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Myopically Forward-Looking Agents in a Network Formation Game: Theory and Experimental Evidence

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Abstract

A population of players is considered in which each agent can select her neighbors in order to play a 2×2 Hawk-Dove game with each of them. We design our experiment in *continuous time* where participants may change their Hawk-Dove action and/or their neighborhood at any point in time. We are interested in the resulting formation of networks and the action distributions. Compared with static Nash equilibrium (e.g., Berninghaus and Vogt, 2004, 2006; Bramoullé, López-Pintado, Goyal, and Vega-Redondo, 2004) and social optimum as theoretical benchmark solutions, subjects seem to employ a more complex, forward-looking thinking. We develop an other benchmark solution, called one-step-ahead stability, that combines forward-looking belief formation with rational response and that fits the data much better.

JEL classification: C72, C92

Keywords: Hawk-Dove game, local interaction, network formation, network experiment

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1 Introduction

This paper aims to shed some light on the question: What guides people in building a social network in a competitive environment? We conduct an experiment where participants both choose an action in a 2×2 base game and the partners they interact with. The base game is a Hawk-Dove game, which may be considered competitive in the sense that the cooperative outcome of both participants playing Dove is not an equilibrium but both equilibria in pure strategies are composed of a Hawk and a Dove with asymmetric payoffs. Snyder (1971) points out that its spirit "... is that of a contest in which each party is trying to prevail over the other."

Imagine, for example, a two-person project that needs at least one person who really aims at completing the task. Such a person would be a Dove in the game. Two Doves complete the task and share the payoff equally. If one person acts as a freeloader (i.e., chooses the Hawk strategy), the other person will increase the effort to complete the task anyway (i.e., act as a Dove) or not (choose Hawk), such that the task is not completed and both get less than if the task were completed. Such a situation can be represented by the Hawk-Dove game.

Another common example motivated by the origin of the Hawk-Dove game (Maynard Smith, 1982) is some cake to be divided. If both behave cooperatively the cake is shared equally; if one person acts aggressively, she either receives more than her opponent but still the whole cake is divided, or both receive an equal part of the shrunken cake, depending on how the opponent acts. In this sense, the game represents a situation of bilateral bargaining.

In this paper the two-person game is extended in that players do not interact with random partners in a population, but can build connections to other players in the population and play the game with each partner simultaneously. That is, they can choose one action in the Hawk-Dove game and play the game with all of their so-called neighbors. For a connection to be built, one of the partners has to bear connection costs to maintain the connection.

The analyses of Bramoullé et al. (2004) and Berninghaus and Vogt (2006) on games with action choice and endogenous network formation consider the model we used for our experiment. Other related models with different underlying 2×2 base games are, for example, those of Jackson and Watts (2002), Skyrms and Pemantle (2000), and Hojman and Szeidl (2006) on coordination games and the model of Ule (2005) on prisoner's dilemma games.

Kosfeld (2004) gives an overview of experiments on coordination games with different fixed interaction structures and experiments on network formation and the related theory. Most closely related to our experimental work is the work of Corbae and Duffy (2007), who investigate coordination games and network formation, and that of Riedl and Ule (2002), who conduct an experiment with network formation and action choice in a prisoner's dilemma game. Besides the different base game, the different connection costs structure and the link-building process, and other components of the experimental design, their experiments differ from ours in that they were conducted in discrete time, that is, in periods, where players have in one period the opportunity to adjust the network and in the following period or several periods choose only the action.

In the experiment of Riedl and Ule (2002), participants in each of 60 rounds choose links and action simultaneously. Corbae and Duffy (2007) have five to nine periods of two stages, a network-determining stage, and a stage where actions are chosen. Conducting the experiment in discrete time imposes some constrictions on the participants. For example, in such an environment it is much harder to signal via the action choice which network is preferred. Especially when the constellation at the end of the action choice period determines the payoff, it might not make sense to send a signal in this period for the next period of link adjustment.

In our experiment participants can change every component of their static strategy vector at every point in time. We do not constrain the players in their adjustment but let them choose for themselves *when* and *what* they want to change. In particular, they also decide how long a specific constellation influences their payoff. If they do not concur with the current constellation, they can immediately change the situation (as far at it is in their power) and therefore give this situation only a slight relevance for cumulated payoff. In an experiment in discrete time, on the contrary, every payoff-relevant constellation is weighted equally. Another difference is that players in our experiment decide sequentially and thus know the constellation before and directly after their change (even though the time period in which the constellation after a change prevails might be small). When they decide in periods, many players may change action and links simultaneously, which might give rise to miscoordination.

As far as we know, we are the first to conduct an experiment on pairwise interaction in a base game with endogenous network formation in continuous time, such that the players can choose at every point in time if and how they want to deviate from their (static) strategy choice. We think that this aspect is relevant and important for network formation as it helps prevent miscoordination that might occur due to simultaneous changes in discrete rounds. It might simplify the game for the participants, as they know exactly the situation after their change (thus, uncertainty decreases) and it facilitates sending signals.

Neugebauer, Poulsen, and Schram (2006) conduct an experiment on the Hawk-Dove game to elicit preferences of participants. They find that in their game a majority acts selfishly and rationally, in contrast to showing some kind of behavior determined by reciprocity or fairness. Our theoretical prediction and the experimental analysis is also mainly based on the assumption of some kind of rational behavior. In addition, we find that in a situation where the possibilities to increase the payoff during the experiment are restricted (due to high connection costs), we observe an interesting reciprocal behavior in one of the groups (see Subsection 4.2.2).

In the following sections, we describe the theoretical model and discuss several solution concepts with respect to their predictive power for the experiment (Section 2). In Section 3 we explain our experimental design. Section 4 contains the results of our experiment and Section 5 concludes.

2 The model and theoretical considerations

We consider a population of players who determine their interaction structure via their choice of costly links and who choose an action in a 2×2 normal form game that they play with each of their interaction partners. In the following, we describe the 2×2 game and the game of choosing interaction partners and then we combine both to the strategic-networking game[1].

2.1 The strategic-networking game

We consider a set $I = \{1, \ldots, n\}$ of n agents who are engaged in playing the same 2×2 Hawk-Dove game with each of their neighbors, who are linked via a network of players (=local interaction structure). To avoid trivialities, we assume $n \geq 3$. If two players i and j are linked, they play the symmetric 2×2 normal form game $\Gamma = \{\{i, j\}, \Sigma, \pi(\cdot)\}$ with strategy set $\Sigma := \{H, D\}$ and payoff function $\pi(\cdot)$: $\Sigma \times \Sigma \to \mathbb{R}$ characterized by the payoff table in Table 2 with $a > b > c > d$.

Table 1: Hawk-Dove game

	H	D
H	$\frac{V-C}{2}, \frac{V-C}{2}$	$V, 0$
D	$0, V$	$\frac{V}{2}, \frac{V}{2}$

$C > V > 0$

Table 2: Generalized Hawk-Dove game

	H	D
H	d, d	a, c
D	c, a	b, b

$a > b > c > d$

The game in Table 1 is the traditional Hawk-Dove game of Maynard Smith (1982), whereas Table 2 shows a generalized Hawk-Dove game, also known as Chicken game. Action H is called "Hawk" action while D is called "Dove" action. In the following, strategies in the 2×2 Hawk-Dove game will be called "actions." Typically, in Hawk-Dove games Dove players are better off when matched with other Doves rather than Hawks, although playing Dove against a Dove player does not constitute an equilibrium of the game Γ.

