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PNAS published online Apr 20, 2007;
doi:10.1073/pnas.0702077104

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Contributed by Reinhard Selten, March 6, 2007 (sent for review November 3, 2006)

We investigate in a series of laboratory experiments how costs and benefits of linguistic communication affect the emergence of simple languages in a coordination task when no common language is available in the beginning. The experiment involved pairwise computerized communication between 152 subjects involved in at least 60 rounds. The subjects had to develop a common code referring to items in varying lists of geometrical figures distinguished by up to three features. A code had to be made of a limited repertoire of letters. Using letters had a cost. We are interested in the question of whether a common code is developed, and what enhances its emergence. Furthermore, we explore the emergence of compositional, protogrammatical structure in such codes. We compare environments that differ in terms of available linguistic resources (number of letters available) and in terms of stability of the task environment (variability in the set of figures). Our experiments show that a too small repertoire of letters causes coordination failures. Cost efficiency and role asymmetry are important factors enhancing communicative success. In stable environments, grammars do not seem to matter much, and instead efficient arbitrary codes often do better. However, in an environment with novelty, compositional grammars offer considerable coordination advantages and therefore are more likely to arise.

communication | compositionality | economics of language

According to the linguist André Martinet, language is shaped "by the permanent conflict between man's communicative needs and his tendency to reduce to a minimum his mental and physical activity" (1). This means that the benefits of communication are compared with the memory and articulation costs of linguistic expression. A tendency toward the optimization of the difference between benefits and costs is postulated.

Even if many contemporary linguists would disagree with Martinet's view, it is widely recognized that some sort of economizing principle is at work in shaping human language: for example, Chomsky's (2) "minimalist program" relies on assumptions of economy of derivation and representation, and on principles of least effort. However, he maintains that "questions concerning abstract computational mechanisms are distinct from those concerning communication" (3). Another interesting approach to language structure is optimality theory (4), which postulates a process of constraint satisfaction that guides the shaping of linguistic outputs.

A recent, growing body of literature has exploited principles of communication effectiveness and efficiency to model, mathematically or by computer simulation, the emergence of grammatical languages from initial no communication (5–10). As will become apparent later, the basic models used in this literature have some resemblance with the structure of our experiments.

Moreover, we should mention a long tradition of using principles of least effort to explain and model language statistical regularities like Zipf's law in word distribution (11–13).

There is also a small but growing literature on the economics of language that relates language structure to cost–benefit considerations. On the theoretical side, Rubinstein (14) has shown how optimization considerations can contribute to explain the properties of binary relations appearing in natural language. Blume (15) has modeled how learning efficiency is favored by modularity of language. Weber and Camerer (16) report an experimental study of the emergence of a common code based on natural language under efficiency pressure.

The experiments described here try to explore how costs and benefits of linguistic expression affect the emergence of simple languages or codes in a coordination task. At the beginning, the subjects do not yet have a common language; they must therefore develop it in the course of interaction.

We look at the emergence of languages in an extremely simplified laboratory environment. We consider only the benefits of transferring meaning correctly and the cost of language expression. Thus, factors emphasized by sociolinguists (17) are not present in our experimental setup. This permits us to isolate the two "economic" factors.

In psycholinguistics, there is a tradition exploring how interacting individuals adapt natural language to coordinate in some unfamiliar task (18, 19). Weber and Camerer (16) have successfully extended such type of experimental design to the investigation of economic issues. Our experiments are different because our subjects cannot use a natural language but have to shape an artificial one. This permits us to put more in focus the emergence of common codes and to explore their structural properties.

Our experiments are also very different from those that investigate the acquisition of artificial grammar (20), because our focus is on the emergence of an artificial language rather than on its acquisition. Moreover, we do not look at the evolution of linguistic competence. Of course, all our subjects are already endowed with this competence. We investigate how simple languages are created by linguistically competent subjects in a situation where no common language is available in the beginning.

A recent paper by Galantucci (21) explores the emergence of graphical signs in the environment of a video game that requires cooperation of two subjects. This paper offers some interesting insights based mostly on a qualitative discussion of the behavior of 10 pairs of subjects. Our experiment was developed independently and differs in many respects from Galantucci's. First, our focus is more on the structure of language rather than the nature of signs. In our experiments, signs are predefined and have to be combined. Moreover, our communication protocol is more constrained, communication is costly (unlike in Galantucci's experiment), and the payoff structure is quite different. Finally, our experiment is based on a much broader sample of subjects, permitting a deeper statistical analysis.

