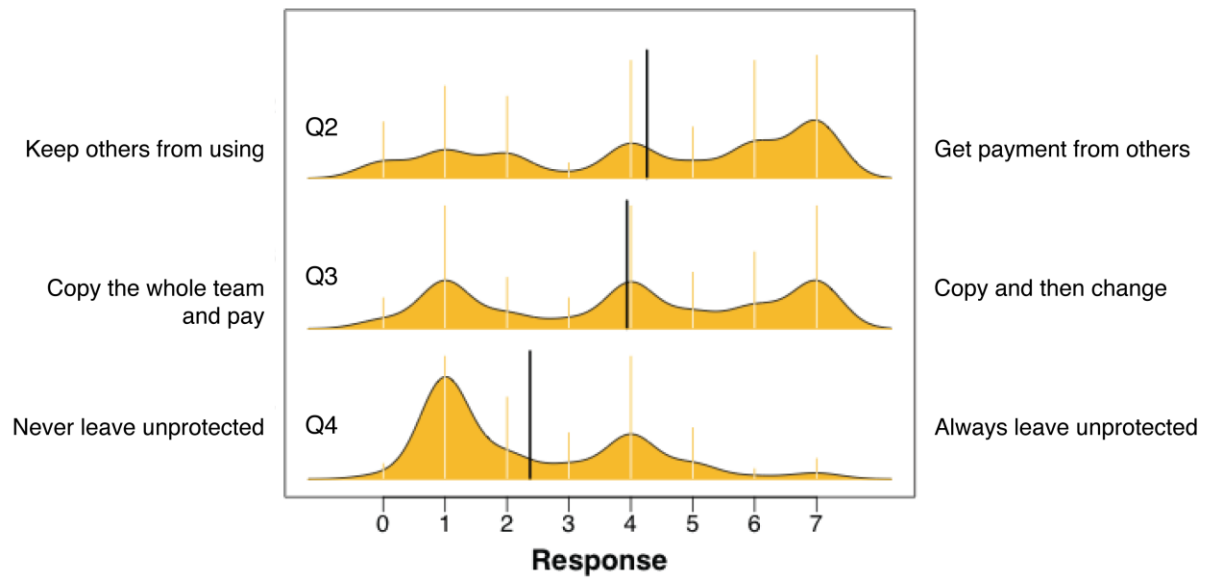
The survey distributed to participants after the end of the last game in each session is included in appendix 7.A. The first eight questions on the survey were multiple-choice, with possible responses on a 7-choice Likert scale, coded 1-7. Questions 2, 3, and 4 were related to protection and had an additional option for “does not apply,” which was coded as 0. The last two questions were free-response; one asked participants to describe their strategies, and most responses were some variation on a “copy-if-better and then make small changes” strategy; the other asked for any further comments, and most responses were either blank, or short (generally positive) comments like “fun” or interesting.” For quick reference, the eight multiple-choice questions are shown in Table 7.4. Stripcharts of responses with kernel density estimates are shown in Fig. 7.19.

Table 7.4: Multiple-choice survey questions, with responses associated with the extreme low and high ends of the scale. Those significantly associated with higher individual scores are shown in bold.

