

Original Article

# The establishment of communication systems depends on the scale of competition

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## Abstract

How communication systems emerge and remain stable is an important question in both cognitive science and evolutionary biology. For communication to arise, not only must individuals cooperate by signaling reliable information, but they must also coordinate and perpetuate signals. Most studies on the emergence of communication in humans typically consider scenarios where individuals implicitly share the same interests. Likewise, most studies on human cooperation consider scenarios where shared conventions of signals and meanings cannot be developed de novo. Here, we combined both approaches with an economic experiment where participants could develop a common language, but under different conditions fostering or hindering cooperation. Participants endeavored to acquire a resource through a learning task in a computer-based environment. After this task, participants had the option to transmit a signal (a color) to a fellow group member, who would subsequently play the same learning task. We varied the way participants competed with each other (either global scale or local scale) and the cost of transmitting a signal (either costly or noncostly) and tracked the way in which signals were used as communication among players. Under global competition, players signaled more often and more consistently, scored higher individual payoffs, and established shared associations of signals and meanings. In addition, costly signals were also more likely to be used under global competition; whereas under local competition, fewer signals were sent and no effective communication system was developed. Our results demonstrate that communication involves both a coordination and a cooperative dilemma and show the importance of studying language evolution under different conditions influencing human cooperation.

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## 1. Introduction

Explaining the origin of human communication has been a long-standing challenge in both cognitive science and evolutionary biology (Fitch, 2010; Hurford, 2007; Maynard Smith & Szathmari, 1997; Tomasello, 2008). Despite this, only recently have researchers started to look at whether and how new communication systems could emerge de novo in the laboratory (Galantucci, 2005; Garrod, Fay, Lee, Oberlander, & MacLeod, 2007; Healey, Swoboda, Umata, & Katagiri, 2002; Healey, Swoboda, Umata, & King, 2007; Selten & Warglien, 2007; see Scott-Phillips & Kirby, 2010 and Galantucci 2009 for a review). This new approach, called “experimental semiotics” (Galantucci, 2009), has

allowed for the investigation of important processes that occur between human participants, such as how shared systems of signals and meanings arise (Galantucci, 2005), or how individuals recognize that a behavior is communicative at all (Scott-Phillips, Kirby, & Ritchie, 2009).

Communication has been invoked as a potential mechanism favoring cooperation because it would reinforce existing forces such as reciprocal altruism or indirect reciprocity (Smith, 2010). However, communication itself presents two types of cooperative dilemmas: communicative cooperation and informative cooperation (Scott-Phillips, 2010). Not only must individuals cooperate by signaling and coordinating to reach a consensus as to the meaning of a given signal (referred to as “communicative cooperation”), but they must also convey honest information once a shared system of signals and meanings has been reached (referred to as “informative cooperation”). These different types of

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cooperation have sometimes been conflated in the communication literature (see [Scott-Phillips, 2010](#) for a discussion).

Theoretical studies investigating the link between communication and cooperation have shown that communication is expected to evolve differently when individuals have conflicting interests compared to when they share common goals ([Krebs & Dawkins, 1984](#)). Signals between rivals would tend to be costly and exaggerated ([Grafen, 1990](#); [Wheeler & Debourcier, 1995](#); [Zahavi, 1977](#)). On the other hand, signals between allies or relatives would tend to be cost-minimizing “conspiratorial whispers” ([Bergstrom & Lachmann, 1998](#); [Krebs & Dawkins, 1984](#); [Noble, 1999](#)).

