Growth as a solution to coordination failure in the minimum effort game

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Abstract

This paper examines growth as a possible solution for the well-established phenomenon of large group coordination failure in the minimum effort game. A simple model of adaptive behavior shows that starting with small groups and then "growing" the groups at a sufficiently slow rate leads to (stochastically) more successful coordination in large groups - a result impossible to obtain when group size is initially large. This result is supported by experiments which also show that subjects acting as managers and determining the group size fail to anticipate the large group coordination failure and initially "grow" the group too quickly.

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1 Introduction

Experiments consistently show that large groups always fail to coordinate on the efficient equilibrium in the minimum-effort game (Van Huyck, Battalio and Beil, 1990; Weber, Camerer, Rottenstreich and Knez, 1998). This presents an important problem since one of the main reasons for our interest in coordination games lies in the fact that they model problems routinely encoutered by firms and other economic decision makers. Therefore, the above laboratory result implies that efficient coordination in large groups may be impossible to obtain.

This paper argues that the ability of large groups to coordinate successfully is critically affected by the growth process itself. Specifically, if successfully coordinated small groups are grown slowly by adding new entrants at a slow rate and if these entrants are aware of the history of successful coordination, then it may be possible to create large efficiently coordinated groups. This paper provides two separate pieces of support for the above argument. First, using a formal model of behavior in weak- link coordination games (based on one developed by Crawford (1995)), I show how slow growth and exposure of new entrants to previous history of play can lead to more successfully coordinated large groups. Second, experiments are used to investigate whether the result from the model holds in the laboratory. The experiments look at whether large groups playing the minimum-effort coordination game are more efficiently coordinated when they are "grown" – i.e., start off small and have players enter slowly – than when they begin playing at a large size. A second set of experiments examines the behavior of subjects placed in the role of "managers" and allowed to determine the group size. These second experiments are conducted for two reasons. First, it is possible that the managers might discover growth paths that work better than those used in the first experiments. Second, evidence from previous experiments indicates that subjects are not aware of the difficulty in coordinating large groups (Weber, Camerer, Rottenstreich, and Knez, 1998). If this is true, then the managers might grow the groups too quickly, leading to coordination failure.

The next section presents and discusses the minimum-effort coordination game. Following that, the formal model is developed and a series of results on the effects of growth are presented. Finally, experiments are used to demonstrate the importance of the growth process in obtaining successful coordination in large groups.

2 The minimum-effort coordination game

The minimum-effort coordination game is an n-person generalization of the stag hunt game in which players choose numbers – or orderable strategies such as effort or contribution levels – and the group payoff depends on the lowest number selected by any player.[1] These are sometimes called "weak-link" coordination games, (because everyone's payoff is a function of the lowest effort selected by any player, or the "weakest link" in the group) and are a special kind of order-statistic game.[2]

Minimum-effort coordination games were first studied experimentally by Van Huyck,

[1]For applications of the minimum effort game to economic problems see Camerer and Knez (1997) and Weber (2000).

[2]See Van Huyck, Battalio and Beil (1990 & 1991), Crawford (1995), and Camerer (in progress, Chapter 7)

Battalio, and Beil (1990) .[3] The game can be represented by Table 1, which gives each player's payoff as a function of her choice and the minimum choice of all n players.

Player's choice	Minimum choice of all players 7	6	5	4	3	2	1
7	.90	.70	.50	.30	.10	-.10	-.30
6		.80	.60	.40	.20	.00	-.20
5			.70	.50	.30	.10	-.10
4				.60	.40	.20	.00
3					.50	.30	.10
2						.40	.20
1							.30

Table 1: Payoffs (in dollars) for minimum-effort game

The diagonal cells correspond to outcomes in which the player is making the same choice as the group minimum. These outcomes, in which everyone makes the same choice and receives the same payoff, are the pure-strategy Nash equilibria. Notice, however, that the equilibria are different because those corresponding to higher choices also yield higher payoffs. The Pareto-dominant (or "efficient") equilibrium results when all of the participants select the highest choice, 7, and receive \$.90. It is in the players' mutual interest to reach this outcome and the players realize this.

However, the efficient equilibrium may not be easy to achieve because players are faced with strategic uncertainty. Simply being unsure about what others will do may lead different players to take different actions, and when groups are large the minimum may therefore be

[3]These games have also been studied experimentally by Cachon and Camerer (1996), Knez and Camerer (1994) and (1996), Camerer, Knez and Weber (1996), Weber, Camerer, Rottenstreich and Knez (1998), and Keser, Berninghaus and Ehrhart (1998); and theoretically by Anderson, Goeree, and Holt (1996) and Crawford (1995).

quite low.

Previous experiments with minimum-effort games have established clear regularities. Coordination on the efficient equilibrium is impossible for large groups. Of the seven sessions initially conducted by Van Huyck, et al. (1990) (VHBB) with groups of size 14 to 16, after the third period the minimum in <u>all</u> games was the lowest possible choice. For small groups (n = 2), coordination on the efficient equilibrium was much easier – it was reached in 12 of 14 (86%) of the groups studied (a result replicated by Knez and Camerer (1996)). Table 3 summarizes the distribution of fifth-period minima in several different experiments, all using the Van Huyck, et al., game in which subjects choose integers from 1 to 7 and choosing 7 is efficient.

1	2	3	4	5	6	7	Group Size	N	Source
9	0	0	0	0	0	91	2	28	VHBB, 1990; Knez & Camerer 1996
37	15	15	11	0	4	18	3	60	Knez & Camerer 1994, 1996
80	10	10	0	0	0	0	6	114	Knez & Camerer 1994
100	0	0	0	0	0	0	9	18	Cachon & Camerer 1996
100	0	0	0	0	0	0	14-16	104	VHBB, 1990

Table 2: Fifth period minimums (by %) in various 7-action minimum-effort studies (1 = inefficient; 7 = efficient)

The effect of group size could hardly be stronger. Subjects in a group of size 2 are almost assured to coordinate on the efficient equilibrium. Subjects in larger groups (six or more) are almost assured to converge to the least efficient outcome.[4] Thus, there is a strong negative

[4]Once these groups reached the inefficient outcome, they were not able to subsequently increase the minimum.

relationship between group size and the ability of its members to coordinate efficiently.[5]

3 Modeling growth in minimum-effort games

The minimum-effort game provides a way to test the connection between growth and coordination experimentally. While it is well- established in experiments that large groups coordinate poorly and small groups coordinate well, no previous research has tied these phenomena together by exploring behavior in small groups as they grow larger by adding members.

This section presents a simple formal model showing that slow growth can lead to large groups coordinated at higher levels of efficiency in the minimum-effort game. The intuition behind this result is simple. Players in a minimum-effort game are initially unsure of what action others will take (and, therefore, what the optimal response will be). Taking players first period choices as exogenous and independent of group size,[6] this uncertainty leads to choice error, represented by an exogenous mean-zero error term which is added to players' choices. Since the expected value of the minimum is determined by the distribution of first period strategies and by the variance of the error term, if this variance is positive and sufficiently small, the expected value of the minimum choice in small groups may be the action corresponding to the efficient equilibrium, while the expected value of the minimum in large enough groups may be considerably lower. If players adjust their choices towards

[5]This result has also been replicated using slightly different versions of the game (e.g., Weber, Camerer, Rottenstreich and Knez, 1998).

[6]In previous experiments using the minimum-effort game, the distribution of first period choices is similar across group sizes, indicating that players are not aware of the group size effect (see Weber, et al., 1998).

the previous minimum and the variance of the error term decreases with repeated play, small groups can remain efficiently coordinated while large groups collapse toward the inefficient equilibrium. Crawford (1995) uses this type of model to explain the laboratory result that small groups coordinate successfully while large groups do not.

What the model in this paper shows is that a growth process that starts off with two-player groups, allows them sufficient time to coordinate successfully, and then adds players at a slow enough rate can create large groups that are coordinated at higher levels of efficiency in expected value than groups that start off large. A key assumption underlying this result is that future entrants to the game who are allowed to watch the outcomes of the group actually playing the game will experience a similar decline in the variance of their error term to those actually playing the game. This is because observing outcomes reduces their uncertainty similarly to those actually playing the game (they receive the same information). While this may seem an unreasonable assumption to adherents of pure choice reinforcement learning models in which players only learn by experiencing outcomes, there are two reasons why this is not the case. First, the error term represents trembles due to uncertainty concerning the behavior of other players. If information about previous outcomes in the game is commonly known to both players and future entrants, then this uncertainty is unlikely to be as high as if it is not, and should be reduced for everyone. Second, there is experimental evidence that players' behavior in games is affected by observing the outcomes of other groups of players playing the game (Duffy and Feltovich, 1998) or by simply asking players to think about what other players might be doing (Weber, 1999). This implies that players and future entrants are more sophisticated than choice reinforcement models suggest and that they do, in fact, update their beliefs concerning the strategies of others based on more than just experienced outcomes.

The model used here is similar to work by Crawford (1995) and Kandori, Mailath, and Rob (1993) in that it assumes equilibrium arises in repeated play out of a dynamic adjustment process rather than by arising initially through a refinement of the set of supergame equilibria. The advantage of this type of model is that it does not require players to be coordinated initially, but rather they begin by making choices under uncertainty and converge to one of the equilibria once the uncertainty is reduced. The goal of this model is not to provide a complete description of behavior in minimum-effort coordination games (for a much better example of that, see the paper by Crawford), but rather to formalize the above intuition about why growth should.

Assume that $N = \{1, \cdots, n\}$ is the set of $n \geq 2$ players playing the minimum-effort game represented in Table 2. Let the action taken by player $i \in N$ in period t be determined by a latent variable, x_{it}, where:

$$x_{it} = s_{it} + \epsilon_{it} \tag{1}$$

The terms x_{it}, s_{it}, and ϵ_{it} can be any real number. A player's choice, $a_{it} \in \{1, 2, \cdots, 7\}$, results from a function mapping x_{it} into the integer choice set. Let this function be weakly increasing such that if $x_{it} > x'_{it}$ then $a_{it} \geq a'_{it}$. Further, assume that if $x_{it} = m$, where m

is an integer between 1 and 7, then $a_{it} = m$ as well. A function consisting of cutoff points satisfies these criteria.

The error term in the above equation, ϵ_{it}, represents noise in player i's choice due to uncertainty about what others will do. Let the error terms for all players be independent identically distributed normal random variables with mean zero and common variance σ_t^2. The term s_{it} represents player i's intended choice in the absence of uncertainty. Assume that in the first period every player intends to play the action corresponding to the efficient equilibrium ($s_{i1} = 7$ for all i) – since everyone wants to coordinate on the optimal equilibrium – but that the resulting actions may not all be seven because of players' trembles due to uncertainty about what others will do, reflected in the error term.[7]

The n players' payoffs are then determined according to Table 2, which shows the payoff to every player resulting from a combination of his or her choice, a_{it}, and the minimum of all the choices. The following result has been shown previously by Crawford (1995) for a similar model of behavior in minimum-effort games.

Proposition 1 *Assume $\sigma_t^2 > 0$. Holding all else constant, then the expected value of the minimum choice in a period will be (strictly) lower if n is (strictly) larger. If $\sigma_t^2 = 0$, then the expected value will be unaffected by n.*

The proof is simple and is shown in Appendix A.

[7] The results below are not changed if players' initial choices are assumed to result from any common distribution, as long as the distribution is independent of n. However, this assumption is made for simplicity and to argue that with sufficient communication and decreased error, efficient coordination in the first round is possible.

Thus, if players are not allowed to communicate prior to playing the game for the first time and there is therefore strategic uncertainty and σ_t^2 is greater than zero, then the expected value of the minimum will be higher when N consists of two players than when it is a large group. The intuition behind this result is clear and it should not come as a surprise. It is supported by the results of several experiments showing that while first period choices are similarly distributed, the first period minimum is lower when group size is higher.[8]

In periods after the first, players' s_{it} converge toward the minimum in the previous period.[9] Assume this takes place according to the following linear adjustment process:[10]

$$s_{it} = (1-b)s_{it-1} + by_{t-1} \tag{2}$$

where y_t is the minimum of the a_{it} for all $i \in N$ in period t. The parameter b represents the weight placed on the previous period's minimum. When $b = 1$, every players' s_{it} is exactly equal to the previous period's minimum (which corresponds to a noisy best response when $\sigma_t^2 > 0$). When $b = 0$, on the other hand, the s_{it} remain stationary across periods. Since it is unreasonable to believe that players will fail to react to the previous minimum entirely,

[8]See, for instance, Van Huyck, et al. (1990) and Weber, et al. (1998).

[9]Crawford (1995) also includes a drift parameter that measures trends in players' adjustment of their beliefs. This additional parameter allows players' beliefs to change systematically in addition to reacting to previous outcomes. This parameter is not included because, as mentioned above, the goal is not to include a complete description of players' behavior in minimum-effort games, but rather to formally demonstrate the intuition behind why growth works. Also, Crawford's estimation of his model using experimental data showed that this drift parameter was usually close to zero and statistically insignificant.

[10]This model assumes that the only feedback players obtain at the end of a period is the minimum choice (which they can then use to calculate their payoff). This is the case in most experiments using the minimum-effort game of the experiments.

assume that $0 < b \leq 1$.

Again, the x_{it} and the players' choices are determined by equation (1), with the uncertainty terms ϵ_{it} determined as before by n i.i.d. draws from a random variable distributed $N(0, \sigma_t^2)$. Since the error term represents uncertainty regarding other players, assume that its variance decreases with experience so that $\sigma_{t+1}^2 < \sigma_t^2$ for all t less than some $T^* > 1$, as long as outcomes are publicly announced.