In our experiments, subjects see a list of geometrical figures on a computer screen. These figures differ by shape (circle, square,

Author contributions: R.S. and M.W. designed research; R.S. and M.W. performed research; R.S. and M.W. analyzed data; and R.S. and M.W. wrote the paper.

The authors declare no conflict of interest.

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This article contains supporting information online at www.pnas.org/cgi/content/full/0702077104/DC1.

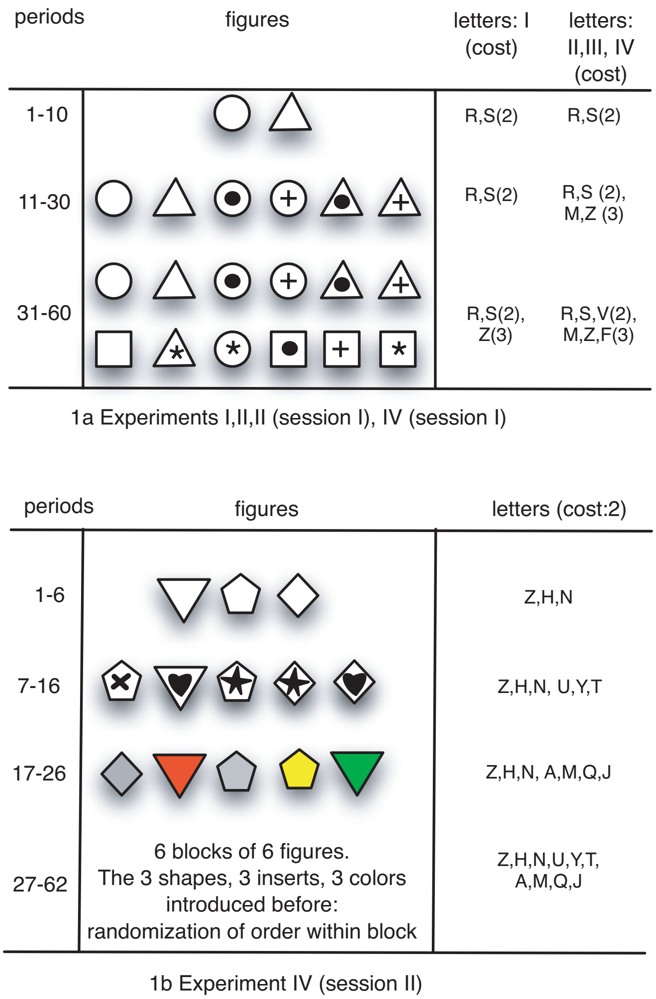

Fig. 1. The experimental treatments.

Fig. 2. Figures in experiment IV's second session.

etc.), inserts (star, dot, etc.), and sometimes by color. To each of the figures in the screen, a subject must assign a message, a string of permissible letters. The subjects interact anonymously in pairs. They both always face the same list of figures and the same repertoire of permissible letters. In each period, one subject and one figure are randomly chosen, and then the message specified by the code is transmitted to the other player. The transmission is successful if and only if the messages specified by both codes are the same. A payoff is obtained for a communication success, but the letters have costs that must be borne by the sender. After each period, both players receive feedback on the chosen figure and the messages specified by the code of the receiver. After receiving the feedback, they can change their codes.

We are interested in whether a common code is developed, and what enhances its emergence. We also explore the structure of common codes, which may or may not have a grammatical structure. We compare environments that differ with respect to the size of the repertoire of permissible letters and with respect to novelty (i.e., the frequency with which new figures occur).

We conducted four versions of our experiment. The rules apply to all of them. The versions differ with respect to the figures presented and the repertoire of permissible letters and their costs. All experiments begin with a small number of figures and small repertoires (two or three figures and the same number of letters). The set of figures and the repertoire of letters expand over time in different ways.

Fig. 1 gives an overview of the four versions of our experiment (referred to as experiments I, II, III, and IV). It shows which figures were presented in which periods and which repertoire of letters was available. We use the name "block" for a section of an experiment in which figures and repertoire of letters remain unchanged. Each of the experiments I and II had only one session of 60 periods. In experiments III and IV, the participants stayed for a second session, which began after a short pause in which they could not communicate. The first and the second session of experiment III were identical with experiment II. The same is true for the first session of experiment IV, but not for the second one. There, first, sufficiently many features are introduced, to induce some familiarity with the structure of the environment. Then, 36 new combinations of three features (shapes, inserts, and colors) are presented in blocks of six and selected for communication just once (Fig. 2). This "novelty" structure was explained to the subjects just before the beginning of the second session. Also, in experiment III, subjects were not informed about the conditions of the second session before the end of the first one.