Despite the link with communication, cooperation has not been a central focus in research on human language evolution in the laboratory until very recently ([Roberts, 2010](#); [Scott-Phillips, 2010](#); [Smith, 2010](#)). In many experiments, subjects did not face conflicting interests and even had a mutual interest in communicating, either because they were rewarded only if communication successfully occurred or because they had to perform a common task that could only be achieved through communication ([Fay, Garrod, Roberts, 2008](#); [Galantucci, 2005](#); [Garrod et al., 2007](#); [Healey et al., 2002](#); [Healey et al., 2007](#); [Scott-Phillips et al., 2009](#); [Selten & Warglien, 2007](#); [Tamariz, 2009](#); [Walker, Fay, Rogers, & Swoboda, 2009](#)). Similarly, most experiments on human cooperation have focused on situations where communication was avoided, or if allowed, individuals could not have the opportunity to develop a communication system ([Dreber, Rand, Fudenberg, & Nowak, 2008](#); [Fehr & Gächter, 2002](#); [Ostrom, Walker, & Gardner, 1992](#); [Rand, Dreber, Ellingsen, Fudenberg, & Nowak, 2009](#); [Rockenbach & Milinski, 2006](#); [Wedekind & Braithwaite, 2002](#); [Wedekind & Milinski, 2000](#); [West et al., 2006](#)).

Here, we used economic experiments to investigate the role of the inclusion of a social dilemma between participants on the development of shared communicative conventions. Using an experimental economics approach to study communication allows us to bring together both the field of experimental semiotics and the field of human cooperation by identifying the dilemmas involved in the development of a communication system. We introduced a potential conflict of interest by varying the way individuals within groups compete with each other, that is, by altering the scale of competition. In the human cooperation literature, it is well established that the level of cooperation within a group depends on the scale of competition between participants ([Burton-Chellew, Ross-Gillespie, & West, 2010](#); [Kümmerli, Burton-Chellew, Ross-Gillespie, & West, 2010](#); [Puurtinen & Mappes, 2009](#); [West et al., 2006](#)), but this has not been used in studies of language or communication. For example, if individuals compete locally with other group members for resources, cooperation will be disfavored; whereas if competition for resources occurs between other groups, then cooperation is favored (e.g., [West et al., 2006](#)). Here, we investigated the effect of changing the scale of competition, both when signals were noncostly and compulsory, a

condition that is conducive to communication, and when signals were costly and optional, which is a more challenging condition as regards to communication.

## 2. Methods

### 2.1. Participants

Ninety students (45 men, 45 women, with a mean age of 24 years, from 20 different study disciplines within economics, natural, social, and political sciences) from the University of Zürich and the Swiss Federal Institute of Technology in Zürich played in 10 sessions, each consisting of nine participants. Their written informed consent was obtained prior to the experiment.

The procedure of a session was as follows. The nine participants were seated in isolated cubicles and interacted anonymously via computer terminals through software specifically designed for the purpose of the experiment. The experimenter started by reading a summary explanation of the experiment, and participants were asked to read the game instructions (included in the supplementary material). A trial run was then performed to ensure that every participant understood the structure of the game correctly. At the end of the session, participants were paid out as in [Wedekind & Braithwaite \(2002\)](#), that is, retaining their anonymity. In addition to their earnings, they received a show-up payment of 10 CHF (at the time of the experiment, 1 CHF ≈ 1 USD). The average length of a session was 1 h.

### 2.2. Game structure

[Fig. 1](#) outlines the procedure of a session. The nine participants were randomly distributed into three groups of three. Each of these groups played one block of 12 games. In each game, the participants played a sequential learning task. One group member was randomly chosen to play first. The other group members could not see the first player performing the task and waited for their turn. In this task, the player could click on three different noncolored symbols (a square, a triangle, or a star). Only one of the symbols (“the winning symbol,” chosen at random for each game) gave 2 points for each click, whereas the other two gave 0 points for each click. The player had four clicks, following which they could then choose a color (out of five: blue, red, yellow, purple, and brown) to transmit to the next player. The second player played the same learning task with the same winning symbol and could also choose a color to transmit to the last player in the group who only played the learning task. New games with a new winning symbol and a new order of player were played until all players had played twice in every possible order (of a total of six possible orders). At the end of games 6 and 12, the group or the individual player with the highest score (depending on the treatment; see below) received a monetary reward of 5 CHF per individual, and the scores were reset to zero. In the rare cases where group members shared the top