We do not impose a fixed interaction structure on the population of players but assume that networks can be built up by individual decisions. We assume that all players participate in a *network game*, which is a normal form game. An individual strategy of player i in the network game is a vector of ones and zeros, $g_i \in \{0, 1\}^n$. We say that player i establishes a link to player j if $g_{ij} = 1$, otherwise, it is equal to zero. A link between two players allows both players to play the Hawk-Dove game Γ. As a

[1]This type of game is sometimes also called a "social game" in the literature.

player cannot play the game with herself, we assume that $g_{ii} = 0$ for all i by convention. Note that a connection between two players is assumed to exist bilaterally if at least *one* player expresses interest in opening one.[2]

Each strategy configuration $g = (g_1, \dots, g_n)$ in the network game generates a directed graph denoted by $\mathcal{G}_g$, where the vertices represent players and a directed edge between i and j, that is, $g_{ij} = 1$, indicates that i opens a link with j. The set of i's neighbors, given a network $\mathcal{G}_g$, is defined to be the set of all players to whom i opens a link (neighbors connected via an "active link" of i, $g_{ij} = 1$) and the set of all players who open a link with i (neighbors to whom i is connected via a "passive link" $g_{ji} = 1$). We define the *set of i's neighbors* as

$$N_i(\mathcal{G}_g) := \{j \mid \max\{g_{ij}, g_{ji}\} = 1\}.$$

The set of *neighbors reached via an active link* depends solely on i's network strategy vector g_i. It is defined as

$$N_i^a(g_i) := \{j \mid g_{ij} = 1\}.$$

The cardinality of this set is defined by $n_i^a(g_i) := |N_i^a(g_i)|$.

Opening a link to another player is not costless. For the sake of simplicity, we assume that connection costs k (> 0) are constant per connection and do not vary among the players. Player i's total payoff in the network game consists of the aggregate payoff she can extract from playing with her neighbors along with the costs of establishing her active links.

Combining the two components, we model the strategic situation of a player as a *non-cooperative game* in which an individual strategy choice is composed of the *simultaneous choice of neighbors* via links $g_i \in \{0,1\}^n$ in the network game and *actions* $\sigma_i \in \{H, D\}$ in the Hawk-Dove game. Let us denote this *strategic-networking game* by

$$G = (I, S_1, \dots, S_n; P_1(\cdot), \dots, P_n(\cdot)),$$

with $S_i := \{0,1\}^n \times \{H, D\}$ and $P_i : S_1 \times \ldots \times S_n \to \mathbb{R}$ where

$$P_i(s_i, s_{-i}) := \begin{cases} 0, & \text{if } N_i(\mathcal{G}_g) = \emptyset \\ \pi(\sigma_i, H) \sum_{j \in N_i(\mathcal{G}_g)} 1_{\{\sigma_j = H\}} + \pi(\sigma_i, D) \sum_{j \in N_i(\mathcal{G}_g)} 1_{\{\sigma_j = D\}} - k\, n_i^a(g_i), & \text{else.} \end{cases}$$

The vectors s_{-i} and σ_{-i} denote the strategies $s_j \in \{0,1\}^n \times \{H, D\}$ resp. the actions $\sigma_j \in \{H, D\}$ chosen by each player $j \neq i$. G is a normal form game, where each strategy configuration $s = (s_1, \dots, s_n) = ((\sigma_1, g_1), \dots, (\sigma_n, g_n))$ induces a network represented by a directed graph $\mathcal{G}_g$ and a vector of actions in the Hawk-Dove game's action set $\{H, D\}$. An important consequence of our particular payoff definition is that player i may benefit from a connection to j even though she does not have to pay for it (i.e., if $g_{ij} = 0$ but $g_{ji} = 1$ holds).

[2]Beneath this assumption, which goes back to Bala and Goyal (2000), another common assumption is that both players have to agree to build a link and both have to pay (Jackson and Wolinsky, 1996). As in our formulation only the player who builds the link has to pay for it, we assume that the other player agrees to interact with her.

2.2 Analyzing the strategic-networking game with different solution concepts

As a natural benchmark solution of the strategic-networking game G we consider the *Nash equilibria*, which are in our context defined as follows:

Definition 1 *The strategy configuration* $s^* = (\sigma_1^*, g_1^*, \ldots, \sigma_n^*, g_n^*)$ *is a Nash equilibrium of* G *if*

$$\text{for all } i \in I: \; P_i(s_i^*, s_{-i}^*) \geq P_i(s_i, s_{-i}^*) \; \text{ for all } s_i \in S_i.$$

In an equilibrium no player has an incentive either to change her link choice or her action choice $\sigma_i^* \in \{H, D\}$ or both unilaterally.

The Nash equilibria s^* for the strategic-networking game G are characterized completely in Bramoullé et al. (2004) and Berninghaus and Vogt (2006). An overview of the Nash equilibria is given in Table 16 in Appendix A. We will illustrate them by a simple numerical example on which our experimental design is based.

Let the Hawk-Dove game Γ be characterized by the payoff matrix presented in Table 3. There, the payoff parameters of the traditional Hawk-Dove game (Table 1) are chosen as $V = 40$ and $C = 80$ and the matrix is transformed by adding 40 to each payoff, such that the parameters in the generalized Hawk-Dove game (Table 2) are $a = 80$, $b = 60$, $c = 40$, and $d = 20$. The population size is $n = 6$. We consider connection costs $k \in \{30, 50, 70\}$.

Table 3: Payoff table of the Hawk-Dove base game

	H	D
H	$20, 20$	$80, 40$
D	$40, 80$	$60, 60$

A Nash equilibrium of the strategic-networking game G is characterized both by a network structure and a distribution of H and D players denoted by n_H and n_D (with $n_H + n_D = n$). The network structure determines which types of connection exist between H and D players. The quotient $n_H : n_D$ determines how many H and D players in the population are compatible with the Nash property. Usually, there does not exist a unique equilibrium network and/or a unique number of H players for a given parameter value k. Applying the results of Berninghaus and Vogt (2006) to our numerical example, we obtain a complete overview of all *Nash equilibrium structures* in Table 4. Of course, all links mentioned in Table 4 are unidirectional, as a bidirectional link, that is, both players build a link with each other, does not increase the net payoff of either player. Connections that are not mentioned are not established in Nash equilibrium.

Table 4: Nash equilibrium structures of the numerical example

k	Network structure	$n_H : n_D$
30	All H and D players are connected via an active link of H or D, D players are connected with each other.	3:3[3], 4:2
50	H players have active links to all D players, D players are connected with each other.	3:3, 4:2, 5:1, 6:0
70	Complete bipartite graph (of H and D players) with active links of H players.	2:4, 3:3, 4:2, 5:1, 6:0

Remarks:

(1) Opening a connection is always profitable when the net payoff of linking is positive. For costs per link of $k = 30$, it does not pay for an H player to open a link to another H player. However, a D player benefits from an active link either to an H player (net payoff 10) or to another D player (net payoff 30), and an H player benefits from an active link to D (net payoff 50).

(2) For $k = 30$, the action distribution $3H : 3D$ constitutes a Nash equilibrium only if no D player has more than two active links to H players. If any D player has exactly two active links to H players, then the Nash equilibrium is non-strict.

(3) For $k = 50$ and $k = 70$, the empty network of H players is an equilibrium network structure. This does not hold for the empty network of D players, in which each player may benefit from switching to action H and opening links to the remaining players.

For both k-values, only active links from H to D players are compatible with the Nash property. Links from D to D players can be opened from either of them when $k = 50$ holds. But no active links from D to D players are compatible with the Nash property for $k = 70$.