Results

The Impact of the Size of the Repertoire. In our first experiment (I), only two (and then three) letters were permissible. After running the experiment, we observed less convergence to common code then we had expected. In the literature on language evolution (22), it is common to emphasize the role of the human capability to produce a great variety of phonetic signals for the development of linguistic competence. Therefore, we supplied a larger repertoire of permissible letters in all further experiments.

Table 1 reports results of experiments I on the one hand and experiments II and the first sessions of III and IV on the other hand. The latter three sessions are identical and can therefore be pooled. We refer to them as the "pool."

The table shows in how many cases a common code was reached. We say that a pair has reached a "common code" if the codes of the two players for the last period agree with respect to all figures chosen for communication in the course of the game. (Because figures are chosen randomly, some of them may never be chosen for a pair. Of course, one cannot expect code agreement for such figures.)

As Fig. 1 shows, experiment I and the pool differ only with respect to the size of the repertoire of the letters. This difference is important for the emergence of a common code. This effect is significant on the 10% level ($P = 0.069$) according to a Fisher's

Table 1. Pairs reaching a common code in experiments I and II–III–IV (pool)

	Common code	No common code
Pool	28	29
Experiment I	5	14

exact test, one-tailed. This suggests that a greater repertoire is in fact facilitating the emergence of linguistic coordination.

From a logical point of view, two symbols are sufficient for the construction of a code. In principle, communication could be based on a binary code. However, it seems to be the case that the availability of a sufficiently large variety of letters not only makes it easier to achieve communication efficiency but also has a cognitive effect that facilitates linguistic coordination. Later, in connection with our discussion of grammars, we shall come back to this point.

The Influence of Role Differentiation and Efficiency on Payoffs. In this section, we restrict ourselves to the analysis of the pooled experiments (II, and the first session of III and IV). We shall look at rank correlations among a number of aggregate variables defined for pairs as follows:

Agreement. Average number of figures with the same code for the two players, over all periods.

Changes. The sum of all code changes for all periods. A code change is a change of a message attached to a figure (e.g., if, in a period, the messages for three figures are changed, this counts as three code changes).

Asymmetry. The fraction of all code changes made by the player with more code changes.

Code costs. The sum of code costs for all figures and both players averaged over periods.

Payoff. The sum of all net payoffs for both players in all period.

Fig. 3 shows a graph whose nodes stand for the variables defined above and whose edges indicate Spearman rank correlations significant at least at the 1% level, one-tailed. The number at an edge is the Spearman rank correlation coefficient of the variables associated to the points connected by the edge.

A causal interpretation of Fig. 3 from left to right suggests itself: code costs reflect the efficiency of coordination within a pair. The higher the code cost, the lower its payoff. A high degree of asymmetry results in few changes and much agreement. Payoffs in turn are higher the more agreement and the fewer changes there are. The negative correlation of changes and agreement is a consequence of the common causal influence of asymmetry.

Total asymmetry means that one of the players acts as the leader (or the teacher) and the other as a follower who passively adapts to the leader's code. This role differentiation avoids

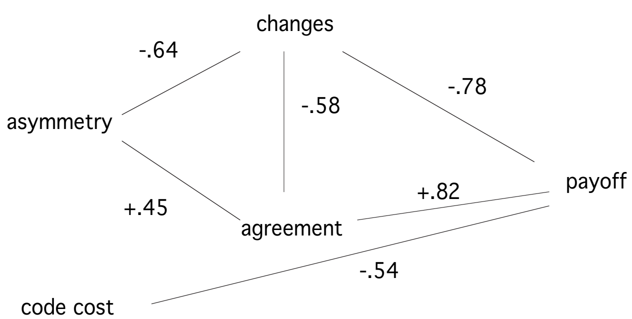

Fig. 3. Spearman rank correlations among aggregates for pairs significant at least on the 1% level, one-tailed.