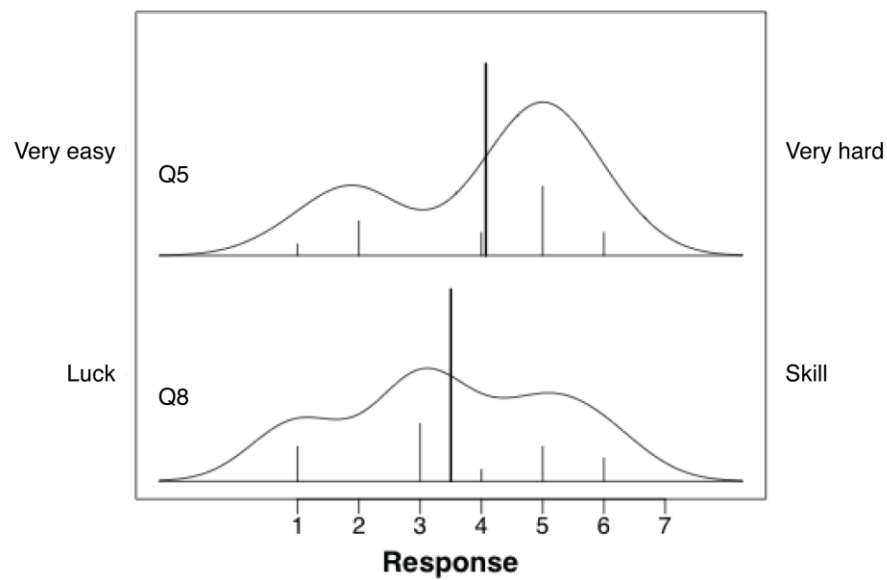
Q1	During the game, did you mostly try to...?	increase your own score (without regard to the scores other players might have)
		score higher than other players
Q2	If/when you protected your solutions, was it mostly to...?	keep others from using your solutions
		get payment for others' use of your solutions
Q3	When you wanted to use another player's protected team, did you generally prefer to...?	copy the whole team and pay the fee
		copy it and then change it to avoid paying
Q4	When you found a team with a relatively high score, did you ever intentionally leave it unprotected so that others could copy it for free?	Never
		Every time
Q5	How did you feel about the difficulty of the task?	Very easy
		Very hard
Q6	Did you choose creatures more often from ...?	other players' teams
		the league
Q7	Did you find that your scores were better when you chose creatures from ...?	other players' teams
		the league
Q8	Do you feel that success in this task was based more on ...?	Luck
		Skill



(a)



(b)



(c)

Figure 7.19: Responses to the multiple-choice survey questions in Table 7.4, plotted as stripcharts with kernel density estimates and mean lines, separated as follows for clarity: responses from grouped participants to (a) non-protection-related questions and (b) protection-related questions, and (c) responses from isolated participants to Q5 and Q8.

Relationships between player scores and responses to each question were analyzed using a mixed-effects linear model with participant group as a random effect. Higher scores were associated with responses at the upper end of Q1 (score better than others) ($F(1,256)=22.68, p<.0001, B=0.236$), the upper end of Q2 (get payment from others) ($F(1,252)=6.39, p=.0122, B=0.140$), the lower end of Q3 (copy the whole team and pay) ($F(1,243)=14.91, p=.0001, B=-0.210$), the lower end of Q4 (never leave unprotected) ($F(1,242)=6.73, p=.0100, B=-0.142$), the lower end of Q6

(choose from others' teams) ($F(1,254)=19.88, p<.0001, B=-0.225$), and the upper end of Q8 (performance based on skill) ($F(1,254)=8.15, p=.0047, B=0.148$). In examinations of response trends across participant group size, we found just one significant trend: responses to Q2 were significantly higher (get payment from others) in larger groups ($F(1,29)=8.88, p=.0058, B=0.243$).

7.4. Experiment 4 Discussion

7.4.1. Similarities with Experiment 3

As predicted, results in the protection unavailable condition of Experiment 4 (E4PU) were generally similar to those in the visible-scores condition of Experiment 3 (E3SV). Performance was slightly better in E4PU than E3SV as predicted, which may have been due to the incentive of cash payment, or the extra time to make decisions about each round's candidate solution, though unfortunately we cannot differentiate between these two factors as causes. Isolated participants in E4 also did better than those in E3, which reinforces this explanation. Imitation was markedly lower and Innovation higher in E4PU than in E3SV, which may have been a carryover effect from the PA condition, in which these differences were even more extreme. Trends of Retention and Retrieval over group size that were present in E3SV were not present in E4PU, and there was a negative correlation of score with Retrieval in E4PU that was not present in E3SV, but in each case the missing relationship was nominally present in the other experiment, but not significant. The less equitable distribution of improvement share in E4PU relative to E3SV could be attributed to a differential crowding-out (Frey and Jegen, 2001) of intrinsic motivation to achieve improvements for some participants and not others by the cash payment offered in E4.