The following proposition shows that for $t > 1$ the expected value of the minimum y_t will be greater when the minimum in the previous period was higher.

Proposition 2 *Holding all else constant, then the expected value of the minimum choice in period t will be higher if the minimum choice in period $t-1$ was strictly higher.*

The proof is simple and is again left for Appendix A.

So far, we have assumed that N is constant across periods. However, given that the purpose of this chapter is to study growth and coordination together, it is necessary to relax this assumption. Therefore, replace N with $N_t = \{1, \cdots, n_t\}$ ($n_t \geq 2$, $\forall t$), which is the set of players playing the game in period t. Thus, the number of players can change between periods.

We now need to define a growth path:

Definition 1 *Let $T > 1$. Then, define a **growth path**, $\mathbf{G}$ as a collection of ordered sets $\{N_1, \cdots, N_T\}$, where $N_t = \{1, \cdots, n_t\}$, such that $N_t \subseteq N_{t+1}$ for all t, $N_t \subset N_{t+1}$ for at least one t, and $N_t = N_{t-1}$ for all $t > T$.*

Therefore, a growth path is defined as a series of sets of players that are weakly increasing in size over time and where the number of players at period T is strictly greater than at period 1. Note also that the maximum number of players is attained by period T, after which the size of the group does not grow.

Given the definition of a growth path, there is some period t in which there are individuals who are not participating in the game but who will be playing the game in a future period (i.e., $i \in N_T \setminus N_t$). If these individuals are present in the room when the game is being played and the outcomes in every period are announced publicly, then these future entrants' uncertainty concerning the behavior of other players is reduced similarly to the uncertainty of those playing the game since they observe the same outcomes. Since the choice error is due to this kind of uncertainty, it is reasonable to assume that the variance of ϵ_{it} will decrease for these future players in the same way as for actual players. Therefore, let σ_t^2 be the same for all $i \in N_T$.

Recalling that a growth path G reaches its maximum number of players in period T, we are now ready to prove the first main result. Assume in both of the following propositions that σ_1 is always strictly positive.

Proposition 3 *Holding all else constant, the ex ante expected minimum choice for all periods will be higher for a growth path G ending at a group size of n_T than for a repeated game in which the group size is constant at n_T.*

Proof. Start by labelling the group following growth path G the "grown" group and the other group the "constant" group. Then, by the definition of a growth path, we know that

$n_1^{grown} < n_1^{constant}$. Therefore, by Proposition 1, we know that the expected value of y_1^{grown} will be higher than the expected value of $y_1^{constant}$. Proceeding by induction, we know that there are only two ways in which the games will differ in period t. First, starting with $t = 2$, we know that (ex ante) y_{t-1}^{grown} will be higher than $y_{t-1}^{constant}$ and that by Proposition 2 this implies that in expectation $y_t^{grown} > y_t^{constant}$. The only other way in which the games will differ is that for $t < T$, $n_t^{grown} \leq n_t^{constant}$. By Proposition 1, we know this implies that in expectation $y_t^{grown} \geq y_t^{constant}$. In either case, the result holds. *Q.E.D.*

This shows that growing large groups – by starting off with smaller ones and adding players – will always lead to more efficiently coordinated groups (in expectation) than starting off at large group sizes. This implies that growth is a way to solve the large group coordination failure in minimum-effort games.

The following definition introduces the concept of outcome-equivalence, which indicates that two growth paths start and end with the same number of players.

Definition 2 *Two growth paths, G and G' are* ***outcome- equivalent*** *if and only if $N_1 = N_1'$ and $N_T = N_T'$.*

Note that this does not imply that they need to grow at the same speed or reach the maximum group size in the same period. In fact, this definition allows the possibility that one growth path jumps from size n_1 to n_T between the first and second periods and the other growth path takes any finite number of periods to do so.

If two growth paths are outcome-equivalent, then we can compare the speed at which they grow.

Definition 3 *If two growth paths, G and G', are outcome- equivalent, then G is* ***faster*** *than G' if $N_t' \subseteq N_t$ for all t and $N_t' \subset N_t$ for at least one t. Growth path G is* ***slower*** *than G' if $N_t \subseteq N_t'$ for all t and $N_t \subset N_t'$ for at least one t.*

Therefore, a faster growth path will always have at least as many players in a given period, and will have at least one more player in at least one period. The opposite will hold for a slower growth path.

In the next result, we compare two outcome-equivalent growth paths where one is faster. The result shows that slower growth paths will lead to more efficient coordination (in expectation).

Proposition 4 *If two growth paths, G and G' are outcome- equivalent and G is faster than G', then the ex ante expected value of y_t will be weakly lower than the ex ante expected value of y_t' for all t and will be strictly lower for at least one t.*

Proof. To prove this result, first look at the most extreme case where the definition of "faster" is minimally satisfied (i.e., $N_t = N_t'$ for all t except one (labeled t^*) at which $n_{t^*} = n_{t^*}' + 1$). Therefore, for all $t < t^*$, we know that $n_t = n_t'$ and, since everything else is also equal, the expected values of y_t and y_t' are equal as well. In period t^*, the only difference is that $n_{t^*} > n_{t^*}'$. Therefore, by Proposition 1 this implies that (in expectation) $y_{t^*} < y_{t^*}'$. Now, we know that for $t > t^*$, $n_t = n_t'$ and the only difference between the two games is in the previous period's minimum. We can then show by induction that, starting with

$t = t^* + 1$, if the only difference at t is that $y_{t-1} < y'_{t-1}$, then by Proposition 2 we know that in expectation $y_t < y'_t$.

Having shown this, the remainder of the proof is simple. By definition, the only way in which the difference between the two growth paths can change for any t is for $n_t - n'_t$ to increase. By Proposition 1, we know that by increasing n_t relative to n'_t and holding all else constant, the result will be that the expected value of y'_t will increase relative to the expected value y_t. Since by Proposition 2, we know that this in turn will only lead to lower values (in expectation) of y_{t+1} relative to y'_{t+1}, the effects of moving the growth path away from the extreme case will only increase the difference between the expected values of the minima in the direction indicated in the proposition. *Q.E.D.*

The first main result above (Proposition 3) shows that starting off small and growing a group leads to a more efficiently coordinated group (in expectation) than one that starts off at a large group size. However, it is perhaps unreasonable to assume that introducing new players will have no effect on the uncertainty that underlies error in all players' choices. Since the new entrants have not actually played the game before, it is likely that their introduction will increase the uncertainty and trembles in players' actions.[11] We can model this increase in uncertainty as a positive shock to σ_t^2 whenever $n_t > n_{t-1}$, meaning that the trembles caused by strategic uncertainty increase with the introduction of new players. In any period t, this shock is represented by the term z_t, where:

[11] In addition, we may want to model growth when there is not common knowledge about outcomes.

$$z_t = z(\tilde{n}_t, n_{t-1}, r) \tag{3}$$

The term $\tilde{n}$ is the increase in group size between periods $t-1$ and t and is therefore equal to $n_t - n_{t-1}$. The number of previous periods in which the group grew is given by the term r, which represents experience with growth.

The function z is increasing in $\tilde{n}_t$, decreasing in n_{t-1} and r, and always lies between 1 and some positive value $z^{MAX} < \infty$. Moreover, $z_t = 1$ whenever $\tilde{n}_t = 0$ and is greater than 1 otherwise. Letting σ_1^2 be exogenous, assume that in every period σ_t^2 decreases geometrically by a constant $k < 1$ so that

$$\sigma_t^2 = k\sigma_{t-1}^2 z_t \tag{4}$$

for all $t > 1$. As mentioned above, z_t is equal to 1 unless the group grows in period t and is greater than one otherwise. Since z is increasing in $\tilde{n}_t$, a larger increase in group size will result in a larger increase in the variance of the choice error term. Conversely, since z is decreasing in n_{t-1} and r, the increase in the variance will be smaller when the size of the group about to grow is larger and when the group has had more experience with growth.

We can then prove the following result, which shows that a version of Proposition 3 holds even when σ_t^2 increases whenever the group grows.

Proposition 5 *For any function $z(\tilde{n}_t, n_{t-1}, r)$ such that $1 \leq z \leq z^{MAX}$ and such that z is increasing in $\tilde{n}_t$ and decreasing in n_{t-1} and r, it is possible to construct a growth path, G, ending at a group size of n_T, such that the expected value of the minimum for this grown group will be higher in all periods than for a repeated game in which the group size is constant at n_T.*

Proof. Start by again labelling the group following growth path G the "grown" group and the other group the "constant" group. For any final group size, $n_T \geq 2$, start the grown group at a group size of 2. This smallest group size means that the expected value of y_1^{grown} will be the highest, and that it will be higher than $y_1^{constant}$ (by Proposition 1). Also, by Proposition 2, the expected value of the minimum for the grown group will be higher for all periods before the group grows. Since $z(\tilde{n}_t, n_{t-1}, r)$ is increasing in $\tilde{n}_t$, let growth path G never grow the group by more than 1 player (i.e., $\tilde{n}_t = 1$ for all t in which $\tilde{n}_t \neq 0$). Therefore, since $z(\tilde{n}_t, n_{t-1}, r)$ is decreasing in its remaining two arguments, n_{t-1} and r, it is sufficient to show that there exists a period t' in which increasing the group size from 2 to 3 results in an expected value of $y_{t'}^{grown}$ that is greater than the expected value of $y_{t'}^{constant}$. As long as the result holds in this case, it will hold in subsequent growth episodes when $\tilde{n}_t$ is unchanged and n_{t-1} and r are both greater.

Note that $z_{t'} = z(1, 2, 0)$ is independent of t' and that, therefore, $\sigma_{t'}^2$ is equal to $k^{t'-1}\sigma_1^2 z(1, 2, 0)$. From Proposition 3, we know that the expected value of y_t^{grown} is greater than the expected value of $y_t^{constant}$ for any value of t and for $\sigma_t^2 = k^{t-1}\sigma_1^2$. This implies that as long as there exists a period t' in which $k^{t'-t}z_{t'}$ is less than 1, then $y_{t'}^{grown}$ will be greater than $y_{t'}^{constant}$ in expectation. Since z is bounded from above by z^{MAX} and $k < 1$ we know that there exist large enough values of t' for which this is true. *Q.E.D.*

Note that the introduction of an increase in variance coincident with growth means that growth will have to be slower. If z is increased by less shared information between players, then the intuition that slower growth is required when there is lack of common knowledge about past outcomes is supported by the model.

The last three results show how the growth process itself can lead to more efficient coordination, first relative to a group that starts off at a large size and then relative to a group growing more quickly. This result holds when uncertainty and choice error are increased with growth. While the model is simple and does not capture all the elements of behavior in minimum-effort coordination games, the intuition behind the results is quite clear: by starting off small and then growing a group slowly, it is possible to create large, efficiently coordinated groups.

Since it is often beneficial to discipline theory by testing its implications, it seems worthwhile to test the predictions of the model. One way to do so is with controlled laboratory experiments that look at whether or not slow growth produces more efficiently coordinated large groups. This is ideal since the laboratory provides a controlled environment in which to directly test the model. This test is performed in the next section.

4 Experiments on growing efficient coordination

This section uses experiments with the minimum-effort game to test the effects of growth. The experiments are conducted similarly to previous experiments by Van Huyck, et al.. (1990) and Weber, et al. (1998). The goal of these experiments is simply to test the main result from the previous section that "grown" groups are more efficiently coordinated than groups that start off at a large group size.

Two sets of almost identical experiments were conducted. In experiment 1, the rate of growth was determined by the experimenter prior to the experiment. These experiments were intended to test whether growth paths that satisfy several desirable criteria can produce large groups coordinated at higher levels of efficiency than control groups. A second set of experiments was also conducted in which a participant not playing the minimum-effort game determined the size of the group. In these experiments, groups were again grown as before, but the rate of growth was endogenous and not determined until the experiment. Each experiment will be discussed in detail, and then the aggregate results of both growth experiments will be used to determine the effectiveness of growth for solving large group coordination failure.

4.1 Experiment 1: Can controlled growth solve large group coordination failure?

4.1.1 Experimental Design

Since large groups of ten or more subjects have never consistently coordinated efficiently in previous experiments – in fact, they almost always end up at the least efficient outcome – this first set of experiments was designed to explore whether a slow, controlled growth rate determined by the experimenter could create large groups that coordinated efficiently. In the experiments, groups of 12 Stanford or UC Santa Cruz students were assembled in one room. The game was presented in the context of a report completion as in Weber, et al. (1998).[12] Instructions were read aloud and subjects answered several questions to check their comprehension of the instructions.[13]

In each experimental session, subjects were anonymously assigned participant numbers. Each session consisted of 22 periods. In the first several periods, only participants 1 and 2 played the minimum-effort game while the other subjects sat quietly.[14] In each period, participating subjects recorded a number from 1 to 7 (indicating the contribution time for

[12] Adding this context to the instructions was found to have no effect on behavior in Weber, et al. (1998).

[13] Instructions are available in Appendix B.