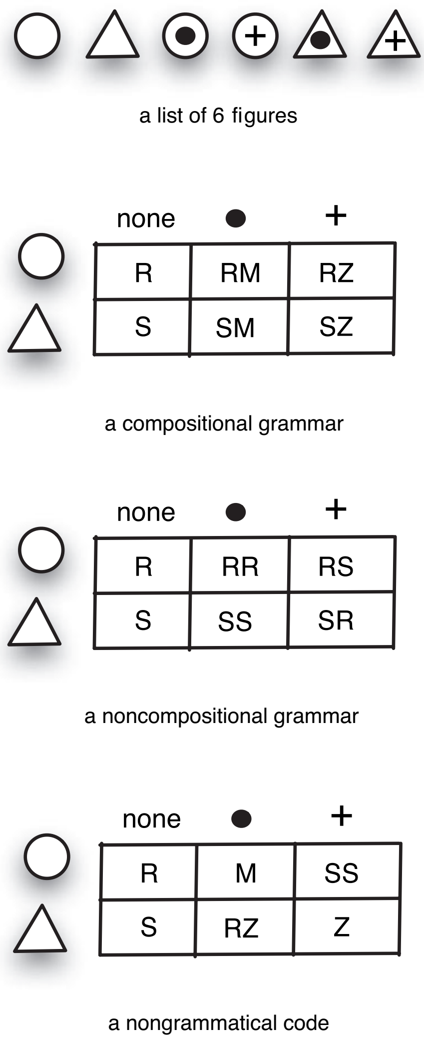

Fig. 4. Types of code.

confusion by simultaneous changes: if, after a period, both players adjust to the code of the other, differences in codes are not reduced. Asymmetry ensures that any change reduces code differences.

It is good for the payoff of the pair if they choose low-cost codes and define asymmetric roles as early as possible. The two factors seem to be independent: there is no significant correlation between asymmetry and code cost, notwithstanding the relatively high number of 57 observations.

Language Structure: Forms of Grammar. It is a further purpose of this study to investigate factors affecting the structure of common codes. We distinguish between common codes with and without a grammar. A code has a compositional grammar if it is obtained by mapping instances of features to letters or strings of letters, called graphemes, and by arranging them in a fixed order of features. Thus, there may be two features, shapes and inserts, two instances of "shape," circle and triangle, and two instances of "insert," dot and cross. The compositional grammar shown in Fig. 4 uses the graphemes "R" and "S" for circle and triangle, and "M" and "Z" for dot and cross. In the fixed order, shape precedes insert. Thus, our use of the word "compositional" conforms to the tradition that begins with Frege (23), according to which a language is compositional when the meaning of a

Table 2. Communication achievement of pairs in the last period

No common code	Common code: Ungrammatical	Common code: Noncompositional grammar	Common code: Compositional grammar	Number of pairs, all experiments
66 (58%)	32 (28%)	1 (1%)	14 (12%)	113

In experiments III and IV, the two sessions are counted separately.

complex expression can be derived uniquely from the meaning of its constituents and the rules for combining them. This definition survives in modern semantics (24).

One also finds noncompositional grammars and ungrammatical codes in the data. Admittedly, we cannot offer an exact general definition of the boundary line between these two categories. We speak of a noncompositional grammar if a principle suggests itself that generates the relationship.

The noncompositional grammar of Fig. 4 maps circles and triangles to the letters "R" and "S," respectively, and maps the instances of inserts into the number of letters. Obviously, the code has a regular structure but not a compositional one. The nongrammatical code of Fig. 4 also follows a principle. The first letter stands for the shape, a star is indicated by two equal letters, and the cross by two different letters.

Of course, our concept of grammar does not capture the intricacies of the use of the term in linguistics. It does not go beyond what is called a "protolanguage" by Jackendoff (25) (i.e., a combination of linear order and semantic roles). However, it is sufficient within the frame of our experiments.

Table 2 shows what kind of status, with respect to a common code, pairs have achieved in the last period. As one can see, no common code is reached in the majority of all cases. Among the common codes, approximately two of three are ungrammatical. Noncompositional grammars are rare, and grammars, if they are present in the last period, tend to be compositional.

Extendability and the Persistence of Grammars. At the end of the experiments, most grammars are compositional, but many noncompositional grammars can be found at the end of block two. In the course of our experiments (with the exception of the second session of experiment IV), new figures and new letters are introduced from one block to the next. The old figures remain in the list, and new ones are added. We speak of an "extension" of an earlier code if the figures that were present before are associated with the same messages as before. We say that a common code of a pair at the end of block two is "persistent" if, at the end of block three, this pair has a common code that is an extension of its earlier code.