7.4.2. Performance

Predictions concerning the PA condition were generally borne out as well. Maximum scores were slightly higher, but overall scores were actually slightly lower in the PA condition, though neither difference was significant. This, along with the increased Innovation, decreased Imitation, and increased guess diversity relative to PU, accords with the predictions made for this condition: the greater incentives for exploration led to increases in Innovation and less convergence, and some good returns in the form of slightly more improvements. However, the greater general risk of exploration, as well as less efficient propagation of better performing solutions through Imitation (because the best solutions were generally protected) led to a washing out of the benefits of improvements by lower scores encountered along the way, rather than further improvement of the better solutions that were found.

7.4.3. Strategy

As predicted, the availability of team protection also affected the use of other kinds of information in imitation strategies: PA participants showed weaker similarity bias, and a reversal of frequency bias, at least for Imitation. The former could have been due to an inclination toward saltationist strategies as seen in E3SI, while the latter could have been due to higher-frequency icons typically being on protected teams. The decrease in Imitation incidence and increase in Imitation proportion when protection was available indicates that the fee for imitation was a disincentive for Imitation, but when Imitation was pursued, participants either kept the imitated guess unchanged (to take advantage of the presumed improvement in

score and “get their money’s worth” for the use fee), or changed relatively less (in order to “invent around” the protected solution without as much risk of lowering the score).

The association of higher scores with higher use of protected teams was likely due to the fact that the use fee was quite small relative to the potential benefit in most cases. The lack of a relationship between protection and score could have been due to general overuse of protection; the typical response to Q4 on the survey indicates that for most participants the default action upon discovering a high-scoring solution was to protect it, and this is borne out in Figure 7.10c. In the PA condition, the increased use of Imitation in improvements relative to non-improvements shows that for those who recognized the value of using protected teams, Imitation was quite a productive strategy.

The decrease in protection and increase in use of protected teams over rounds can both be explained by the fact that improvements available for discovery became increasingly rare as participants discovered better solutions and moved higher in the score distribution. Protection decreased because fewer and fewer guesses yielded protection-worthy, relatively higher scores, and the use of protected teams increased because the dwindling supply of score-improving solutions stoked the demand for using those of others and made participants more willing to pay the related fee. The increase in use of protected teams across participant group size can be considered an extension of the generally greater Imitation in larger groups.

Though there was no significant change in score or choice sources across game order within conditions, the decrease in the number of games per condition

relative to previous experiments made for less data in which to detect trends of this sort. The decrease in protection over game order was likely an adaptation to the failure of the always-protect strategy (displayed in Q4 responses and the near-universal protection of the best-scoring solutions) to turn a consistent profit (as shown in the flat score versus protection results).

7.4.4 Self-reported motivations and methods

Despite receiving instructions that the goal of the task was merely to maximize one's own total score over the course of each game, as well as being informed that payment was contingent only on individual performance, responses to Q1 revealed that many participants were just as motivated (or more) to increase their performance relative to others. Those who reported such relative performance motivation also tended to score higher than others, as did those who saw performance in the game as a matter of skill rather than luck in Q8 (though most participants believed it was the latter). Q2 showed that participants were somewhat evenly divided between protecting to keep others from using their solutions and getting payment for them, and responses to Q3 showed that participants were also fairly evenly divided between "licensing" and "inventing around" others' protected teams.

7.5. Conclusions

7.5.1. Similarities and differences with previous results

In this experiment, we found patterns of results very similar to those in previous experiments, but there were also some curious new combinations of these effects. Specifically, we observed in both conditions the by-now familiar result that a conservative approach to this task paid off: relatively high usage of Imitation and Retention were associated with high scores, and Innovation and Retrieval with low scores; trends displaying these relationships differed very little across conditions.