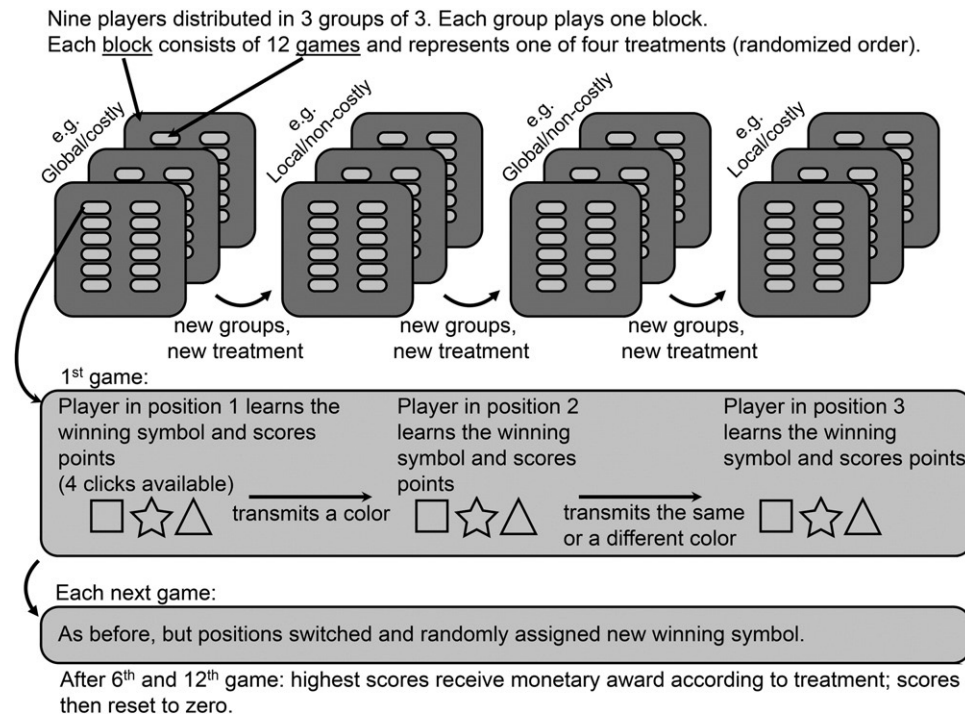


Fig. 1. Structure of a session in the experiment. The four different treatments are defined by local vs. global competition (i.e., highest score within group receives monetary award vs. group with highest score receives award) and costly vs. noncostly signaling (i.e., transmitting a color is optional but costs a point vs. transmitting a color is nonoptional but costs nothing). The players earn two points for each click on the winning symbol.

scores, the reward was equally distributed. Participants were rewarded not only at the end of the block (i.e., game 12) but also at game 6, so that they could have an indication of whether their strategy was successful.

Participants played four different blocks of 12 games, each block consisting in a new treatment. After each block, new groups were randomly formed, and all subjects played all four treatments in a randomized order (i.e., within-subject design), which allowed us to minimize the number of participants. Among all of the 10 sessions, a total of 30 groups, each consisting of three players, played in each treatment. The four blocks in Fig. 1 represent the four different experimental treatments in a randomized order.

We did not inform participants of the goal of the experiment. In addition, we avoided the use of loaded words such as “information,” “transmit,” “communicate,” or “signal,” opting instead for “send a colour.” We believe that our decision to allow players the opportunity to send one of five different colors (when we had three symbols in our learning game) made our results more conservative than if we had used three colors, because players had to coordinate with a larger “vocabulary” of signals. It also gave them more opportunities to confuse others when preventing communication under local competition.

### 2.3. Treatments

We varied the scale of competition by either rewarding the player with the highest score in each group (“local

competition”; i.e., within-group competition) or rewarding all individuals of the group with the highest total score among the three groups (“global competition”; i.e., between-group competition). These two levels of competition were investigated in a “non-costly” condition, where transmitting a color was compulsory and costless, as well as in a “costly” condition, where transmitting a color cost 1 point but was optional (i.e., the option “send none” was present). Thus, a total of four different treatments were used: (i) local competition/noncostly, (ii) global competition/noncostly, (iii) local competition/costly, and (iv) global competition/costly.

Reaching communication in the compulsory noncostly signaling condition only requires coordination of signals between group members, while in the optional costly signaling condition, it also requires that players cooperate by signaling as well as paying the cost of signaling. We chose to compare both conditions because they represent extreme cases where the establishment of a communication system should be challenging to players.

