Cognitive Science 29 (2005) 737–767

An Experimental Study of the Emergence of Human Communication Systems

Bruno Galantucci

Haskins Laboratories and University of Connecticut

Received 12 June 2004; received in revised form 5 October 2004; accepted 29 November 2004

Abstract

The emergence of human communication systems is typically investigated via 2 approaches with complementary strengths and weaknesses: naturalistic studies and computer simulations. This study was conducted with a method that combines these approaches. Pairs of participants played video games requiring communication. Members of a pair were physically separated but exchanged graphic signals through a medium that prevented the use of standard symbols (e.g., letters). Communication systems emerged and developed rapidly during the games, integrating the use of explicit signs with information implicitly available to players and silent behavior-coordinating procedures. The systems that emerged suggest 3 conclusions: (a) signs originate from different mappings; (b) sign systems develop parsimoniously; (c) sign forms are perceptually distinct, easy to produce, and tolerant to variations.

Keywords: Human communication; Social cognition; Situated cognition; Emergence of communication

1. Introduction

Human communication systems as we know them today are the end result of the complex processes that interleaved the cognitive abilities of many individuals, over many generations, into a socially shared set of conventional behaviors and artifacts (A. Clark, 1997; de Saussure, 1916/1983; Hutchins, 1995; Millikan, 1984, 2004; Tomasello, 1999; Wittgenstein, 1953). The scientific understanding of such complex processes would greatly benefit from direct observations of the emergence of human communication systems or, even better, from experiments that elucidate how these systems emerge and develop in the context of joint human activities. Unfortunately, however, a major obstacle has prevented this from happening, and that is that there are very few opportunities to observe directly the emergence of human communication systems. Established human communities have very little need to originate novel communication systems. For the most part, they acquire the systems in place for previous generations of users.

There are exceptions of course. They include pidgin communication systems that originate when members of two or more language communities need to communicate (e.g., Bickerton,

Requests for reprints should be sent to Bruno Galantucci, Haskins Laboratories, 300 George Street, New Haven, CT 06511. E-mail: bruno.galantucci@haskins.yale.edu

1981), sign languages created from scratch (Kegl, 1994), and homemade sign systems developed by deaf children interacting with hearing parents (Goldin-Meadow & Feldman, 1977; Goldin-Meadow & Mylander, 1998). However, these exceptions do not provide opportunities for experimental manipulation within the context in which the novel communication systems emerge and evolve.[1]

An indirect method that permits experimental manipulation is provided by computer simulations of interactions among artificial agents. The latter line of research has offered important insights into how communication systems might emerge (e.g., Cangelosi & Parisi, 2001; Hurford, 1989; Kirby, 2002; Skyrms, 2002; Steels, 1997) and how they might evolve over time (e.g., Briscoe, 2000; R. Clark & Roberts, 1993; Hare & Elman, 1995). However, although current simulations are designed to model ever richer aspects of human communication (e.g., de Boer & Vogt, 1999; Hazlehurst & Hutchins, 1998; Oudeyer, in press; Steels, 1998), there remains a wide gulf in behavioral complexity between artificial agents and humans. In other words, drawing inferences from simulations to natural human phenomena is often problematic. The experimental study of human interactions during the emergence of a communication system would provide an ideal source of complementary knowledge to that provided by simulations.

To date, most experimental research on human communication has relied on one of two options: (a) methods that entail the use of natural languages (e.g., H. H. Clark & Wilkes-Gibbs, 1986; Garrod & Anderson, 1987; Garrod & Doherty, 1994; Krauss & Weinheimer, 1964; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995) and (b) methods that entail the use of artificial languages designed by the investigator (e.g., Christiansen, 2000; Hudson & Newport, 1999; Saffran, Aslin, & Newport, 1996; Yang & Givon, 1997). Pursuing these two options has provided substantial understanding of the processes that underlie the acquisition, the use, and the change over time of linguistic structures. However, because both options rely on preestablished languages, they tap into the processes that lead to the emergence of communication systems only indirectly. A method that introduces the complexity of human behavior into a controlled experimental setting, in the absence of preestablished human communication systems such as speaking and writing, would provide an opportunity to tap into the processes that lead to the emergence of communication more directly. This article describes a study conducted with a method that exhibits such features.

The article has two sections. The first section introduces the method used for the study, both in its basic idea and in the details of one specific implementation, Game 1. The second section presents two related studies conducted using the method: Studies 1A and 1B. Study 1A was conducted with Game 1 and 10 pairs of participants and focused on the emergence of communication systems. Study 1B was conducted with two modified versions of Game 1 (Games 2 and 3) and 8 of the successful pairs from Study 1A. Study 1B focused on the development of the communication systems that emerged during Study 1A.

2. Method

2.1. General idea

The general idea behind the method is the following. Two or more humans share the virtual environment of a multiplayer video game in which each player controls one agent.

Players do not know one another's identity and play the game from different sites with interconnected computers. Success in the game critically depends on cooperation between the agents that, in turn, requires communication between the players. However, the use of standard communication systems such as speaking and writing is prevented, and the use of other preexisting means of communication such as pictorial representations or body language is minimized. In particular, players do not see each other and cannot use spoken language because they are not in acoustic contact. Only graphic communication is possible, but through a medium that prevents the use of common graphic symbols such as letters or numerals and minimizes the use of pictorial representations (e.g., drawings of humans). In other words, to reliably succeed in the game, players must converge onto a nonobvious way of using the graphic medium to extemporaneously set up a communication system. If this occurs, two opportunities arise for research. On the one side, the emergence of a human communication system becomes observable under conditions that can be manipulated. On the other side, if the players who generated the communication system play a different game in which the same communication medium is used, we may observe the development of the original communication system, due to repeated use and/or adjustments to new communicational demands.

2.2. *An implementation of the idea: Game 1*

Game 1 was a simple implementation of the general idea introduced previously. The game was played by pairs of participants, its environment was composed of four virtual rooms, and the cooperative task was reduced to the coordination of two moves.

2.2.1. *Game setup*

Two adults—henceforth Players A and B—participated in a real-time two-dimensional video game with interconnecting computers located at different sites (Fig. 1A).

Players A and B each used a computer keyboard to control the movements of an agent in a virtual environment composed of four intercommunicating rooms (Fig. 1B). Each room in the game was marked by a different icon (Fig. 1B). Players saw the environment one room at a time, the room in which their agent was currently located (Figs. 1C and 1D).

As an agent moved through one of the doors of the current room, the room that was displayed to the player controlling the agent changed according to the environment layout (Fig. 2). When both agents were in the same room, they were visible to both players (Fig. 2B); otherwise, a player had no direct visual information about the location of the other player's agent (Fig. 2A).