Besides the resemblance between the protection unavailable condition of Experiment 4 (E4PU) and Experiment 3 (E3SV) noted earlier, the protection available condition (E4PA) showed some results that resembled those of the invisible-scores condition in Experiment 3 (E3SI) as well. For instance, there was a reduced tendency to imitate top-scoring solutions in E3SI was due to the impossibility of distinguishing the quality of solutions, and in E4PA due to the disincentive of paying the use fee for top-scoring solutions (which were generally protected). There was also increased diversity and innovation relative to the alternate condition for both, and a decrease in the use of similarity- and frequency-biased imitation. However, these changes led to the discovery of fewer improvements in E3SI relative to E3SV, while there were more found in E4PA relative to E4PU, though this did not lead to greater overall or final scores. Overall, it appears that the extra incentive for Innovation in E4PA led to some improvements whose benefits were canceled out by the worse solutions encountered in the exploration process, and there was a disincentive for imitation that resulted in fewer sequential improvements, which otherwise could have improved average performance with less risk.

7.5.2. Similarities and differences between experimental and real-world patent systems

This experiment featured a patent-like system for governing the use of innovations, but was in no way meant to accurately represent the complexities of a real patent system. Major differences between this task and such real systems include: our automatic “licensing” of patented innovations, with no ability for patentees to refuse to grant a license, negotiate the licensing fee, or infringe others’ patents without licensing; unambiguous patent scope and no ability to vary or dispute the breadth of patented features; no distinction between discovery and production of innovations; no ability to “open source” innovations such that they could be used freely by others but not patented; and no ability to sell or otherwise transfer patent rights between participants. We felt that testing the effect of a change in incentives to innovate in a more general search domain, and establishing continuity with our previous experiments in this domain were more important than attempting to replicate more features of patent systems. However, an experiment that did include all of the features noted above actually found that a completely commons-based (patent-free) system outperformed both a patent-only system and a mixed patent-commons system (Torrance & Tomlinson, 2009).

Besides the distinction between discovery and production of innovations in the real world, there is also the fact that physically producing many innovative products depends on rivalrous raw material resources. Again, there was no provision for this fact in our experiment, but it was incorporated in another study to

create a market-based mechanism for promoting innovation (Meloso, Copic, & Bossaerts, 2009). Similar to our experiment, participants in this study explored varying combinations of options to solve a problem; the primary difference was that in the “patent” condition, a monetary prize was given to the first to discover the optimal solution, and in the “market” condition, participants bought and sold shares in each option, and shares of options contained in the optimal solution paid a monetary dividend at the end of the game. Meloso et al. (2009) found no benefit for the patent-based system over the market-based system: the optimal solution was found in an equal number of runs of each condition. However, the optimal solution was found by a greater proportion of participants in the “market” condition. The incentive of profiting from the sales of shares in the optimal solution motivated more participants to find the optimal solution than a prize that only one of them could win. The share price of each option in Meloso et al.’s study also signaled participants about the group’s collective belief in its value, which supported a learning strategy similar to the frequency bias seen in our results, and the “filtering” of options used in the social learning strategies tournament of Rendell et al. (2010).

7.5.3. Polycentric innovation

There remain large differences between the above experimental treatments and many real-world intellectual discovery contexts, most obviously in the scale of discoveries, and the investments of time and other resources required. But the fact that many predictions from the traditional “reward” and “prospect” theories of patents have been contradicted or remain unconfirmed in the above experimental

results, as well as cross-national econometric studies (Park & Ginarte, 1997), large-scale reviews of data related to patenting behavior and changes in patent law (Bessen & Meurer, 2008; Boldrin & Levine, 2008), and a variety of other measures (see Chapter 6) should give us pause in continuing to endorse such theories. The increasingly well-studied performance of alternate models of innovation by individual users and groups engaged in open collaboration (Baldwin & von Hippel, 2009; Strandburg, 2009; Benkler, 2006) show us that there are many possibilities for more equitable, efficient, and sustainable ways of creating beneficial innovations and supporting a knowledge commons.