[14] An important design challenge is how much to pay the non-participants for the periods in which they sat by waiting to be "hired." If they were paid nothing, they might be resentful at earning less than early participants which could, in turn, inflame or introduce social utilities. Announcing a fixed amount they earn per period could create a focal point which would influence the choices participants made. On the other hand, simply informing subjects that they would receive an unspecified fixed amount might lead them to believe that the amount would be determined by the experimenter as a result of behavior in the experiment. As a solution, the design allowed the experimenter to precommit to a per-period payment for non-participants by writing it in envelopes, which were handed to them, but were only opened at the end of the experiment.

their section of the report) on a piece of paper and handed it to the experimenter.[15]

At various preannounced and commonly known points, other participants joined the group of those actively playing the game. For each session, there was a schedule of such additions that was handed to all subjects at the beginning of the experiment. These schedules will be referred to as *growth paths.* For example, in one of the growth paths a third participant was added in period 7, joining the first two participants who continued to participate. Subjects all knew the predetermined growth path which explained when they began to participate, and they knew that earlier participants always continued to participate.[16] At the end of each period, the report completion time (minimum) was announced to all the subjects, including those who were not actively participating yet. In all growth paths, all 12 subjects were participating by the last few periods.

In addition to the above design, control sessions were conducted to ensure replication of previous results. In these sessions, 12 groups of subjects played the game for 12 periods. The game was similarly framed in the context of a project completion and personal contribution times. However, no mention was made of growth or of participants not actively participating in any rounds.

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[15]To prevent players from knowing which others were participating, all players handed in slips of paper; non-participants simply checked a box saying they were not participating.

[16]In addition, at the beginning of each period the experimenter announced which participants would actively participate in that round.

4.1.2 Results

Four control sessions (n = 48) were conducted using undergraduates at both Stanford (2 sessions) and the California Institute of Technology (2 sessions) between February and December 1998.[17] The results of these experiments are reported in Figure 1, which presents the minimum choice across all 12 periods for each session. In addition, two lines indicate both the average choice across sessions and the average of the minima in all four control sessions.

(Figure 1 about here)

Overall, the results replicate previous experimental results on large groups playing minimum-effort coordination games. In two of the sessions, the minimum choice is initially 4. In the first Caltech session (Caltech 1), the minimum is again 4 in the next period but declines to 3 in the third period and then falls to 1 for the remaining periods. In the first Stanford session (Stanford 1), the minimum continues to be 4 through the fifth period and then falls to 1 for the final 7 periods.[18] In session Stanford 2, the minimum is initially 1 and continues to be so for the entire session. In the second Caltech session (Caltech 2), the minimum starts off at 2, but then goes down to 1 in the next period and remains there for the rest of the experiment. The solid line in Figure 1 indicates the average of the session minima. Finally, the average of all subjects' choices is also given. Note that both the average choice and the

[17] Some of the controls were conducted at the California Institute of Technology because this is where additional experiments on endogenous growth (experiment 2) were conducted.

[18] The results of session Stanford 1 are a bit perplexing. It is rarely the case that large groups are able to maintain a minimum greater than 1 for more than a few periods. Here, the minimum remained at 4 for longer than the few initial periods that it usually takes for coordination failure to occur and for the minimum to collapse to 1. The fact that the minimum finally falls to 1 is encouraging, as is the fact that the other control sessions exhibit behavior more consistent with previous results.

average of the minima consistently decrease and end up at or near one by the final periods. Note also that the average choice is initially high, indicating that many subjects are initially selecting high effort levels but that the minimum is nonetheless low since it is sensitive to outliers.

The results of the control sessions indicate that, while behavior in one of the sessions is unusual and does not immediately converge to a minimum of 1, the expected result of coordination failure in large groups is obtained. Thus, if the growth sessions establish more successful coordination (minima greater than one), the main hypothesis that controlled growth can lead to less large group coordination failure will be supported.

Seven growth sessions (n = 84) were conducted between January and March 1998. Four sessions were conducted at Stanford using graduate and undergraduate students with little or no formal training in game theory and three sessions were conducted at UC Santa Cruz using undergraduate students. It is important to note that each session of 12 subjects making 22 choices represents one data point, since the group either succeeds in coordinating efficiently or fails. It is therefore difficult to firmly establish strong results using such data, but there are clear regularities that can be observed by examining the individual session data and from which conclusions can be drawn. Thus, in this section the behavior in individual sessions will be analyzed. In a subsequent section, the aggregate results will be examined to establish more firm results.

The goal of these experiments was to explore the possibility that growth can lead to more efficiently coordinated large groups. Therefore, each of the growth paths used was selected with hopes that it would be slow enough to create a large group that behaved more efficiently than large groups had in earlier experiments and in the control sessions. The principles driving the choice of this path were based on the results of the formal model, which shows that slower growth stochastically improves coordination. Slow growth can be implemented by adding only a few players at a time and by allowing more time between growth periods or "spurts", particularly initially. Therefore, the growth paths were designed to first establish repeated successful coordination in the group of size two (by allowing them to play several periods before adding more participants) and then to add players in a slow and regular manner. Thus, with one exception (the last two players added in growth path 3), the growth paths add only one player at a time. Figure 2 shows the three growth paths used in these experiments.[19]

(Figure 2 about here)

Sessions 1 and 2, presented in Figure 3, both used growth path 1. The figure presents the growth path as well as the minimum choice by period in each of the two sessions.[20] Both sessions began with six periods in which only participants 1 and 2 played. As predicted based on earlier results, these two-person groups reached efficiency (in both sessions, the minimum was 7 in periods 5-6). However, when a third participant was added in period 7,

[19]Note that growth paths 2 and 3 differ only in period 18.

[20]The choices in the final two periods (21 and 22) are not reported here because there is often a strong end of experiment effect in these games, in which subjects change their choices in the final period (perhaps to punish or do better that others, or perhaps because they believe that others will do so – in which case doing so is a best response). While this phenomenon is interesting, this paper is not concerned with what occurs in the final rounds (after growth is completed), but rather with coordination during and immediately after growth.

the minimum dipped below 7 in both sessions.

In session 1, the minimum was 6 in periods 7-8. When a fourth participant was added, in period 9, the minimum fell further to 5 and stayed there in period 10. When a fifth participant was added, in period 11, the minimum fell to 4. This pattern suggests an interesting conjecture. Earlier research showed that precedents often matter dramatically, in the sense that a group expects the minimum in one period to be the minimum in an upcoming period. That is, the previous choice establishes a strong precedent that is reinforced by subsequent actions. In Figure 3, however, players seem to be inferring a precedent from the relation between changes in structure (group size) and changes in behavior. The fact that the minimum fell by one when group size increased from 2 to 3, and from 3 to 4, seems to create a precedent that "when we grow the minimum falls by 1," which is self-fulfilling in later periods.[21]

(Figure 3 about here)

The results of session 2, however, show a different pattern. In that session the minimum was 7 in the two-person group in periods 5-6, but the minimum fell to 5 when a third player was added in round 7. The minimum rose to 6 in the next round, which indicates a possible recovery to an efficient minimum of 7, but a fourth player was added in round 9 and the minimum fell back to 5, where it remained – even when the group reached a size of 12. Note that while the minimum is not at the maximum of 7, a minimum of 5 is still much more

[21]Notice that while the minimum falls to 1 (inefficiency), the collapse is slow and regular. This contrasts with previous results and the control data where the collapse is typically much more rapid.

efficient than the usually observed minimum of 1 in large groups. Thus, the fact that the minimum for a 12 person group is 5 in session 2 provides support for the hypothesis that growth can lead to successful coordination.

Because the first transition lowered the minimum from 7 to 5 in session 2, but then the minimum recovered to 6 in the next period, the question arose of whether full efficiency (a minimum of 7) could be reached by allowing the three-person group to recover by playing more periods before growing further. This was explored in growth path 2 (Figure 4), which begins with five periods of 2-person play, followed by four periods of 3-person play, to give the 3-person group more time to recover from any drop in the minimum after the 2-to-3 group size transition.

(Figure 4 about here)

Figure 4 also presents the results for sessions 3 and 4, which used this growth path. In session 3, the minimum in the two-person group is reliably 7 for all five periods, then drops to 5 when the third person is added, and stays there. When more players are added, the minimum stays at 5 until period 17, when the 10th player enters and chooses 1. The minimum is 1 after that. While the minimum falls to 1 when the group reaches a size of 10, the fact that it remains at 5 until then provides some additional (though modest) support for the successful controlled growth hypothesis.

In session 4, the two-person group was again able to coordinate efficiently. In this session, however, when the third person was added the minimum continued at 7 and remained there through the entire growth path. Efficient coordination was obtained in all periods and an efficient group of size 12 was obtained. The results of this session provide strong evidence of successful growth.

Sessions 5 through 7 were conducted at UC Santa Cruz. These sessions used growth path 3 (Figure 5) which is identical to growth path 2 except that participant 12 enters at the same time as participant 11. This modification was made because of the concern that selecting one individual to be the last entrant might create greater incentives for this participant to want to punish other players.

(Figure 5 about here)

In session 5, the two-person group coordinated efficiently in periods 3-5. When the third person was added, the efficient equilibrium was again achieved. Efficient coordination continued until period 14, when the seventh participant entered and the minimum fell to 4. The minimum fell to 3 the next period, where it remained. While a drop in efficiency occurred when group size reached 7, the minimum did not fall the whole way to 1. This again provides some evidence that more efficient coordination in large groups can be obtained using growth.

Behavior in session 6 was initially very similar. The minimum was 7 through period 13 when 6 subjects were participating. When the seventh participant was added, the minimum fell to 5. It then continued to fall by one every period. While the minimum eventually reached 1, note that the decline was much more regular and gradual than in the control data.

In session 7, the two person group was not able to coordinate on the efficient equilibrium. Instead, the minimum was 6 for all first five periods. The minimum continued to be 6 through period 12. In period 13, the sixth participant entered and selected 1. The minimum then went up to 4 and remained there through the 18th period, when the final two participants entered. It then dropped in the next two periods to 1. Thus, while efficient coordination was not maintained through all the periods, a large group coordinated on a minimum higher than one was obtained.

This analysis, though mainly a casual examination of behavior in individual sessions, nonetheless helps shed light on several behavioral regularities.[22] First, while efficient coordination does not occur in all cases, efficiency (measured by the value of the minimum) is higher for large groups than in previous experiments. In only three of the seven sessions is the minimum initially 1 for the groups of size 12 – after having already played several periods in large groups (of size 11, 10, etc.). In the other four sessions the minima are 3, 4, 5 and 7. In the following period, efficiency declines in only one of the sessions (the minimum falls from 4 to 3 in session 7).

In addition, in all the sessions that end up at a minimum of 1, the minimum is higher at least through a group size of 9. This higher level of efficiency for groups of size 9 (the minima are 2, 5, 5, 7, 3, 3, and 4) is surprising in light of the fact that the minimum was always 1 for the large groups (nine or larger) in Table 2.[23] Thus, there is support for the

[22] A more rigorous analysis of the data follows in section 4.3.

[23] While Table 2 reports the fifth period minima, the minima in the first period were not as high as in the sessions reported here and there was never a minimum of 7.

hypothesis that starting with a 2- person group, which reliably reaches efficiency, and adding players slowly enough, enables much better coordination than starting with large groups.[24]

Second, it appears that early experience with growth is important in determining subsequent success. In sessions 2 through 7, the minimum did not drop when the fourth person was added compared to what it was when the third participant entered. In these groups, the minimum was 5 or greater through at least period 12, indicating that subjects may have learned that controlled growth was possible (at least for a while). In session 1, however, the minimum dropped both of the initial times the group grew and continued to drop with growth, indicating that the initial experience with growth led subjects to believe that the group could not grow successfully.

Third, the results of session 1, in which efficiency declined steadily, suggest that players may form "higher-order" precedents based on not just levels of previous play (e.g., expect the previous minimum to be the minimum again), but also on the relation between levels of previous play and group sizes or transitions. The fact that the minimum falls by one unit when a third person is added, and falls again by that same amount when a fourth person is added, seems to create a belief that adding a person leads the minimum to fall by one (which is self-fulfilled when the fifth, seventh, ninth and tenth people are added, though not when the sixth and eighth are added). This kind of behavior had not been observed in previous work because nobody had changed structural variables repeatedly from period to period, in

[24]In addition, the results of the experiments by Knez and Camerer (1994) which showed that "merging" two three person groups leads to coordination failure (the minimum fell to 1 80 percent of the time) indicate that growth can be too rapid. This provides additional evidence that controlled growth can play an important role in obtaining successful coordination in large groups. Note that the minimum for a group of size 6 was 1 in only one of the seven sessions in experiment 1.

a way which allows formation of higher-order relational precedents. However, it is impossible to make any generalizations based on the results of this session alone.[25]

The results of these sessions indicate that controlled growth can help solve the problem of large group coordination failure. However, the growth paths used do not always succeed in creating large, efficiently coordinated groups and, in fact, in only one of the sessions did the minimum remain at 7 throughout. Given the difficulty of obtaining successful growth, an interesting question is whether subjects are aware of the need for slow, regular growth paths and, if so, whether they can discover more effective growth paths than those used in experiment 1. Experiment 2 addresses this question by endogenizing the growth path.

4.2 Experiment 2: Can subjects discover successful growth paths?

4.2.1 Experimental Design

In experiment 2, one participant was randomly selected to act as a "manager" and determine the growth path. This subject was placed in a separate room from the remaining subjects and an experimenter carried information between the two rooms. The game that the other participants would be playing was described to the manager (again framed in the context of a project completion), who was instructed that he or she would be responsible for selecting the size of the group for all periods after the first. In the first period, the group size was fixed at 2 and this was the smallest size that the manager was allowed to pick in any period. The experiment lasted 35 periods.