2.2.2. *Game logic*

Players engaged in a cooperative game. At the beginning of each round of the game, the agents were located in two different rooms at random. The players' goal was to bring the agents into the same room but limit each agent to a single change of room. If the two agents were not in the same room when players completed their moves, the round was lost.[2] The end of the round was signaled to players by the change in score and the appearance of four squares at the corners of the room they were in (Fig. 2B). A new round started whenever both agents entered one of the squares, either in the same or in different rooms. This reset procedure gave the pair

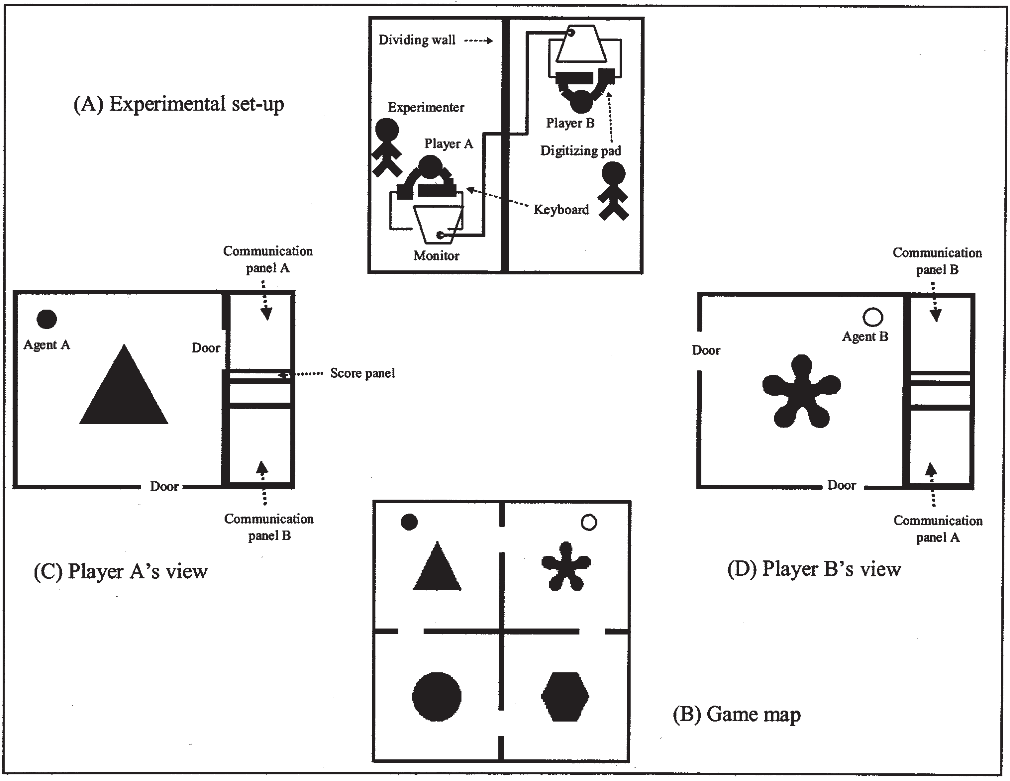


Fig. 1. Overview of the basics of the game. (A) Experimental setup. (B) Game 1 map. (C) Player A's view of the map. (D) Player B's view of the map.

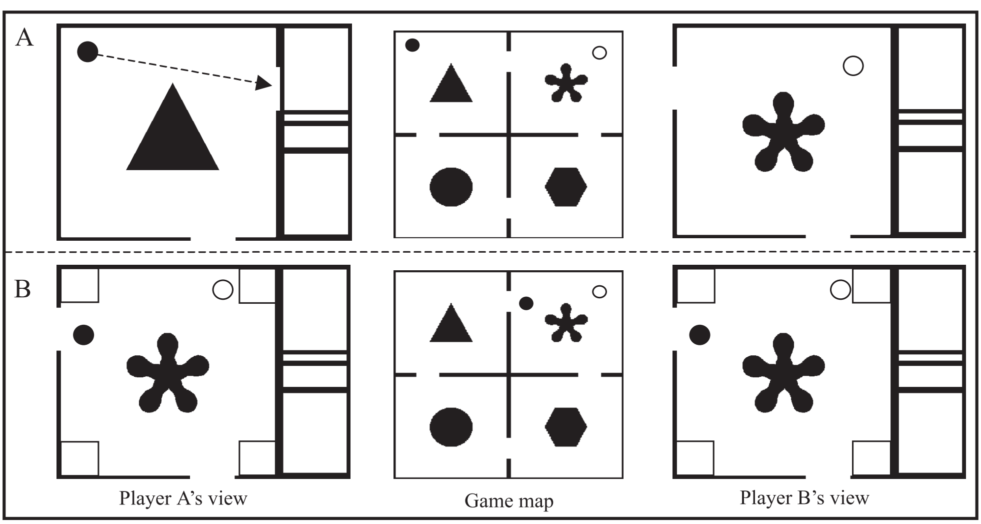
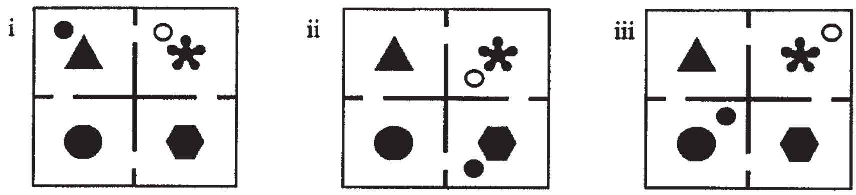


Fig. 2. A move in the game. (A) Agents are in different rooms. Player A's agent (black dot) moves rightward from the triangle room. (B) Player A's agent has passed through the doorway and found Player B's agent (white dot) in the adjacent room. Notice that, when in the same room, players see the same display.



In the 4 room version of the game presented here a rather simple logic holds and the chance level performance can be easily computed. There are only two possible initial scenarios: in (i) and (ii) agents are in adjacent rooms; in (iii) agents are in non adjacent rooms (henceforth double-move scenario). In both cases, the odds of winning by chance are 50%. As for (i) and (ii) we have a simple 50% choice: the player that moves his/her agent first can either choose the winning move (ending into the room where the other agent is) or not, with equal probability. As for (iii), let us consider the case in which Player A moves his/her agent first. Given the layout of the rooms, after Player A's move the agents must be in adjacent rooms and Player B's move falls under the same logic of (i) and (ii). The same reasoning holds if Players B moves his/her agent first.
The logic would get a bit more complicated if we were to consider the possibility that one player made more than a room change or that the two players changed rooms simultaneously. However, both cases are highly improbable. The former case is improbable because players are told that a double room change by a single player leads to an automatic loss and the latter because the program that operates the game samples the agents' locations at 20 Hz., while the moves occur in a time window that typically ranges from 15 to 45 seconds.

Box 1. Chance-level performance in Game 1.

shared control over the game's pace, allowing indefinite extensions of the time in between rounds. During this time, agents could freely move around the environment.

Chance-level performance in the game was 50% (see Box 1 for an explanation) and could be improved only if information about the location of the agents and/or the intended movements was communicated.

Once this occurred, however, the game reduced to an easy win. Players had a common score that was visible on both monitors (Fig. 1C). The score decreased by 1 point a min throughout the game. Also, the score decreased by 4 points for a loss and increased by 2 points for a win. Under these scoring conditions, chance-level performance led to a quick decrease in the score over time. The pair's score was initially set at 50 points, and players were told that their goal was to achieve 100 points as soon as possible.[3] If the score reached zero, it ceased to drop.

2.2.3. Communication medium

Players could not see or hear each other, but they could communicate by using a magnetic stylus on a small digitizing pad.[4] The resultant tracings, relayed to the communication panels of both players (Fig. 3A), faded quickly (Fig. 3B). Moreover, whereas the horizontal component of the stylus' motions directly controlled the horizontal component of the trace's motion on the panel, the vertical component of the trace's motion was independent of the stylus' motions, moving with a constant downward drift (Fig. 3B).