Mazzoleni and Nelson (1998) note that the theories used to justify IP (those of incentives for creation, disclosure, commercialization, and efficient exploration of innovations) are not universally applicable and in some circumstances conflict with each other. They also note that these theories make assumptions (implicitly or explicitly) about several important features of contexts in which innovation occurs: (1) “The nature and effectiveness of means other than patents to induce invention and related activities” (a general effectiveness question); (2) “Whether the group of potential inventors is likely to work on diverse and non-competing ideas, or whether the group is likely to be focused on a single alternative or a set of closely connected ones.” (i.e. the structure of the search space); (3) “The deterrent effect of the presence of patents on unauthorized use of a technology and on the transaction costs involved in licensing an invention.” (issues related to competing follow-on innovations and anticommons concerns); (4) “Whether the multiple steps in the invention, development, and commercialization of a new technology tend to proceed

efficiently within a single organization, or whether efficiency is enhanced if different organizations are involved at different stages of the process.” (issues related to competition and centralization); (5) The “topography of technological advance,” i.e. “the manner in which inventions are linked to each other temporally, and as systems in use” (also dealing with sequential innovations and the structure of the problem space) (Mazzoleni & Nelson, 1998, p. 1033).

Variations in these conditions across different innovation contexts prompt a change from asking “Which theory is correct?” to “Where does each theory apply?” It is easy to see where alternate modes such as user innovation or open collaboration could gain purchase under this framework, by making changes to the assumptions embodied in traditional IP theories. Rather than centralizing innovation decisions in patent-holding individuals or firms, these alternate modes increase the flexibility of the governance of provision and appropriation in a knowledge commons, and subject them to norms determined by the relevant communities of users and innovators. As seen in the analyses of patent performance and value across industries (Bessen & Meurer, 2008), conditions around invention processes in different fields (e.g. pharmaceuticals versus software) could support a variety of different practices and organizational structures around the discovery and use of innovations, with different rules governing actions such as coordination and disclosure of contributions to the commons. Some of these practices are already in use in situations such as a nonprofit patent pool for AIDS treatments in developing countries (UNITAID, 2010), and royalty-free license requirements for internet technology standards (World Wide Web Consortium, 2004). At the same time, there

is a place for higher levels of organization and governance. As mentioned earlier, IP rights can be used to resolve or pre-empt legal disputes between knowledge users or user communities (O'Mahony, 2003). It has also recently been argued that the World Intellectual Property Organization (historically a coalition for the promotion of IP rights and enforcement) should be re-tooled as a more general international administrative forum for considering and implementing policies related to evolving modes of innovation (Strandburg, 2009). This reliance on mixtures of various forms and scales of authority with overlapping jurisdictions (as opposed to completely centralized or decentralized authority) has been found to be an important factor in the governance of public goods and common-pool resources, in which it has become known as "polycentric" governance (Ostrom, Tiebout, & Warren, 1961; Andersson & Ostrom, 2008; Ostrom, 2008).

There are undoubtedly some innovations that may have been delayed or not created at all apart from some form of patent system, but there are also innovations that were made mostly without it (such as many open-source software projects and much academic research) which would probably not have been created if each component were subject to patent protection. Rather than arguing for the abolishment of the patent system, these innovations demonstrate that a polycentric system of knowledge commons governance is possible, desirable, and in fact is already upon us. Studies such as those described in this dissertation can aid in understanding the causes, consequences, and dynamics of discovery under various forms of governance, and therefore in improving the practical processes of discovery for the benefit of all.

7.A. Protection choice wording in Experiment 4

Protection choice dialog: at the end of each round except the last, participants in the protection available condition whose team was not already protected by another participant were shown a dialog box with the following text (in quotes) and buttons (in brackets):

“Do you want to protect your team? This will cost you 4 points.”