(4) Besides the exception described in Remark 2 and the $6H : 0D$ configurations, all Nash equilibria are strict.[4]

Determining Nash equilibria in the strategic-networking game G is a standard exercise to generate benchmark solutions for an experimental scenario. However, we do not consider this concept as appropriate for our dynamic game in continuous time because players can immediately respond to action changes. For example, in some constellations profitable deviation is only possible because opponents keep links with negative net payoffs, which

[3] See Remark 2 on constraints on links for this distribution of players' actions.

[4] In the case $6H : 0D$, switching from H to D does not change a player's payoff of zero.

is unlikely when they have the possibility to delete those links immediately.[5] Thus, we take other theoretical concepts into account.

First we consider at the concept of subgame perfect equilibrium for our game in extensive form. Assuming that players are able to react immediately on other players' action changes, one can show that the (subgame perfect) *folk theorem* for infinitely repeated games in discrete time also applies for repeated games in continuous time with a given finite end (Simon and Stinchcombe, 1989; Ehrhart, 1997): every payoff combination within the convex hull of all feasible payoff combinations of the stage game G (see Subsection 2.1), which assign to each player $i \in I$ at least her *minimax payoff* v_i of the stage game, is reachable as average payoff via a subgame perfect equilibrium path of the repeated game in continuous time. In our networking game G the maximin payoff of player i is attained if each of her opponents chooses H and does not open a link with i, which leads to $v_i(k = 30) = 50$, $v_i(k = 50) = 0$, and $v_i(k = 70) = 0$. In all three treatments, the maximum payoff a player can achieve in a subgame perfect equilibrium is equal to 400 if each opponent chooses D and opens a link with i. Thus, we face a wide range of equilibrium payoffs. Moreover, the underlying equilibrium strategies are very complex in many cases. For these two reasons, this solution concept has to be considered as inappropriate to serve as a theoretical reference point for our game.

Recapitulating, we exclude the concept of Nash equilibrium of the static game as a reference point for our experiment because it does not take reactions into account and we exclude the concept of subgame perfect equilibrium of the dynamic game in continuous time because it makes too great of a demand on rationality, foresight, and coordination of strategies and does not give clear-cut predictions.

Before presenting an alternative behavioral concept, we emphasize some feature of our game, that is, changing a link or the action have different characteristics: a link change influences only the bilateral interaction with one other player, whereas an action change affects all interactions with the neighborhood. Therefore, a link change in response to an action change of some other player is more straightforward than the change of the action. Following these considerations, we would expect that a player who observes a change of an action is more likely to decide about deleting, keeping, or building a link than to decide to change the action.

This leads us to consider the following type of forward-looking behavior: At linking costs $k = 50$, for example, an H player may switch from a Nash equilibrium configuration to action D, anticipating that the remaining H players will open links to her afterwards because these links have positive net profit for both only if Hawks build them. Together with existing links to the remaining D players, the deviating player may finally benefit from this decision.

(1) Consider the equilibrium network structure and the equilibrium action constellation $3H:3D$ for parameter value $k = 50$ (see Table 4). An H player i, connected

[5] As we will see, we observe Nash equilibrium configurations only very rarely during the course of the experiment.

with all D players, earns 90. Changing the action from H to D and keeping her active links to D players will result in a payoff of 30. Faced with this new constellation, the best reaction of the remaining two H players would be to build links to i.[6] Anticipating this rational reaction of the H players, i could expect a total payoff of 110 induced by deviating from H to D, which is higher than the equilibrium payoff.

(2) Consider now the resulting constellation $2H:4D$ for parameter value $k = 50$ and the corresponding equilibrium network structure (see Table 4):

- This is not a Nash equilibrium since, for example, a D player could alter her action and keep her links fixed. As an H player she increases her payoff from each previous D connection by 20 (=80-60) and decreases her payoff from previous H connections by 20 (=40-20). Since her number of (active or passive) D connections is larger than the number of H connections, profitable deviation is possible.[7]
- However, by forward induction arguments we can argue that changing the action from D to H will induce all other H players to drop their connections because they generate negative net payoffs for them. The player who changed from D to H can build profitable links to D players, but the highest profit she can get is still lower than what she got before, no matter how many active links to other D players she had before. Therefore, a D player will not change her strategy if she anticipates her opponent players' rational reactions in dropping links (compare Figure 1).

To summarize, on the one hand, there are strategy constellations $s \in S$ which have the Nash property but, nevertheless, players can better themselves by taking best-reply linking reactions of the opponent players into account. On the other hand, non-Nash constellations exist which are stable against strategy deviations which put the deviator into an inferior situation by anticipating best-response linking decisions of the remaining players. In the following, we call this type of strategy configurations *one-step-ahead stable states*. Note that a deviating player only takes best linking responses of her opponent players into account and neglects action responses. We emphasize this concept since subjects in our experiment stayed at such states or at least came close to them for a significant part of total time. We formalize the previous arguments as follows. As candidates for one-step-ahead stable states, we consider all strategy configurations $s \in S$ such that[8]

[6] Because of resulting losses ($40 - 50 < 0$), it would not pay for i to open new links to the remaining H players.

[7] Note that the profitable deviation is not possible for the H players.

[8] Obviously, strategy configurations which do not satisfy criteria (1)–(3) will soon be made obsolete by changing actions or links unilaterally.

(1) all existing links show positive net payoff,

(2) all profitable links are realized,

(3) there does not exist any bidirectional link between a pair of players.

We denote these strategy configurations by $\tilde{S} \subset S$.

Testing the one-step-ahead stability of a configuration $s \in \tilde{S}$ means that a deviating player i may consider changing her action σ_i and/or links g_i while she expects the other players to respond via link changes only (at the "next step"). Which responses will the deviating player i expect? To deal with this problem, we need a further characterization of links:

Definition 2 *A connection between two players has an* unambiguous direction *if one of the two connected players extracts positive net payoff when she pays this link, while the other player would obtain a negative net payoff when paying the linking costs. We call a connection with unambiguous direction an* unambiguous connection*. The player with the positive net payoff pays for the unambiguous connection.*

If both players would obtain positive net payoffs when paying for the link, the connection would be called ambiguous.[9]

Thus, for example, in HD50 a connection between H and D is unambiguous (H has to pay for it), while in HD30 a connection between H and D is classified as ambiguous (both would obtain positive payoffs of 50 and 10, respectively). Based on this definition, we employ the following behavioral hypothesis concerning possible deviations in action choice and expected linking responses.[10]

Behavioral hypothesis: A player who considers deviating from a given configuration expects that

- her previous neighbors will keep their ambiguous and unambiguous links and delete their unprofitable links,
- other players will build new connections with unambiguous direction toward her but will not build ambiguous links.

Let us denote the set of these responses on player i's deviation s_i by $ER(s_i)$ (*expected response*). Using these concepts we are able to formalize our new stability concept.

Definition 3 *A strategy configuration* $s^{**} = (s_1^{**}, \ldots, s_n^{**}) = (\sigma_1^{**}, g_1^{**}, \ldots, \sigma_n^{**}, g_n^{**}) \in \tilde{S}$ *is one-step-ahead stable iff*

$$\text{for all } i: \quad P_i(s^{**}) \geq P_i\left(ER(s_i), s_i\right) \quad \text{for } s_i \in S_i.$$

[9]The magnitude of the positive net payoff does not matter for our classification.

[10]We postulate these behavioral rules to have some definitive criteria for an alternative solution concept which is observed very often during the course of the experiment.

Thus, a configuration s^{**} is one-step-ahead stable if for all i

(1) building new links does not pay,

(2) changing the action considering unambiguous linking reactions and own rational adjustment of links does not pay.