[25] There is even more convincing evidence of this result, however, in experiment 2.

The manager was told that his or her earnings in each period would be determined by the number of active participants and by the group minimum (completion time). Table 4 describes the possible earnings for the manager.[26] Note that, for any group size, the manager is better off when the group coordinates efficiently. Also, the manager's payoff is higher when efficiently coordinated groups are larger, but the opposite is true for inefficient groups. Therefore, the manager has an incentive to create a large group, but only if it is coordinated successfully.

Number of participants	Completion Time (weeks early) 1	2	3	4	5	6	7
2	0.00	0.02	0.04	0.06	0.08	0.10	0.12
3	-0.03	0.01	0.04	0.07	0.10	0.13	0.16
4	-0.05	-0.01	0.03	0.07	0.11	0.15	0.19
5	-0.08	-0.03	0.03	0.08	0.13	0.18	0.23
6	-0.10	-0.04	0.02	0.08	0.14	0.20	0.26
7	-0.13	-0.06	0.02	0.09	0.16	0.23	0.30
8	-0.15	-0.07	0.01	0.09	0.17	0.25	0.33
9	-0.18	-0.09	0.01	0.10	0.19	0.28	0.37
10	-0.20	-0.10	0.00	0.10	0.20	0.30	0.40
11	-0.23	-0.12	-0.01	0.11	0.22	0.33	0.44
12	-0.25	-0.13	-0.01	0.11	0.23	0.35	1.00

Table 3: Manager's payoffs (in dollars)

Following the manager's determination of the group size in each period, a group of up

[26]The earnings are determined according to the following formula (rounded to the nearest cent if necessary):

$$\pi = \frac{n(min - 3.5)}{100} + 0.05$$

except for the payoff when the group size is 12 and the minimum is 7. Since the goal was for managers to attempt to reach this outcome, a large bonus was awarded for achieving it.

to 12 subjects played the game in the same format as in experiment 1. The instructions for these subjects were the same as before, except that they were now informed that the number of active participants would be determined at the beginning of each period by the manager. The manager would select a number, and then the participants whose numbers were 1 through that number would play the game.[27]

The experiments were conducted between June and October at the California Institute of Technology. Subjects were graduate and undergraduate students with little or no formal training in game theory. The experiments lasted about 2 hours.

These experiments allow us to test whether the subjects randomly assigned the role of managers are aware of the need for slow, controlled growth.[28] In addition, the growth paths generated by the managers allow us to further investigate the effectiveness of varying growth paths.

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[27]The one other difference with experiment 1 was that the manager was given the option, at the beginning of each period, to randomly reassign participant numbers. This was intended to allow the manager to "restart" the group in case the first few participants became stuck at a bad equilibrium. Previous results indicate that this does occasionally happen (though rarely) in small groups (see Table 2).

An important question has to do with how the game is changed by the modifications. The introduction of another player whose strategy choice consists of determining the group size and deciding whether to reassign participant numbers changes the game, in that there are now possibly punishment strategies available to both the manager and players in the game. However, pure strategy equilibria in which players coordinate efficiently if growth is sufficiently slow but more than one player decreases his or her choice if growth is too fast remain, as do multiple other pure strategy equilibria.

[28]Note that these experiments are also subject intensive and financially costly since 13 subjects are required to obtain one data point: a manager's success or failure. One possible solution to this is to study the managers separately, giving them feedback that is either artificially constructed by the experimenter or determined according to some model developed from the data from experiment 1. Economists are typically opposed to using deception in experiments, though, so the first option can be ruled out. The second option requires large amounts of data to be able to determine feedback in all contingencies. However, this is a possibility for future work. Particularly since several simulation programs already exist (usually used as part of the MBA curriculum) in which students "grow" companies (see, for instance, Graham, Morecroft, Senge, and Sterman, 1992).

4.2.2 Results

Four sessions were conducted using 52 subjects.[29] While the number of sessions provides data on the choices of only four managers, the results provide interesting insights into the managers' cognition of the need for controlled growth as well as further evidence supporting the main growth hypothesis. Again, the results will first be examined by looking at behavior in individual sessions. In the next section, the aggregate results of experiments 1 and 2 will be analyzed more rigorously.

Figure 6 presents the growth paths selected by managers in each of the four sessions. Each line corresponds to one of the sessions and indicates how many participants were included in the group in each period. Note that all four of the managers initially grew the groups quickly. In the first period in which they were allowed to determine the group size (period 2), all of the managers added at least three new players. To examine the effects of this rapid growth, we need to look at behavior in individual sessions.

The results of the first session (E1) are presented in Figure 7. Figure 7 provides the same information as the figures for experiment 1. The minimum choice in the first period was 6, which represents a high level of efficiency. In the second period, the first period in which the manager determined the group size, the manager raised the group size to 6. The minimum remained at 6, but then dropped to 5 when the manager increased group size to 9 in the next period. While group size remained at 9 in period 4, the minimum fell to 4 and remained there for several periods while the manager varied the group size between 8 and

[29]Due to the high concentration of male students at Caltech, the manager ended up being male in all four sessions.

12 and reassigned participant numbers a few times. At a minimum of 4, the manager earned \$0.11 per period for a group of size 12, but this is less than he could earn by having a group of size 2 coordinating efficiently.

(Figure 7 about here)

The manager then proceeded to "fire" several participants and start over with a group of size 2. This succeeded in raising the minimum back up to 6. The manager then added one more participant, which did not reduce the minimum, and remained at a group size of 3 for 4 periods. He then increased the group size by one every period until reaching a group size of 12 in period 25. The minimum remained at 6 through the remaining periods.[30] Thus, while the manager initially failed to realize the need for controlled growth and added participants too quickly, he started over with a group size of 2 and proceeded to add participants at a slow enough rate to create a large group playing a minimum of 6.

In session E2 (Figure 8), the first two participants coordinated efficiently on 7 in the first

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[30]The minimum fell to 1 in the final period. This was the result of one participant's choice and is an example of the end game effect discussed earlier.

At least one subject lowered his or her choice below the previous minimum in either of the last two periods in two out of seven sessions in experiment 1 and two out of four sessions in experiment 2. Therefore, a better design might have been one that prevented subjects from unilaterally taking an action that could either prove very costly to others or affect the data so strongly. Such designs include using a stochastic stopping rule or a different order statistic. With a stochastic stopping rule, subjects would not know when the final period might come so it would be more costly to deviate from successful coordination and impossible to do so with certainty in the last period. With a less punishing order statistic, such as the second, one subject alone would not be able to affect the completion time or payoffs to others by unilaterally deviating from efficient coordination. Van Huyck, Battalio and Rankin (1996) conduct experiments using the second order statistic. While they find that some groups are able to coordinate efficiently, the game they study is substantially different in that there are 101 actions available instead of 7 and the cost to being one effort level away from the order statistic is much smaller. However, while these alternative designs would likely have reduced the phenomenon of players choosing lower numbers than the previous minimum, the goal was to study the most punishing coordination problems and to maintain a similar design to the one used in the majority of previous weak- link studies.

period. When the manager increased the group size to 5 in the next period the minimum remained at 7, but it then fell to 6 when the manager added 5 more participants in the next period. The manager then tried to raise the minimum by varying the group size (between 8 and 12) and reassigning participant numbers in the next few periods. However, while the minimum initially remained at 6, it fell to 1 in period 8 (when group size increased from 10 to 12). The manager then decreased the group size to 8 and the minimum went back up to 5.

(Figure 8 about here)

During the remaining periods, the manager tried to increase the minimum by varying the group size. Although the smallest size he then selected was 4 (until the last period), when he did so the group almost always recovered to a minimum of 6. However, the manager did not let the group remain at a size of 4 for more than one period and tried to increase the group immediately by adding at least 2 more participants. This resulted in a drop in the minimum every time. The manager continued to vary the group size (with a resulting effect on the minimum) for the remaining periods, but was unable to find a growth path allowing him to create a large, efficiently coordinated group.

The results of session E3 (Figure 9) are similar. In this session, the minimum was 3 in the first period. Rather than allowing the two first participants time to coordinate, however, the manager immediately increased the group size to 7 and the minimum remained at 3. He decreased group size to 2 in period 4 – increasing the minimum to 6 – but then proceeded to add participants right away, leading to a drop in the minimum. Similarly to the manager in session E2, this manager varied the group size (between 3 and 10) in the remaining periods, increasing the group size too quickly after any increase in the minimum.

(Figure 9 about here)

The behavior of the manager in session E4 was more like that of the manager in session E1. The minimum was 6 for the group of size 2 in the first period. The manager then tried to grow the group too quickly (increasing the size to 10) and the minimum fell to 1 in the next period. The minimum remained at 1 while the manager tried group sizes of 12, 7, and 5 unsuccessfully, and then moved up to 3 when he set group size at 3. The manager then increased the group size by one and allowed the group of size 4 enough time to raise the minimum to 6. When group size again increased by one, the minimum again fell to 3, but then rose to 7 as group size remained the same for several periods. For the remainder of the experiment, the manager always added only one or two participants at a time and the minimum fell to either 3, 4, or 5 every time the group grew. However, after the initial drop following growth, the minimum increased by exactly 1 in every period in which the group size remained the same. This continued until period 33, when the entire group of 12 participants coordinated successfully on 7. Thus, after initially growing too quickly, the manager in session E4 discovered a growth path slow enough to lead to efficient coordination.

(Figure 10 about here)

The results of session E4 also point to an interesting phenomenon similar to the reaction to growth in session 1 of experiment 1, in which the minimum fell exactly by one when the group grew. In all periods after period 7, the group reacted in the same manner to growth. Every time the group grew, the minimum fell, but then increased by exactly one for every period that the group did not grow. Thus, similarly to session 1, a self- enforcing norm was established concerning how the group would react to growth.

While there are only four sessions, it is again possible to draw some conclusions based on an examination of the data. First, in all four sessions the subjects participating in the role of manager initially grew the groups too quickly, resulting in coordination failure. This points to a lack of cognition of both the difficulty of coordinating large groups – which is consistent with previous research (see Weber, et al. (1998)) – and the need for controlled growth to solve coordination failure.

Following this initial failure, however, there is evidence that some subjects learned to grow using a slower and more regular approach. While two of the managers failed to realize this and continued to grow too quickly, the other two started over with small groups and then grew slowly (never adding more than 2 participants at a time) to create large groups coordinated on minima of 6 and 7. The two managers that started over and grew slowly had higher earnings than the managers that did not (Managers in sessions E1 and E4 earned $7.39 and $7.37, respectively, while the managers in sessions E2 and E3 earned $4.28 and $2.54).[31] It is interesting to note that the growth path used by the manager in session E1 is

[31] While the managers in sessions E2 and E3 did "poorly" in that they tried to grow the groups too quickly and therefore failed, they still made positive profits because they were always able to decrease the size of the group which usually led to improved coordination (or at least less negative earnings). In fact, while the average per period earnings of both the successful managers was $0.211, this number was $0.097 for the other two managers. The latter number is close to the average per period earnings ($0.087) that would have resulted if the payoffs in Table 4 had been applied to the results from experiment 1 (in which the experimenter served as manager). That these two numbers are close is surprising since in experiment 1 the

very similar to the growth paths used in experiment 1.

There is also further support in these experiments for the hypothesis that slow, regular growth can lead to successful coordination in large groups. In the two sessions in which the managers started over at a small size and grew slowly (sessions E1 and E4), the result was large groups that coordinated on high minima. In addition, the failure to succeed of the other two managers indicates that the rate of growth is important in obtaining efficient large group coordination.

Finally, the results of session E4 provide strong additional support for the previously mentioned conjecture that experience with growth plays an important role in subsequent reactions to growth. In this session, as in session 1 of experiment 1, subjects responded not just to the previous minimum, but to what happened to the minimum as the group grew. Therefore, a precedent was established indicating that every time the group grew, the minimum fell, but that in every period that the group did not grow, the minimum went up by exactly one. The strength of this precedent and the extent to which it was a self-reinforcing belief held by <u>all</u> players is evident in the last few episodes of growth. When the group grew to a group size of 10, the minimum fell to 5. In the next two periods, all 10 players played first 6 and then 7. When the group grew again to a size of 12, the minimum fell to 4.[32] In the next three periods, all 12 players played first 5, then 6, and then 7. This points to a

group was constrained to grow even if the minimum fell to one and this was not true in experiment 2.

[32] Since this was the first time that the group had grown successfully by more than one, there was noticeable agitation (e.g., fidgeting, longer response time) by several participants in the experiment. This points to the importance of the precedent since players were nervous because they had never experienced this kind of growth before and were therefore uncertain about what the outcome would be. As a result, the minimum fell below (to 4) what it had fallen the last few times the group grew (to 5).

strong coordinating effect of previous experience with growth.

The above examination of behavior in the two experiments supports the notion that growth can lead to higher efficiency in large groups and points to additional interesting results. However, in order to establish more conclusively that growth works, the aggregate results must be examined more carefully.

4.3 Aggregate Results

In order to test the main hypothesis of the paper – that groups that are grown slowly are more efficiently coordinated than groups that start off at a large group size – it is necessary to look at the aggregate data. The sessions in experiment 1 are all examples of 12 person groups that were grown slowly since they started off at small group sizes (2) and grew in size by only adding one or two players at a time to a large size (12). In addition to these sessions, however, an examination of Figure 6 reveals that two of the sessions in experiment 2 also provide data on groups that were grown slowly. In both sessions E1 and E4, following initial unsuccessful rapid growth, the managers started the groups over at small sizes (2 and 3, respectively) and then grew the groups slowly – never adding more than two players at a time – until reaching a group size of 12. Therefore, these two sessions are pooled together with the results of experiment 1 in Table 4.