[Protect My Team]

[Don't Protect My Team]

Protection confirmation: If the participant clicked the [Protect My Team] button, a dialog box was displayed with the following text until the next round began:

“Your team will be protected for 3 rounds. You have been charged 4 points.”

Protection denied: If the participant clicked the [Protect My Team] button and another participant had protected the same team first during the same post-round choice period, a dialog box was displayed with the following text until the next round began:

“Sorry, someone else protected this team before you.”

Protection decline confirmation: If the participant clicked the [Don't Protect My Team] button, a dialog box was displayed with the following text until the next round began:

“You chose not to protect your team.”

Previous protection: If a different player had protected the same team or a team within one icon difference in a previous round, the following message was displayed instead of the *Protection choice dialog*:

“Your team this round cannot be protected. Waiting for others to protect their teams...”

7.B. Post-task survey in Experiment 4

The following survey was distributed to participants following the end of the last game in each session.

Front

Player ID# _____ (shown at bottom of screen)

Please fill out this questionnaire as honestly and completely as you can. By doing so, you will help us understand more about the motivations of participants in the experiment you just completed. Your name will never be associated with your game scores or your answers to these questions.

Instructions: Please place an X in the box that most closely corresponds to your answer to the following questions. Thank you for your participation!

1. During the game, did you **mostly**:

try to **increase your own score** (without regard to the scores other players might have), or try to **score higher than other players**?

Increase my own score			Both about equally			Score higher than others

2. If/when you protected your solutions, was it **mostly**:

to **keep others from using** your solutions, or to **get payment** for others' use of your solutions?

Does not apply, I never protected my solutions

Keep others from using			Both about equally			Get payment

3. When you wanted to use another player's protected team, did you **generally** prefer to:

copy the whole team and pay the fee, or copy it and then **change it to avoid paying**?

Does not apply, I never copied any protected teams

Copy the whole team and pay			Both about equally			Copy and change it to avoid paying

Please continue on other side

Back

4. When you found a team with a relatively high score, did you ever intentionally **leave it unprotected** so that others could copy it for free?

Does not apply, I never had a team with a relatively high score

Never			Sometimes			Every time

5. How did you feel about the difficulty of the task?

Very easy						Very hard

6. Did you choose creatures more often from **other players' teams**, or from the **league**?

Other players			Both about equally			League

7. Did you find that your *scores were better* when you chose creatures from **other players' teams**, or from the **league**?

Other players			Both about equally			League

8. Do you feel that success in this task was based more on **luck or skill**?

Luck			Both about equally			Skill

9. Briefly describe the strategies you used in this game: _____

10. Do you have any further thoughts about this experiment? _____

Thank you! Please bring this questionnaire to the experimenter.

8. General Discussion

8.1. Conclusions and continuations

When one observes others for clues about beneficial behaviors, it is important to be attentive to the many possible differences between the contexts they encounter and the related situations in which one expects to find oneself. These can be due to changes in an environment over time, or differences within and between environments due to things like climate, culture, or the capabilities brought to the present from previous experience. Similarly, the experimental results we have shared in this dissertation are subject to caveats about the context in which we obtained them, but we believe they offer some insight into common conflicts and merit substantial further study.

The goal of these experiments was to examine how groups of people find solutions to problems, by adapting their behavior to their environments and to each other over time, under varying combinations of information and incentives. Situations that fit this description are ubiquitous in the lives of humans and other social animals, but not yet well understood. They are full of complicating and confounding factors that make it difficult to find the important factors that cause the outcomes we see. In these experiments, we pared away many of the complexities of real-world social learning to enable relatively simple interactions in a controlled problem environment, so that we could observe participants' behavior unencumbered by at least some of these complicating factors. For instance, we did not allow participants to spend points on imaginary lawyers with which to sue each other for virtual patent infringement (Torrance & Tomlinson, 2009), nor did we

build an artificial foraging apparatus for them to peck at. We hoped to find commonalities between aspects of different kinds of exploration, such as birds searching for food and people searching for good ideas, by abstracting from many of their specifics.