### 2.4. Assessing communication quality

In order to measure the quality of information that was transmitted within groups, we calculated a “communication score” that ranged between 0 and 1 and was the mean of two indices: (i) the “imitation score,” that is, the frequency at which individuals playing the learning task in the second position transmitted the same color as they had received, and (ii) the “color informativeness score,” reflecting, for the

individuals playing the learning task in the first position, how sent colors were associated with symbols. To calculate this score for a given group, we assume a perfect communication system at the end of a block such that the last color used for each symbol is different and not used for other symbols. For example, imagine that in a given group, the last time of all 12 games the square was the winning symbol, the first player of the game sent the red color. Assuming an established and perfect communication system at the end of a block, red means square. We first calculate the frequency at which red was sent when square was the winning symbol (for players in the first position):

$$f(\text{red, square}) = \sum(\text{red, square}) / N_{\text{square}}$$

where  $N_{\text{square}}$  is the number of times the square was the winning symbol. We then calculate the frequency at which red was sent when the star was the winning symbol  $f(\text{red, star})$  and when the triangle was the winning symbol  $f(\text{red, triangle})$ . The level of accuracy to signal square is then given by:

$$A_{\text{square}} = f(\text{red, square}) / f(\text{red, square}) + f(\text{red, star}) + f(\text{red, triangle})$$

Finally, the color informativeness score is:

$$\text{color informativeness score} = (A_{\text{square}} + A_{\text{star}} + A_{\text{triangle}}) / 3$$

In summary, a perfect communication system where second players always sent the same received color and where each symbol was associated with a different color (i.e., for each symbol, the same color was always sent) resulted in a communication score of 1. Fig. S1 shows the correlations

between signaling frequency, imitation, and color informativeness for all treatments. Table S3 shows an example of a complete set of interactions for a group that finished with a communication score of 0.75.

## 2.5. Statistical analyses

Our statistical analyses were performed at the group level (i.e., group of three players) using linear mixed models that included the ID of the three subjects in each group and the session number as random factors to account for the fact that the same individuals played in all treatments but with different partners and to account for session effects. When exploring treatments separately (Fig. 3; Table S1), only the group session number was included as a random factor in the model. When exploring the relationship between game and third player's probability of clicking on the correct symbol (Fig. 2C; Table S2), we used a logistic linear mixed-effect model (GLMM) with a binomial family distribution, as the response variable (i.e., third player's first click correct: yes/no) was binary. Moreover, in this GLMM, the group ID was entered as a random factor.  $p$  Values were based on Markov chain Monte Carlo simulations (10,000 runs). Bonferroni correction was used when all four treatments were explored separately. All statistical computations were carried out with R 2.10.1 (R Development Core Team, 2010), and we used the lme4 package for mixed-effect model analyses (Bates & Sarkar, 2007).

## 3. Results

### 3.1. Signaling and communication quality

We found that the signaling frequency in the costly condition depended on the scale of competition, with fewer