Table 5 gives an overview of all one-step-ahead stable configurations for our numerical example (with $n = 6$). For a general characterization of one-step-ahead stable configurations, see Table 17 in Appendix A.

Table 5: One-step-ahead stable configurations of the numerical example

k	Network structure	$n_H : n_D$
30	All H and D players are connected via an active link of H or D, D players are connected with each other.	2:4, 3:3, 4:2[11]
50	H players have active links to all D players, D players are connected with each other.	0:6, 1:5, 2:4[12]
70	Complete bipartite graph (of H and D players) with active links of H players.	1:5, 2:4

The proposed solution concept of one-step-ahead stability bases on the assumption that players indeed decide rationally on their actions but form their beliefs other than in the Nash equilibrium. That is, we impose certain beliefs on players and assume that they act rationally with respect to these beliefs, which mirror players' assumed forward-looking thinking.[13]

Table 6 contrasts the two solution concepts with respect to the compatible numbers of Hawks. A "yes" in italics indicates an action distribution where the networks compatible with the solution concept are not fully characterized by a description of connections between types but need to satisfy additional restrictions on the number of links of Doves (cp. tables 16 and 17). Note that the general conditions on the network structure of Nash equilibria and one-step-ahead stable states are identical. In our numerical example, the additional restrictions also coincide when the action distribution is a candidate for both concepts (at $k = 30$, $n_H = 3$).

From Table 6 we see that for most configurations one-step-ahead stability and the Nash property do not coincide and that one-step-ahead stability mostly favors action

[11] For $k = 30$ and $n_H = 2$ and $n_H = 3$, the additional condition restricts the number of links of D to H to 0 and 2 respectively (cp. Table 17). For $n_H = 4$, the restriction does not apply.

[12] For $k = 50$ and $n_H = 0$ and $n_H = 1$, the additional condition restricts the number of links of D to 3 (cp. Table 17). For $n_H = 2$, the restriction does not apply.

[13] For some discussion of beliefs in repeated games see e.g. Morris (1995), Subsection 5.1.

constellations with a majority of Doves. The higher number of Doves is in accord with our experimental results, which are characterized by action proportions $n_H : n_D$ with large n_D not compatible with the Nash property (see Section 4.1).

Table 6: One-step-ahead stable constellations and Nash equilibria

		$n_H : n_D$						
		0:6	1:5	2:4	3:3	4:2	5:1	6:0
$k = 30$	One-step-ahead stable	–	–	*yes*	*yes*	yes	–	–
	Nash equilibrium	–	–	–	*yes*	yes	–	–
$k = 50$	One-step-ahead stable	*yes*	*yes*	yes	–	–	–	–
	Nash equilibrium	–	–	–	yes	yes	yes	yes
$k = 70$	One-step-ahead stable	–	yes	yes	–	–	–	–
	Nash equilibrium	–	–	yes	yes	yes	yes	yes

In Figure 1 an example to illustrate the difference between Nash equilibrium and one-step-ahead stability is given. The first graph shows a $2H : 4D$-network with $k = 50$, where all links with positive net payoff exist and all links are unidirectional. An arrow pointing from an H to a D indicates that H pays for the link. The payoffs of the players are also given. The second graph shows the result of an unilateral deviation of the northeastern D changing her action to H. This deviating player increases her payoff from 210 to 230. But in this network, several links with negative net payoff exist (indicated by gray arrows). The deviating player might rationally expect that those links will be deleted, as shown in graph 3. The best response in this situation is to build links to the Doves and increase the payoff to 90. This payoff is below the original payoff of 210. To check for one-step-ahead stability, one compares 210 with 90 and finds that the network shown in graph 1 is stable.[14] It is not a Nash equilibrium because of the increase in payoff shown in graph 2. If one assumes that players realize links with negative net payoffs and are able to delete them quickly, Nash equilibrium is not an appropriate concept to apply to this game.

In the previous part of this section, we discussed two theoretical benchmark solutions – Nash equilibrium states and one-step-ahead stable states – for the strategic-networking game G. Looking at Table 6, we find a clear tendency that one-step-ahead stable states favor "Dove populations," which, however, are not compatible with the Nash concept. In all treatments of our experiment, we found a rather large number of Dove players. This motivated us to look for further solution concepts which could, among others, give a better explanation for the amount of Dove players. One-step-ahead stability seems to

[14]Deviation of an H in graph 1 results in a payoff of 80 as the relevant point of comparison for one-step-ahead stability which is lower than 120. Unilateral deviation of an H in graph 1 results in a payoff of 40 as the relevant point of comparison for Nash equilibrium.

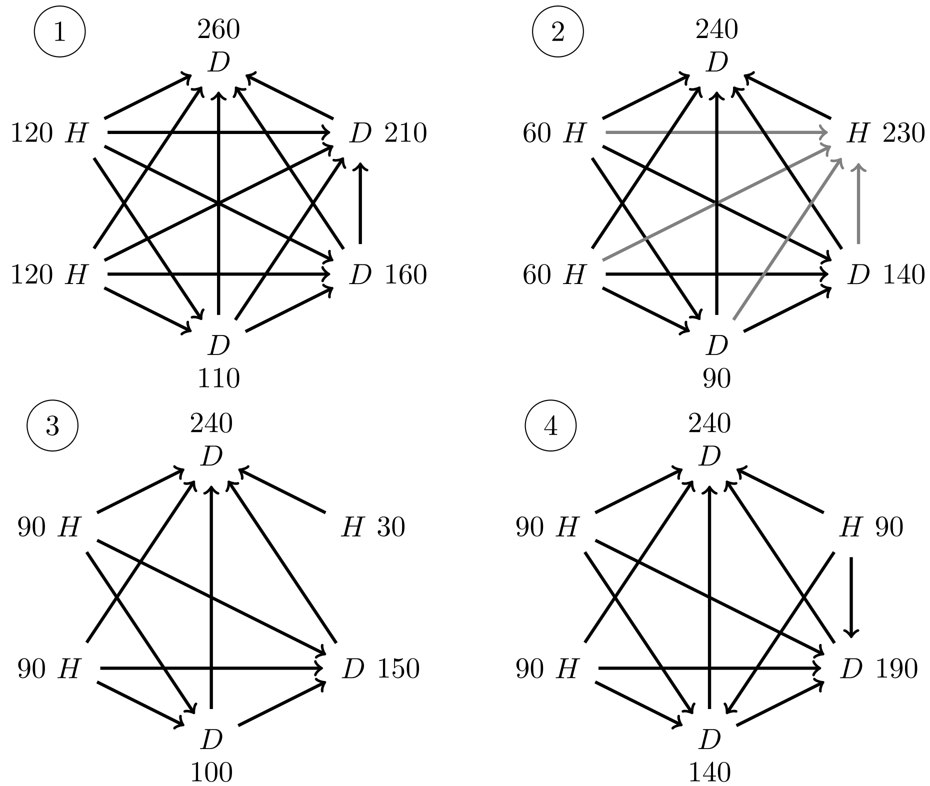

Figure 1: An example demonstrating the difference between Nash equilibrium and one-step-ahead stability ($k = 50$)

be one appropriate tool. Another theoretical benchmark solution which might deliver an additional argument for the formation of rather large Dove populations is the concept of *socially optimal states*, which denotes the set of strategy configurations maximizing the sum of net payoffs.

