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THEORY ARTICLE

The impact of diversity on group decision-making in the face of the free-rider problem

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Abstract
Although diversity has often been proposed to improve group performance, its impact on group cooperation has largely been overlooked. This article uses a theoretical approach to examine the effects of diversity on group tasks in the context of the free-rider problem. We identified 3 kinds of diversity that have been commonly reported to improve a group's performance: (1) ability, (2) cognitive style, and (3) information sources. Each type of diversity was formalized within an evolutionary simulation based on a foraging metaphor. The simulations were run under different environmental assumptions, covering complexity, costs for cooperation, cue redundancy, and cue compensatory level. Our results indicate that diversity in cognitive style and information sources generally increase cooperation. Both diversity factors also improve group members' average outcome in non-compensatory environments. However, the outcome results are mixed in compensatory environments. We did not find robust and reliable effects of diversity in ability. Our study provides the first approach to modeling isolated diversity effects on group decision-making in the face of the free-rider problem. It may serve as a theoretical framework for future studies.

1. Introduction

In today's rapidly advancing world, decision-making processes are becoming increasingly complex. People with different educational backgrounds, work and life experiences, and varying cognitive capabilities must work together to achieve common goals. As a result, diversity is becoming more prevalent across various contexts.

The impact of this increasing diversity has been studied for decades (Horwitz and Horwitz, 2007). The main focus has been on how diversity affects group performance. Empirical studies have focused on comparing groups with different levels of a specific kind of diversity and investigated work-specific outcome variables. However, this approach is challenging, as many real-world factors can influence the results, and diversity is difficult to isolate. Theoretical approaches have been used to formulate scenarios and measure how scenario-specific diversity types influence performance. Such approaches have the advantage of allowing an isolated investigation of diversity. However, theoreticians focusing on pure diversity effects have only accounted for completely cooperative groups, a rare occurrence in the real world.

In this study, we model diversity using an evolutionary paradigm in which cooperators and free-riders coexist (Kameda et al., 2011). We identify isolated diversity factors based on the literature. We then discuss how environmental changes may affect diversity effects, and we apply them to the paradigm. Finally, through an evolutionary simulation, we show how diversity affects performance and cooperation.

1.1. Types of diversity

The term *diversity* refers to the differences between individuals that influence a group's composition (Roberson et al., 2017). Scholars using descriptive approaches have made various attempts to differentiate types of diversity, mainly concerning individual attributes that are directly important for the specific job (task-related) and visible characteristics (biodemographic) without a direct job connection (Horwitz and Horwitz, 2007; Pelled, 1996; Yadav and Lenka, 2022). This article takes a theoretical approach to examine the effects of diversity on the problem-solving capabilities of its members, which we call *cognitive diversity*. The term implies 'member characteristics that, regardless of the origin, expand the cognitive resource capacity of the team' (Mello and Rentsch, 2015, p. 626).

Cognitive diversity may have a positive effect on a group's performance. Three factors behind cognitive diversity have been discussed: (1) ability, (2) cognitive style (Sulik et al., 2022), and (3) the informational background of the agents (Dahlin et al., 2005). Here, we review previous research on the 3 factors.

One study has suggested that diversity trumps ability regarding the performance of a group (Hong and Page, 2004). The authors simulated agents with different heuristics who searched for peaks in a landscape. They found that groups of the best-performing strategists (experts) performed worse than groups of random strategists. However, this study has been criticized for having an optimum that favors randomness and for making too strong a claim relating the theoretical finding to human behavior (Thompson, 2014). Other articles have stated that diversity can trump ability, but only under certain circumstances (Grim et al., 2019; Luan et al., 2012). However, other findings suggest that it is not diversity in ability but diversity in cognitive style that influences a group's outcome (Sulik et al., 2022).

Cognitive style has been described as 'adaptation to the external world that develops through interaction with the surrounding environment on the basis of specific cognitive abilities and personality traits' (Kozhevnikov et al., 2014, p. 21). In the current article, we narrow it down to differences in information processing (Martinsen et al., 2011). A common approach to studying diversity in cognitive style has been using epistemological landscapes, which represent an abstraction of the research process. A group of agents has to find peaks in a simulated world. To do so, agents have 2 options. They can follow other agents who have already been successful in finding a peak. Then, they can try to find another peak nearby. Alternatively, they can become mavericks and try to find new peaks away from the others. Simulations have shown that groups of agents have the best success when the group is diverse—that is, when followers and mavericks coexist (Pöyhönen, 2017; Weisberg and Muldoon, 2009). West and Dellana (2009) were the first to compare diversity in ability versus cognitive style directly. They simulated different types of agents and tested their group decision accuracy for bankruptcy detection. Their study revealed that diversity in style could improve performance much more than diversity in ability. In addition, the previously discussed paper of Hong and Page (2004), who argued in favor of diversity in ability without mentioning style, might be interpreted differently. They showed that random performers do better than higher-ability performers who converge in their strategies, which hinders them from finding the most optimal solution in different situations. However, hindrance from the convergence of opinions through diversity in ability is difficult to separate from diversity in style. Rather, this diversity in ability effect may be partly explained by changes in style, which may make cognitive style causative for the effects found.

Cognitive style has been operationalized as strategy preferences. Such preferences have been identified for the choice between compensatory and non-compensatory strategies (Zakay, 1990). The terms *compensatory* and *non-compensatory* describe the weighting of cues to decide between 2 or more alternatives. In non-compensatory strategies, the cues are processed in order of decreasing validity. As soon as a cue differentiates, a decision can be made without looking at subsequent cues because the subsequent cues cannot compensate for the more valid cues. Under a compensatory strategy, less valid cues or their combination can compensate for more valid cues. Thus, a compensatory decision-maker might prefer an option supported by all cues except the most valid cue. In contrast, a non-compensatory decision-maker would prefer the option indicated by the most valid cue. Another style question is the preference for analytical-rational versus intuitive-experiential strategies (Epstein et al., 1996). The former represents deliberate and slow decision-making, whereas the latter is a heuristic approach. An analytical-rational example is a normative approach that involves the optimal weighting of all available information. The option with the highest sum is then chosen. Compared with the normative approach, heuristics simplify decision-making and reduce decision effort (Shah and Oppenheimer, 2008). Efforts can be reduced by ignoring relevant information or by simplifying the weights. In the adaptive toolbox approach (Gigerenzer and Todd, 1999), it is assumed that heuristics are ecologically rational and can lead to better decisions than normative approaches when they are adapted to the statistical structure of the environment (Gigerenzer and Brighton, 2009; Hammerstein and Stevens, 2012; Todd and Gigerenzer, 2012). Heuristics from the adaptive toolbox are formulated based on building blocks that describe how information is searched, how the search is stopped, and how the information found determines decisions. Equal weights heuristics, for example, state that information is searched in any order, cues are weighted equally, and the alternative with the larger sum is chosen. Other heuristics, such as take-the-best or minimalist heuristics, ignore some information, with decisions being based on only one cue (one-reason decision-making). In the present work, we define diversity in cognitive style as inter-individual differences in preferences for specific heuristics.

Diversity in informational backgrounds was first proposed in the R&D literature to improve teams' innovative performance (Cohen and Levinthal, 1990; Katz, 1982). It has been applied to team efforts in general and predicted to improve performance (Dahlin et al., 2005). This article defines agents as having a specific informational background only available to a fraction of people. Although different styles could add different perspectives by focusing on subsets of the available information, our definition makes the informational background a structural setting that gives agents access to a specific information source. A real-life example is the active recruitment of employees from other companies. They are expected to bring contacts and problem-solving abilities from their old company. This means they can exclusively access specific information not available before joining the new company, thereby adding new perspectives. The literature has suggested that demographic factors that may increase informational background diversity, such as functional background diversity, positively impact a group's outcome (Bell et al., 2011; Dahlin et al., 2005).

We have synthesized 3 factors of cognitive diversity that were commonly discussed to influence a group's performance. Our literature review suggests that style and informational background may positively affect a group's performance, and diversity in ability may have mixed effects. However, while the studies we discussed have focused on group performance, little attention has been paid to any potential effects on cooperation. Nonetheless, in real-world scenarios, some group members may try to benefit from the group without contributing. In the following, we discuss the free-rider problem.

1.2. The free-rider problem

In many cases, groups are tasked with solving a problem and gaining a collective reward equally shared among their members. However, as contributing can be costly and the personal benefit of doing so may be low, some group members may decide not to contribute but to benefit from the work of others—that is, to free-ride (Hardin and Cullity, 2020). Real-world examples are group tasks for students for which each group member receives the same grade, decision-making processes in company boards that will benefit all board members equally, or research that results in publications. The main question to the common problem is as follows: How can a high cooperation rate be ensured?