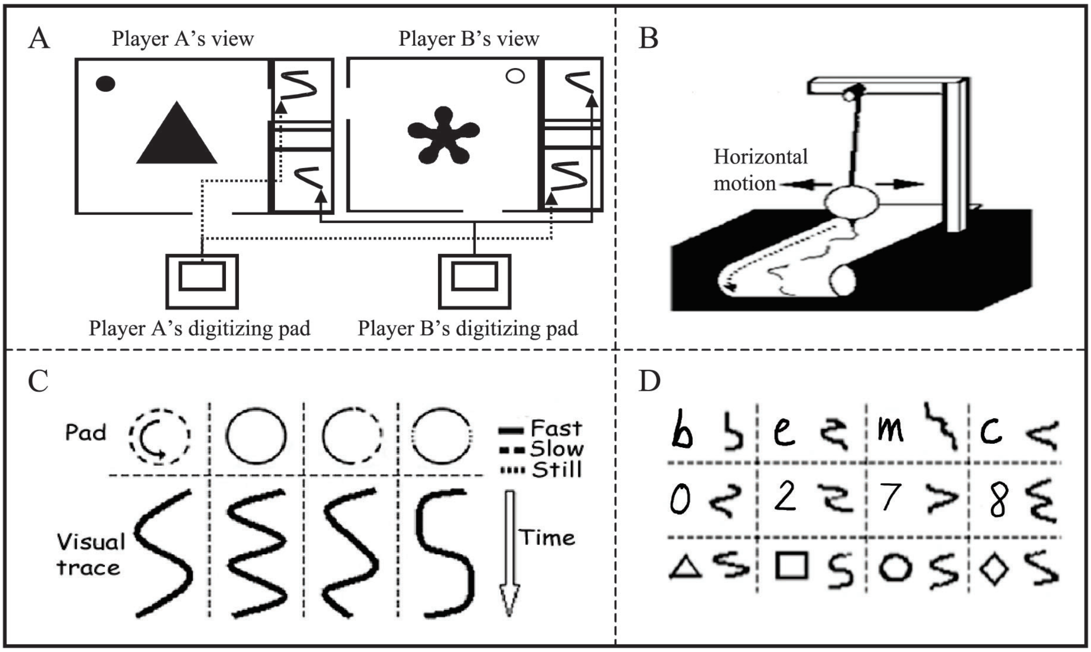


Fig. 3. The communication medium. (A) The signal generated by players' digitizing pads is relayed to both players' communication panels. (B) The signal has the properties of a quickly fading intermittent time series such as the signal generated by a seismograph that allows discontinuities. (C) The visual outcome of the same geometric shape depends on the velocity profile of the drawing movement. (D) How the drawings of familiar letters, numerals, and shapes appear on the communication panel.

The design of the communication medium reflected three main desiderata. One was to reproduce in the visual domain fundamental properties of spoken communication. In particular, signals quickly faded (Fig. 3B) and the relation between actions and their perceptual consequences was not straightforward (Fig. 3C).[5] A second desideratum was to systematically prevent the use of common graphic symbols (e.g., letters or numerals) or direct pictorial representations (Fig. 3D). A third was to provide participants with a novel signal for which there was no preestablished dimension of variation for coding signs. That is, signals' properties as diverse as amplitude, frequency, thickness,[6] location on the panel, presence versus absence, and so forth, could all become dimensions of variation to distinguish signs.

3. Study

3.1. Study 1A: The emergence of communication systems

3.1.1. Procedure

Ten pairs of participants were recruited to play Game 1. Players in a pair played the game from different sites, they did not know each other's identity, and precautions were taken to ensure that they did not discover each other's identity before the end of the study.[7]

Before playing the game players were briefly instructed (see Appendix A) and informed that their partners received the same instructions. Players did not have access to the map shown in Fig. 1B and did not know the transformations underlying the communication medium. However, they were encouraged to practice for a few minutes by exploring the environment and the communication medium before beginning to play the game. After the brief exploratory phase, players were encouraged to focus on the score as their primary goal in the game,[8] and communication with the experimenter in the room was reduced to a minimum. However, players were asked to comment aloud about salient moments in their playing and were occasionally prompted by the experimenters to provide more details about their behavior or the behavior of their partner.

The score and the agents' location were automatically and continuously recorded by the program that ran the game. On "solving" the game (i.e., on reaching a score of 100 points), players were tested in a separate session designed to assess the communication system developed by the pair (test session).

3.1.1.1. Test session. In the test session, players were asked to play the game for 10 min. For the first 5 min they played without the communication medium; then they played with it. The difference between the score obtained while the pair played in the presence of the communication medium (communication score [CS]) and the score obtained while the pair played without it (no-communication score [NCS]) estimated the benefits of communication.

After the test of the communication benefit, each player was asked to explain in detail the communication system the pair had developed, how the system was developed, and how it was used to solve the most common scenarios of the game (see Appendix B for details).

3.1.2. Results I: Communication systems emerge

A compact summary of performance in Study 1 is provided by Fig. 4. The figure depicts the changes in the cumulative scores of the pairs over time during the game. As shown by the figure, 9 pairs (Pairs 1–4 and 6–10) solved Game 1 within 3 hr of playing (mean time for solution 76 ± 46.5 min). In other words, communication systems emerged in a relatively reliable manner, and did so quickly.

Further inspection of the plots reveals that (a) converging on a communication system was not a trivial task, as exemplified by Pair 5's failure; (b) the typical profile of the scores conformed to the profile expected on the basis of the game logic provided previously (see Section 2.2.2). In what follows (a) and (b) are discussed in some detail.

3.1.2.1. Convergence is not trivial. As shown in Fig. 4, Pair 5 was not able to solve the game. In particular, after more than 160 min of playing, Pair 5's score approximated zero. At that point the study for the pair was terminated, primarily because one of the 2 players began showing signs of increasing frustration.[9] The main problem for Pair 5 seemed to be that Player B used an inconsistent communication system. In fact, Player B had developed a system whereby the same sign could mean either the agent's current location or the location the player intended to move the agent toward. Player B seemed not to realize that, without information about which meaning was intended, the signs were ambiguous and often followed the production of the sign for current room by leaving it, miscuing Player A. When Player A began using Player B's signs consistently,

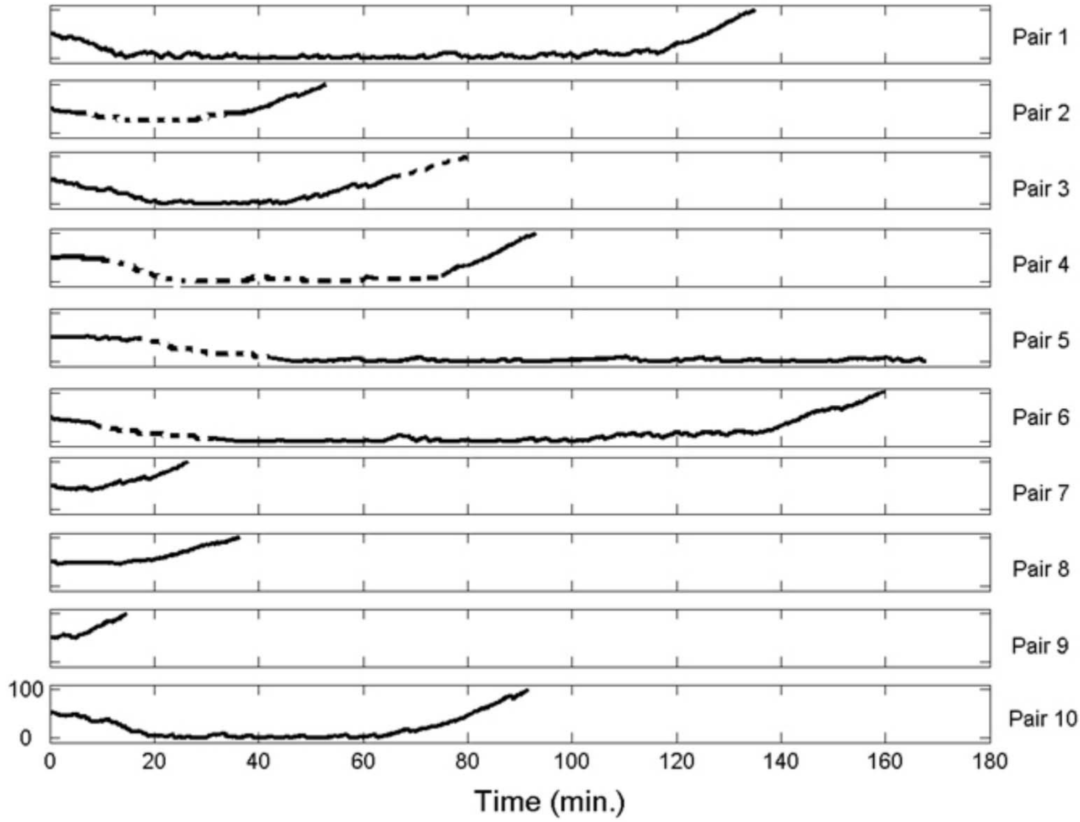


Fig. 4. Score plots for Study 1A. The ticks on the axes for Pairs 1 to 9 have the same values as the ticks on the axes for Pair 10, namely 0 to 100 points on the ordinate and 0 to 180 min on the abscissa. (The dashed portions of the lines for Pairs 2–6 signal that the lines are not plotted on the basis of the history files the computer generated for the game, but have been reconstructed on the basis of the experimenters' notes. The reconstruction became necessary because of computer failures.)