Given our particular payoff table of the Hawk-Dove game, in a socially optimal state either all n players choose Dove or $n-1$ players choose Dove and one players chooses Hawk, and in both cases all players are connected (complete network). This results in a payoff per connection of $120 - k$ and a total payoff equal to

$$\sum_{i \in I} P_i = \frac{n(n-1)}{2} \cdot (120 - k) = 1800 - 15k.$$

With varying link costs k, we obtain three different socially optimal payoff values (see Table 7).

The average payoff in Table 7 of the players is not a good predictor of a single player's actual payoff since it is not determined a priori how links among players are distributed.

Table 8 gives an overview of the respective relation between the networks for the different concepts when they apply to the same H/D-constellation. For $k = 30$, every

Table 7: Social optimum (max. sum of payoffs)

	$k = 30$	$k = 50$	$k = 70$
$\sum_{i \in I} P_i$	1350	1050	750
$0H\colon 6D$: gross payoff Dove (D)	300	300	300
$1H\colon 5D$: gross payoff Hawk (H)/Dove (D)	400/280	400/280	400/280
Avg. link costs per player	75	125	175

Nash equilibrium is also a one-step-ahead stable network (see Footnote 15). Neither ever coincide with socially optimal states. For $k = 50$, one-step-ahead stability and social optimum coincide for the constellations with no and with one Hawk. The conditions on links for socially optimal networks, however, are more relaxed since they only require that all players have to be connected by unidirectional links, whereas one-step-ahead stability additionally restricts the number of active links of Doves. Thus, the one-step-ahead stable states are a subset of the socially optimal states for zero or one Hawk. At $k = 70$, Hawks have to pay for the links to Doves and Doves are not connected. The second constraint results in disjoint sets of the two concepts even at the action constellation that they have in common (one Hawk). The relations between the solution sets of the three concepts over all action constellations are given in the last row of Table 8. In this summary, "$\neq \emptyset$" means that the solution sets have vectors in common but cannot be described by a subset relation. Note that Nash equilibria and socially optimal states never coincide.

In addition, in Table 8 the sum of payoffs of all players is given by the values in the brackets. For $k = 30$ and $k = 50$, the sum of payoffs decreases in the number of Hawks in the society. For $k = 70$, one-step-ahead stable states and socially optimal states differ in the sum of payoffs when there is one Hawk, because the Doves are not connected at costs of 70 under one-step-ahead stability whereas they are in social optimum. In the Nash equilibria and in the one-step-ahead stable states with two Hawks, the sum of payoffs is 400 but it increases to 450 in the Nash equilibria with three Hawks and then it decreases with an increased number of Hawks in the Nash equilibrium.

3 Experimental design

The computerized experiment was conducted in the experimental laboratory at the University of Karlsruhe. Subjects were randomly selected from a pool of students of various departments. The experiment was organized in three treatments with six groups of six subjects per treatment. One session consisted of three groups. The software for the experiment was developed in our laboratory to conduct experiments in continuous

Table 8: Relations between the concepts for the numerical example. The sum of payoffs is given in brackets.

	Relation		
	$k = 30$[15]	$k = 50$	$k = 70$
$0H6D$	only SO (1350)	OSAS $\subset$ SO (1050)	only SO (750)
$1H5D$	only SO (1350)	OSAS $\subset$ SO (1050)	OSAS $\cap$ SO$= \emptyset$ (250,750)
$2H4D$	only OSAS (1260)	only OSAS (980)	OSAS $=$ Nash (400)
$3H3D$	OSAS $=$ Nash (1080)	only Nash (840)	only Nash (450)
$4H2D$	OSAS $=$ Nash (810)	only Nash (630)	only Nash (400)
$5H1D$		only Nash (350)	only Nash (250)
$6H0D$		only Nash (0)	only Nash (0)
Summary	OSAS $\cap$ SO $= \emptyset$	OSAS $\cap$ SO $\neq \emptyset$	OSAS $\cap$ SO $= \emptyset$
	OSAS $\supset$ Nash	OSAS $\cap$ Nash $= \emptyset$	OSAS $\cap$ Nash $\neq \emptyset$
	SO $\cap$ Nash $= \emptyset$	SO $\cap$ Nash $= \emptyset$	SO $\cap$ Nash $= \emptyset$

SO: socially optimal states
OSAS: one-step-ahead stable states

time.

In our setting the network game as described in Section 2.2 is repeated in continuous time. Each game lasts 30 minutes. The game starts when all subjects have made their first decision, that is, each subject has to decide for every possible active link whether this link is built or not and to choose an action in the bilateral Hawk-Dove game. Thereafter, subjects can change their strategies, that is, either open or sever links or change their action in the Hawk-Dove game, at any time. Information is updated by the computer 10 times per second. Particularly, the current payoff flow is computed every tenth of a second and accumulated payoff is "integrated" up to the given moment. The information presented on every subject's computer screen throughout the game includes the elapsed time, her current payoff flow, and her current accumulated payoff. A subject's own and the other subjects' active links and actions H or D[16] are illustrated graphically on the screen by directed arrows in a graph and by indicating the chosen actions at the vertices of the graph. Moreover, the subjects with whom a player is connected are shown in a different color on her screen than the remaining ones.

The return per connected player depends on the action choices in the bilateral Hawk-Dove game, whose payoff table is given in Table 3 and whose payoffs are measured in

[15]The equality of sets of one-step-ahead stable states (OSAS) and Nash equilibria for $k = 30$ at $3H3D$ and $4H2D$ results from the fact that the conditions on the number of links from any Dove to Hawks $l^{D \to H}$ coincide for our numerical example (cp. tables 16 and 17).

[16]In the experiment actions were denoted by the more neutral letters X and Y.

ExCU per minute (ExCU = experimental currency units). The treatments differ in the costs per link of $k = 30$ ExCU per minute, $k = 50$ ExCU per minute, and $k = 70$ ExCU per minute, and are denoted by HD30, HD50, and HD70 respectively. The characteristic features of Nash equilibria and one-step-ahead stable strategy configurations, depending on costs, are given in Tables 4 and 5.

Six groups in each of the treatments HD30, HD50, and HD70 give us six independent observations for these treatments. The payoff for each subject is accumulated over 30 minutes and paid out in cash after the experiment. For example, suppose a player extracts a payoff of 140 ExCU per minute from the network for 15 seconds and then switches her action and obtains 200 ExCU per minute for 54 seconds. Her accumulated payoff for these 69 seconds is equal to (140 ExCU/60)*15 + (200 ExCU/60)*54 = 215 ExCU.

The maximum and minimum payoff earned in the experiment is equal to €8.85 and €22.27, respectively (€14.16 on average). Since subjects may end up in negative payoffs, we pay for all treatments a show-up fee equal to 500 ExCU. Since expected payoffs in the treatments differ, we vary the conversion rate.[17]

Before the experiment starts, subjects have to solve some selected problems on building links in a network and calculating the resulting payoff to ensure that subjects understand the rules of the game.

4 Experimental results

To give an impression of the experimental results, we first describe some characteristics of our observations in the different treatments and then provide a detailed analysis with respect to different solution concepts. Here, we consider Nash equilibrium and social optimum as alternative reference points to compare with one-step-ahead stability.

4.1 Description of the results

In continuous time experiments, subjects typically change actions very often (e.g., Berninghaus and Ehrhart, 1998; Berninghaus, Ehrhart, and Keser, 1999; Berninghaus, Ehrhart, and Ott, 2006). Therefore, we consider the performance variable "number of changes" and differentiate between the percentage of link changes and changes of the action in the Hawk-Dove game in relation to the total number of changes, including link changes. The average number of links in a group and the average number of Hawks is also presented.