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There are 3 main reasons for cooperation. First, individuals may be compelled to cooperate by an authority or a group (Dawes and Messick, 2000; Fehr and Fischbacher, 2003). Second, general social norms (Dawes and Messick, 2000; Fehr and Schurtenberger, 2018; Szekely et al., 2021) or altruism (Fehr and Fischbacher, 2003; Wang et al., 2020) can motivate a person to cooperate. Third, the structure of the task may make cooperation beneficial for the individual if it leads to a better personal outcome (Kameda et al., 2011; Motro, 1991). To encourage people to cooperate, at least one of these motives should be addressed. The aim of this study is to explore the impact of diversity on group performance and cooperation. As diversity is inherently a structural aspect, we will subsequently delve into how the structure of a task could potentially influence one's motivation to cooperate based on self-interest.

1.3. Diminishing returns and self-interested cooperation

A classic example of self-interested cooperation can be observed in producer–scrounger (PS) games (Barnard and Sibly, 1981; Giraldeau and Caraco, 2000). PS dynamics describe a foraging process in which not all members contribute to the search for food. While some group members produce and check out different spots for food (i.e., cooperate), others observe the producers and scrounge once the producers are successful (i.e., free-ride). Under PS dynamics, an equilibrium is usually reached, where producers and scroungers receive equal amounts of food (Barnard and Sibly, 1981). At this point, producers cooperate because free-riding would lower their benefit, and scroungers keep free-riding because they could not increase their benefit from cooperation. This means both groups act selfishly, making cooperation just as self-interested as free-riding. Note that free-riders in the PS game differ from other social dilemmas, where free-riding is often conceived as being negative to the group gains. If all members cooperated in the PS game, the gains would be less than optimal, which reflects ancient hunter-gatherer groups, or modern work teams, where some groups members are assigned to different tasks.

Generally, self-interested cooperation occurs when the costs of contributing are lower than the shared benefit of an individual contributor (Motro, 1991). Although in many tasks, greater cooperation leads to better joint outcomes, the motivation to cooperate may decrease as the number of contributors increases. The more people cooperate, the less an additional cooperator can improve the outcome, implying diminishing growth. The simple rule that an individual group member applies could be to cooperate as long as the costs of doing so are lower than the increase in the individual benefit.

Group tasks with diminishing returns across the number of contributors can be found in many real-world settings (for a review of non-human examples, see Foster, 2004). For example, paper wasps (polistes dominula) benefit from cooperation while breeding (Grinsted and Field, 2018). One dominant poliste mainly procreates, and its conspecifics secure food and housing. However, the more cooperators there are in the nest, the more the fitness increase diminishes (Grinsted and Field, 2018). Therefore, poliste nests increase the number of group members only to a certain threshold (Grinsted and Field, 2018; Kennedy et al., 2021). Bees' honey production growth has also been found to diminish with a larger stock because of the limited amount of nectar in the environment (Champetier et al., 2015). In higher-developed animals, such as birds, mongooses, and primates, sentinel behavior has been shown to have diminishing returns. Although the information difference between one sentinel and none is substantial, it decreases with more individuals participating as sentries (Bednekoff, 1997).

In the human realm, evidence from various areas has also shown diminishing performance benefits as the number of contributions increases. For example, in forecasting judgements based on expert advice, the increase in accuracy achieved by obtaining additional opinions diminishes. In a review, Yaniv (2004, p. 75) state that 'a small number of opinions (e.g., 3–6) is typically sufficient to realize most of the accuracy gains obtainable by aggregation.' Another example is the relationship between team performance and the number of star performers, which has been extensively investigated in human resource management (Gula et al., 2021; Hendricks et al., 2023; Joo et al., 2022). The evidence suggests that hiring additional star performers yields diminishing returns across various employee teams and

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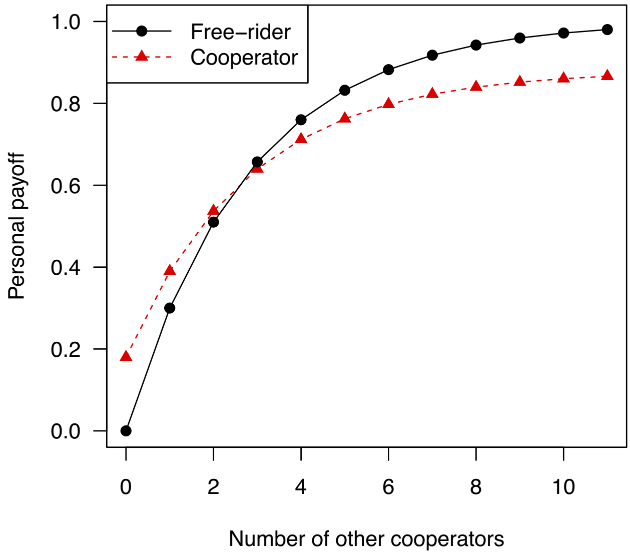

Figure 1. *Expected payoff of an individual (red = cooperator; black = free-rider) in dependence of the number of other cooperative members. Expected payoffs were calculated from the base function* $f(x) = 1 - (1 - .3)^x$ *(Kameda et al., 2011; Lorge and Solomon, 1955), where x = number of other cooperators. The payoff of a cooperator corresponds to* $f(x)$ *− costs; the payoff of a free-rider corresponds to* $f(x)$*.*

performance measures, including agricultural workers' efficiency in planting rice and lawyers' revenue generation (Joo et al., 2022).

Kameda et al. (2011) showed that humans' cooperation can be stably sustained without force or altruistic attitudes in a task with diminishing returns. They conducted an evolutionary simulation using a foraging metaphor with a diminishing reward structure (Motro, 1991). In this simulation, an ancient group of foragers has to find food. There are several places available, one of which is chosen by vote. Group members can conduct a costly inspection of the alternatives (cooperation) or free-ride. For each place, noisy cues (c) indicate the approximate amount of food. When cooperating, the agents access those cues. Perception is noisy, so an additional individual perception error (pe) is added to the cues. From the received information ($c + pe$), cooperators can make a decision about which place to choose and participate in the voting process. The place receiving the most votes is chosen, and the food found there is equally distributed among all group members, whether cooperators or free-riders. The reward structure for cooperators and free-riders is exemplified in Figure 1. It depicts the expected payoff for the individual given the number of other cooperating members and the individual's choice (free-ride vs. cooperate). The point at which the 2 reward curves intersect marks the equilibrium for the setting. The equilibrium is the point at which cooperators and free-riders co-exist. Up to that point, it is in the individual's interest to cooperate because this improves their personal outcome. If the group is already filled with cooperators, the individual may decide to free-ride. The existence of the equilibrium has been proven by Kameda et al. (2011) through simulations and experimentally. Furthermore, it has been shown that agents change their behavior (i.e., cooperators become free-riders and vice versa) to maintain a certain ratio (Kim et al., 2019). This means cooperation can be stably sustained at a specific ratio without force or altruism, but only because of structural settings.

In conclusion, diminishing returns are common throughout the animate world. These structural settings may allow equilibria of cooperators and free-riders within groups with individuals that are trimmed to improve their own benefit. Therefore, the free-rider problem may be mitigated solely by adapting the structural settings.

1.4. Environmental effects on group decision-making

Cooperation can be sustained in the face of the free-rider problem by adapting structural settings, as we have theoretically discussed in the previous paragraph. A scenario's structure consists of 2 aspects: the environment and the group members. In the previous sections, we have already discussed the group member aspect. In the following, this article proposes how the environmental aspects of a scenario can be adapted in the paradigm of Kameda et al. (2011) and explores which effects can be hypothesized given the current literature. In their seminal paper, Kameda et al. (2011) took costs and the number of places into account. The current study adds the cue structure as a factor, as different personal strategies (e.g., cognitive style) are adapted differently for specific cue structures (Gigerenzer and Brighton, 2009; Gigerenzer and Todd, 1999). The structure of the cues can vary in its compensatory level and redundancy (Gigerenzer and Brighton, 2009). In the following, we briefly discuss each of the factors.

When cooperating, costs > 0 occur. If costs were ≤ 0, cooperation would be the only rational behavior, and free-riding could not be sustained. The higher the costs are, the fewer individuals cooperate and the lower the individual payoff (Kameda et al., 2011). The decrease in payoff is a direct consequence of rising costs: The more to pay, the less to get out of cooperation. The decrease in the cooperation rate follows from the decreased incentive to cooperate. Additional cost effects are conceivable; for example, higher costs could be settled using fewer cues rather than decreasing the cooperation rate.