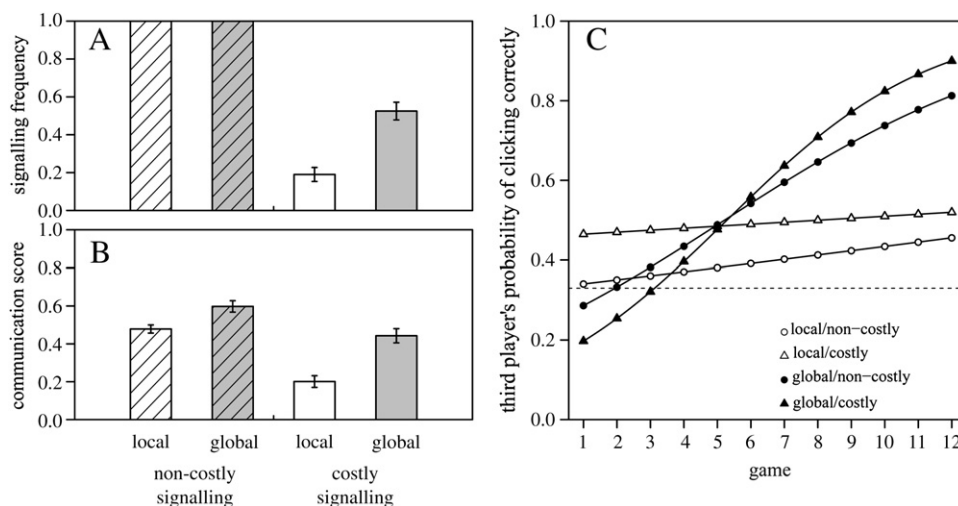


Fig. 2. Signaling frequency and communication quality within groups (means±SE over all 30 groups). (A) When signaling was costly and optional, groups sent fewer signals when they were competing on a local scale compared to the global scale (signaling was nonoptional in the noncostly treatments). See text for statistics. (B) Groups reached higher communication scores under global than local competition. See text and Table 1 for statistics. (C) The probability of correct first clicks of the player at position 3 during the second six games of a block in the best groups. See text and Table S2 for statistics. The dashed line shows the one-third probability of randomly clicking on the correct symbol with the first click.

signals sent under local than under global competition (Fig. 2A;  $t=5.9$ ,  $p<.0001$ ). The signaling frequency under the local/costly condition was significantly different from 0 (Fig. 2A;  $t=4.1$ ,  $p<.001$ ). Imitation frequencies were also lower under local competition and lower when signaling was costly (Fig. S2; Table S4). As signaling was compulsory in the noncostly condition, higher imitation levels were found (Fig. S2; Table S4).

The communication score also depended on the scale of competition and on whether signaling was costly. Higher communication scores were achieved under global than under local competition, and lower ones were achieved when signaling was costly (and optional), as opposed to when it was noncostly and compulsory (Fig. 2B; Table 1A). The significant interaction between global and costly shows that

Table 1

Linear mixed-effects model fits on (a) the group's communication scores and (b) the group's total points at different scales of competition (i.e., local/global) and cost of signaling (i.e., costly/noncostly) as fixed effects and players ID and session as random effects

(A) Group communication score		
Fixed effects	Estimate (S.E.)	<i>p</i>
Local/noncostly (intercept)	0.48 (0.03)	<.001 <sup>a</sup>
Costly <sup>b</sup>	−0.28 (0.04)	<.001 <sup>a</sup>
Global <sup>b</sup>	0.12 (0.04)	.004 <sup>a</sup>
Costly×Global <sup>c</sup>	0.12 (0.06)	.046 <sup>a</sup>
Random effects	Variance (% of total)	
Player 1 ID	0.0007 (2.5)	
Player 2 ID	<0.0001 (0)	
Player 3 ID	0.0045 (16.0)	
Session	0.0012 (4.2)	
Residual	0.0215 (77.4)	
(B) Group total points		
Fixed effects	Estimate (S.E.)	<i>P</i>
Local/noncostly (Intercept)	219.5 (9.2)	<.001 <sup>a</sup>
Costly <sup>b</sup>	−3.1 (9.8)	.75
Global <sup>b</sup>	−28.1 (12.1)	.023 <sup>a</sup>
Communication score <sup>d</sup>	−0.4 (18.5)	.98
Costly×Global <sup>c</sup>	9.0 (13.8)	.51
Costly×Communication score <sup>c</sup>	8.6 (23.0)	.71
Global×Communication score <sup>c</sup>	52.2 (22.6)	.023 <sup>a</sup>
Costly×Global/Communication score <sup>f</sup>	−5.9 (28.7)	.84
Random effects	Variance (% of total)	
Player 1 ID	2.7 (1.7)	
Player 2 ID	23.6 (15.2)	
Player 3 ID	<0.001 (0)	
Session	19.9 (12.8)	
Residual	109.6 (70.3)	

*p* values are derived from *t* tests.

<sup>a</sup> Significant.

<sup>b</sup> Estimates relative to the local/noncostly treatment.

<sup>c</sup> Estimates relative to the costly and global estimates.

<sup>d</sup> Slope estimate in the local/noncostly treatment.

<sup>e</sup> Slope estimates relative to local/noncostly slope estimate.