In all treatments, we observe many changes (e.g., 412 changes in 30 minutes correspond to almost 14 changes per minute), whereas subjects change links more often than actions, that is, the change of an action is on average associated with five to six link changes. On the other hand, every player can change one action but five links. So one

[17]The conversion rate is €1 per 400 ExCU in HD30, €1 per 300 ExCU in HD50, and €1 per 170 ExCU in HD70.

Table 9: Changes, links, and actions in the groups

	HD30	HD50	HD70
Avg. number of changes in a groups	411.8	478.8	340.7
Link changes [%]	82.3	86.2	87.3
Action changes [%]	17.7	14.8	12.7
Avg. number of links in a group	12.5	12.0	7.0
Avg. number of Hawks (H) in a group	2.2	2.0	1.7

might also adopt the position that a player changes every component of his strategy vector with similar frequency. Table 10 shows that we did not find significant differences between groups in the number of changes.

The number of links in treatments HD30 and HD50 is similar. On average we observe about 12 links in our groups of six players. Thus, neglecting bidirectional links, 12 of 15 possible pairs are built. In Treatment HD70 only 7 of 15 possible unidirectional links are built on average. The significant decrease in links from HD50 to HD70 (see Table 10) can be understood if we compare link costs and payoffs. By raising link costs to 70, only active links from H to D are profitable for both participants. With an average of 1.7 Hawks in HD70, we expect approximately eight links on average (each of the two H with four links). On the other hand, the increase in costs from HD30 to HD50 does not have this influence on the number of links. This is the case because in HD30 active links between Doves, active links from H to D, and active links in the other direction (from D to H) have a positive net payoff, whereas in HD50 positive net payoff can be achieved via active links between H and from H to D. Thus, the only type of link that does not pay anymore in HD50 compared to HD30 is the active link of D to H, which can be compensated for by having these links paid by Hawks. As the number of Hawks is similar, the number of links should be likewise. With about two H on average, we expect 14 links. This is a bit more than the 12.5 and 12.0 links per group that we observe. In HD30 there are more Hawks than in HD70. The numbers of Hawks observed are discussed in detail in the next section.

We conclude that the groups in the three treatments behave similar with respect to the number of changes and the percentage of action changes. Significant differences in the *number of links* and *number of Hawks* are revealed by the Kruskal-Wallis test. The pairwise comparison of treatments by means of the Mann-Whitney test gives more information. Considering the number of links, the difference between HD30 and HD50 is not significant, but it is significant between HD30 and HD70 as well as between HD50 and HD70. The only significant pairwise difference in the number of Hawks is between HD30 and HD70.

Table 10: Statistical comparison of treatments

	Kruskal-Wallis: Test statistic (p-value)	Mann-Whitney: Test statistic (p-value,two-tailed)		
	HD30, HD50, HD70	HD30, HD50	HD30, HD70	HD50, HD70
Avg. number of changes	2.47 (0.29)	14 (0.59)	15 (0.70)	7 (0.09)
Percentage of action changes	2.06 (0.36)	14 (0.59)	8 (0.13)	14 (0.59)
Number of links	**11.88 (0.003)**	12 (0.39)	**0 (0.002)**	**0 (0.002)**
Number of Hawks	**7.69 (0.02)**	10 (0.24)	**2 (0.01)**	7 (0.09)

4.2 Analysis of experimental results

In this section we test our behavioral hypothesis developed in Section 2.2 and compare one-step-ahead stability with Nash equilibrium and social optimum concerning their adequacy to explain our experimental results.

4.2.1 Explaining the results with the concept of one-step-ahead stability

First, we focus on the observed numbers of Hawks and Doves by neglecting the network. According to Table 11, in all treatments the number of Hawks lies within the range predicted by one-step-ahead stability for a greater percentage of time.

Table 11: Observed percentage of time of action distributions compatible with one-step-ahead stability, Nash equilibrium, and social optimum

Percentage of time (number of Hawks)	HD30	HD50	HD70
One-step-ahead stability	88.5 (2–4H)	75.8 (0–2H)	92.5 (1–2H)
Nash equilibrium	29.8 (3–4H)	24.2 (3–6H)	61.9 (2–6H)
Social optimum	11.4 (0–1H)	25.7 (0–1H)	38.1 (0–1H)

In Treatment HD30 the Nash equilibrium constellations (three or four Hawks) are a subset of the one-step-ahead stable constellations (two to four Hawks). We observe action configuration with two Hawks 58.7% of the time and configurations with three or four Hawks only 29.8% of the time. In Treatment HD50 the three constellations compatible with one-step-ahead stability (zero to two Hawks) are observed 75.8% of the time, whereas the four opposed Nash compatible constellations (three to six Hawks) are played only 24.2% of the time. In Treatment HD70 the two concepts have one constellation in common (two Hawks), whose action configuration is observed 55.3% of the time. The other one-step-ahead stable constellation (one Hawk) adds another 37.2%, whereas five additional Nash constellations (three to six Hawks) together add only 6.6%.

We now consider socially optimal constellations. In HD30 we observe that constellations compatible with one-step-ahead stability are played much more often than those compatible with the social optimum. In HD50 the set of socially optimal states and the set of one-step-ahead stable states both include constellations with zero and one Hawk, which are played 25.7% of the time. Constellations with two Hawks, which are compatible with one-step-ahead stability but not with the social optimum, account for 50.1%. The situation is similar in HD70: 0.9%, 37.2%, and 55.3% of the time, zero, one, and two Hawks are observed, respectively. This results in the 38.1% constellations being compatible with the social optimum and 92.5% being compatible with one-step-ahead stable constellations of Table 11, where both have constellations with one Hawk in common (37.2%).

Hence, the examination of the observed distribution of Hawks and Doves indicates that one-step-ahead stability might explain the data much better than the Nash equilibrium or efficient networks. In order to evaluate the descriptive power of the concept more accurately, we also have to analyze the observed networks.

As every player has five links to decide on and a lot of deviations from the predicted network are possible, we allow for individual link errors in our analysis. Table 12 presents the results of one-step-ahead stable networks, Nash networks, and socially optimal networks. The column for zero link errors gives the results when we do not allow for any deviation from the respective network. In the next columns we allow for one, two, and three individual link errors in the network. Individual errors are counted whenever a link of a player deviates from the network prescribed by the respective concept, that is, a link that should not be built as well as a missing link. As a consequence, a double link is counted as one error if the link should be there and as two errors if no link should be there. In case of a single link between a Hawk and a Dove in treatments HD50 and HD70 which is initiated by the Dove and thus has the wrong direction, we count two errors, because a Dove has an excessive link and a Hawk has a missing link.[18]

We conclude from Table 12 that one-step-ahead stability explains a much larger part of the observed constellations than Nash equilibrium or social optimum do. For more detailed results, see Table 18 in Appendix B. Table 13 presents the results of the statistical comparison of the three concepts. As we have only six observations per treatment, the applied sign test (and the Wilcoxon signed rank test) only allows for rejection of the null hypothesis of equal median if *all six* differences between the durations of observed states compatible with two concepts feature the same sign.

When we allow for one link error, one-step-ahead stability fits a significantly larger part of our results than Nash equilibrium in all treatments. Moreover, in HD30 and

[18] In this case one might also argue that the Hawk does not do wrong in not building the link because the link of the Dove already connects them. Counting like this results in a slight increase in the numbers in Table 12.