The number of places has a positive effect on cooperation. More alternatives increase the variance of the food that can be found at specific places, leading to a better-expected outcome when an informed decision is made. This improvement in the expected outcome improves the benefit side of the cost/benefit ratio. This can be further confirmed by simulating an array with a different number of alternatives from $\mathcal{N}(\mu = 0, \sigma = 30)$: one obtains $max_2 = 16.9$ and $\sigma_2 = 23.9$ when the choice has to be made between 2 alternatives, and $max_{10} = 46.2$ and $\sigma_{10} = 29.2$ when 10 alternatives are available.

The compensatory level is a dichotomous factor analogous to the compensatory preference in strategies. An environment can also have a compensatory or non-compensatory structure. When the cue structure is compensatory, the combination of values of less valid cues can compensate for a more valid cue. In a non-compensatory environment, no combination of less valid cues can outweigh a decision based on a more valid cue. An example of a non-compensatory strategy is a number comparison (Martignon and Hoffrage, 2002). One has to decide whether a number x is smaller or greater than a number y. Let us assume that the numbers have a specific length, and if a number is smaller, the leading values are filled with 0. The digits from left to right can be seen as cues. After the first cue differentiates, the other cues cannot add further information. Let $x = 1000$ and $y = 0999$. It is obvious that $x > y$ because the first cue differentiates with $1 > 0$. The latter cues can be ignored even though all their cue values strongly support the number y, as they cannot compensate for the first cue. Previous research has found that more frugal heuristics perform better in non-compensatory environments, whereas for compensatory environments, less frugal strategies are better suited (Martignon and Hoffrage, 2002). As the compensatory level makes the group benefit more from group members that deploy less frugal strategies, frugal strategists should die out and the average costs for each cooperator increase. Because of this effect, the cooperation rate should decrease. Because more cues contain more information, fewer cooperators that deploy deeper information searches should be more productive, increasing their outcome. Therefore, we expect a decrease in cooperation but an increase in gain for compensatory environments.

Redundancy describes the cues' inter-correlation (Dieckmann and Rieskamp, 2007). If redundancy is high, the cues entail much overlapping information. In the most extreme case of 2 cues with an inter-correlation of 1, the cues decrease and increase similarly, making them redundant. It has been shown that higher redundancy favors more frugal strategies (Dieckmann and Rieskamp, 2007; Martignon and Hoffrage, 2002). In addition, frugal heuristics have been shown to be clearly subordinate when redundancy is low and the environment is compensatory (Dieckmann and Rieskamp, 2007). With redundancy favoring more frugal (i.e., less costly) strategies, more redundancy should lead to increased

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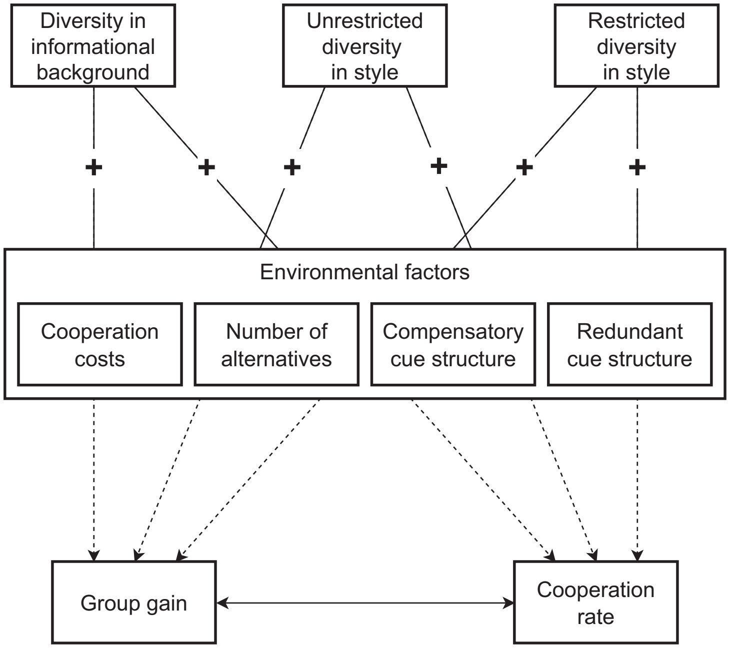

Figure 2. *Model of group diversity effects on the group gain and cooperation rate. The environmental factors moderate the diversity effects. Group gain and the cooperation rate reciprocally influence.*

cooperation. For the performance, 2 effects are conceivable. First, because the information overlap of multiple cues is too high, agents might make biased decisions leading to worse outcomes. Second, the increased cooperation rate leads to more independent opinions, which could improve the performance, as already suggested by Hong and Page (2004). In this case, the negative effect of less information from multiple cues may even become irrelevant because the cooperators use only a few cues.

1.5. Effects of diversity in different environments

We have presented different diversity and environmental factors that may influence cooperation and gain rates in group cooperation tasks. In the following, we briefly summarize those findings and combine them into a comprehensive model to be tested in this study (see Figure 2).

Our literature review identified diversity factors in style, information sources, and ability. The following will discuss how these factors may be modeled and affect group cooperation and performance.

Diversity in style will be modeled through different search heuristics. Two cases can be differentiated. (1) The first style type is restricted diversity, where a group is forced to apply diverse strategies without the ability to adapt to the environment. (2) The second style type is unrestricted diversity, where different search heuristics can vary in frequency. We hypothesize that both diversity types make the group to be better adapted to the specific environment, as they allow the group to use a mixture of more and less expensive strategies. Following this reasoning and the reviewed literature, we generally predict positive diversity in style effects on team performance, resulting in a higher gain. A higher gain makes cooperation more profitable; therefore, we hypothesize that this may result in a higher cooperation rate.

Diversity in informational backgrounds will be modeled through access to more information sources. We argue that different informational backgrounds enhance a group's problem-solving capabilities. Therefore, in line with the reviewed literature, we hypothesize higher performance. From this, we also hypothesize a higher cooperation rate.

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Diversity in ability will be modeled by introducing variability in the perception quality. We included this diversity type in the analysis because of its frequent discussion within the literature. However, we do not expect systematic effects on the gain or cooperation rate, given the more recent literature.

We expect different environmental effects. As discussed in the previous section, we hypothesize (1) a lower gain and a lower cooperation rate from higher costs, (2) a higher gain and a higher cooperation rate from more alternatives, (3) a higher gain and a lower cooperation from a compensatory environment, and (4) mixed effects on the gain and a higher cooperation rate from a more redundant environment. These environmental factors may further influence the diversity effects.

1.6. Objective of this study

While previous studies on cognitive diversity have primarily focused on its effects on group performance, they have often disregarded free-riding. Kameda et al. (2011) developed a theoretically sound and empirically proven framework for studying self-interested cooperation in the face of the free-rider problem. Their work showed that cooperators and free-riders can coexist within the context of the PS dynamics, which may also be applicable to many real-world tasks.

Our study is the first to combine diversity with the PS dynamics to investigate how different diversity factors may influence group outcomes and cooperation rates. Specifically, we examine how the actual dynamics of producers and scroungers changes, that is, how the cooperation rates and the average group members' outcome change when different kinds of diversity are introduced. In doing so, our study aims to contribute to a theoretical understanding of diversity effects on group decision-making in the face of the free-rider problem.

2. Material and methods

We conducted an evolutionary simulation to test the effects of different kinds of diversity on the cooperative behavior of agents and the individual's outcomes. In the following, we describe the group foraging task, the structure of the environment, the diversity implementation, and the details of the evolutionary process.

2.1. Group foraging task

The previously described evolutionary metaphor of a group of ancient foragers (see Kameda et al., 2011) was used. The evolutionary process is depicted in Figure 3 and described in the next paragraphs that guide through the figure.

The whole simulation process is nested within 3 loops. We start with the description from the group task (i.e., inner loop).

The most inner loop describes *what* the simulated agents have to do. As a group of 12 members,[1] they have to find a good place for food out of a set of alternatives. For each alternative, 4 noisy cues are available. Each member has the option of participating in the costly search or free-riding (see the inner loop of Figure 3). After the information search, group members come together to decide through voting. The majority rule is used throughout the simulation, as it is fairly efficient and requires little effort (Hastie and Kameda, 2005). Depending on the majority votes of the cooperators, one place is chosen. In the case of a tie between 2 or more places, one of the favorites is randomly chosen. If no one votes (i.e., when there are no cooperators), a place is chosen randomly from all available options. After the voting, the food is equally distributed across all group members, whether they cooperated or

[1]The setting for the group size was derived from Kameda et al. (2011), as their simulations showed that with this size, cooperators and free-riders coexist. This coexistence is necessary in our study to allow for the comparison of different effects. If the cooperation rate were to be either 0% or 100% under some models, it would be impossible to determine whether 2 different models had equally strong or not equally strong effects on the cooperation rate.