This quest for an ideal abstraction can create two kinds of flaws: first, it can leave out important qualities of the events we are attempting to model; second, the specific details that are chosen to implement the general qualities we wish to study will by necessity introduce distortions of their own. To conclude this dissertation, we will discuss some of the relevant aspects of real-world social learning and exploration that our tasks did not take into account, as well as some of the artificial characteristics that may have distorted participants' behavior, before summarizing the findings that we believe have validity beyond our specific paradigms and should be examined further.

8.2. Omissions and commissions

We attempted to provide appealing, understandable, and fairly neutral problems for participants to solve, which did not unduly favor certain cognitive assets (e.g. verbal or mathematical knowledge) that could have introduced differences in behavior unrelated to our desired phenomena. In real search situations, of course, history and preparation matter -- people bring all sorts of previous knowledge and experience to bear on novel situations, and these affect outcomes enormously. There is no such thing as a "pure" search task, unmoored from any specific skills. Traits that are presumably important to performance in our

tasks such as large working memory and strategic thinking are by no means evenly distributed among the population, nor is enthusiasm for puzzles, virtual pets, or fantasy sports leagues, elements of which we tried to incorporate in order to make the task interesting.

In addition, much of the knowledge and experience that people bring to new tasks concerns their fellow problem solvers, particularly trust and other beliefs about others' capabilities and intentions. People are political animals as well as social animals, and these beliefs, and how they are created, maintained, and manipulated, are absolutely central to sustained interactions in groups. Using participants who (presumably) knew little about each other beforehand reduced the possibility of these important phenomena having effects on the coordination of behavior. The development and use of such interpersonal knowledge was also prevented by limiting participants' interactions strictly to the passive sharing of information about their solutions; they were not permitted other methods of communication with each other (such as a chat interface), or manipulation of the environment (such as tagging of icons). We also omitted explicit identifying information about peers, and prevented implicit identification by avoiding consistent positioning of each participant's choices in the task displays. Capabilities such as stable evaluation of group members' behavior, discussion and collective determination of norms are particularly known to affect outcomes in public good and common-pool resource dilemmas (Ostrom, Gardner, & Walker, 1994). Relatedly, each game in our task lasted only a few minutes, and the whole session was less than an hour; in reality, the long-term sustainability of any system, let alone

something as complex as a knowledge commons, cannot be estimated in such a short time.

Beyond the specific details of patent systems that we mentioned omitting in Chapter 7, the economic validity of our task is limited by the fact that there was no cost for exploration beyond the opportunity cost of foregoing other options. Many real exploration tasks (e.g. pharmaceutical trials, mineral exploration, or software debugging) involve substantial investments of time and other resources both up front and on a continuing basis. The relatively short length and narrow breadth of protection, amounts for protection and use fees, and the overall level of monetary payment could raise similar objections.

Because of the above differences, we must be cautious about generalizing our results too broadly, and our conclusions must be tested in other social learning and exploration paradigms to observe the effects of these and other contextual factors.

8.3. Summary of findings

Despite these concerns, we believe that (a) our results make a substantial contribution to knowledge about the causes, consequences, and dynamics of social learning and search; (b) that they have substantial validity beyond the task and participants that generated them; and (c) that they can lead to further fertile investigation in the laboratory and the field.

We found that our human participants used several social learning strategies previously studied in other species (Laland, 2004), such as copying better-performing peers, copying solution elements that are more frequent among peers,

and copying when uncertain about the returns to asocial learning. We also found evidence for copying solutions similar to one's own, which has been examined in studies of innovation diffusion as backwards compatibility (Rogers, 2003), as well as copying solution elements that are increasing rather than decreasing in frequency among peers, as observed in a recent study of baby-naming data (Gureckis & Goldstone, 2009). We also found that, rather than simply falling back on alternate social learning strategies (such as frequency bias) when performance-based imitation was unavailable, the use of each source of information was used in different ways according to the specific incentives and risks involved.