Table 12: Observed percentage of time of one-step-ahead stable networks, Nash networks, and socially optimal networks, allowing for link errors

Number of link errors		0	1	2	3
HD30	One-step-ahead stable [%]	16.3	37.2	56.6	68.9
	Nash equilibrium [%]	4.0	11.0	17.7	22.2
	Socially optimal [%]	1.4	3.8	6.8	8.8
HD50	One-step-ahead stable [%]	5.5	19.8	34.5	47.6
	Nash equilibrium [%]	2.1	4.6	7.7	10.5
	Socially optimal [%]	1.5	4.2	9.3	15.4
HD70	One-step-ahead stable [%]	26.7	46.6	57.2	65.3
	Nash equilibrium [%]	15.8	27.5	33.8	39.5
	Socially optimal [%]	0.0	0.0	0.1	0.2

HD70 one-step-ahead stability fits significantly better than social optimum. In HD50 there is one group that plays socially optimal networks more often than one-step-ahead stable networks. Note that one-step-ahead stability with zero or one Hawk restricts the number of active links of a Dove to a maximum of three, whereas social optimum only demands that all players are somehow connected via unidirectional links. Relaxing the conditions on links by allowing for two or three errors always favors one-step-ahead stability. Nash equilibrium dominates the fit of the social optimum only in HD70. In this treatment, all socially optimal networks imply links with negative payoffs.

Concluding, one-step-ahead stability explains the results better than the Nash equilibrium of the static game or the social optimum. The percentage of time that is covered by one-step-ahead stability might appear low at first glance, but it strongly increases if we allow for some minor deviation in links. Another aspect to take into account when appraising the concept is the number of possible networks. In our experiment, the number of possible different constellations is equal to 68 719 476 736 while the number of one-step-ahead stable constellations, for example in HD30, is equal to 63 520. The ratio of approximately 1 : 1 000 000 lets us conclude that one-step-ahead stable networks do not just arise by chance.[19]

4.2.2 The phenomenon of "circular sponsoring"

In Treatment HD70, costs for links are rather high, such that only active links from Hawks to Doves give both participants a positive net payoff. Thus, there are not many possibilities to increase a player's payoff. One way, which is not in line with individual

[19]There exist 229 376 socially optimal networks in all treatments, 21 one-step-ahead stable networks in HD70, and 62 560, 89 793, and 57 Nash equilibria in HD30, HD50, and HD70, respectively.

Table 13: Comparison of the observed percentage of time of one-step-ahead stable networks (OSAS), Nash networks, and socially optimal networks (SO) for zero to three allowed link errors (le) (sign test, two-tailed, $\alpha = 0.05$; given is the number of groups with positive differences, significance is indicated by bold numbers, p-value is given in brackets)

	OSAS vs. Nash			OSAS vs. SO			Nash vs. SO		
	HD30	HD50	HD70	HD30	HD50	HD70	HD30	HD50	HD70
0 le	**6 (.03)**	4 (.69)	5 (.06)	**6 (.03)**	5 (.22)	**6 (.03)**	5 (.22)	4 (.69)	**6 (.03)**
1 le	**6 (.03)**	**6 (.03)**	**6 (.03)**	**6 (.03)**	5 (.22)	**6 (.03)**	4 (.69)	4 (.69)	**6 (.03)**
2 le	**6 (.03)**	**6 (.03)**	**6 (.03)**	**6 (.03)**	**6 (.03)**	**6 (.03)**	4 (.69)	3 (1)	**6 (.03)**
3 le	**6 (.03)**	**6 (.03)**	**6 (.03)**	**6 (.03)**	**6 (.03)**	**6 (.03)**	4 (.69)	3 (1)	**6 (.03)**

incentives, is to build links between Doves. The Dove that pays the link gets a net payoff of minus 10 ExCU, but the pair of Doves together receives a net payoff of 50 ExCU. Thus, two Doves increase their payoff by bilateral sequential sponsoring, that is, two Doves are connected for some time (for example a minute) by an active link of one of them and then the link is replaced by a link in the opposed direction for about the same duration. However, this kind of sponsoring is rather risky for the player who pays first. A more elegant way to increase the payoff of Doves is directed circular sponsoring, that is, three Doves are connected via unilateral links, such that all three players pay for one link each. Such a circle increases the payoff of each of the three Doves by 50 ExCU per minute. In groups 1, 2, and 6 in HD70, we observe circular sponsoring. Especially in group 6, where the other concepts do not fit the data well (see Table 12), the occurrence of circles 31.35% of the time speaks for sponsoring as an alternative explanation. In this group we even observe two different circles at the same time. However, about 30% of the time the circle is built by the same three players, who change the direction of the circle several times.

Circular sponsoring is also possible in HD30 between Hawks. There, the gain per player is only 10 ExCU and in this treatment there are many more possibilities to increase the payoff, such that players maybe do not feel the pressure to cooperate as in HD70. This might explain our observation of circular sponsoring in HD30 only in two groups for about 5 seconds, which is most probably only a phenomenon due to the transition between networks.

Thus, the sparse opportunities to earn money in HD70 and the simpler networks (only active links of Hawks to Doves show positive net payoff) seem to have led to cooperative behavior in the form of circular sponsoring.

4.2.3 Hawks and Doves

Concerning the results, one might ask what kind of behavior proved to be successful in the experiment. A related question is whether Hawks or Doves receive a higher payoff. As players change their action choice during play, we analyze the question by looking at the average payoff of players' earnings from acting as a Hawk or as a Dove.

Table 14 presents the average payoffs for Hawks and for Doves by assuming that all links that pay are built. Note that Nash equilibria and one-step-ahead stable states are included in the set of considered networks. In HD50 and HD70, in almost all cases Doves earn more than Hawks. Doves may benefit from the presence of the Hawks if the connection of the two types is only profitable for the Hawks. An extreme case is $k = 70$ when the high payoffs of Doves depend on Hawks paying the links. In HD30, the average payoffs of Hawks and Doves are interdependent as it is not unambiguous who pays the connection between both types. Thus, we specify the lowest and highest average payoff as well as the average payoffs with the smallest difference in Table 14.[20] As a result, whether a Dove or a Hawk earns more in HD30 depends on who pays the links.

Table 14: Theoretical average payoffs of H and D when all links with positive net payoff are maintained (in ExCU per minute)

	HD30 (avg. payoff)		HD50 (avg. payoff)		HD70 (avg. payoff)	
n_H	H	D	H	D	H	D
0	–	225	–	175	–	0
1	150–300 (210)	220–190 (208)	150	180	50	40
2	200–320 (215)	215–200 (207.5)	120	185	40	80
3	150–240 (180)	210–120 (180)	90	190	30	120
4	100–180 (130)	190–70 (130)	60	195	20	160
5	50–80 (74)	200–50 (80)	30	200	10	200
6	0	–	0	–	0	–

In Table 15 the average payoffs of H and D in the treatments are given. In detail, the numbers given are treatment averages of group averages of each player's payoff per minute from his time as a Hawk or a Dove, respectively. Applying the sign test reveals that in each treatment the payoffs from being a Dove is significantly higher than that of being a Hawk ($p = 0.03$; in each treatment in all six groups, the difference between the average payoff of being a Dove and of being a Hawk is positive).

From tables 15 and 14 we conclude that the observed higher average payoff of Doves is what theory predicts in most of the cases. Behaving hawkishly does not pay in this

[20]The lowest payoff of Doves is of course related to the highest average payoff of Hawks and vice versa. The payoffs with the smallest difference are obtained with 3/2, 7/1, 6/3, 4/4, and 1/4 links of Hawks/Doves in HD30 for one to five Hawks, respectively.

Table 15: Observed average payoffs of H and D in the experiment (in ExCU per minute)

	Avg. payoff of H	Avg. payoff of D
HD30	145.5	168.7
HD50	108.3	133.2
HD70	36.1	60.1

environment. In our experiment in each population of six players, the Doves have on average a higher payoff that the Hawks.