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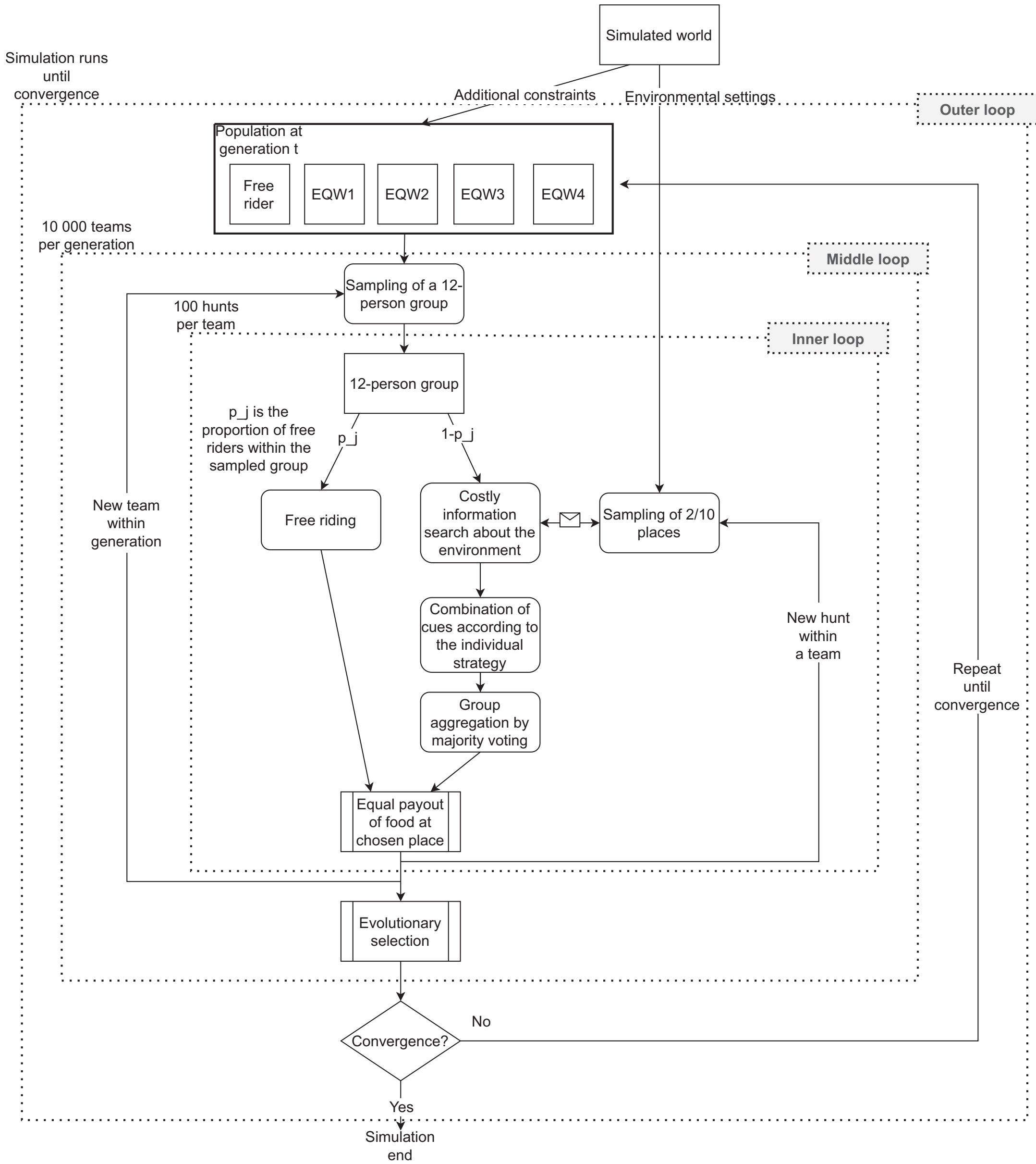

Figure 3. *Depiction of the evolutionary simulation process. There are 3 loops. The foraging process takes place in the inner loop (see inner dotted square). The middle loop (middle dotted square) shows the sampling of the group. The outer loop depicts the population at generation t. Outside the outer loop is the simulated world, in which settings regarding the environment or constraints within the population are made.*

not. This means that a cooperator is worse off for a specific round than a free-rider in the same group, as the cooperator has to pay cooperation costs. The group repeats this task 100 times.

The middle loop describes *who* belongs to the current generation and has to do the group task. Groups are sampled out of a population. That sampled groups are passed toward the inner loop, where they do the described group task. Within the middle loop, 10,000 groups are sampled and forwarded to the inner loop.

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The outer loop represents the *evolutionary process*. Different strategies exist with specific proportions within a generation. After each generation, the fitness values of the different strategies (see the subsection on foragers) were calculated, and the proportions of the strategies were adapted accordingly.

Outside of the 3 loops is the simulated world, where general simulation setting were made. The general task and simulation setup was varied according to 5 factors: (1) type of environment (compensatory/non-compensatory), (2) redundancy of information (low/high), (3) costs (4 levels), (4) number of alternatives (2 levels), and (5) diversity (6 levels). Details are given below.

2.2. Environment

Each place was represented by a vector of 4 cue values and a food outcome. The places were generated from a multivariate normal distribution $\mathcal{N}(\mu, \Sigma)$ with a mean vector μ of 0 and covariance matrix Σ using the faux package in R (DeBruine, 2021). Inter-cue-correlations were set to .1 and .5 to implement low and high redundancy, respectively. First-order correlations between the 4 cues and the food variable were chosen such that the beta weights of the corresponding regression models adhered to the definition of compensatory and non-compensatory environments (Martignon and Hoffrage, 2002). In simulations with 2 information sources, both cue sets were always generated from a single covariance matrix, with equal inter-cue and first-order correlations for each set. Note that to have 2 sets with equal beta weights and redundancy, it was necessary to specify the correlations between the sets. The corresponding correlation and covariance matrices for all of the simulated conditions are listed in Appendix B of the Supplementary Material.

The cues within each set were decreasingly correlated with the true amount of food and followed the strict order $c1 > c2 > c3 > c4$. In the compensatory structure, each β weight for each cue could be compensated on all levels (i.e., $c1 + c2 + c3 + c4 > c2 + c3 + c4 > c2 + c3 > c3 + c4 > c1$). In the non-compensatory case, no combination of less valid cues could compensate for a more valid cue (i.e., $c1 > c2 + c3 + c4, c2 > c3 + c4, c3 > c4$). In all of the scenarios, regressing all of the cues of one cue set on the amount of food explained its variance with $R^2 = .65$, representing moderately predictable foraging environments. In simulations with 2 information sources, both cue sets together explained the variance of food with $R^2 = .80$. However, each group member could only access one cue set, which always gave that member the same explained variance of $R^2 = .65$. Nevertheless, groups had access to a more informative environment in the 2 information source case than in the 1 information source case.

Cooperation generated cooperation costs to be paid cuewise. In different simulations, these costs varied with the *cooperation costs* $\in \{.03, .12, .21, .30\}$, following the well-tested cost range within the original paradigm (see Kameda et al., 2011). When an agent used all 4 cues of a set, the full cooperation costs had to be paid. When only some cues were used, the corresponding fraction had to be paid (e.g., $1/4$ cooperation costs for 1 cue). For cooperators, the corresponding cost fraction was reduced from the share of the group outcome in each hunting round. Let us clarify this with an example: A group receives a joint group outcome x. This outcome x is equally divided across all 12 group members, so a single member receives $x/12$. A free-rider does not have to pay any costs and keeps the share $(x/12)$. A cooperator who used 1 cue has to pay $1/4$ of the cooperation costs cs. This means, after paying the costs, this member can keep $(x/12) - (cs/4)$. A cooperator who used all 4 cues has to pay the full $4/4$ cooperation costs cs, which makes this member keep $(x/12) - cs$.