Table 3 shows the persistence of different types of grammars in the sessions of the pool. The compositional grammars are all persistent, whereas all noncompositional ones are nonpersistent (Fisher's exact test yields a significance of 1%, two-tailed). Moreover, all pairs with noncompositional grammars at the end of block two have no grammar at the end of the session.

The results show that compositional grammars are easily extendable, whereas the same is not true for noncompositional grammars. The easy extendability of compositional grammars is facilitated by the availability of one new letter for every new instance of a feature. The extendability of compositional grammars seems to be related to the concepts of productivity and systematicity, usually associated to compositionality in the semantic literature (26); however, we do not want to go into more details in this respect here.

Actually, there is no necessity to use a different letter for every instance of every feature. A fixed position for shapes, positions, and colors has to be fixed anyhow, given the constraints of the experiment. Thus, the same letter could be used for a circle, a star, and blue. However, it seems to be very difficult for the subjects to devise positional codes that rely heavily on positions of letters to convey meaning. This is probably an important reason why less common codes are found in experiment I, where only one additional letter is made available for two new instances of features in the transition from block two to block three. Therefore, no compositional grammar was ever adopted by a pair during experiment I. In this respect, it is interesting that a full positional system of expressing numbers evolved only relatively late in history (27). Less efficient systems like the roman numbers lasted for a long time before positional notations were introduced.

Emergence of Grammar in Response to Expressive Needs. An advantage of grammar is the possibility to express new contents never expressed before, but nevertheless having them understood by other speakers of the same language. Bickerton (28) and Pinker and Bloom (29) discuss this point from an evolutionary standpoint (although from different perspectives). This advantage counts in a sufficiently rich environment.

Experiment IV provides such an environment in the second session. After introducing sufficiently many combinations of two features, 36 new combinations of three features are presented just once. This is explained in the instructions before the session begins [see supporting information (SI) *Text*].

In the second session of experiment IV, only 5 of 17 pairs developed grammars, all of them compositional, and reached agreement soon after the beginning of the last phase.

Table 4 shows the average payoffs for pairs with and without grammars in experiment IV's second session. All five pairs with grammar had higher payoffs than each of the 12 pairs without grammar (the Mann–Whitney U test yields a significance of 0.001 for this).

Compositional grammars are highly successful in the novelty-providing environment of experiment IV and languages without such grammars are far less successful. The relationships between grammar and the expressive needs created by novelty are further illustrated by the comparison between experiment III and experiment IV.

The first sessions in experiment III and IV follow the same rules. In experiment III, the same rules apply also to the second session. The comparison of experiment III and IV aims at the

Table 3. Persistence of grammar types present at the end of block two

	Persistence	No persistence
Compositional	5	0
Noncompositional	0	5

Table 4. Average payoff per pair in experiment IV, second session

Pairs in IV, second session	Average payoff
With grammar	635 talers
Without grammar	211 talers

Table 5. Code structure by independent groups, experiments III and IV

	With grammar	Without grammar
First session		
Experiment III	2	7
Experiment IV	1	5
Second session		
Experiment III	1	8
Experiment IV	4	2

exclusion of mere experience effects as an explanation of the emergence of grammars in the novelty treatment of the second session of experiment IV.

At the end of the first session of both experiments III and IV, subjects had to be reassigned to new pairs for the second session. Thus, in comparing such experiments, we will consider independent subject groups as a unit of observation (i.e., groups of participants such that there is no matching across groups in the first and second sessions).

We are primarily interested in numbers for the second session because, there, a comparison of the effects of novelty and mere repetition is possible. Fisher's exact test yields a significance of 2%, one-tailed, for the four-field table for the second session (Table 5, session 2). Significantly more groups with a grammar emerge in the second session of the novelty condition. We can exclude the possibility that the increase of the number of grammars is due to a learning effect that should also be there in the second session of the "repetitive" experiment III.

Discussion

Our experiments present a very simplistic and constrained environment for the evolution of common codes. Nevertheless, the results surprisingly reproduce many features of natural languages, and may throw light on interactive factors affecting the evolution of a language. In the following, we discuss some broader implications of our findings, which of course runs the risk of exaggerating the transferability of our laboratory results to broader contexts.