5 Conclusion

Recapitulating, we introduced a concept that assumes more forward-looking behavior than the Nash equilibrium of the one-shot game does, but imposes less requirements on the rationality of players than the subgame perfect equilibrium of the game in continuous time. The analysis of our experimental data shows that one-step-ahead stability is a useful concept to explain the observations.

Even as there is a lot of dynamic in the experiment, we are able to explain a non-negligible part of the observations with our concept, which combines Nash equilibrium ideas with forward-looking aspects.

In our model the neighborhood is fully observable. If a Nash equilibrium is reached, it is relevant for a player i to know the actions of all players and her actual passive links (in order to calculate who will keep links and to whom new links will pay). For one-step-ahead stability, it is relevant for a player i to know the actions of all players and to know who observes her (in order to calculate who will build new links and to whom new links will pay). Thus, a bit more information is needed for one-step-ahead stability. But the network does not need to be confined to the observed players. For the decision of a player i it is relevant, which part of the population she observes. But it is not relevant for her, based on the observation of which part of the population *they* choose their action. Of course, for one-step-ahead stability, it is also relevant that this observation is bilateral, that is, whenever a player i observes a player j, j also has to observe i in order to react according to the concept, and a player k, who is not observed by i, also does not observe i. But as all reactions that a player i considers are restricted to her observed population and all reactions are only in links, that is, they exclusively concern their bilateral interaction, there are no additional network effects. The stability conditions on the numbers of Hawks can also be interpreted as having to be valid locally. In this sense one might interpret the small population as part of a larger network.

Recall the example of the introduction of a task that needs two persons to be completed but in which both can act like a Hawk or a Dove. At $k = 50$ and $k = 70$ the freeloader aspect of choosing Hawk is combined with the aspect that the high costs prevent Doves from building links to them. To freeride on Doves, Hawks have to bear the costs to maintain the connection. Especially for high costs, there is a specialization both in theory and in the experiment: Either a player is a Dove and concentrates on the project that the interaction is aimed at, or the player is a Hawk and invests time and money in maintaining the connection but less in the project itself. Hawks have to invest in the network because they are less attractive as partners. They compensate for this by maintaining the links.

At low costs of $k = 30$, the freeloader aspect becomes more prominent and one-step-ahead stability predicts more Hawks.

We conclude that the behavior we observed in our competitive environment with endogenous network formation is guided by rational behavioral aspects. Under the pressure of scarce resources, an interesting kind of simultaneous reciprocal behavior could also be observed.

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A One-step-ahead stable states and Nash equilibria

Table 16: Nash equilibria (cp. Bramoullé et al., 2004; Berninghaus and Vogt, 2006)

	Number of Hawks (n_H)	Link structure
$k > a$	n_H arbitrary	No links.
$a > k > b$	$n_H \geq \frac{(n-1)(a-k)}{a-k+c-d}$	Complete bipartite graph (of H and D players) with active links of H players.
$b > k > c$	$n_H \geq \frac{(n-1)(a-b)}{a-b+c-d}$	H players have active links to all D players, all D players are connected with each other.
$c > k > d$	$\frac{n(a-b)+c-k}{a-b+c-k} \geq n_H \geq \frac{(n-1)(a-b)+l_a^{D\to H}(k-d)}{a-b+c-d}$	All H and D players are connected via an active link of H or D, all D players are connected with each other and $l_a^{D\to H} \leq \frac{(n-n_H-1)(b-a)+n_H(c-d)}{k-d}$ for all D.
$d > k > 0$	$\frac{n(a-b)+c-d}{a-b+c-d} \geq n_H \geq \frac{(n-1)(a-b)}{a-b+c-d}$	All players are connected.

Table 17: One-step-ahead stable configurations

	Number of Hawks (n_H)	Link structure
$k > a$	n_H arbitrary	No links.
$a > k > b$	$\frac{n\,(a-k)+c}{a+c-k} \geq n_H \geq \frac{(n-1)(a-k)}{a+c-k}$	Complete bipartite graph (of H and D players) with active links of H players.
$b > k > c$	$\frac{n\,(a-b)+c}{a+c-b} \geq n_H$	H players have active links to all D players, all D players are connected with each other and $l_a^D \leq \frac{(n-n_H-1)(k+b-a)+n_H c}{k}$ for all D.
$c > k > d$	$\frac{n(a-b)+c-k}{a+c-k-b} \geq n_H \geq \frac{(n-1)(a-b)}{a+c-b}$	All H and D players are connected via an active link of H or D, all D players are connected with each other and $l_a^{D\to H} \leq \frac{(n-n_H-1)(b-a)+n_H\cdot c}{k}$ for all D.
$d > k > 0$	$\frac{n(a-b)+c-d}{a-b+c-d} \geq n_H \geq \frac{(n-1)(a-b)}{a-b+c-d}$	All players are connected.

Annotation to tables 16 and 17:
Notation: l_a^D: number of links initiated by a Dove.
$l_a^{D\to H}$: number of links to a Hawk initiated by a Dove.
Additional conditions: There are no bidirectional links in the network. Types of connections that are not mentioned are not established.
Tables 16 and 17 show for all constellations $a > b > c > d > 0$ and all $k > 0$ the properties of Nash equilibria and one-step-ahead stable states, respectively. These conditions also serve as a basis for the proof of existence.

B Detailed experimental results

Table 18: Details on one-step-ahead stable constellations, Nash equilibria, and socially optimal states considering different Hawk-Dove constellations and zero to three link errors (le) [% of time]

	HD30											
	One-step-ahead stable				Nash equilibrium				Social optimum			
	0 le	1 le	2 le	3 le	0 le	1 le	2 le	3 le	0 le	1 le	2 le	3 le
$0H6D$									0.00	0.00	0.02	0.08
$1H5D$									1.40	3.75	6.75	8.72
$2H4D$	12.34	26.20	38.83	46.63								
$3H3D$	3.90	10.63	16.59	20.14	3.90	10.63	16.59	20.14				
$4H2D$	0.05	0.39	1.14	2.11	0.05	0.39	1.14	2.11				
$5H1D$												
$6H0D$												
	HD50											
	One-step-ahead stable				Nash equilibrium				Social optimum			
	0 le	1 le	2 le	3 le	0 le	1 le	2 le	3 le	0 le	1 le	2 le	3 le
$0H6D$	0.00	0.00	1.00	1.83					0.25	0.29	1.05	1.94
$1H5D$	0.52	2.71	6.42	11.09					1.24	3.88	8.22	13.46
$2H4D$	4.94	17.08	27.10	34.63								
$3H3D$					2.11	4.53	7.59	10.03				
$4H2D$					0.00	0.03	0.07	0.48				
$5H1D$					0.00	0.00	0.00	0.02				
$6H0D$					0.00	0.00	0.00	0.00				
	HD70											
	One-step-ahead stable				Nash equilibrium				Social optimum			
	0 le	1 le	2 le	3 le	0 le	1 le	2 le	3 le	0 le	1 le	2 le	3 le
$0H6D$									0.00	0.00	0.00	0.00
$1H5D$	11.79	20.68	25.52	29.20					0.00	0.00	0.10	0.19
$2H4D$	14.86	25.94	31.68	36.13	14.86	25.94	31.68	36.13				
$3H3D$					0.94	1.51	2.14	3.32				
$4H2D$					0.00	0.00	0.00	0.00				
$5H1D$					0.00	0.00	0.00	0.00				
$6H0D$					0.00	0.00	0.00	0.00				

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