2.3. Foragers

Group members could cooperate or free-ride. Free-riding members neither searched for cues nor voted[2] but received a share of the group outcome. Cooperative group members paid costs and then observed

[2]We assumed that individuals who did not engage in information search would also not participate in voting, because they could not provide a valuable contribution. The randomness of their votes would further slightly diminish the impact of the cooperators who engaged in the information search before. We showed through a simulation in Appendix A of the Supplementary Material that the uninformed voters may have a negative impact on the group outcome. Moreover, it is possible that voting also

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the cue(s) of all available places to make an informed vote in the group aggregation. Different strategies were available in the population. Within a group, each cooperator used only one strategy throughout the 100 hunts. The available strategies were equal weights ($EQW_{1..4}$) with a different number of cues (ranging from 1 to 4). Depending on the number of cues, they had to pay the corresponding fraction of the cooperation costs. Cues for a cooperator always stemmed from only one cue set. Agents received the cues with an added individual perception error ($\mathcal{N}(\mu = 0, \sigma = pe)$; details about the values of pe are described below). This means that 2 agents with the same cue set and the same strategy could end up with different preferred options.

We simulated diversity in style, ability, and information sources. In the following, we describe the implementation for each diversity factor.

Cognitive style was altered through changes in the search heuristic. We introduced different restrictions on the number of cues agents could use. Fewer cues come with lower costs but also a decrease in accuracy. This change in cue use can be directly related to a strategy's frugality (see Gigerenzer and Todd, 1999). Combining several agents, some using more and some using fewer cues, changes the group structure and may, therefore, influence cooperation rates and group gains. Three settings of diversity regarding cognitive style are conceivable. (1) Agents within a group could be restricted to using one and the same strategy (non-diverse/homogeneous cognitive style). Still, adaption in the strategy proportion on the population level could be allowed. (2) The ratio of agents using different cooperative strategies ($EQW_{1..4}$ could be equal and always remain the same, which would ensure the highest possible amount of diversity (restricted diversity/hetero-diverse style). In this case, only the cooperation rate could be adapted, but not the strategies of cooperators. (3) The ratio could vary freely within the population and the groups (unrestricted diversity/heterogeneous style). This study considered all 3 variants. The cooperation rate was allowed to differ for all types of diversity in cognitive style. Strategies were drawn personwise in heterogeneous and hetero-diverse groups and groupwise in homogeneous groups. In the homogeneous setting, we implemented within-group homogeneity such that group members always used only one strategy. However, the strategies could differ between groups. This was done to compare within-group diversity and homogeneity between populations independently of the success of individual strategies.

The second diversity factor was information sources. We introduced this diversity type by implementing 2 structurally similar cue sets. When there was only one information source, group members only had access to this source (i.e., non-diverse information source). In groups that deployed 2 sources, each member had a 50% chance of receiving the cues from source 1 or source 2 (diverse information source).

The last diversity factor was ability, which was implemented as higher (lower) variability in the perception of cues for less (more) able cooperators. It was altered as a factor in the perception error. We defined 3 cases. In the homogeneous case, the ability was held stable with a perception error of $\mathcal{N}(\mu = 0, \sigma = pe)$ with $pe = 20$ (derived from Kameda et al., 2011), which implied an explained variance of $R^2 = .59$. In the hetero-low ability condition, pe was uniformly distributed with $pe \in \{20, 25, 30\}$ leading to variance explanations $R^2 \in \{.59, .56, .53\}$; In the hetero-high ability condition, pe was uniformly distributed with $pe \in \{10, 15, 20\}$ leading to variance explanations $R^2 \in \{.63, .61, .59\}$.

2.4. Evolutionary process

To determine the optimal distribution of strategies within a population under specific diversity and environmental conditions, an evolutionary process was employed. Initially, available strategies were set to have equal proportions in an infinite population. From this population, 10,000 random samples of 12-member groups were drawn, and each group was tasked with performing the foraging task

comes with costs. In this case, the nonsearcher-voter hybrids would not only lower the chance of choosing the optimal place, but they would also have to bear additional costs. Such a hybrid cannot be sustainable, which was also proven by a human experiment (see Kameda et al., 2011.

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as previously described. The average outcome obtained by individuals from each strategy was then calculated and interpreted as a fitness value, consistent with the replicator dynamics assumption (Cressman and Tao, 2014).

Using the fitness values, changes in the proportion of each strategy were calculated through the replicator equation (see Equation (2.1)). Strategies that outperformed others had their proportions increased, while those that underperformed had their proportions decreased. This process was repeated until an equilibrium was reached, or until only one strategy remained. We now give a technical description with the details of the evolutionary process.

The proportion p_i of a certain strategy i (with $i \in \{$free-Riding, EQW_1, EQW_2, EQW_3, $EQW_4\}$ if simulation ≠ hetero-diverse style; with $i \in \{$free-Riding, cooperation$\}$ if simulation = hetero-diverse style) at a point in time $t+1$ was calculated based on the fitness outcome f_i (i.e., the mean outcome over all hunts the strategy was involved) and the proportion in the previous generation at time t:

$$p_i^{t+1} = \frac{p_i^t \cdot (30 + f_i^t)}{\sum_i (p_i^t \cdot (30 + f_i^t))}. \tag{2.1}$$

The constant of 30 represents the baseline-fitness (e.g. Kameda et al., 2011). Throughout the simulation, strategies with a better outcome slightly increased in their proportions, whereas strategies with a worse outcome slightly decreased. The simulation ended when the sum of all of the absolute changes (i.e., the proportions of strategies) between time points t and $t-1$ became less than the threshold of .00001.

2.5. *Analysis*

We conducted 192 simulations in different environments to test the effects of diversity on cooperation rates, individual gains (food each group member receives), and the prevalent strategies (i.e., the number of cues most often used).

The simulations reflected 3 hypothetical population types: homogeneous, restrictive heterogeneous (hetero-diverse), and unrestricted heterogeneous population. The first provides merely baseline values for comparison of the cooperation rates and gains in different environmental structures. The latter 2 population types are compared to the homogeneous one.

For the homogeneous population, we analyzed the effects of the experimental factors on cooperation rates and individual gains through regression. We also report strategy usage through a central tendency (arithmetic mean of the cues used) and dispersion (Interquartile range).

For the hetero-diverse and heterogeneous populations, we calculated relative change values compared to the base model for each variable of interest (cooperation rate, gain, average cue, and cue interquartile range). Therefore, we took the difference in the variable of interest between the diverse and the base model. Then, we standardized this value by dividing it by the value of the base model:

$$\frac{diverse - base}{base}.$$

This gave us relative change scores that expressed in a %/100 value how much the diverse model was different from the base model. Possible values for change lie in the interval $[-1;\infty]$. In the case of a change of -1, the corresponding value would become 0 in the diverse model. In the case of ∞, the corresponding value is ∞ times higher in the diverse model than in the base model. All of the diversity analyses refer to these change values.

3. Results

3.1. *The base model: Homogeneous groups*

The results are summarized in Figure 4 (detailed depiction in Figure 8 in Appendix C of the Supplementary Material). A visual inspection of Figure 4 shows that there are systematic environmental

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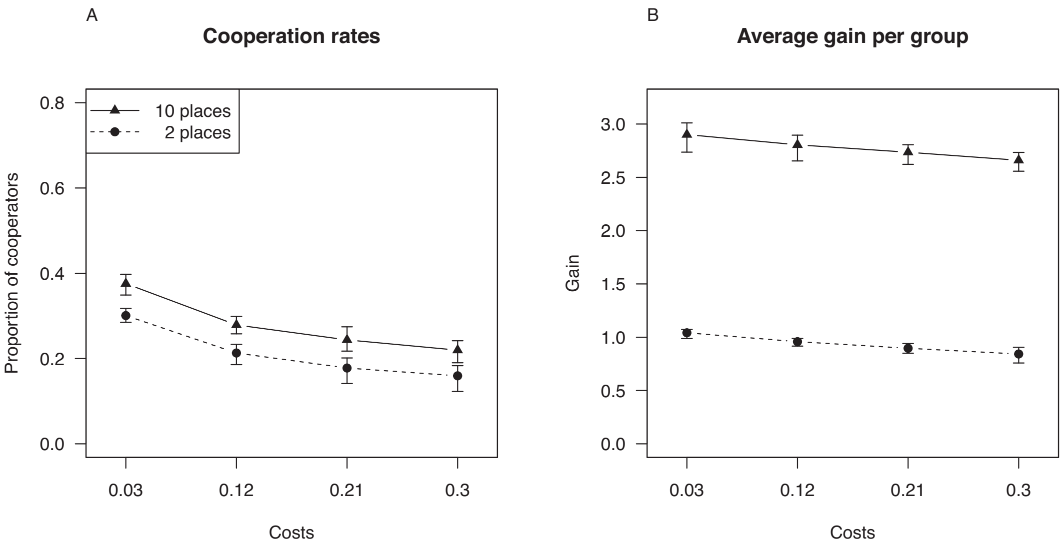

Figure 4. *Non-diverse base model where only environmental factors were varied. Part A shows the proportion of cooperators per 1. Part B shows the average gain of a group member. The depicted environmental factors are costs and the number of alternatives (i.e., places). The spread due to the 2 other factors, redundancy and compensatory level of the environment, is symbolized by the vertical intervals going through each data point.*

effects on the cooperation rate and gain. (1) The cooperation rate is always slightly higher when there are more alternatives (i.e., places) to choose from. (2) Increasing costs lowers the cooperation rate. These effects are stronger when the costs are low. (3) The average gain within a group is much higher when there are more alternatives to choose from. (4) Increasing costs lowers the average gain linearly. (5) There is dispersion in the cooperation rates and average gains when the costs and number of alternatives are fixed. The dispersion comes from the other environmental factors (compensatory cue structure and level of cue redundancy), which have a small effect.