Table 4 presents the growth paths (number of active participants) and minimum choices by period for each of the grown groups. For each of the five growth sessions used (two of which were determined by the managers in experiment 2), the results of groups growing at that rate are presented.[33] Of the resulting nine 12 person groups, two were successfully coordinated on 7 for more than one period (though the final two periods for session E4 in which all 12 players selected 7 are not included in the table). There was one 12-person group in which the minimum was 6, another in which it was 5, and another in which it was 3. In another group, the minimum at size 12 was initially 4, but it then fell to 3 and then 1. In the remaining three groups, the minimum was 1 by the time group size reached 12 and it remained there. While a majority of the groups are not efficiently coordinated, the fact that two are playing minima of 7 and another three are coordinated at levels of efficiency higher than 1 indicates that growth does work, even if only limitedly. In addition, as mentioned before, the majority of groups are also playing higher minima at intermediate group sizes (such as 9) than they did in previous experiments.

A better test of whether growth works or not can be obtained by comparing the distribution of choices between the grown groups and the control sessions, in which group size was constant at 12. In order to make this comparison, however, it is necessary to decide on a valid comparison period. The control groups played as large groups for 12 periods. The grown groups all started off at small sizes and did not reach a group size of 12 for several periods. The earliest period in which a grown group reached the maximum size was period 18. Also, the grown groups did not all reach that size in the same period. The key question, then, is when the comparison should be made. A reasonable comparison is to compare the

[33]All of the periods are not included in the table for sessions E1 and E4 since these experiments lasted longer and the focus is on what occurred when the groups reached larger sizes. The complete data for these sessions is available in Figures 12 and 18.

	Period																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Growth path 1	2	2	2	2	2	2	3	3	4	4	5	6	7	8	9	10	11	12	12	12
Session 1	7	7	7	7	7	7	6	6	5	5	4	4	3	3	2	1	1	1	1	1
Session 2	6	5	7	6	7	7	5	6	5	6	5	5	5	5	5	5	5	5	5	5
Growth path 2	2	2	2	2	2	3	3	3	3	4	4	5	6	7	8	9	10	11	12	12
Session 3	7	7	7	7	7	5	5	5	5	5	5	5	5	5	5	5	1	1	1	1
Session 4	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Growth path 3	2	2	2	2	2	3	3	3	3	4	4	5	6	7	8	9	10	12	12	12
Session 5	6	6	7	7	7	7	7	7	7	7	7	7	7	4	3	3	3	3	3	3
Session 6	7	7	7	7	7	7	7	7	7	7	7	7	7	5	4	3	2	1	1	1
Session 7	6	6	6	6	6	6	6	6	6	6	6	6	1	4	4	4	4	4	3	1
Growth path E1		2	3	3	3	3	4	5	6	7	8	9	10	11	12	12	12	12	12	12
Session E1		6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Growth path E4		5	6	6	6	6	7	7	8	8	8	9	9	10	10	10	12	12	12	12
Session E4		5	4	5	6	7	5	6	5	6	7	5	6	5	6	7	4	5	6	7

Table 4: Minimum choices by period for sessions 1 through 7

control groups in period t with the tth period in which the grown groups played as groups of size 12. In this case, subjects in both treatments have $t-1$ periods of play in 12-person groups and therefore share a similar history. This is still not a perfect comparison since the grown groups have a much longer history that includes the periods spent growing, and the question remains about when the comparison should be made (i.e., what the value of t should be). Should the first period of play in the control groups be compared to the first period in which the grown groups reached the maximum size? Another issue has to do with how many periods as 12-person groups there is data for in the grown groups. Since the maximum number of periods (after reaching a size of 12) in which there is data for all the grown groups is four, and since by period 4 the majority of 12-person groups have coordinated on some equilibrium, this was decided upon as the appropriate comparison point. Table 5, therefore, compares the distribution of subject choices in the four control sessions and the nine growth sessions in the fourth period in which participants played at a group size of 12.

		Control		Growth	
Choice	7	2	(4.2 %)	20	(18.5 %)
	6	0	(0.0 %)	15	(13.9 %)
	5	5	(10.4 %)	13	(12.0 %)
	4	16	(33.3 %)	8	(7.4 %)
	3	5	(10.4 %)	10	(9.3 %)
	2	9	(18.8 %)	9	(8.3 %)
	1	11	(22.9 %)	33	(30.6 %)
Total		48		108	
Minima		1,1,1,4		1,1,1,1,3,4,5,6,7	

Table 5: Distribution of subject choice in fourth period as 12-person groups

The first thing to note is that the number of subjects choosing 1 is high in both conditions (11 of 48 in the control sessions and 33 of 108 in the growth sessions). While this number is higher for the growth sessions, this is not surprising since in three of the nine grown groups the minimum was 1 even before the group reached a size of 12. In these groups, therefore, there were more previous periods for subjects' choices to converge towards the inefficient equilibrium than in the control treatment, where only one session started off in at a minimum of 1 in period 1.

Just as interesting, however, is the difference in the distribution of high choices (6 or 7) between the two treatments. In the control sessions, only 2 of 48 subjects (4.2%) played either a 6 or a 7, while this is true of 35 of 108 subjects (32.4%). Therefore, the number of subjects playing the two highest strategies is much higher in the grown groups than in the control sessions.

The distributions of choices in Table 5 are significantly different when compared using a Chi-Square test ($\chi^2_{(6)} = 29.97$, $p < 0.001$). In addition, when the cumulative choice frequencies (which can be derived from Table 5) are compared, the null hypothesis that the distributions are the same can be rejected in favor of higher choices in the grown groups at the $p < 0.01$ level (Kolmogorov-Smirnoff one-tailed, $\chi^2_{(2)} = 11.85$) .[34] Some additional support for the hypothesis that growth leads to greater efficiency can be found in a comparison of the minima in the fourth period after growth. These minima are reported in the final row of Table 5. Note that the minimum in all but one of the control sessions is 1 and that while the minimum in four of the growth session is also 1, the minimum is greater than 1 in the remaining five session and there are grown groups with minima of 6 and 7. A Mann-Whitney U test of the minima yields the test statistic $z = 1.09$. While the corresponding p-value of 0.13 is greater than the usual significance levels, it must be noted that this test and p-value are extremely conservative since they treat each group of twelve subjects as just one observation.

As the results of the above tests indicate, choices in the fourth period as a group of size twelve tend to be higher in the grown groups than in control groups. When each subject's choice is treated as an indedpendent observation, the difference is highly significant. However, this significance is exaggerated as the assumption of complete independence between

[34]Both of these tests, however, rely on the assumption that all the observations in each treatment are independent. In this case (as in much of experimental data) this assumption is not satisfied since the choices of all of the subjects in a session in a particular period are affected by the common history shared by these subjects. Therefore, the level of significance reported by the statistics is exaggerated.

subjects' choices is most likely unreasonable for subjects with a shared history in the same group. Therefore, as the last test indicates, when each session is treated as only one observation, the results are not quite significant. However, this extreme assumption of complete lack of independence results in a test that is too conservative and underestimates the true significance level.

A better test of the difference between the two conditions has to control for the lack of independence between subjects' choices, but also has to recognize that this dependence is limited. Therefore, the test should control for the within session subject dependence without treating all subjects within a group as one observation. This interdependence in subject choices arises because of the shared history that the subjects in a session have jointly observed in previous periods. Therefore, one possible test is to consider the difference between subject choices by treatment in a period while controlling for dependence arising from shared history. Using Crawford's (1995) dynamic model of behavior in weak link games allows for the inclusion of this dependence. In Crawford's model, a player i's choice in period t (x_{it}) can be described as a partial adjustment between her own previous choice (x_{it-1}) and the minimum in the previous round (y_{t-1}), along with a drift parameter (α_t) and an idiosyncratic error term (ϵ_{it}):[35]

[35] Crawford's model is used rather than the model from the previous section, because Crawford's model is a more complete description of behavior in order-statistic coordination games. Since the goal here is to test the difference between the two treatments while controlling for non-treatment sources of variation, the more descriptively complete model is used. For the purpose of this section, the only difference between the two models lies in the drift parameter. Omitting it from the analysis does not change the results.

$$x_{it} = \alpha_t + \beta_t y_{t-1} + (1-\beta_t)x_{it-1} + \epsilon_{it} \tag{5}$$

Subjects' choices in period 4 after growth (period 4') are not independent because players have jointly observed all the previous minima with other players in their session. However, controlling for all the prior common information within a session, subjects' choices are conditionally independent. Therefore, one way to control for lack of independence in period 4' choices is to include the effect of the previous minima (for periods 1' through 3'). In the growth sessions there are periods before period 1' (since period 1' is actually the first period at a group size of 12) and interdependence in subject choices may arise due to shared history in these prior periods, However, most of the effect of this interdependence on period 4' choices can be captured in subjects' period 1' choices. Therefore, the lack of within-session independence in subjects period 4' choices is controlled for in a regression of period 4' choice on a treatment dummy variable and on the three previous minima as well as on choice in period 1'. This model was estimated using ordinary least squares. The estimated coefficient for the treatment dummy variable (growth = 1) was 0.496 and was significantly greater than zero ($t = 2.199$, $p < 0.03$) indicating that subject choices were higher in the growth treatment, even after controlling for the shared history.

Taken together, the above analysis convincingly indicates a positve effect of the growth treatment on subject choices. While the lack of independence between subject choices within sessions complicates the initial analyis, the result persits when controlling for this interdependence.

There is also evidence that the rate of growth mattered. All four of the managers in experiment 2 encountered problems after growing the groups too quickly. The two successful managers (sessions E1 and E4) were able to grow efficiently coordinated groups only by starting over at a small size and then growing slowly. The other two managers did not attempt to do so – but instead continued to try to grow quickly – and subsequently failed. The correlation between change in group size (number of players added or dropped) and change in the minimum in experiment 2 is -0.497, indicating that the minimum decreased when group size increased by a large amount.[36]

The above tests support the result that grown groups are more efficiently coordinated than groups that start off large. Even without examining the aggregate results, however, the fact that two 12-person groups were able to successfully coordinate on the efficient equilibrium (a result never previously obtained) shows that growth <u>can</u> work to help solve large group coordination failure.

4.4 Discussion

Coordination problems have been recognized as an important economic issue. The minimum-effort coordination game models the most punishing forms of coordination – where the lowest level of any input has a strong effect on efficiency. Given the punishing nature of the game, it is not surprising that efficient coordination becomes much more difficult as the number of

[36]This correlation is -0.166 for experiment 1.

players grows. Previous experimental results indicate that it is impossible for large groups to coordinate on the efficient equilibrium.

Motivated by a model suggesting that slow growth may work to solve large group coordination failure, experiments were run testing whether growth was one way to obtain efficient coordination in large groups. Evidence from the experiments indicates that growth may play an important role in determining the ability of large groups to coordinate efficiently. Starting with small groups that play efficiently and adding players slowly enough resulted in groups of size 12 at efficiency levels above the usually observed minimum. In fact, some of the minima in large groups reached the highest levels of efficiency. This was true for groups starting out small and growing slowly both by growth paths determined by the experimenter and by growth paths determined by a subject in the role of manager. The endogenous growth experiments also indicated that slow growth may be critical, as all four managers initially grew too fast and met with failure. However, some of the managers learned to grow slowly from experience. In addition, there is evidence that subjects' initial experiences with growth may be critical for determining subsequent success with growth and that previous experiences with growth may set precedents concerning what will happen the next time a group grows.

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5 Appendix A: Proofs

Proof of Proposition 1. In order to show that the proposition is true, assume without loss of generality that the choices of all participants are drawn from a common distribution (i.e., $s_{it} = s_{jt}$ for all i and j). If the result holds in this case, then it is simple to show that it holds when the s_{it} are not the same (as long as their choices are independent of group size). Therefore, we can now describe each choice by a common cumulative distribution function $F(x)$, which gives the probability that a player's x_{it} is smaller than the value x. It is then sufficient to show that the c.d.f. of the minimum for a smaller group first order stochastically dominates the c.d.f. of the minimum for a larger group. To see why this is true, first note that the c.d.f. of the minimum is given by $1 - (1 - F(x))^n$. This is the probability that at least one of n choices drawn from $F(x)$ is less than x. Since $1 - F(x)$ is less than one by definition, the c.d.f. of the minimum is higher (for all values of x such that $F(x) < 1$) as n increases. Therefore, the minimum is stochastically greater when n is larger. If $\sigma_t^2 = 0$, then $F(x)$ jumps from zero to one at the mean, and the c.d.f. of the minimum is unaffected by n. *Q.E.D.*

Proof of Proposition 2. Recall that every players' choice is determined by an increasing function of the x_{it}, where these are determined by:

$$x_{it} = (1-b)s_{it-1} + by_{t-1} + \epsilon_{it}$$

and that $0 < b \leq 1$. It follows that since the minimum is determined by the smallest of the x_{it} and the x_{it} are all increasing in y_{t-1}, then the expected value of the minimum will also increase with y_{t-1}. *Q.E.D.*

6 Appendix B: Instructions for minimum-effort game (experiment 1)

This is an experiment in the economics of decision making. Several research institutions have provided funds for this research. You will be paid for your participation in the experiment. The exact amount you earn will be determined during the experiment and will depend on your decisions and the decisions of others. Your earnings will be paid to you in cash at the conclusion of the experiment. If you have a question during the experiment, raise your hand and an experimenter will assist you. Please do not talk, exclaim, or try to communicate with other participants during the experiment. Participants violating the rules will be asked to leave the experiment and will not be paid.