Player B suffered the consequences of the signs' ambiguity, often making the wrong moves because of an erroneous interpretation of the signs. However, Player B did not make explicit efforts to change the situation and did not consider any of the many attempts to stabilize the signs' meanings that Player A proposed. In other words, solving Game 1 is not a trivial matter.

Also, although Pair 6 solved Game 1 in 152 min, its involvement in the study was terminated after solution because Player A had to be repeatedly cued by the experimenter on how to play the game effectively. For example, at the beginning of the game Player A was convinced that the game was a matter of luck ("You cannot use your brain to decide; it's luck") and that players could not do much to improve the pair's performance. In particular, Player A did not consider using the communication medium for most of the first hour of playing ("You can't draw or do useful stuff with it") and, when told that the presence of a partner was an important part of the game, began thinking that Player B was a confederate, who intentionally pursued loss in the game. Due to the repeated interference with the spontaneous behavior of the participant, the measures of Pair 6's performances are not comparable with the measures from other pairs and will not be considered in the rest of the analyses presented here.

3.1.2.2. The score accurately captures the presence or absence of communication. Inspection of Fig. 4 reveals a typical temporal pattern for the score: (a) It rapidly falls to zero at the beginning of the game (Pairs 1, 3–6, and 10); (b) it hovers around zero for some time (Pairs 1, 3–6, and 10); (c) it rapidly rises to 100 at the end of the game (Pairs 1–4 and 6–10). As observed by the experimenters, the sharp falls and the hovering around zero points were due to the fact that players were not able to communicate with each other, whereas the sharp rises corresponded to moments at which a communication system had begun to emerge. For the pairs that did not exhibit a sharp fall in score at the beginning (Pairs 2 and 7–9), a communication system emerged very early (see Section 3.1.3.2 for further details on these pairs). Taken together, these observations indicate that the solution to Game 1 critically hinges on communication.

The conclusion is confirmed by the analysis of the test session scores (Table 1).

All pairs obtained a positive score in the presence of the communication medium, whereas only 2 pairs managed to avoid a negative score in its absence.[10] All pairs exhibited a positive difference between CS and NCS, and the overall difference between CS (mean 22.5 ± 4.3) and NCS (–16.5 ± 15.06) was statistically significant, $F(1, 7) = 58.9$, $p < .001$, $\eta^2 = .89$.

3.1.3. Results II: How communication systems emerge

Study 1A revealed the existence of two main types of processes underlying the emergence of communication systems.

3.1.3.1. Learning-by-using. The first type of process, which worked for 6 pairs (Pairs 1, 3–6, and 10), can be illustrated by an example. Imagine that a pair is just starting Game 1 and Player A, whose agent is in room X, sees the sign *S* being produced by Player B, whose agent is in an unknown room. Imagine also that Player A, knowing very little about the environment and

Table 1
Solution times, minimum scores, and test session scores for the pairs in Game 1

Pair	Time to Solution	Minimum Score	CS	NCS	CS–NCS
1	135	0	21	–25	46
2	48	41	15	–39	54
3	80	0	22	1	21
4	90	0	19	–19	38
5	No solution	0	na	na	na
6	160	0	na	na	na
7	27	34	27	–7	34
8	37	42	21	–25	46
9	15	49	26	9	17
10	92	0	29	–27	56
Average	76	20.75	22.5	–16.5	39
SD	46.47	21.09	4.3	15.06	13.44

Note. CS = communication score; NCS = no-communication score; na = not available.

about Player B's behavior, does not know how to interpret the sign and, soon after seeing it, haphazardly decides to move into a different room, say, room Y. Now suppose that on entering room Y, Player A finds the partner there. At this point Player A can conclude that the probability that Player B uses sign *S,* given that Player B is in room Y, is greater than zero.[11] Although this information does not yet specify what the sign exactly means (Is *S* part of a larger sign? Is it about location, or about movement? Is it a request, or a statement?), it offers an opportunity: the player can now *use* sign *S* and observe what happens. For example, what is the probability that Player B will end up in room Y after Player A uses sign *S*? Players in Pairs 1, 3–6, and 10 converged on the use of signs by simultaneously accumulating much information of this kind via a process that can be termed *learning by using.*[12]

It is interesting to notice that the process of learning by using here described in the context of emerging signs shares important similarities with the process of interactive input–output alignment described by Garrod and colleagues in the context of conversations using natural language (Garrod & Anderson, 1987; Garrod & Pickering, 2004; Pickering & Garrod, in press). In other words, the mechanisms that facilitate convergence onto sign systems when they are crafted anew may not be different in kind from the processes that facilitate convergence on the fine details of how to use linguistic items when selecting them from an inventory well-established within a large population.

3.1.3.2. Naming procedures. The second type of process was used by 4 pairs (Pairs 2 and 7–9) and again can be illustrated by an example. Let's imagine that Players A and B have just won a round of the game and are both in room X. At that point, Player B produces the sign *S.* Player A can draw an easy conclusion: *S* is likely about what the 2 players share at that moment, for example, the room their agents are in. Moreover, as long as the agents remain in the same room, they can specify further what they mean by a sign through pantomimes performed by the agents. Let's imagine, for example, that Player B produces the sign *S* while repeatedly moving the agent against the icon on the floor of the room (agents cannot walk over the icons). Player A is now cued that the sign likely refers to the icon.

Players who relied on naming procedures were well aware of the dynamics of the process and governed it explicitly. In particular, early on in the game, players suspended playing and went around the four rooms together, carefully establishing signs for each room. This procedure, which may be termed a *naming tour,* dramatically shortened the time for converging onto a communication system, as is evident in Fig. 4.

3.1.4. Results III: The sign systems

Fig. 5 presents the sign systems developed by the pairs during Study 1A.[13]

There were three main types of sign systems: (a) systems based on numeration; (b) systems based on the icons in the rooms; (c) systems based on the layout of the game map. In what follows each pair's sign system is illustrated in detail, type by type.