<sup>f</sup> Slope estimate relative to the local/noncostly and global/noncostly slope estimates.

the effect of including a cost (combined with allowing signaling be optional) resulted in a stronger decrease in communication scores under local than under global competition (Fig. 2B; Table 1A).

Fig. S1 shows that increasing signaling frequencies led to increasing imitation frequencies and increasing informativeness in the colors, irrespective of the level of competition. Imitation frequencies were also correlated with color informativeness, except under local/noncostly and global/costly competition where some groups sent a different color for each symbol (i.e., high color informativeness score) but did not imitate received signals (i.e., low imitation frequency)—hence, the absence of correlation (Fig. S1).

### 3.2. Benefits of communication

The groups' total number of points in the learning task was significantly correlated with the communication score under global competition only (the effect of the communication score under local competition was not significant, but the interaction between communication score and global was; Table 1B). Also, the slopes of the relationship between communication score and group score under local competition did not differ between the costly and noncostly conditions (costly×communication score interaction not significant; Table 1B). Similarly, the slopes of the relationship between communication score and group score under global competition did not differ between the costly and noncostly conditions (costly×global×communication score interaction not significant; Table 1B). For clarity, Fig. 3 shows the relationship between the communication score and group total number of points for each treatment separately. The corresponding analyses for each treatment separately are shown in Table S1.

A critical measure of the effectiveness of communication is the performance of the last individual who played the learning task in a game, that is, the third player's probability of hitting the correct symbol with the first click. When concentrating on the groups who finished with the highest number of points in the second half of a block, we found that the frequency of hitting the correct symbol with the first click increased with the number of games played under global competition (Fig. 2C; Table S2). This frequency increased such that after game 6, players chose the correct symbol more frequently than would be predicted by chance (i.e., more than one third of the time). Under local competition, however, players did not seem to become more likely to choose the correct symbol.

### 3.3. The importance of early interactions

Not all groups managed to develop an efficient communication system under global competition. When we tested whether a group's success depended on the amount of cooperation and imitation during the first interactions, we found indeed a positive correlation between imitation frequency during the early interactions (i.e., three first