Please look at the number at the top of this page. This is your participant number for the experiment. This participant number is private and should not be shared with anyone. Your participant number will be the same for the entire experiment and should be the same on all your sheets.

In this experiment, you will be one member of a project team that is responsible for producing a series of reports. Each report that the team prepares consists of several sections, where each member of the team is responsible for contributing one of the sections. A report is considered complete only after all members of the team have contributed their sections. Your team will be responsible for producing a total of twenty-two reports. Until a particular report is finished, no member of the team can work on his or her section of the next report.

You earn money based on how rapidly each report is completed. Each report is due in 7 weeks. However, every team member receives a bonus if the team completes the report in less than seven weeks. There are six possible early completion times: 1, 2, 3, 4, 5, or 6 weeks ahead of schedule. Hence, as a team member you must decide whether to contribute your section of a report during week 1, week 2, week 3, week 4, week 5, week 6, or week 7. The earlier a report is completed the larger the bonus. The bonuses associated with the alternative completion times are described in Table 1.

Note that the only way a report can be completed in just one week is if every team member contributes his or her section during week 1. Likewise, the only way a report can be completed in just 2 weeks is if every team member contributes his or her section within two weeks (either 1 or 2 weeks), and so on. Hence, the completion time of a report is equal to the maximum time taken by any one of the team members to contribute his or her section. Every team member receives the same bonus.

As a team member, you must decide how long to take to contribute your section of each report, without knowing how long the other members of the team will take to contribute their sections. Completing your section imposes a personal cost on you. This cost is higher if your contribution time is earlier. Table 2 describes the dollar value of the personal costs you could incur for the possible contribution times of your own section. Note that the sooner you contribute your section the higher the personal cost you incur. However, the sooner that all team members are finished, the higher is the completion time bonus for everyone on the team.

Your total earnings from a given report will be equal to the completion time bonus minus your personal cost. The various possible earnings are given in Table 3 below. Each column in the table represents a possible completion time of the report, which is equal to the maximum time selected by any team member (including you) to contribute his or her section of the report. Each row of the table represents a personal contribution time that you might select. Each of the cells in the table represents the earnings associated with a combination of your personal contribution time and the report completion time for the team.

During the experiment, the size of the team will vary. Please look at Table Each row in the table corresponds to one of the twenty-two reports to be completed. We will start with Report 1 and will proceed sequentially through Report 22. The second column in the table indicates which participants will be on the team for a given report. For example, the team for Report 1 will consist of only Participants 1 and 2. Only the participants on the team will select a personal contribution time, pay a cost, and receive the bonus.

The remaining participants will not have any effect on the completion of the report and will not pay the cost or receive the bonus. These participants will be able to observe the report completion time and will earn a fixed amount per report. The exact amount that these participants will earn will not be revealed until the end of the experiment, however, because we do not want this amount to influence your choices during the experiment. The experimenter will now hand out an envelope to everyone in the room. Inside the envelope is a card with the amount that will be earned each round by participants that are not part of the team. This number is the same for everyone and will be announced at the conclusion of the experiment. Please do not open this envelope until the end of the experiment.

In your folder you are provided with a stack of Reporting Sheets. Please look at these sheets now. There is one sheet for each of the twenty-two reports. On every Reporting Sheet, there is a box corresponding to each one of the seven personal contribution times and an additional box marked "Not on team". You should also have a Record Sheet. At the end of each report, please make sure that you fill out the line on the Record Sheet corresponding to that report.

Each of the twenty-two reports will proceed as follows:

1) First, the experimenter will announce which of the participants are on the team for the current report. This information is also in Table

2) Each of the team members will select a personal contribution time by checking one of the boxes on the Reporting Sheet corresponding to the current report and circling the personal contribution time on their Record Sheet. At the same time, each of the participants not currently on the team will check the "Not on team" box both on their Reporting Sheet and circle "Not on team" on their Record Sheet. Please make sure that your choices on both the Record Sheet and the Reporting Sheet are the same.

3) The experimenter will then collect all the Reporting Sheets, and will announce the report completion time for the team and the corresponding bonus. Every participant should record both the report completion time and corresponding bonus on their Record Sheet.

4) Each participant on the team will then determine his or her earnings for that report by subtracting the personal cost associated with their contribution time from the bonus. These

earnings can also be determined from Table 3 by identifying the row corresponding to the contribution time you selected and the column corresponding to the maximum contribution time selected by the team members. The amount earned for the report should be recorded on the Record Sheet. Participants not on the team for that report should leave the earnings column blank.

5) At the conclusion of the twenty-second report, your earnings for the experiment will be the sum of your earnings for each of the reports plus the $9 participation fee. If there are any reports for which you are not on the team, your earnings for those reports will be the amount in the envelope you have received. Note that it is possible for the sum of your earnings for the 22 reports to be negative, but that the sum of your earnings plus the participation fee will always be positive.

Before we begin the experiment, you will answer a short set of questions to make sure that everyone understands the instructions. Please take a moment to answer the questions on the next page. Once you are done, raise your hand and the experimenter will come by to check your answers. After everyone has completed the questionnaire, the experimenter will read the correct answers aloud and we will proceed with the experiment. There should be no talking from this point on. If you have a question, raise your hand.