3.1.4.1. Numeration based. This type of sign system was used by 3 pairs (Pairs 1 and 6–7). Pairs 1 and 7 used signs composed of horizontal lines produced in rapid sequence. The number of lines corresponded to an arbitrary numbering scheme for the rooms. As illustrated in Fig. 5, Pair 1 adopted a counterclockwise numbering scheme beginning on the topmost rightmost

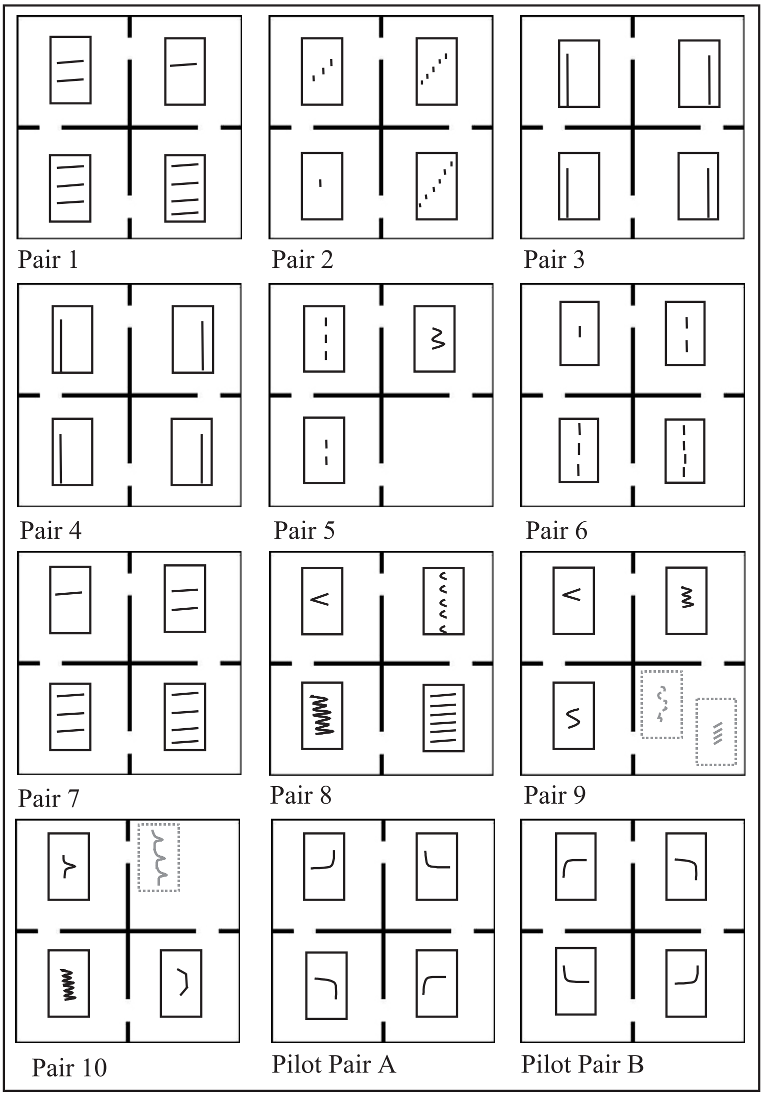


Fig. 5. Pairs' sign systems for Game 1. The signs are presented in the room they stand for. The rectangles around the signs represent the communication panels within which the signs were drawn (Fig. 1). Dotted rectangles in gray indicate signs used only by one player in the pair. Two signs in the same room indicate that players did not use the same signs for that room. Pilot Pairs A and B participated in a pilot study conducted with Game 1 (Galantucci, Fowler, & Richardson, 2003).

room, and Pair 7 adopted a left-to-right, top-to-bottom numbering scheme. Pair 6 used signs composed of short vertical dashes produced in rapid sequence. As illustrated in Fig. 5, Pair 6 adopted the same left-to-right, top-to-bottom numbering scheme as Pair 7.

3.1.4.2. Icon based. This type of sign system was used by 4 pairs (Pairs 2 and 8–10). As illustrated in Fig. 5, Pair 2 used signs composed of short vertical dashes produced in rapid sequence.

The dashes indicated the number of vertices of the icon in the room: three dashes for the triangle, six dashes for the hexagon, five dashes for the flower-like icon, and one dash for the circle. In what follows the system developed by Pair 2 is referred to as the *icon-vertices system.*

As illustrated in Fig. 5, Pairs 8–10 used signs related to the shape of the icons in the rooms. For example, Pair 8 used two lines at an angle to indicate the triangle room, six horizontal lines produced in rapid sequence to indicate the hexagon room, five squiggles to indicate the flower room, and a few periods of a quasi sine wave to indicate the circle room.[14] In what follows, the systems developed by Pairs 8–10 are referred to as the *icon-shape systems.*

3.1.4.3. Map based. This type of system was used by 2 pairs (Pairs 3 and 4). Pairs 3 and 4 used signs composed of continuous vertical lines (produced by holding the stylus still on the pad). As illustrated in Fig. 5, the longitudinal location of the lines on the communication panel corresponded to the longitudinal location of the agent on the game map. In what follows, the systems developed by Pairs 3 and 4 are referred to as the *longitude systems.* Notice that the signs in this system are ambiguous: They specify the longitude of the agent but not its latitude.[15] Nevertheless, the pairs that used this system were very successful (Fig. 4). The next section explains why.

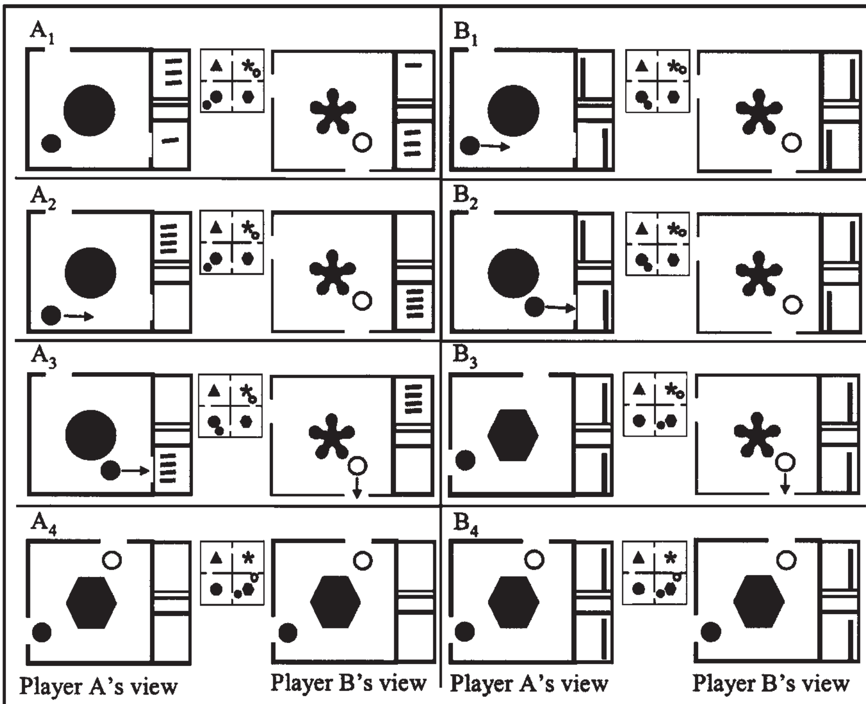
3.1.5. Results IV: Communication systems integrate information from different sources

One of the processes that Study 1A exposed to observation was the meshing of signs with other kinds of task-relevant information. For example, when players discovered (through the use of the signs illustrated in Fig. 5) that their agents were in adjacent rooms, they almost never used signs to negotiate a meeting room but simply moved the agents one toward the other until they were in the same room. In other words, the behavior of players was an expression of the integration between the information contained in the sign (obtained through the communication medium and explicitly shared by the players), information about current location of the agent (obtained privately and not shared by the players), and information about the environment layout (obtained privately through learning and implicitly shared by the players).

Another kind of information that was integrated into the use of signs was that provided by the passing of time. For most pairs, when a player produced a sign and soon after produced a different sign, the first sign was interpreted as the current location of the player's agent, the second as the location toward which player intended to move in the near future. In other words, the temporal dimension of the signing behavior was put in correspondence with the temporal dimension of the moves in the game.

Moreover, signs were often integrated into specific behavioral procedures. A good example was the way most players solved double-move scenarios in Game 1 (Box 1). The main problem of the double-move scenario was that, to solve it successfully, players needed to know not only where the partner was but also where to meet each other. As illustrated in Box 2, pairs solved the problem by carefully synchronizing the use of signs with their reciprocal moves to gradually negotiate a successful solution to the scenario.

In other words, not only was the information provided by the signs constantly integrated with other information available to players, but players' behavior itself adapted to the expressive limits of the sign system.