We calculated regression models and report the partial regression coefficients to better describe the environmental effects on the cooperation rates and gains. For the cooperation rate, we calculated a logistic regression. We found that the cooperation rate cp decreases with costs cs and increases with more alternatives al. Moreover, compensatory environments ce lead to less cooperation and the redundancy re of the cue structure of an environment does not have a relevant impact on the cooperation rate. We obtain the following regression equation:[3]

$$cp = logit(-.77 - .88(cs/.3) + .37al - .21ce + .04re + \epsilon) \qquad (R^2 = .93).$$

For the gain, we estimated a linear regression model. It shows that the gain gn is primarily influenced by the number of alternatives al, with more alternatives leading to higher gains. Lower costs cs also lead to higher gains. The gain is higher in compensatory ce and redundant re environments.

$$gn = 1.00 - .24(cs/.3) + 1.84al + .05ce + .09re + \epsilon \qquad (R^2 > .99).$$

We have visualized the average number of cues that are used by the cooperators within different environments (see Figure 8C in Appendix C of the Supplementary Material). We found that the number

[3]The predictors for alternatives ($al \in \{2, 10\}$), the compensatory environment ($ce \in \{true, false\}$), and the redundant environment ($re \in \{true, false\}$) are dichotomous. Costs are continuous. To make the *beta* parameters comparable, we divided the costs by the maximum cost value (.3), so that $max(cs) = 1$.

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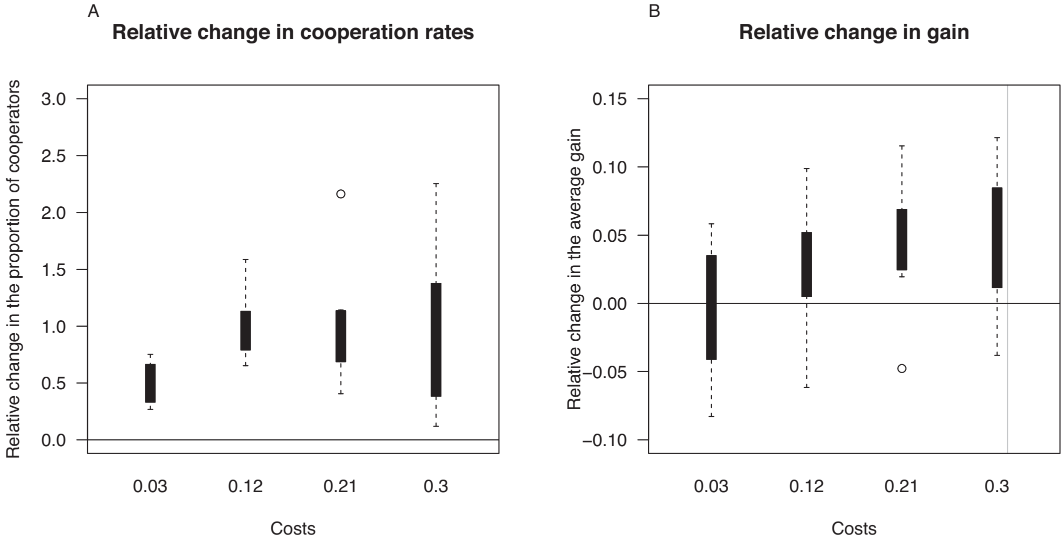

Figure 5. *Comparison of the hetero-diverse (style) model with the base model. Part A shows the relative changes in the cooperation rate, and Part B shows the relative changes in the average gain of a group member. The values can be interpreted as %/100 changes compared to the base model, where positive values indicate higher values for the diverse than for the base model. The depicted environmental factors are costs and the number of alternatives (i.e., places). The spread due to the 2 other factors, redundancy and compensatory level of the environment, is symbolized by the boxplots.*

depends primarily on the compensatory structure of the environment. In compensatory environments, more cues are preferred. There is a general effect for costs, where fewer cues are used as costs rise. This effect is prevalent in (i) non-compensatory environments and (ii) compensatory environments with high cue redundancy and few alternatives. The dispersion is mostly either 0, implying that the usage of a number of cues n_c is predominant, or 1, implying that 2 strategies that use similar numbers of cues (i.e., $\{n_c, n_c+1\}$ or $\{n_c, n_c-1\}$) dominate. These main effects result from different interactions between the number of cues searched, gains, and costs.

3.2. Restrictive diversity: Hetero-diverse style

We simulated diversity using a hetero-diverse style. In this condition, only the proportions of cooperators and free-riders were allowed to vary. The ratio of the different cooperative strategies (EQW1...EQW4) was set equal and was not allowed to vary. The outcome values were compared with the base model. All of the subsequently reported analyses are about relative changes (in %/100) compared with the base model, where positive changes represent a higher value in the diverse model than in the base model.

Figure 5 gives an overview of the relative changes. The cooperation rates are always increased, whereas the effects on gain strongly depend on the specific environment. Figure 9 in Appendix D of the Supplementary Material depicts the changes in more detail under consideration of the different environmental effects. These effects are further summarized through the regression models that we report in the following.[4]

[4]The regression models have change scores as dependent variables. For the regression models on the absolute cooperation rate and gain, see Table 7 in Appendix E of the Supplementary Material.

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The regression model for the change in the cooperation rate Δcp shows a positive intercept, indicating a positive influence of the hetero-diverse style on cooperation. This is further enhanced by higher costs *cs* and a compensatory environment *ce*. A higher number of alternatives *al* and a redundant environment *re* reduce the positive effect of the hetero-diverse style on cooperation:

$$\Delta cp = .80 + .43(cs/.3) - .52al + .30ce - .11re + \epsilon \qquad (R^2 = .47).$$

The regression model for the change in gain Δgn shows a slight positive intercept, indicating a positive influence of the hetero-diverse style on the joint outcome of the group. This positive diversity effect is strongly enhanced by costs and minimally enhanced by a redundant environment. More alternatives and a compensatory environment oppose it. A visual inspection of Figure 9B in Appendix D of the Supplementary Material reveals a negative gain effect from compensatory environments with low redundancy and 10 alternatives:

$$\Delta gn = .05 + .05(cs/.3) - .05al - .04ce + .01re + \epsilon \qquad (R^2 = .66).$$

We again visualized the average number of cues that are used by the cooperators within different environments (see Figure 9C in Appendix D of the Supplementary Material). However, these effects are merely artefacts of the homogeneous model. In the hetero-diverse style, the proportion of strategies (i.e., the number of cues used) is restricted to be uniformly distributed. Thus, the average strategy will always be 2.5 cues (mean of {1,2,3,4}) and the interquartile range (IQR) is always 3.

3.2.1. What explains the effects on gain and cooperation rate?

The cooperation rate is especially increased in those environments which had the lowest cooperation rates in the base model. Therefore, by adding restrictions to the proportions of strategies, the hetero-diverse style compensates for the negative environmental effects of the homogeneous model.

The gain is mostly positively affected. However, for compensatory environments with more alternatives, the gain decreases. These results may be explained through the lowering of the average number of cues. For compensatory environments, the homogeneous model favors more cues, but the hetero-diverse model restricts the number of cues to 2.5. This restriction is maladaptive and therefore lowers the gain. In fact, from the change in the cue usage in Figure 9C in Appendix D of the Supplementary Material, it appears that the strategies with the strongest negative change in cues, in particular, show negative gain effects.

3.3. Unrestricted diversity in cognitive style, information sources, and ability

In the unrestricted simulations, we modeled diversity in ability, style, and information sources. Corresponding restrictions were lifted (see the Methods section on the diversity implementation and foragers for details).