(*i*) The size of the repertoire of elementary linguistic symbols seems to be important in facilitating linguistic coordination. In the experiments of Galantucci (21), there seems to be a high rate of success in creating communication systems. We also find successful coordination (although at somehow lower rates), but our experiment I shows that a too small size of the repertoire may be a serious obstacle for the attainment of a common code. This is not only due to the fact that more symbols permit a higher degree of cost efficiency by shorter expressions but also to some properties of the human cognitive system. If the number of elementary symbols is too small, one has to rely more on positional structure. Positional systems of expressing meaning, like in the Arabic number notation, are hard to devise for the human mind, although they can be easily used once they are available, as shown by the history of mathematics.

(*ii*) In an environment in which the same messages occur many times, cost efficiency and role asymmetry are factors enhancing communicative success, whereas grammars do not offer particular advantages under such circumstances. Role asymmetry between a leader and an imitator avoids mismatches by simultaneous adjustments to the code of the other. In dialogue theory (19), the role of imitation is also emphasized as conductive to the conversational alignment of interlocutors. Our results throw additional light on this phenomenon and suggest looking more closely to how role asymmetry might facilitate alignment processes. The importance of role asymmetry (30) is clearly visible in the experiment despite the fact that there are no natural or social status differences among the subjects. In natural language transmission contexts (e.g., from parents to children, from natives to immigrants), such status differences are pervasive.

(*iii*) In stable environments as those considered in point *ii*, grammar does not matter much, and efficient arbitrary codes often do better. However, compositional grammars have the advantage of being more easily extendable to broader environmental demands. Noncompositional grammars are more fragile and are easily lost if new conditions have to be met.

(*iv*) In an environment with novelty, in the sense that often the need arises to express something that never has been expressed before, compositional grammars offer considerable coordination advantages. Therefore, under such circumstances, compositional grammars are more likely to arise. In this respect, our findings parallel and complement hypotheses proposed in the literature on language evolution (28, 29). In our experiments, all subjects have grammatical competence but they make relatively little use of it unless pressure of novelty gives them an incentive to do so.

Methods

In our experiments, the subjects sit at computer terminals and cannot communicate verbally with each other. The interaction is anonymous and only by formal messages. Subjects are randomly paired at the beginning of a session and the pairs remain the same for all periods of the session. During a session, the subjects in a pair always interact only with each other. We now shortly explain the general features common to all of our experiments. Detailed instructions to subjects are reported in the *SI Text*.

Players. There are two players.

Periods. The experiment runs over 60 (or 62) periods.

Figures. In every period, each of the two players sees the same figures on the screen, listed in different random order.

Structure of Figures. Figures have shapes, inserts, and, in one experiment, colors. These "features" have different "instances" (shapes: circles, squares, etc; inserts: dots, crosses, etc.; colors: red, yellow, etc.).

Codes. In every period, each of the two players has the same repertoire of permissible letters (e.g., "R," "S," and "T") to be used in messages that take the form of strings of permissible letters. Each player has to fix a code assigning a message to every figure. The code can be changed in every period.

Communication. In every period, one player, the sender, and a figure are randomly chosen. The message corresponding to this figure in the code of the sender is transferred to the other player, the receiver. The message is understood if the codes of the sender and the receiver agree with respect to the message assigned to the chosen figure.

Period Payoff. Each player receives 10 units of the experimental currency (taler), if the message has been understood, and zero talers otherwise. However, the sender bears the cost of the message, composed of costs for each letter in the string. The costs of letters (e.g., three talers for "R" and two talers for "S" and "T") do not change over time and are known to the players when they fix their codes.

Feedback. After each period, both players are informed about whether the message was understood. If the message was not understood, feedback is supplied to the receiver about the chosen figure and to the sender about the message attached to the figure in the receiver code.

The experiments were run at the Experimental Economics Laboratory of Trento University (Trento, Italy). In an experimental

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session, 34–40 participants were organized in fixed pairs interacting anonymously by computer terminals. Communication was restricted to the exchange of formal messages according to the rules. An experiment lasted 1–2.5 h. Subjects received monetary payoffs proportional to their earnings in talers. The conversion rate was two euro cents per taler, plus a fixed sum of five euros for their participation.

Marco Tecilla gave invaluable help writing the code of the experimental software. Phil Johnson-Laird provided helpful comments. We thank the Rovereto Cognitive Science Laboratory and the Trento Computable and Experimental Economics Laboratory for their organizational and financial support in running the experiments. Ministero dell'Università e della Ricerca Grant 2005139342 and Fondo per gli Investimenti della Ricerca di Base Grant RBNE03A9A7 contributed to the project funding.

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