($A_{1\text{-}4}$) Pair 1. (A_1) Player A signals being in the circle room by producing three lines; Player B signals being in the flower room by producing one line. Integrating the information received from the partner with knowledge about their current location and about the game map, players realize that they are in a double move scenario and hold their agents still. (A_2) Player A produces the sign for the hexagon room (four lines) to propose a meeting point and moves the agent in the direction of the door that leads to the hexagon room. (A_3) Player B signals agreement by producing the sign for the hexagon room and moves toward the door that leads there. (A_4) Players reach the hexagon room. ($B_{1\text{-}4}$) Pair 3. (B_1) Through their signs, players discover that they are on different sides of the map. In such a scenario Player A always takes the initiative, moving the agent toward the side where the partner is. Player B waits for the partner to switch sides. (B_2) Player B continues to move toward the partner's side, Player B waits. (B_3) Player A enters the hexagon room and signals the switch of side. Player B, seeing that the partner has changed sides but not seeing the partner in the room, begins moving toward the other room on the right side. (B_4) Player B reaches Player A in the hexagon room.

Box 2. Procedures used by Pairs 1 and 3 to handle the double-move scenario.

3.1.6. Discussion

Study 1A provides ground for two general conclusions. The first conclusion concerns the viability of the proposed method for research, and it is that communication systems emerge relatively quickly and reliably in the laboratory. The second conclusion concerns the sign systems developed by the pairs to solve Game 1, and it is that sign systems can originate from very different mappings. In what follows, the two conclusions are discussed in detail.

3.1.6.1. Communication systems emerge relatively quickly and reliably. Study 1A demonstrates that human communication systems emerge in a relatively quick and reliable manner in the laboratory (see Section 3.1.2). This conclusion is consistent with the results of recent studies by Healey and colleagues (Healey, Garrod, Fay, Lee, & Oberlander, 2002; Healey, Swoboda, Umata, & Katagiri, 2002), which demonstrated that adults quickly learn to communicate without using language, solving simple communicative tasks exclusively by means of nontextual graphical interactions. Moreover, these results extend the scope of the results obtained by Healey and colleagues in two regards.

First, participants in Study 1 solved a communication task much more open-ended than the tasks used by Healey and colleagues (Healey, Garrod, et al., 2002; Healey, Swoboda, et al., 2002). Healey and colleagues used tasks such as deciding whether or not two pieces of music participants were listening to independently were the same or not and gave participants the explicit instruction to communicate with each other. In this study, participants were not directly given the task of communicating but were invited to play a video game that required communication as a natural consequence of a more primitive need to coordinate joint actions in the game.

Second, participants in Study 1 used a more restrictive medium than that used by the participants in the studies by Healey and colleagues (Healey, Garrod, et al., 2002; Healey, Swoboda, et al., 2002). Healey and colleagues used standard graphic tablets—essentially the digital equivalent of a whiteboard—with the proscription that the participants avoid using letters or numbers. However, participants in the studies by Healey and colleagues could use other graphic symbols (e.g., the $ symbol for money) and pictorial representations (e.g., drawings of people or animals) and indeed used them frequently. The medium used for this study is much more restrictive: Not only does it systematically prevent the use of any common graphic symbol, but it also prevents the use of most pictorial representations. In other words, the medium offered no opportunities to use signs whose meaning was known to the players prior to the beginning of the game.

3.1.6.2. Sign systems can originate from very different mappings. The minimal requirement for establishing an effective communication system in Game 1 was convergence on two critical dimensions: *what to code* and *how to code.* The what-to-code dimension concerns which properties of the task environment are relevant for the communication system, as Section 3.1.4 has illustrated. The how-to-code dimension concerns the kind of mapping (or mappings) by which the selected properties of the task environment are related to properties of the signs. Table 2 describes the how-to-code dimension, organized by pairs.

The table makes evident an important conclusion about sign systems: Signs can code the same task environment in very different ways. For example, for Pairs 3 and 4, what mattered was the relation between the *location of the sign* on the communication panel and the *location of the agents* in the environment. For Pairs 1 and 6, what mattered was the relation between the *number of units in the sign* and the *location of the rooms* in an abstract numeric grid. For Pair 2, what mattered was the relation between the *number of units in the sign* and the *number of convexities of the room's icon.* In other words, the choices made by the pairs differed dramatically, but the communicative power of the systems did not. In this regard, it is interesting to notice that there is at least one other possibility for successfully coding Game 1's environment into a sign system. Two pairs that were run in a pilot study (Galantucci et al., 2003) used a map-based system whereby the *orientation of the signs* on the communication panel related to the *rooms'*

Table 2
Pairs' choices for the How to Code dimension

Pair	How to Code?
1 (Numeration-based system)	An abstract numbering scheme of rooms on the map is related to the numbers of units in the sign.
2 (Icon-based system)	The number of convexities on the icon in the rooms is related to the number of units in the sign.
3 (Map-based system)	The location of the sign on the panel is related to the location of the agent in the environment.
4 (Map-based system)	Same as above.
5 (Mixed system)	Visual features of the icons in the rooms are related to visual features of the sign "+". The number of convexities on the icons in the rooms is related to the number of units in the sign "+". Arbitrary mapping.
6 (Numeration-based system)	An abstract numbering scheme of the rooms on the map is related to the numbers of units in the sign.
7 (Numeration-based system)	Same as above.
8 (Icon-based system)	Visual features of the icons in the rooms are related to visual features of the sign "+". The number of convexities on the icons in the rooms is related to the number of units in the sign.
9 (Icon-based system)	Visual features of the icons in the rooms are related to visual features of the sign.
10 (Icon-based system)	Same as above.
Pilot A (Map-based system)	The orientation of the sign on the communication panel is related to the orientation of the room on the environment's map.
Pilot B (Map-based system)	Same as above.

location on the game map. In particular, as illustrated in Fig. 5, the 2 pairs used *L*-shaped signs whose rotation mapped onto the rooms' layout.

3.2. Study 1B: The development of communication systems

As anticipated in Section 2.1, the communication systems that emerged in Game 1 offer an interesting opportunity for research. In fact, if a pair that has developed a communication system for Game 1 is faced with the demands of different games, we may observe the pair's communication system develop to befit the demands of the new games. Study 1B, conducted with 8 of the successful pairs in Study 1A (Pairs 1–4 and 7–10), explored this opportunity via two new games: Games 2 and 3.

3.2.1. Games 2 and 3

3.2.1.1. Game 2. Game 2 preserved the basic elements of Game 1, including the properties of the communication medium, but had a different game logic and was played in a larger virtual environment. In particular, the game was played in an environment of nine rooms that, as shown in Fig. 6A, was an expansion of Game 1's four-room environment.

One of the nine rooms contained a prey, whose capture was the goal of the game (for a gain of 4 points). Capture required both agents to be in the prey's room at the same time. On capture,

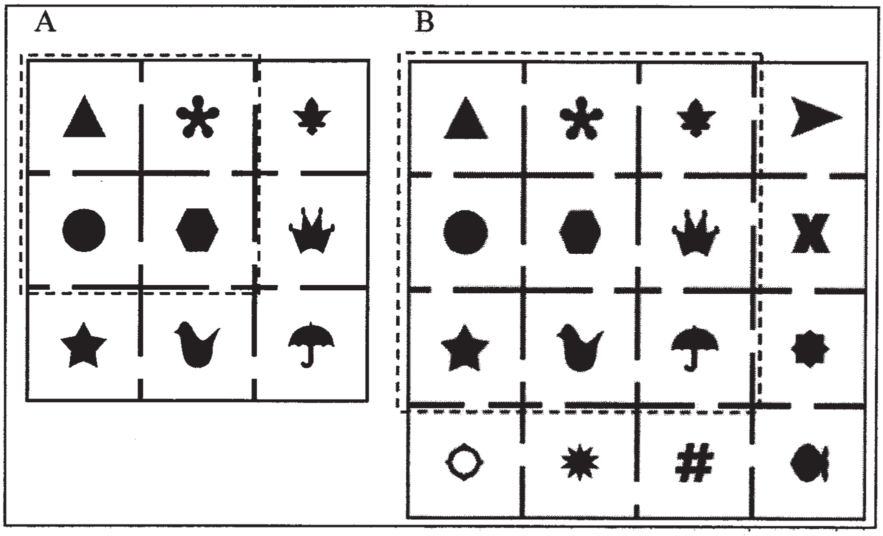


Fig. 6. Game maps for (A) Game 2 and (B) Game 3.

the prey disappeared and reappeared in a new room, but the agents remained where they were. In other words, differently from Game 1, Game 2 was a continuous game: There were no rounds or other clearcut "loss" events (i.e., there was no reset procedure for the random relocation of the agents). However, a positive performance in the game was not trivial: The score dropped at the rate of 1 point a minute, and each time the agents met in a room in the absence of prey the score dropped 2 points. Under these conditions, the pair increased points reliably only if the rate of the preys' capture was high enough to compensate for the losses.