Analogous to the restrictive hetero-diverse style model, we compared different diverse models with the base model. Therefore, we calculated change scores for the relative changes from the base model (i.e., %/100). On these change scores, further analyses were conducted. The relative differences are shown in Figure 6. A more detailed comparison of the diverse models with the base model that depicts the impact of different environments can be found in Appendix D of the Supplementary Material. Furthermore, regressions on the values of the relative changes are listed in Table 1.

There is a general tendency of diversity (see Figure 6A) toward a higher cooperation rate. For example, the average cooperation rate for low costs in the base model is roughly 1/3 (4 of 12 group members cooperate). This increases by 20%–40% for diversity in hetero style (5 or 6 of 12 members cooperate). An exception to the general increase is ability. High ability has a slightly negative or null effect, and low ability has a slightly positive or null effect. Rising costs have a positive impact on

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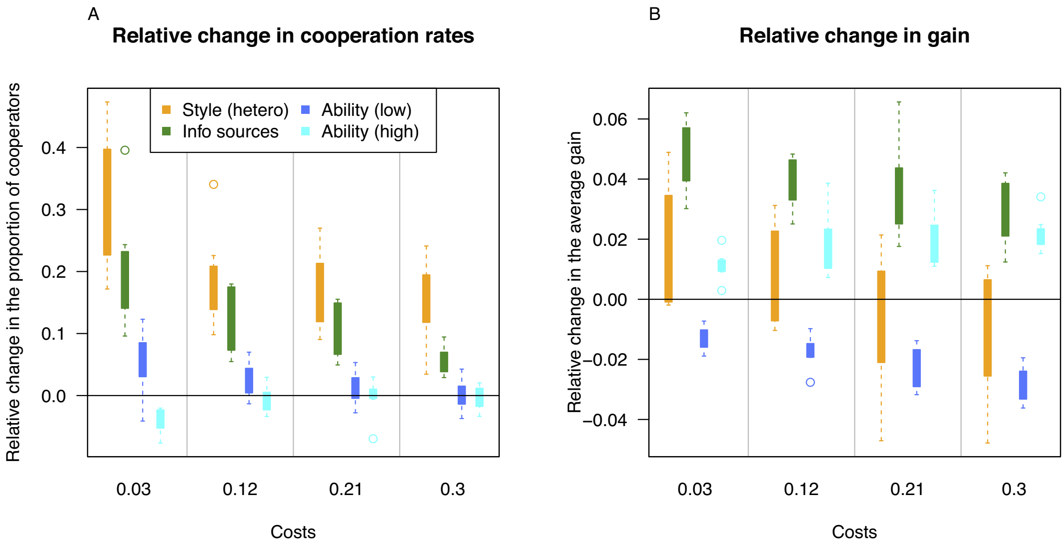

Figure 6. *Comparison of different diversity models with the base model. Part A shows the relative changes in the cooperation rate, and Part B shows the relative changes in the average gain of a group member. The values can be interpreted as %/100 changes compared to the base model, where positive values indicate higher values for the diverse than for the base model. The depicted environmental factors are costs and the number of alternatives (i.e., places). The spread due to the 2 other factors, redundancy and compensatory level of the environment, is symbolized by the boxplots. The boxplots depict the distribution of the diversity effects on all environment types within a specific cost. Boxplots are colored according to the type of diversity, with orange = style (hetero), green = info sources, dark blue = ability (low), and turquoise = ability (high). Within each cost category, the diversity types are depicted in the order as described (from left to right).*

Table 1. *The impact of costs (cs), a higher number of alternatives (10 vs. 2; al), a compensatory cue structure (ce), and the redundancy of cues (re) on changes due to diversity in (1) the cooperation rate and (2) the gain rate. The table shows the β weights and explained variance of linear regression models. The 2 dependent variables are change scores in comparison to the base model. For the regression models on the absolute cooperation rate and gain, see Table 7 in Appendix E of the Supplementary Material.*

Dependent variable	Diverse model	β_0	$cs/.3$	al	ce	re	R^2
(1) Cooperation	Style (heterogeneous)	.30	−.16	.02	−.03	−.003	.35
	Info sources	.24	−.16	.01	−.08	−.01	.73
	Ability (low)	.07	−.05	.02	−.03	−.02	.57
	Ability (high)	−.03	.04	−.02	.003	.01	.42
(2) Gain	Style (heterogeneous)	.04	−.03	.003	−.03	−.01	.83
	Info sources	.06	−.02	.01	−.02	−.004	.81
	Ability (low)	−.02	−.02	.004	−.001	.005	.71
	Ability (high)	.02	.01	−.01	−.004	−.007	.62

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the change in cooperation rates for groups that are low in ability and a negative impact on the other groups. The regression models, listed in Table 1, confirm the described observations from Figure 6A. Additionally, the results show that a higher number of alternatives has a weak negative impact on the relative increase in cooperation for high ability, whereas it has a weak positive impact on the other kinds of diversity. The opposite is true for the impact of an environment's compensatory cue structure. Redundant environments generally lead to a (weak) negative impact on cooperation rates. High ability is the exception, as it has a slightly positive (quasi 0) effect.

The diversity effects on gain are mixed (see Figure 6B). There is a generally positive impact for diversity in information sources and diversity in ability (high), a negative impact for diversity in ability (low) and mixed effects for diversity in style. With rising costs, the effect on gain is increased for diversity in ability (high), and the effect is weaker for the other types of diversity. The regression models depicted in Table 1 confirm the described observations from Figure 6B. Furthermore, a compensatory environment has a small negative effect for all types of diversity, although it is quasi-0 for both changes in ability. The redundancy of an environment generally shows quasi-0 effects, with a slightly negative effect for the heterogeneous style.

The effects on the number of cues that are used (see Appendix D of the Supplementary Material and Figure 6C) are mixed. Diversity in style and information sources leads to a slight decrease in cue usage. The effect is weaker (i.e., relatively more cues are used) as costs rise. Both abilities are narrowly distributed around 0, with low ability being slightly over and high ability being slightly under 0.

3.3.1. What explains the effects on gain and cooperation rate?

The effects of diversity in high and low ability groups were found to be contradictory and consistent with pure ability assumptions. Specifically, high ability leads to higher gains and low ability leads to lower gains. (1) Groups with low ability compensate for their disadvantage through a higher cooperation rate. (2) Groups with higher ability reduced their cooperation rate to save costs. However, there was no clear evidence of pure diversity effects. Therefore, we conclude that, for diversity in ability, changes in ability appear to be the main driving factor for any observed effects, rather than an increase in diversity itself.

The positive effects on the cooperation rate from diversity in style and information source may be partially explained by less cue usage, which reduces the costs for an individual cooperator and therefore allows for more cooperators (i.e., the available work is distributed to more people). There also seems to be a pure, non-mediated diversity effect. The heterogeneous style shows a reduction in the cues used as costs rise, which should predict an increase in the cooperation rate. Instead, the cooperation rate also decreases with costs.

The heterogeneous style increases the individual's gain. The positive effect decreases with rising costs and a compensatory structure. A compensatory structure favors strategies that use more cues. Therefore, diversity in style, which implies that some members might use fewer cues, is maladaptive. This perspective is confirmed when we inspect the results in detail. Figure 10 in Appendix D of the Supplementary Material shows that compensatory environments often lead to a negative gain effect because of diversity in style.

Diversity in information sources always positively impacts the gain, which may be explained by the additional information that a group can gain from the second information source. The negative environmental effects of costs and the compensatory structure on the information source effect may be explained by their effect on the group structure. Higher costs directly reduce the gain, negatively affecting the cooperation rate. A low cooperation rate is suboptimal for an info-diverse group, as the additional information source can only help the group if there are several cooperators. In the most extreme case of only one cooperator, the info-diverse group would automatically become an info-homogeneous group. The compensatory structure increases the benefit of using more cues, lowering the cooperation rate and causing the same effects as the cost increase.

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4. Discussion

We conducted a simulation to investigate the impact of diversity on a group's cooperation rate and the individual outcomes of their members in the face of the free-rider problem. We identified the central diversity factors in cognitive style, ability, and information sources. This allowed us to illuminate how group cooperation and individual strategies are adapted to these factors.

We have proposed a model of diversity factor effects on the group gain and cooperation rate that are subject to environmental effects (see Figure 2). Our study has successfully confirmed the proposed model. In the following, we briefly report our main findings.