Participants used fairly conservative, incrementalist strategies to explore complex problem spaces, so that initial satisfactory solutions could be used as a basis for further development via small amounts of both imitation and innovation. These tactics allowed participants to progressively and collectively narrow their search toward better regions of the problem space without taking excessive risks that could hurt aggregate performance.

Some simple models (Rogers, 1988; Giraldeau, Valantone, & Templeton, 2002) predict that imitation will not improve the overall performance of a group, because agents will simply use it to take advantage of the information provided by others, and avoid the costs of exploration. In contrast, we found that participants often used imitation (in combination with innovation and retention of previous solution elements) to cumulatively improve on one another's solutions and enhance both individual and overall group performance.

When we introduced contextual factors that caused imitation to be either disrupted (hiding performance information about peers' solutions) or discouraged (charging a small fee for using a solution that a peer had previously discovered and "protected"), the use of innovation increased, but improved performance did not result. In the former case, participants could not use imitation to propagate good solutions, and the increased exploration was essentially wasted because the search remained unfocused and inefficient. In the latter case, the additional exploration actually resulted in an increased discovery of improved solutions, but also the discovery of worse solutions in the process, which canceled out the gains; the cost for imitation meant that participants imitated less often and were thus less likely to build on one another's solutions.

8.4. Applications and future directions

In the context of scientific and cultural progress, there are parallels to the models of Rogers (1988) and Giraldeau, Valone, and Templeton (2002) mentioned above, which predict that innovation will be in short supply and inefficiently used unless those who innovate can exclude others from imitating them without permission (e.g. Kitch, 1977).

Our work shows that the above models are perhaps overly simplistic when it comes to human social learning and exploration. Individuals have a capacity to use others' innovations not just to obtain a static benefit in good performance, but to create a dynamic benefit for many by producing sequential improvements; so a disincentive to imitate (in the form of exclusion rights for innovators) may result in

less productive innovation, not more. The work of others in this area (e.g. Torrance & Tomlinson, 2009; Bessen & Meurer, 2008; see Chapters 6 & 7) confirms these findings and shows that there are other theoretical and practical disadvantages to granting exclusive rights to knowledge.

There is a countervailing movement to treat knowledge as a resource that benefits from community management at multiple scales, rather than strict private ownership or centralized state control (Ostrom & Hess, 2007). There are naturally debates between proponents of these various methods of management, but it is clear that the future of knowledge is inextricably bound up in learning how to equitably, efficiently, and sustainably govern the products of its past and present.

Tomasello (1994) contends that the capabilities of humans for selective and cumulative social learning constitute a “ratchet effect” that allows culture to develop stably across generations, and that this effect may be unique to humans. Though the experiments in this dissertation present a greatly simplified environment for such social learning, they confirmed and extended several previous theoretical and empirical results in the field.

The concerns about our experiments noted above (as well as related work discussed in previous chapters) suggest potentially useful variations of our core tasks. For instance: use of various practical knowledge domains for search and various levels of expertise among participants; use of noisy (rather than simply present or absent) score feedback; variations in the structure of the social network that connects participants; explicit costs for innovation and more substantial incentives for performance; and communication among participants, and therefore

opportunities for coordination of their search behavior and more stakeholder-driven governance of the use of the resulting improvements.

The resounding refrain of the large body of research on commons dilemmas and other collective action problems is that many can be solved through careful investigation and modification of the related environmental, cultural, and institutional variables, but there is "no panacea," no universal solution on which we can rely (Ostrom, 2010). Continued study is necessary, of the structure and dynamics of human collaborative exploration, the nature of incentives and innovative effort, and their interaction as manifested in the dynamics of creativity in our economy and culture. We present our work in the hope that others will also find it useful in illuminating our shared problems.

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