3.2.1.2. Game 3. Game 3 was played in an environment of 16 rooms that, as shown in Fig. 6B, was an expansion of Game 2's 9-room environment. The game had a very similar logic to that of Game 2, the main difference being that the environment contained, in two random locations, two enemies: Enemy A and Enemy B. The enemies behaved in different but symmetric ways: Enemy A attacked Player A's agent and ignored Player B's agent, whereas Enemy B did the opposite. When an agent entered a room that contained an inactive enemy, the enemy did not move and nothing happened. When an agent entered a room that contained the active enemy for that agent, the enemy began chasing the agent, causing a steady loss of points for the pair (3 points every minute). The chase was interrupted only when the two agents met each other in the same room, in which case the enemy disappeared and the loss of points returned to the normal rate of 1 point every minute.[16] However, to prevent players from using the drop in score as an indication of the chase (thus bypassing the need for communicating), the extra points lost during a chase were subtracted from the score visible to the players only when the chase was terminated.

3.2.1.3. How Games 2 and 3 increased the need for communication. Games 2 and 3 were expected to increase the need for communication compared to Game 1 in three ways. First, it was expected that the increase in the number of rooms and the consequent need for an efficient search strategy would require an increase in the complexity of the pairs' sign systems. Minimally, new signs for the new rooms would need to be developed. Second, it was expected that, if players were to optimize their search time, there would be two new kinds of events in need of coding, namely, the "found prey" event and, for Game 3, the "enemy here" event. Finally, it was expected that the need to avoid the penalty for double occupancy of a room that contained no prey, as well as the need to avoid prolonged chases by the enemies, would foster communication systems that continuously conveyed information about the current location of the agents and/or their intended moves.

3.2.2. Procedure

On completing Study 1A, players were invited to play Game 2, and on solving Game 2, players were invited to play Game 3.[17] Each game was preceded by standard instructions (see Appendix A) and was followed by a separate test session designed to assess the communication system developed by the pair (see Section 3.1.1.1 and Appendix B). Studies 1A and 1B occurred in succession over four experimental periods of 90 min each. Successful completion of one game and the initiation, playing, and possible completion of another game could occur within a session.

3.2.3. Results I: Communication systems develop

A compact summary of performance in Study 1B is provided by Fig. 7.

As illustrated in Fig. 7A, all of the 8 pairs solved Game 2 within 1 hr of playing. The cumulative score in Game 2 never fell much below its initial value, and the mean time for solution was 26.5 ± 12.01 min. As observed by the experimenters, the rapidity of the solutions to Game 2 with respect to Game 1 was due primarily to two related factors. On one side pairs spent much less time in setting up the communication system than they did during Game 1. This was possible because the Game 1 communication system provided a framework within which signs could be constructed and strategies could be selected befitting the communicative challenges of the new game. On the other side, Game 2 revealed itself to be easier than Game 1, allowing a rise in score even in the absence of an efficient communication system (see Sections 3.2.3.1 and 3.2.6 for further details and an explanation).

As illustrated in Fig. 7B, solving Game 3 was harder than solving Game 2.[18] Two pairs (8 and 10) did not solve the game within the allotted time (despite succeeding in Games 1 and 2), and for the successful pairs, the mean time for solution was 68.3 ± 25.1 min. As observed by the experimenters, Game 3 was harder than Game 2 because, although pairs benefited from the communication systems developed in the preceding games, the higher demands of Game 3 required that either an optimal communication system for the tasks at hand be developed or that a suboptimal communication system be integrated with optimal behavior-coordinating procedures (see Section 3.2.6).

Overall, Study 1B clearly indicates that the pairs adapted their communication systems to the needs of the new games. However, as illustrated shortly, signs were not the only part of pairs' communication systems that underwent development.

3.2.3.1. Overt communication helps, but it is not always crucial. Table 3 provides the measures collected in the test sessions conducted subsequent to the games.

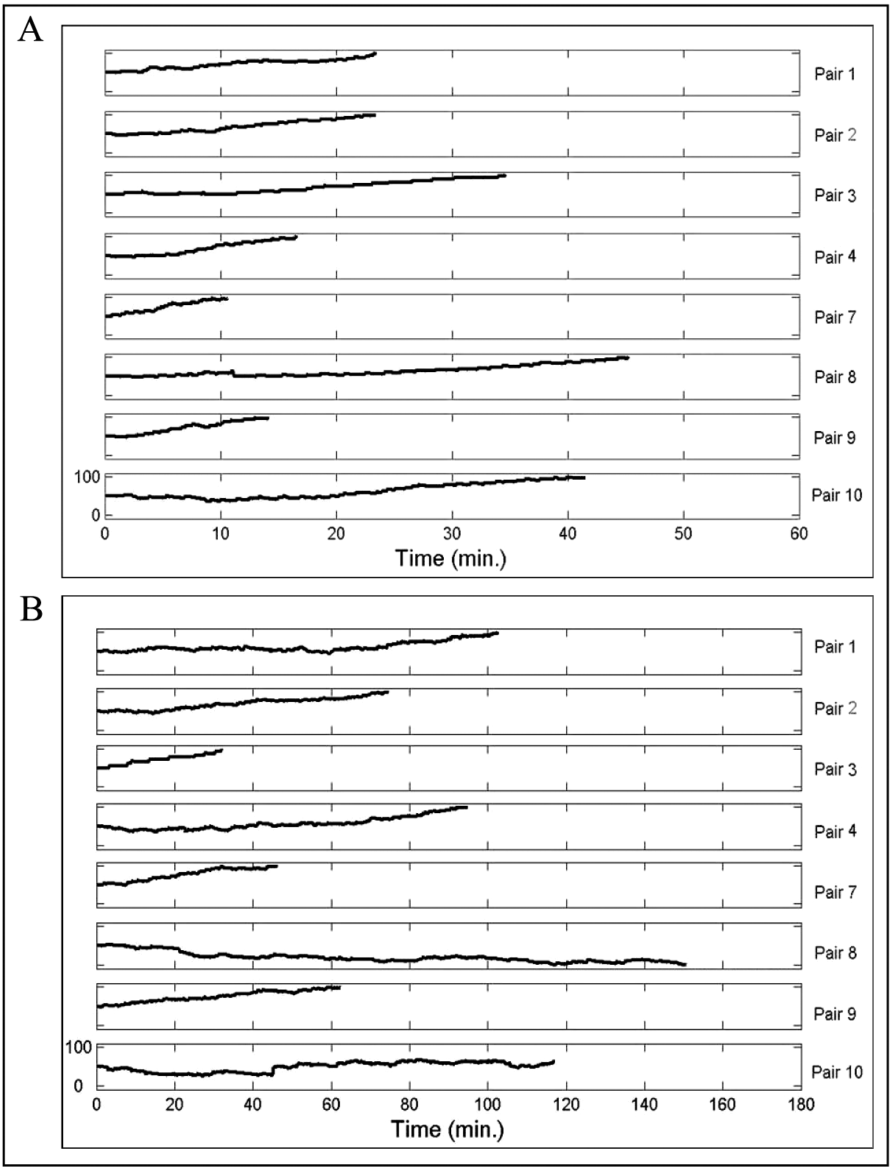


Fig. 7. Score plots for (A) Game 2 and (B) Game 3 (note that the two graphs have different time scales).