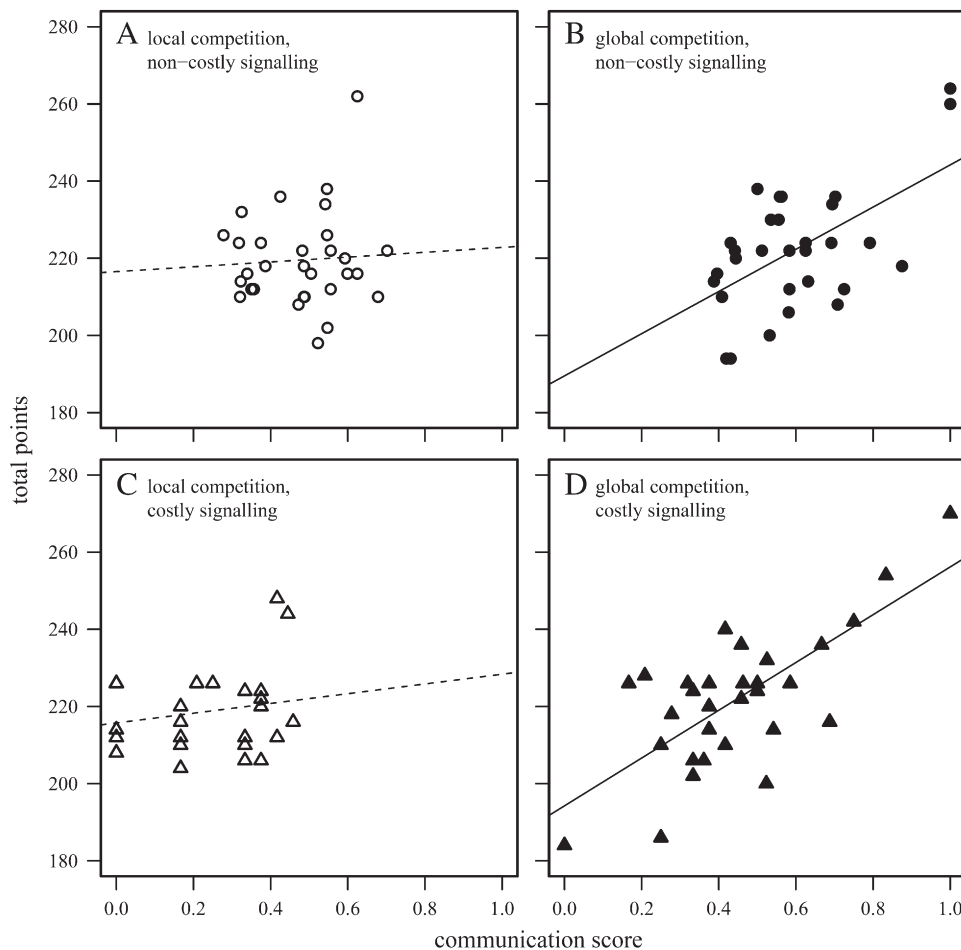


Fig. 3. The benefits of communication. Groups with a higher communication score also finished with a higher total number of points under global competition (B and D), but not under local competition (A and C). See Table S1 for statistics. Regression lines were drawn from the linear mixed-effects model estimates on the total number of points per group, with communication score as fixed effect within each of the four treatment combinations and with session as a random effect (solid: significant linear relationship, dashed: nonsignificant).

games) and imitation frequency during the nine remaining games (Fig. S3). This correlation was not found under local competition where groups either increased or decreased their imitation frequencies after the first interactions when signaling was costly (Fig. S3c). The signaling frequency during the early interactions was also positively correlated with the signaling frequency during the nine remaining games under global competition (Fig. S4b). This correlation was also found under local competition (Fig. S4a), suggesting that some cooperative groups kept their signaling frequency high even though they were losing points.

#### 4. Discussion

Our results show that the scale of competition has a strong influence on the establishment of shared communication conventions between individuals. Introducing a conflict between group members by letting them compete locally had a negative impact on communication such that subjects did not reach a common system of signals and meanings

(communicative cooperation). This was due to group members sharing different interests and resulted in a babel of unintelligible signals. In this case, individuals relied on individual learning by using trial and error to obtain as many points, as opposed to relying on social learning from other group members. While competing globally, however, several groups managed to establish effective communication, thereby increasing the number of points earned during their individual task. Global competition, therefore, not only had the effect of fostering communicative cooperation (reaching a common system of signals and meanings) but also allowed for informative communication (conveying honest information once a shared system has been acquired) to be maintained. There was no incentive for players to deceive their group members with whom they shared common interests. Our results further confirm previous observations that humans change their level of cooperation as a function of the scale of competition (Burton-Chellew et al., 2010; Puurtinen & Mappes, 2009; West et al., 2006), highlighting the importance of considering the scale of competition in studies of cooperation and communication.

Our study also shows empirically the difference between communicative and informative cooperation. In fact, informative cooperation could not take place unless communicative cooperation was present first, which occurred under global competition only. Under local competition, communication scores reflected low or at least random information content in the sent colors, and the lower imitation frequencies observed suggests that players deliberately sent different colors to prevent communication from arising. Moreover, players could not deceive each other by sending different signals than the established ones, since no effective communication emerged in the first place. However, a change in the scale of competition over time has been shown to modify the levels of cooperation between humans (Rand, Pfeiffer, et al., 2009), and if we had incorporated this into our design (e.g., a change in the scale of competition from global to local), it could have given incentives to players with initially overlapping interests to stop informative cooperation (i.e., conveying honest information) and start lying about the winning symbol.

When information was costly under local competition, signaling was not completely avoided, despite no communicative convention arising. One explanation could be that some players did not fully understand the task. We find this unlikely since instructions and trial rounds were played beforehand. Alternatively, players might have neglected the cost of signaling as it was relatively small compared to the average number of points a player could earn just by clicking randomly in a given game (i.e., cost of 1 point of an average of 6). The latter explanation is supported by the fact that the relationship between the communication score and the group's total number of points under global competition was not affected by including a cost and letting signaling be optional. Another explanation could be that some participants might have been genuinely willing to cooperate with their group members. It is well known in the human cooperation literature that a certain fraction of individuals still cooperate even though it is not in their interest to do so (Burton-Chellew et al., 2010; Kümmerli et al., 2010). In fact, cheap signaling, even under conflicting interests, has been shown to evolve if it allows individuals to identify each other's willingness to cooperate, but the system would then be subject to invasion from liars (Skyrms, 2002).