Figure 1. Choices in Control Treatment

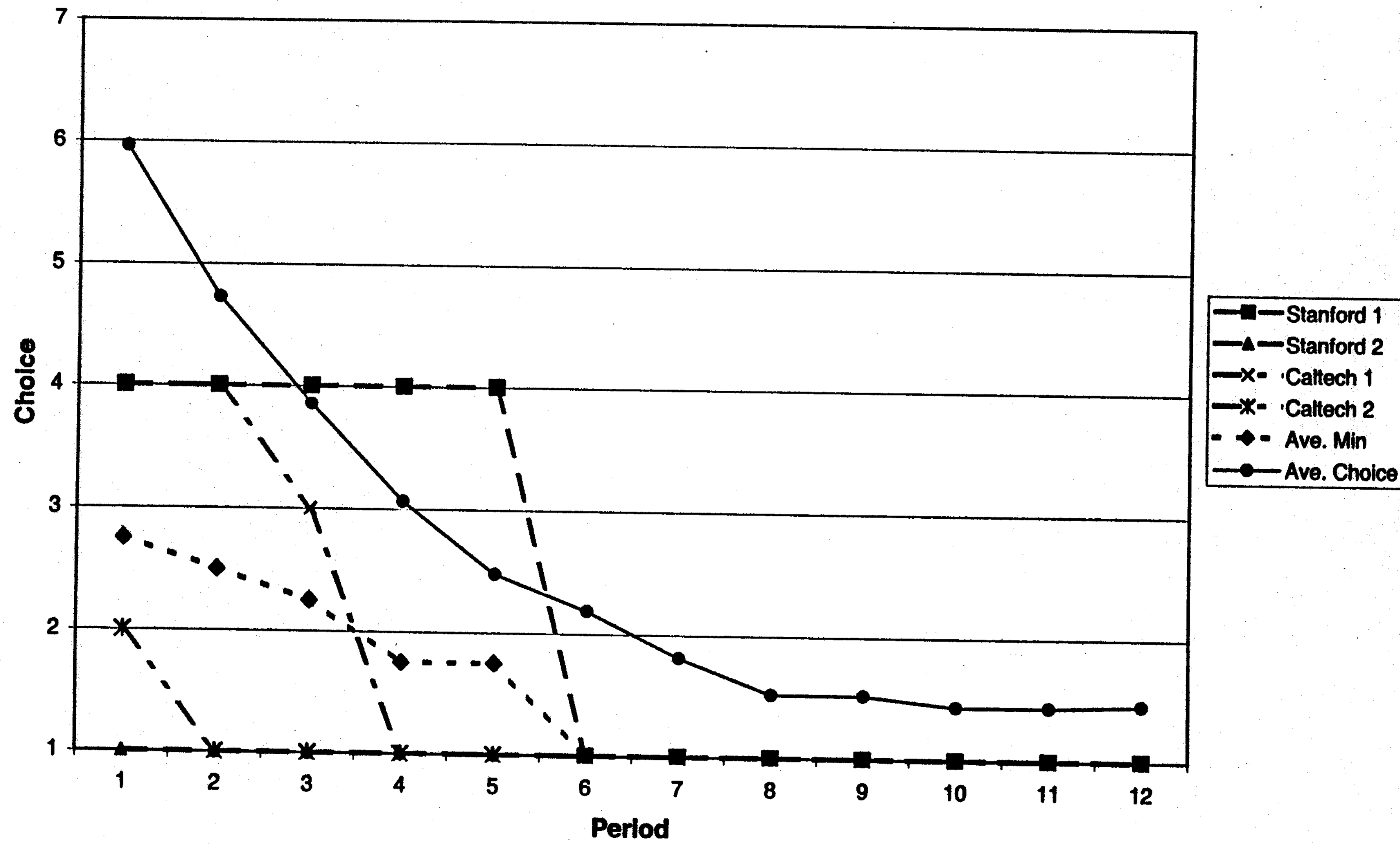

Figure 2. Pre-determined growth paths

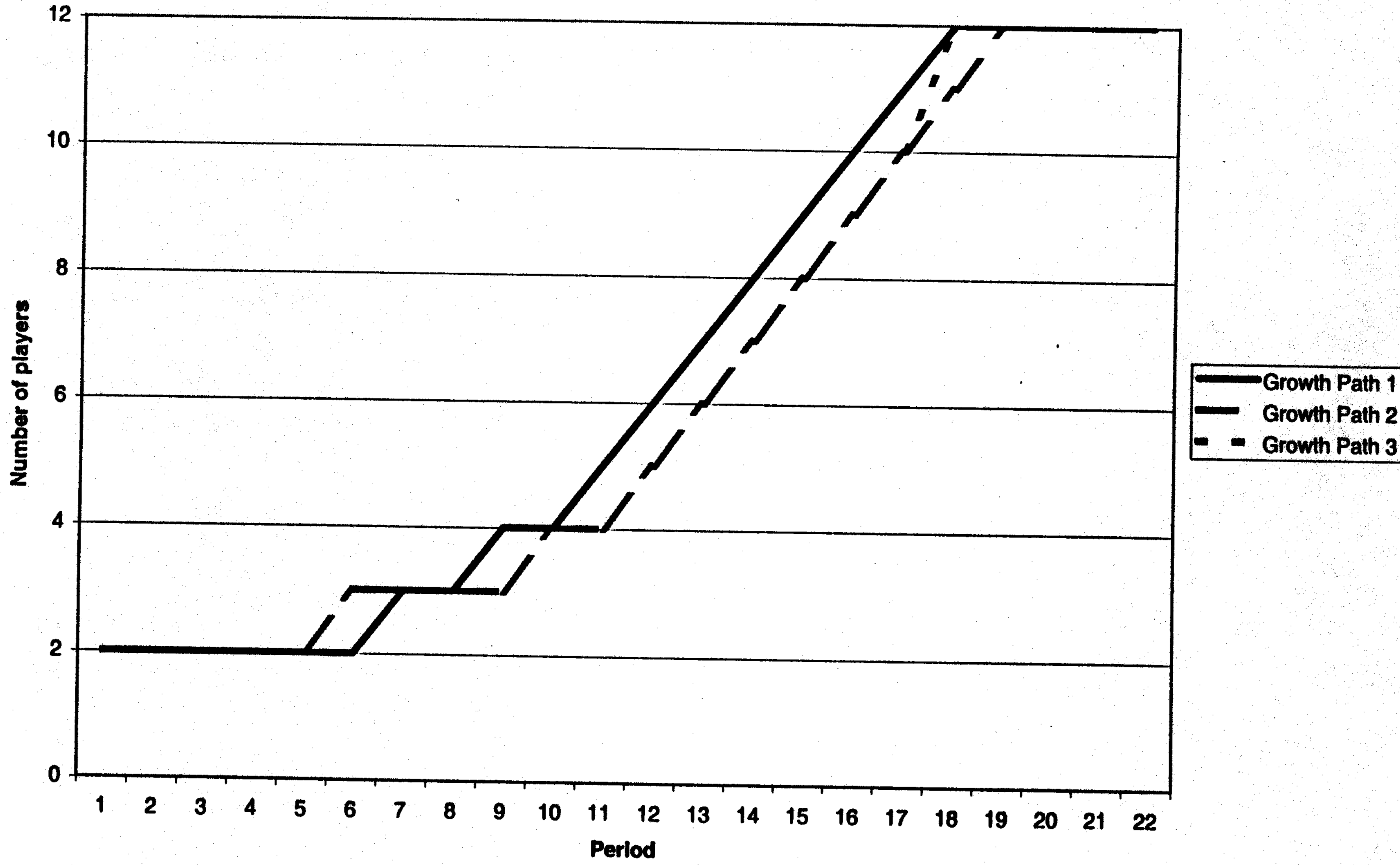

Fig 3. Growth path and minimum choice for sessions 1 & 2

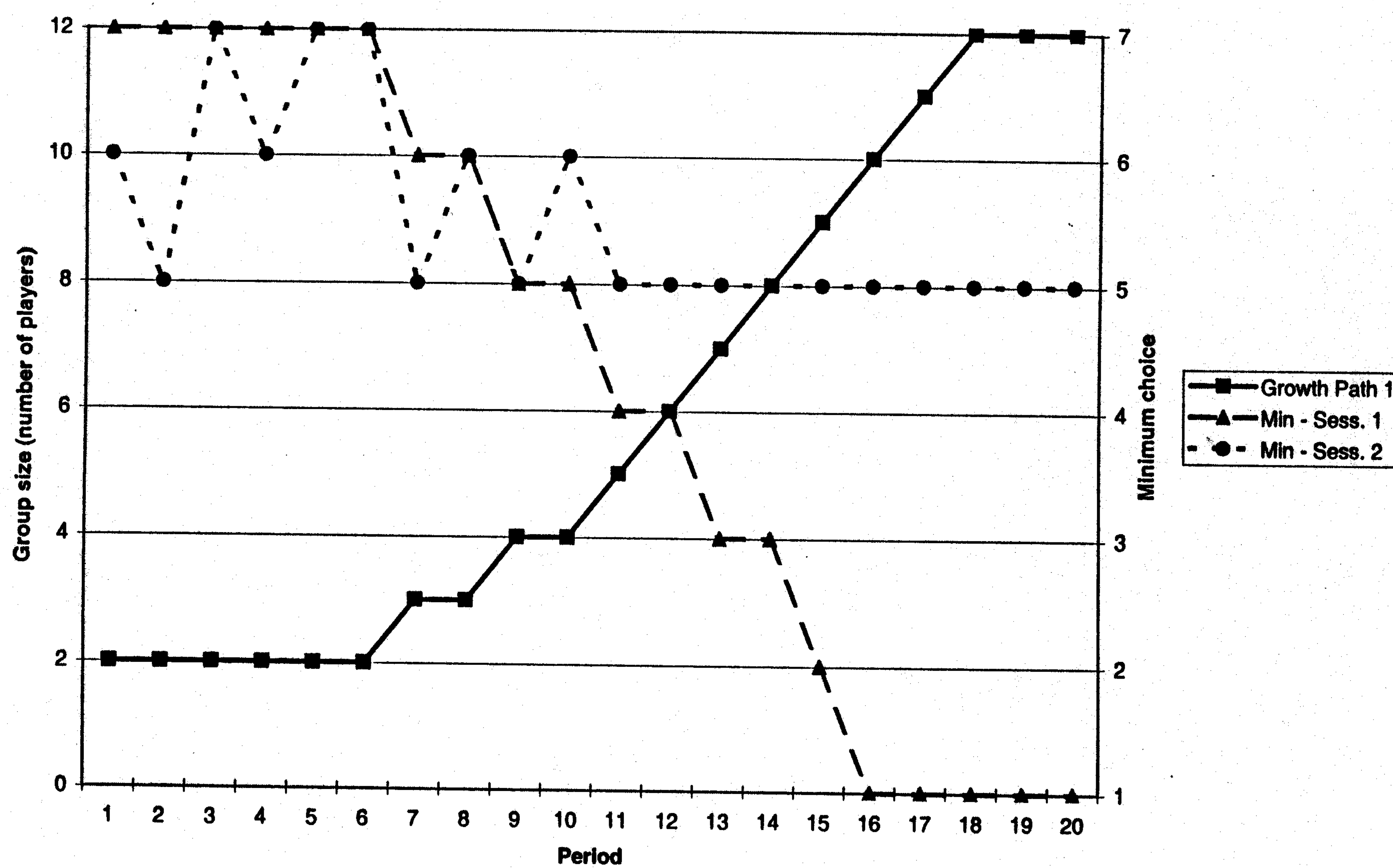

Fig 4. Growth path and minimum choice for sessions 3 & 4

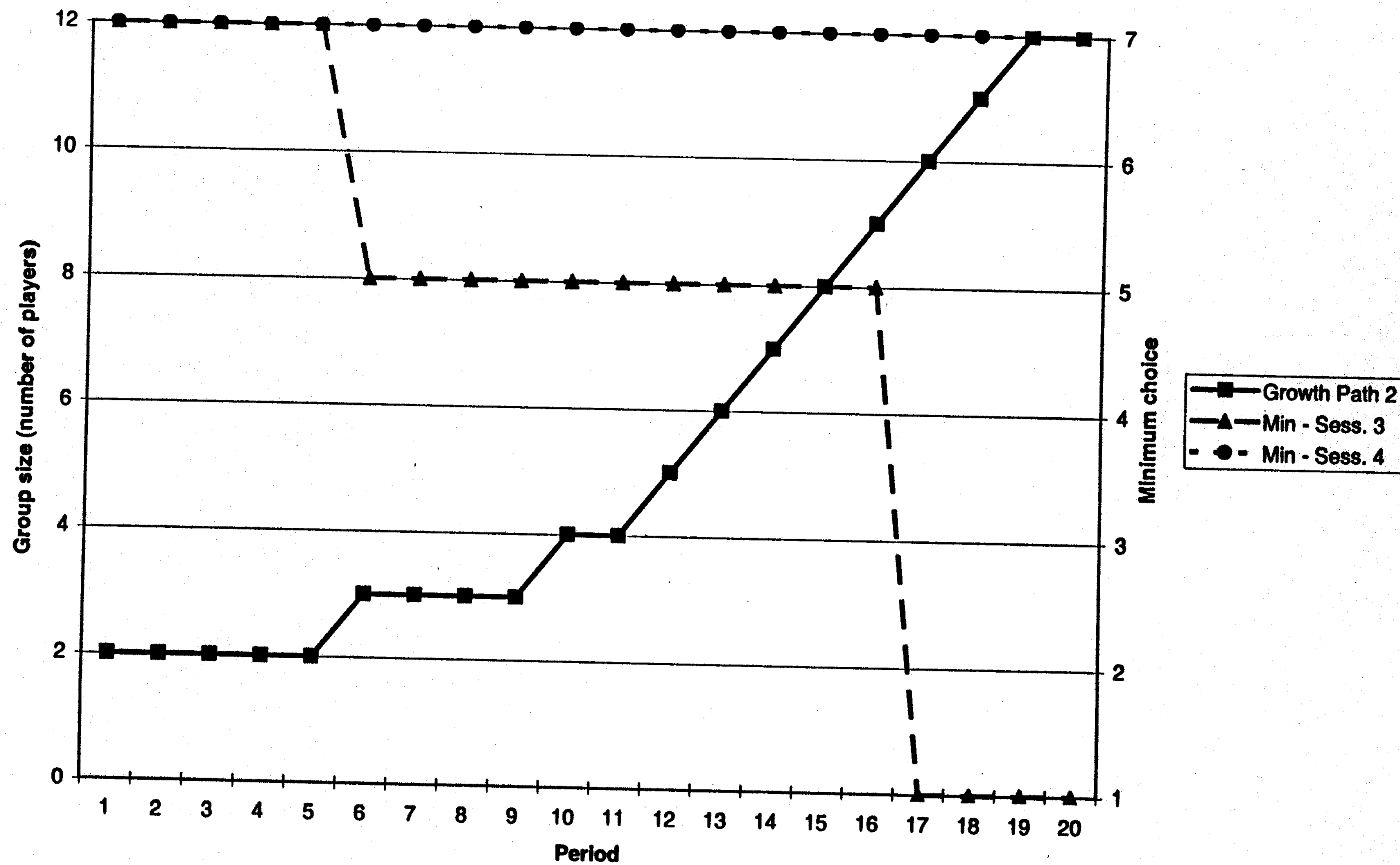

Fig 5. Growth path and minimum choice for sessions 5 - 7

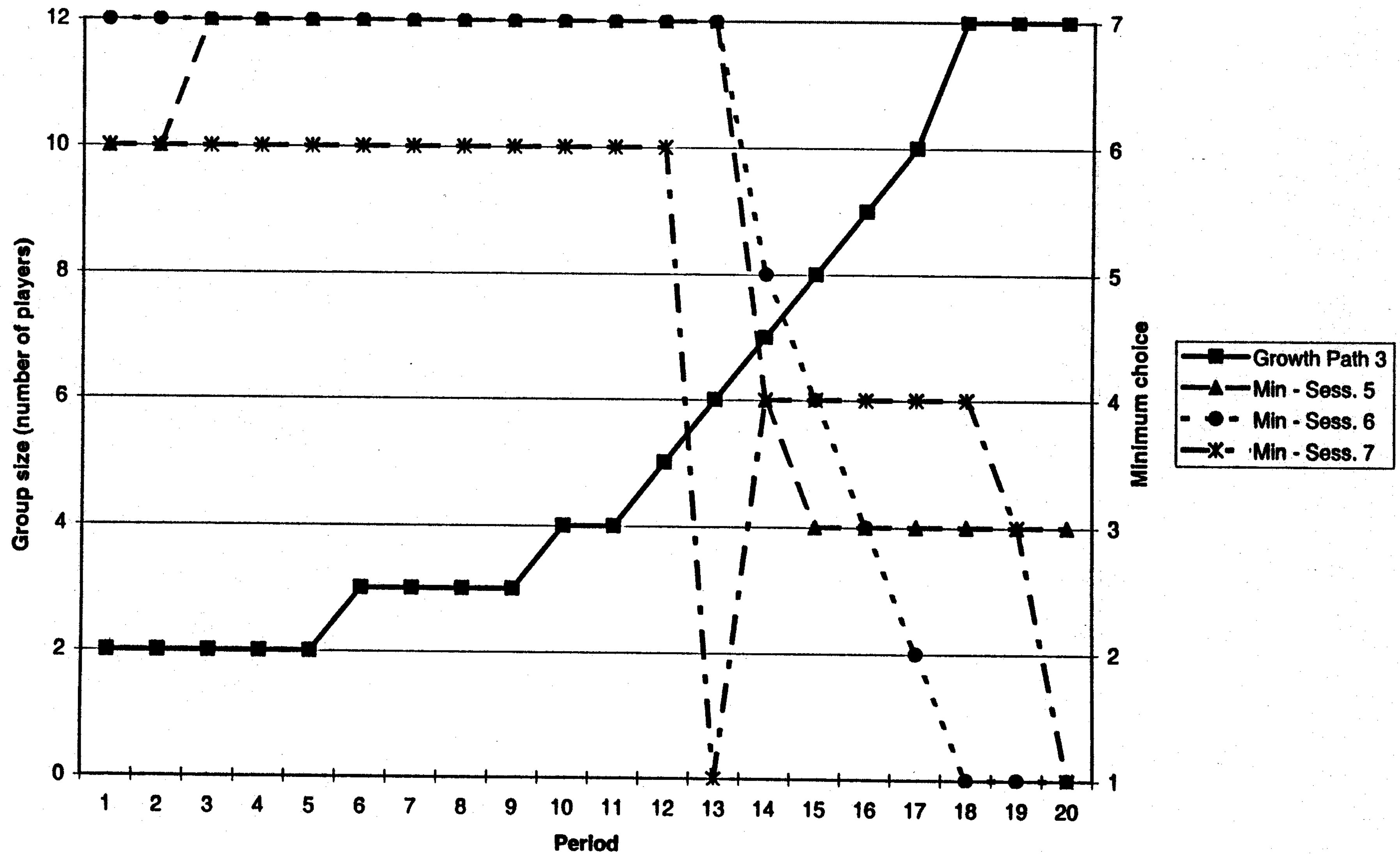