4.1. Which factors influence the cooperation rate?

We found that environmental factors had direct and indirect effects. In line with Kameda et al. (2011), we found that the approach *cooperate as long as the individual's improvement in outcome exceeds the costs* leads to increased cooperation rates with (1) lower costs and (2) more alternatives to choose from. Lower costs directly affect the cost–outcome ratio. More alternatives lead to a higher variance in the amount of food at the places the agents can choose from. This increases the expected outcome of an informed decision-maker and therefore also directly affects the cost–outcome ratio. A new finding of our simulation is the lower cooperation rate in compensatory environments than in non-compensatory environments. The preferred strategy could moderate this effect. In compensatory environments, using a larger number of cues (i.e., a less frugal heuristic) is more beneficial than in non-compensatory environments (Martignon and Hoffrage, 2002). However, using more cues also comes with higher costs, leading to decreased cooperation. In this setting, it seems more beneficial for the group when fewer members cooperate as long as they conduct an exhaustive information search. In contrast, in non-compensatory environments, cooperation rates are higher. Still, individuals search for fewer cues, illustrating the opposite case, where it is more beneficial for the group when more members cooperate using a stingier search. We found that the redundancy of the cues has no relevant effect on the cooperation rate. With higher costs, the number of cues used on average strongly decreases for compensatory and highly redundant environments with 2 places. This reduces costs, opening the possibility of a higher cooperation rate. In less redundant and compensatory environments, using fewer cues would reduce the gain (see Dieckmann and Rieskamp, 2007). Therefore, this indirect increase in the cooperation rate can only occur when redundancy is high.

Diversity in cognitive style and information sources increased the rate of cooperation. We showed that changes in the strategies may explain parts of the effects. Cooperators used fewer cues, which saved costs that could be reinvested into a higher number of cooperators. Our findings are in line with previous research suggesting that diversity changes in style (Pöyhönen, 2017; Weisberg and Muldoon, 2009) and information sources (Bell et al., 2011) have positive impacts on group tasks.

We did not find any evidence in our design that diversity trumps ability. Therefore, our findings are in opposition to the view that diversity in ability has a positive effect (Hong and Page, 2004), being more in line with Sulik et al. (2022), who argued for the positive impact of diversity in style rather than diversity in ability. We argue that with our simulation approach, we were able to provide a formal confirmation for the perspective that diversity does not trump ability.

4.2. Which factors influence the gain rate?

The environmental settings had manifold effects on the group's gain. First, the costs were found to directly reduce the gain. Second, more alternatives increased the expected payoff of an optimal decision-maker, leading to a higher gain. Both findings align with Kameda et al. (2011) and can be explained through their direct effects on the cost–outcome ratio. Third, a compensatory structure increased the gain by allowing for a richer information outcome. Fourth, redundancy also increased the gain. We explain this through a complementary mechanism to the compensatory effect, as the overuse of

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cues was punished. These findings suggesting that frugal strategies are more accurate and efficient than complex strategies in redundant environments are in line with those of previous research (Dieckmann and Rieskamp, 2007; Martignon and Hoffrage, 2002).

Information source diversity directly increased the gain by giving the group access to more information. This confirms empirical findings of positive gain effects from functional background diversity (Bell et al., 2011).

Diversity in style generally positively affected the gain. However, this effect is decreased and partially even reversed for compensatory environments. We showed that this comes from the contradictory mechanisms in the cue usage. While style-diverse groups allow the usage of fewer cues, in compensatory environments, it is better if all cues are used. Nonetheless, our generally positive effect is well in line with previous findings on diversity in style (Pöyhönen, 2017; Weisberg and Muldoon, 2009). Our results further add to this research by showing that the style effects also depend on environmental structures.

We did not find any effects of diversity in ability. This may be seen as further evidence of an absence of an ability effect, supporting the perspective that diversity in style and not ability affects a group's performance (Sulik et al., 2022).

4.3. Limitations and outlook

Our simulation provides a theoretical approach to investigate the effects of diversity on group decision-making in the face of the free-rider problem. Therefore, our findings account for how individuals in a group *should* behave and perform, rather than how they *actually* behave and perform. Previous empirical studies have shown that predicted cooperation rates are often lower than empirical cooperation rates (see Kameda et al., 2011; Kim et al., 2019). However, these studies have also shown that there is a stable trend toward either a stable empirical optimum cooperation rate (Kameda et al., 2011) or a cooperation rate that is always slightly above the optimum (Kim et al., 2019). Although our theoretical approach may, therefore, not provide exact predictions for diversity-induced changes, it offers valuable insights into the direction of the effect.

We modeled diversity in cognitive style, information sources, and ability through changes in model restrictions. We explained our reasoning behind these model decisions, but other approaches may be reasonable as well, which we will briefly discuss. First, regarding diversity in cognitive style, we introduced 4 strategies using equal weights. However, the adaptive toolbox approach (Gigerenzer and Todd, 1999) introduced a wider variety of structurally different heuristics. Our approach may be viewed as a lower boundary on the number of cognitive strategies used in such tasks. The strategies we presented covered the broadest possible range of strategies, ranging from a low-cost, fast, and frugal one-cue comparison to a high-cost linear combination of 4 cues. Second, for diversity in information sources, we used only 2 information sources that followed the same distribution. In real-world scenarios, these information sources may be structurally different, potentially causing further effects on cooperation and gain rates. However, this study aimed to show pure information source effects, necessitating structurally equivalent information sources. Last, we simulated ability through changes in the perception error and could not find pure ability effects. This raises the question of whether the simulation settings were sufficient to produce a meaningful degree of diversity in ability. Another approach could have been the introduction of another less reliable information source. However, the mixing of different diversity types makes dissociation difficult. Furthermore, our approach guaranteed a direct effect on the core of ability: less able agents performed worse and had a larger error added to the cues. Following the argumentation of proponents of the perspective that diversity trumps ability (e.g. Hong and Page, 2004), the error added to the information gives a crowd of less able individuals an advantage. We argue that this mechanism does not bring a relevant advantage to a diverse group over a group with higher ability.

This study assumed group aggregation through majority rule. However, other approaches are also conceivable (for a review, see Hastie and Kameda, 2005). Our findings may not apply to structurally

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different group aggregations. However, we argue that such a generalization may not be necessary. First, majority rule is a widely accepted and well-performing method that requires little cognitive or social effort (Hastie and Kameda, 2005). Second, diversity is only practically relevant in scenarios that require a group to make a decision. If a group uses simple one-member rules, such as best member, adding others who perform less ably than the current decision-maker cannot change the group decisions. Still, the group requires cooperators and within the simulation, specific settings are conceivable that ensure a minimum cooperation rate. Nonetheless, in most real-world settings, decision-making happens repetitively. In such a setting, the group would not benefit from additional cooperators who cannot contribute, and less effective strategies would die out. This implies that any predictions of gain or cooperation changes within one-member decision-making settings are prone to be artefacts. Therefore, we argue that the choice of majority rule was appropriate for covering the relevant space of decision-making scenarios.

The explained variance on the change scores for the cooperation rate and gain were rather small. This means our linear additive combination of environmental effects could not account for the whole variance in differences between the diverse models and the base model. Given that all the effects come from a controlled simulation study, we propose that the unexplained variance comes from a complex interaction of the simulated factors, that possibly involve nonlinear combinations. This raises the question if we should have better developed a complex model involving nonlinear effects that could account for all variance. We posit that the answer is 'no'. Pursuing the best-fitting model in an exploratory manner could result in different model variants, that may imply significant contradictions and can hardly be interpreted. Instead, we advocate for a theoretically grounded analysis to test our hypotheses. We have successfully tested our hypotheses regarding diversity effects on the gain and cooperation rate and showed clear effects. We were also able to model environmental effects affecting these diversity effects.

Future empirical studies could use our model as a framework to gain a better understanding of how diversity interventions can enhance group success. For example, our results showed that in environments where a decision should be made based on multiple, much unrelated (low redundancy) cues of decreasing importance (non-compensatory), a diverse group in terms of cognitive style performs better and exhibits a higher cooperation rate. A potential intervention for such an environment may be to group people with different cognitive abilities together (Kozhevnikov et al., 2014). Our model also highlighted the importance of different information backgrounds in supporting group problem-solving. A possible intervention could focus on promoting cooperation of teams that have diversity in their demographics (Bell et al., 2011; Dahlin et al., 2005), and exploring how access to diverse information may improve their outcomes. This also bears the potential to bridge the gap between biodemographic and task-related diversity by providing a cognitive perspective to explain these mechanisms.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/jdm.2023.47.

Data availability statement. The simulation code and dataset containing the results of the final generation can be downloaded from https://osf.io/r2u34/.

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