The fact that signaling was compulsory (i.e., the signaling frequency was 1) in the noncostly condition was more conducive to communication because it naturally led to higher imitation frequencies and more information content conveyed by the signals than if there was no signaling. For example, communication scores under local/noncostly competition were as high as under global/costly competition because of the compulsoriness as well as because only a few groups under global/costly competition managed to establish communication (e.g., three groups finished with a communication score above 0.7). We think that an additional treatment with noncostly but optional signaling would have led to similar results to the ones from the costly condition,

since players seem to have neglected the cost of signaling (as discussed above).

While in many experiments on the emergence of communication, participants were told how to communicate (e.g., with a drawing medium or with existing words or syllables), in our study, we explicitly avoided using the words “communication,” “information,” and “signal.” As such, no efficient communication could develop unless all three individuals in a group first realized that it was in their interests to communicate under global competition, then learned how they could use the colors to communicate, and finally coordinated their signals. Indeed, not all groups managed to develop effective communication (e.g., six groups under global competition finished with a communication score below 0.3; one group did not signal at all). Communication has been shown to arise in studies that had a far less intuitive design than ours with regard to communication because participants had to create their own signals or did not even have a dedicated channel for communicating (e.g., Galantucci, 2005; Scott-Phillips et al., 2009). The question of how successful groups, in our experiment, noticed that colors could be used as signals is not trivial, and these capacities are probably subject to a large individual variation (e.g., Scott-Phillips et al., 2009). However, we found no relations between communication quality and individual measures such as age, sex, field, and year of study (data not shown). Those groups that managed to exchange reliable information under global competition had, on average, effective signals after six games. This is consistent with previous studies demonstrating the rapid emergence of communication after several interactions (Galantucci, 2005; Healey et al., 2002; Selten & Warglien, 2007). In these previous studies, however, individuals interacted in pairs (Galantucci, 2005; Healey et al., 2002; Selten & Warglien, 2007), which is more conducive to coordination and emergent communication than in our three-person game.

Recently, Roberts (2010) could link communication and cooperation in an experimental setup with humans. In this study, the number of interactions with team members relative to the number of interactions with members from other teams was varied. Players had to recognize when they were interacting with team members and, thus, when to cooperate, using a previously given “alien” language from memory. This allowed the investigation of dialect formation (arising from errors or “mutations”) within teams. In contrast with our study, signals and their corresponding meanings were initially given, and participants always shared the same interests with their team members. Interestingly, Roberts (2010) found that, by communicating, participants could identify other team members and tried to deceive competitors by being perceived as allied. In their case, deception could take place only because a language already existed, and players interacted alternatively with individuals sharing the same or different interests.

In our setup, individuals could only see the signals they received. Such conditions are quite restrictive for the

emergence of communication because they require many interactions until all group members have received enough signals to start associating them with meanings. However, under more realistic conditions, where interactions are public, bystanders could also intercept signals (intentionally or not) between the transmitter–receiver pair. In the presence of such eavesdropping, communication seems more likely to emerge and to become more complex if individual interests converge (Komarova & Levin, 2010). On the other hand, in situations where groups compete with each other, strategies to avoid eavesdropping would be favored.

To our knowledge, our study is the first to experimentally examine the link between group coordination, cooperation, and the scale of competition in understanding how shared communication conventions arise. We have shown that only when individuals share (at least partially) the same interests as those they interact with could communicative cooperation take place. Once individuals were able to coordinate signals to establish conventions, informative cooperation could arise and signals could be used in a honest way, leading to effective shared communicative conventions. We have demonstrated that the scale of competition is essential in driving these processes, both when signaling is cheap and when signaling is costly.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at [doi:10.1016/j.evolhumbehav.2011.09.007](https://doi.org/10.1016/j.evolhumbehav.2011.09.007).

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