Figure 6. Endogenously determined growth paths

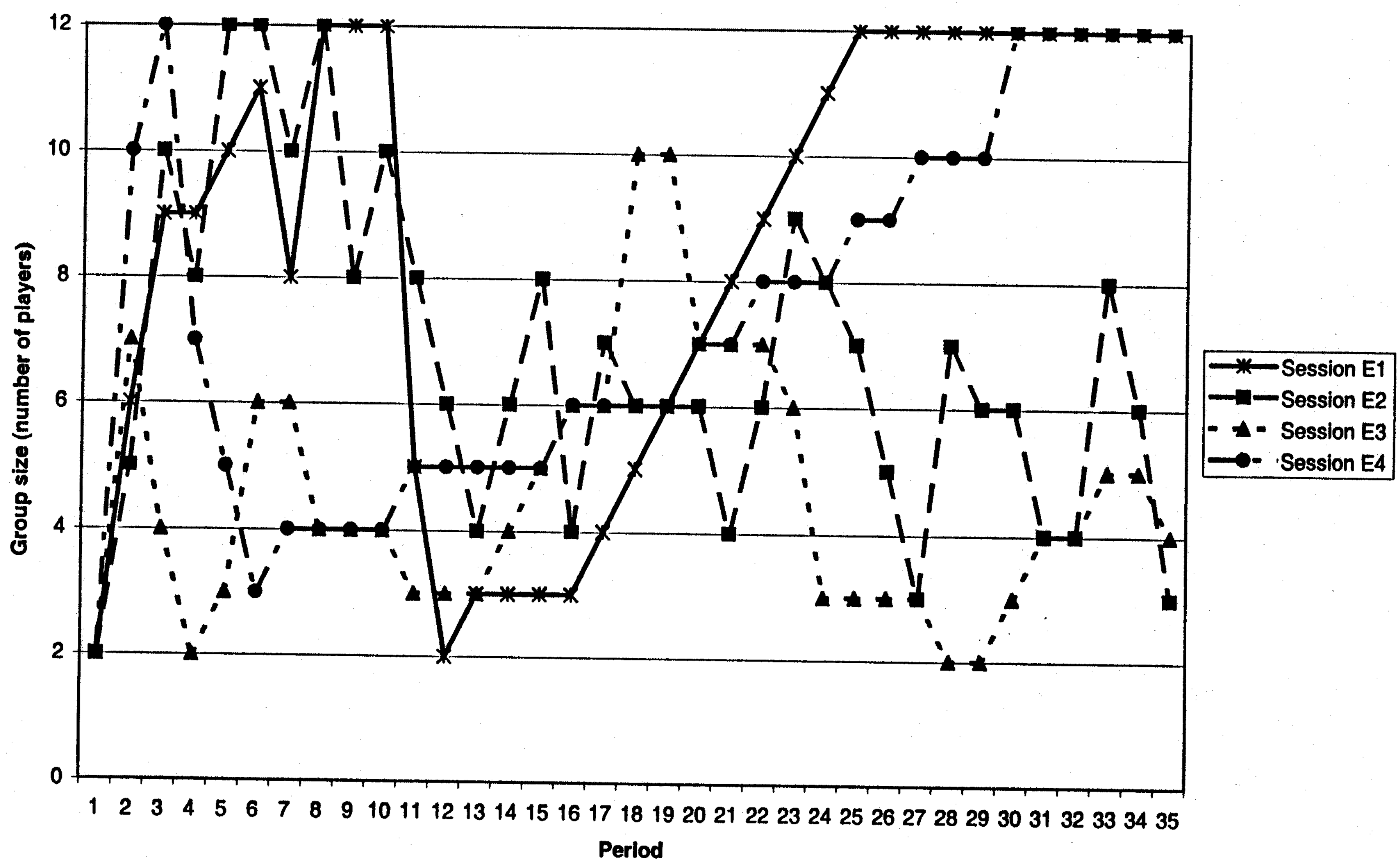

Figure 7. Endogenous growth path and minimum choices in Session E1

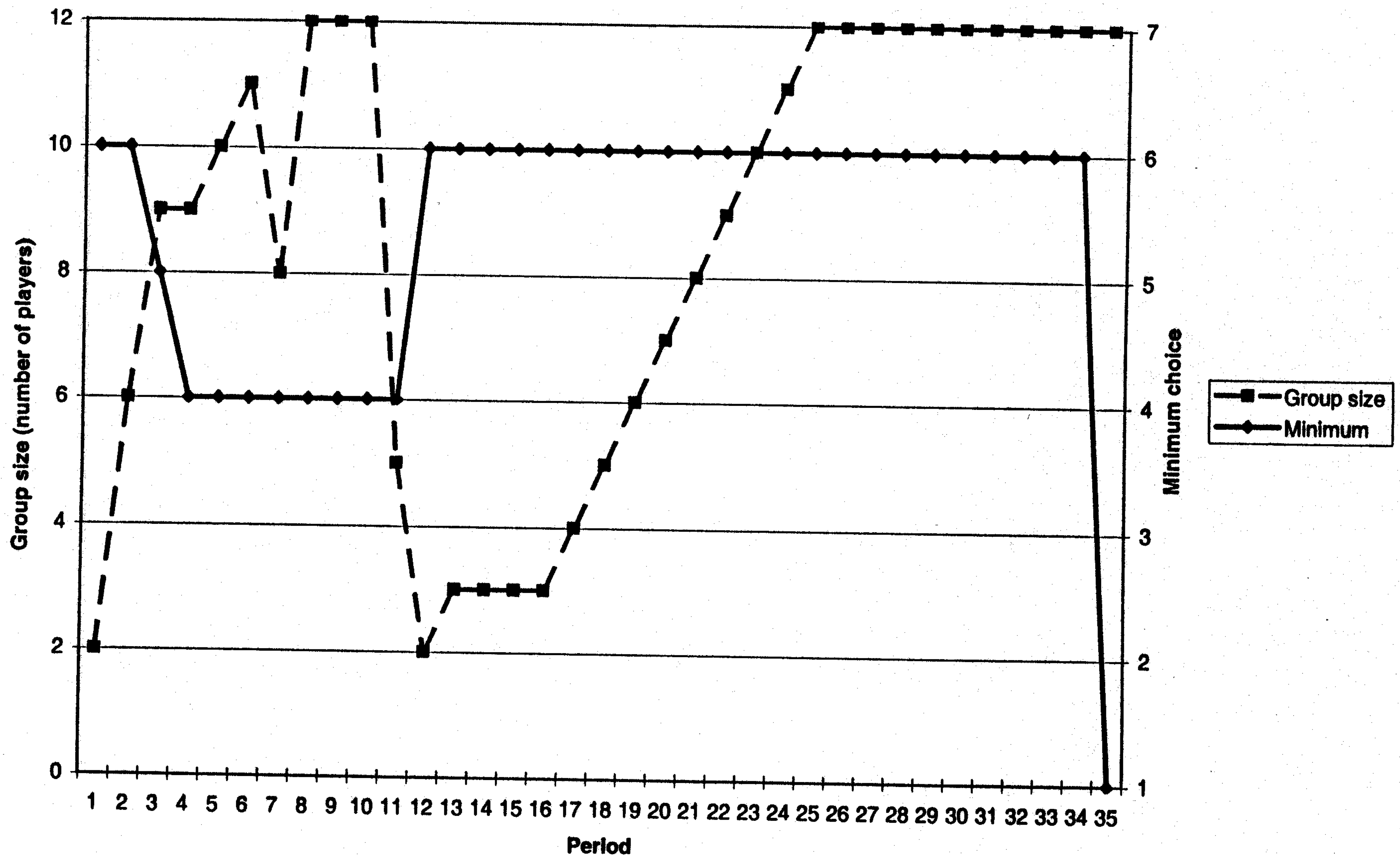

Figure 8. Endogenous growth path and minimum choices in Session E2

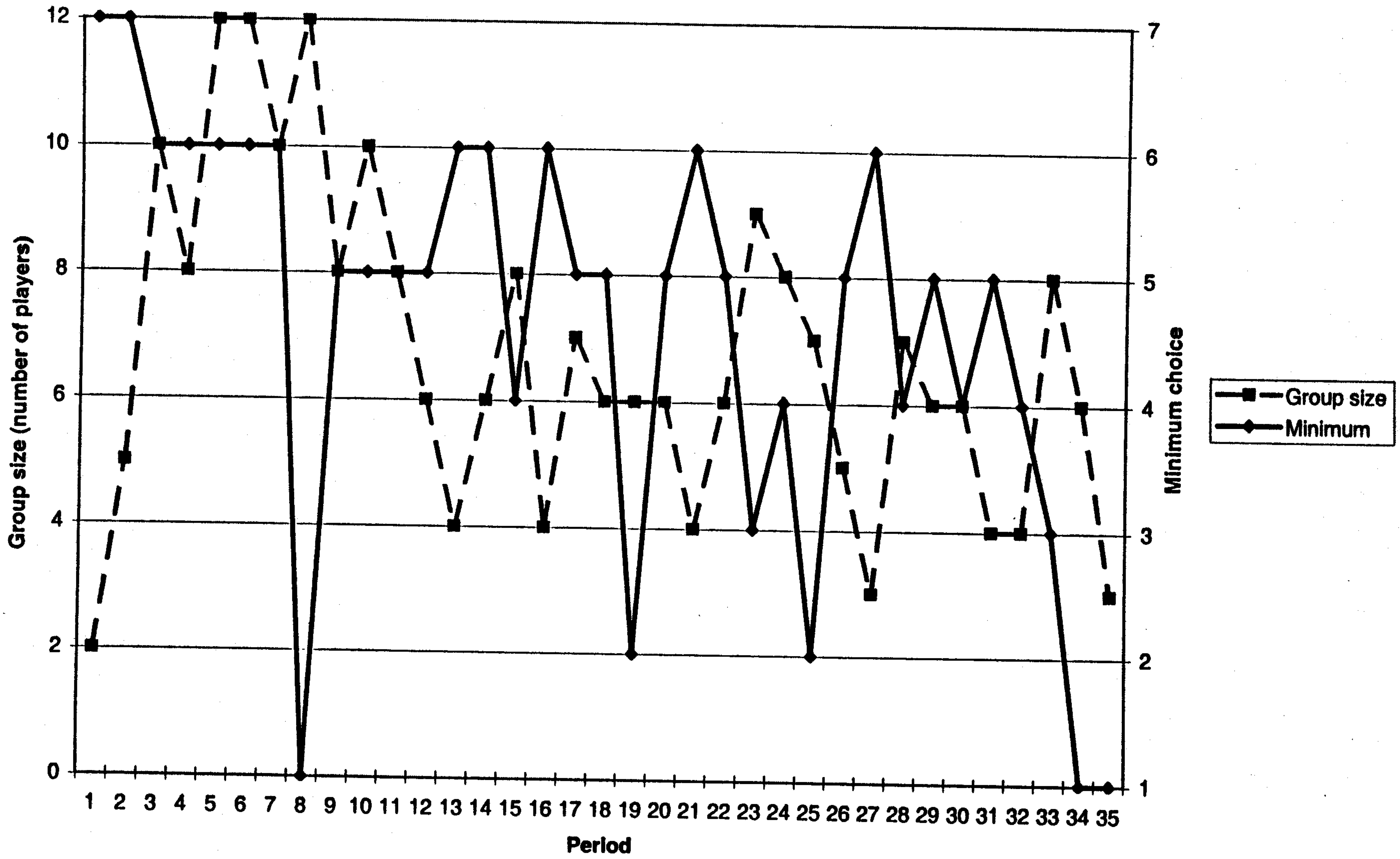

Figure 9. Endogenous growth path and minimum choices in Session E3

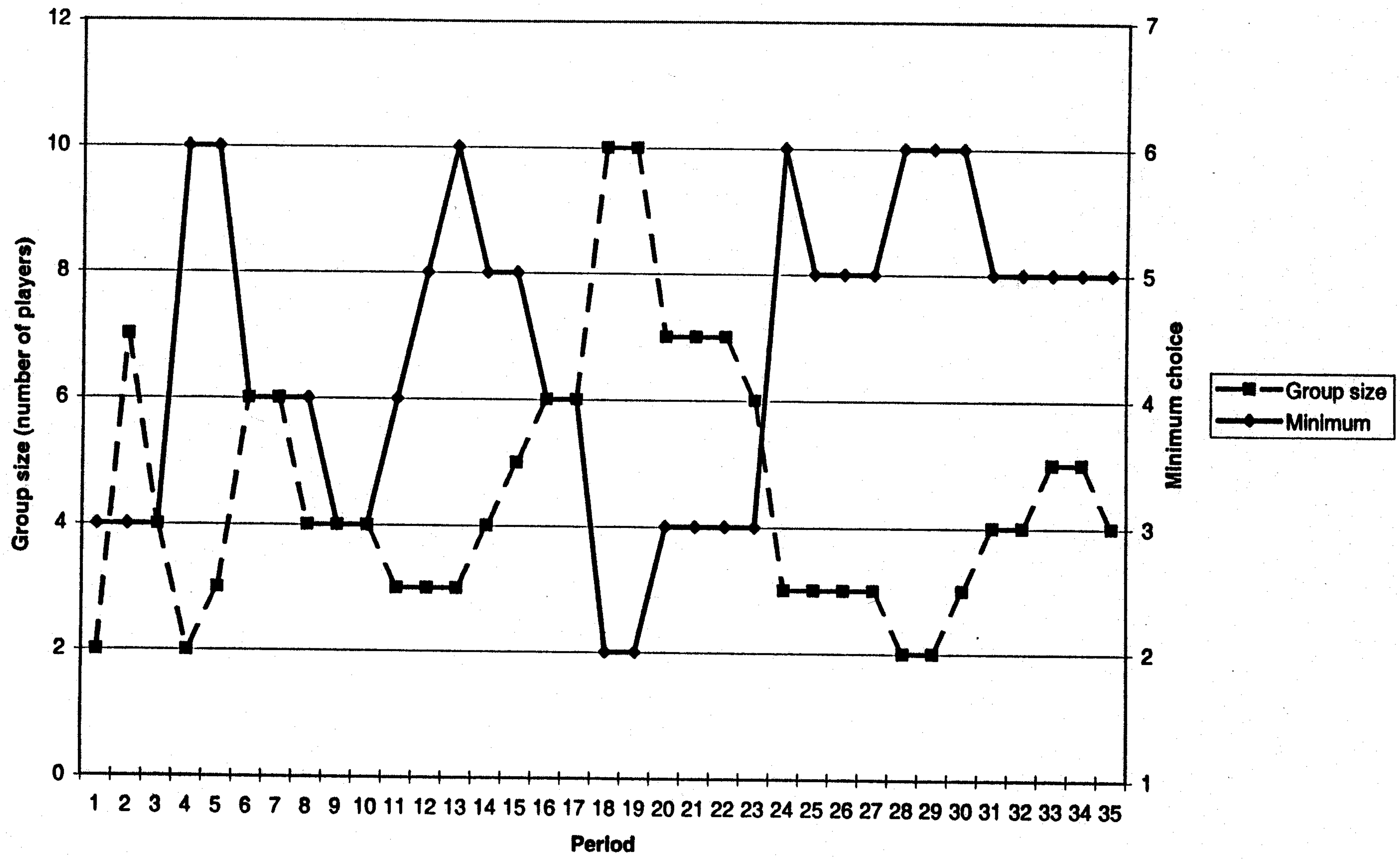

Figure 10. Endogenous growth path and minimum choices in Session E4