Inspection of the table indicates that communication played a role in solving both games. As for Game 2, all pairs with one exception exhibited a positive difference between CS and NCS, and the overall difference between CS (mean 20.75 ± 6.2) and NCS (mean 6.75 ± 8.21) was statistically significant, $F(1, 7) = 10.89$, $p = .013$, $\eta^2 = .61$. However, the difference in effect sizes between Games 1 and 2 suggests that the benefits of the communication medium in Game 2 may have been less than in Game 1. In fact, most pairs were able to collect points in Game 2 without overtly communicating, as indicated by the positive value of

Table 3
Solution times, minimum scores and test session scores for the pairs in Games 2 and 3

	Game 2					Game 3				
Pair	Time to solution	Minimum score	CS	NCS	CS–NCS	Time to solution	Minimum score	CS	NCS	CS–NCS
1	24	49	13	–5	18	102	44	19	–7	26
2	24	45	31	–5[a]	36	74	43	13	–5[a]	18
3	35	50	11	13	–2	32	50	5	–3	8
4	17	46	25	11	14	95	36	1	–4	5
7	11	50	23	5	18	45	48	17	–1	18
8	45	47	17	13	4	150+	0	–1	–3	2
9	14	46	23	19	4	62	47	15	1	14
10	42	35	23	3	20	118+	0	11	3	8
Average	26.5	46	20.75	6.75	14	68.33	33.5	10	–2.38	12.38
SD	12.01	4.52	6.2	8.21	11.22	25.1	19.74	7	3.04	7.52

Note. CS = communication score; NCS = no-communication score.
[a]The pair decided not to play the game and ended the test with the 5 points of penalty for the 5 min that had passed.

the mean NCS for the game.[19] This was because, as observed by the experimenters, most pairs developed silent behavior-coordinating procedures that enhanced the pairs' efficacy in the search for the prey, but reduced the risk of accidental meetings. These procedures (illustrated in Section 3.2.6) greatly facilitated joint tasks in Game 2 and made overt communication partly redundant. However, by themselves the procedures were far from supporting optimal performance, as indicated by the difference between NCS and CS. In fact, when a player found the prey and could not use the communication medium, the player could only wait for the partner to find the right room.

The role played by overt communication was more evident in Game 3. All pairs but one obtained a positive score in the presence of the communication medium, whereas only 2 pairs managed to avoid a negative score in the absence of the communication medium (Pair 9 had 1 point, Pair 10 had 3 points). In addition, all pairs exhibited a positive difference between CS and NCS, and the overall difference between CS (mean 10 ± 7) and NCS (–2.38 ± 3.04) was statistically significant, $F(1, 7) = 18.98$, $p = .003$, $\eta^2 = .73$.

3.2.4. Results II: How sign systems develop

Most pairs developed new signs via the same processes used in Study 1A: Pairs 1 to 4 relied on learning by using, and Pairs 8 and 9 relied on overt naming procedures. Pairs 7 and 10, however, developed their signs via different processes from the ones they used during Study 1A: Pair 7 relied primarily on learning by using, only occasionally resorting to overt naming procedures, and Pair 10 relied primarily on overt naming procedures, only occasionally resorting to learning by using.

3.2.5. Results III: Developing sign systems

Fig. 8 presents the sign systems developed by the pairs for Games 2 and 3.

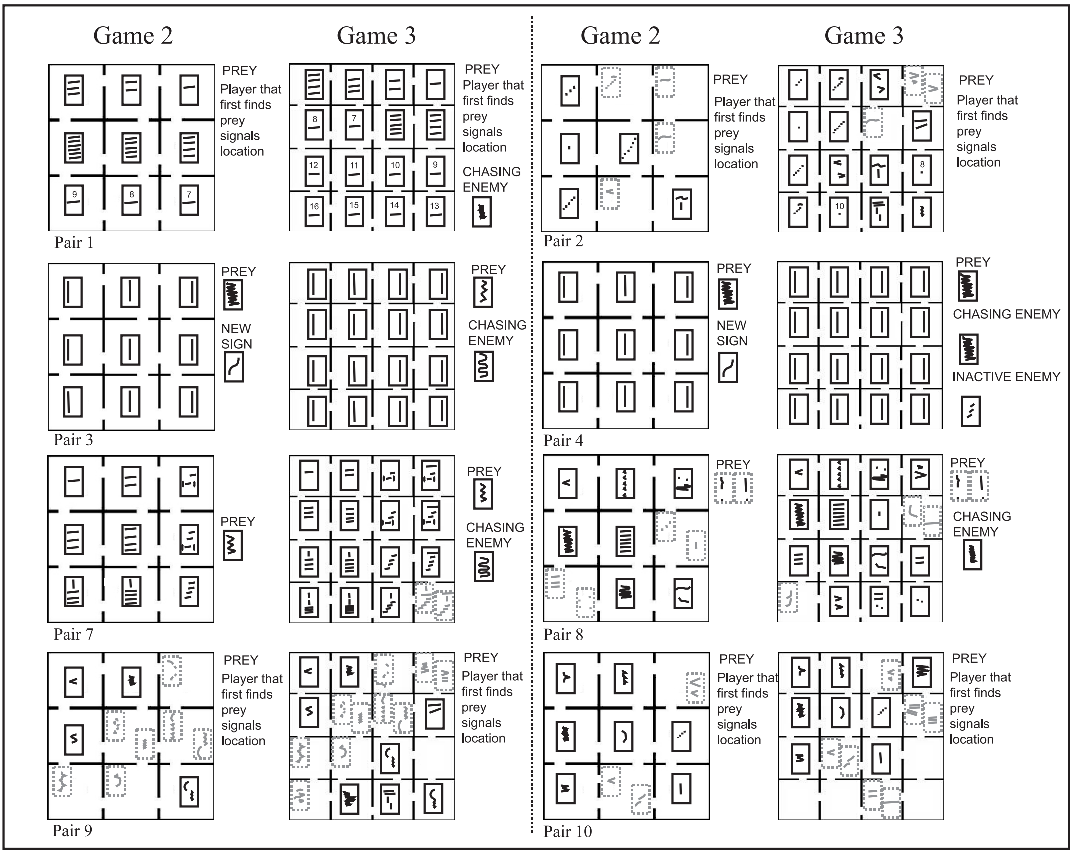


Fig. 8. Pairs' sign systems for Games 2 and 3.

The rest of the section illustrates the development of the sign systems and is organized according to two overarching observations: (a) Sign systems similar at origin can easily diverge during development, and (b) a sign system can integrate new mappings with old ones.[20]

3.2.5.1. Sign systems easily diverge during development. A comparison between the sign systems developed by Pairs 1 and 7 illustrates a first main observation about the development of sign systems: Systems that at the beginning of play are very similar can easily diverge during development. Pairs 1 and 7 ended Study 1A with practically the same sign system. As described in Section 3.1.4.1, both pairs related the number of lines appearing on the communication panel to a numbering scheme for the rooms. However, the pairs developed their sign systems in very different ways during Study 1B. Pair 1 applied the same strategy used for Game 1 throughout the new games. In particular, as Fig. 8 illustrates, the pair kept counting the number of horizontal lines (counting as many as 16 lines in Game 3) and kept using a counterclockwise numbering scheme for the rooms' layout (beginning on the topmost rightmost room).

The development of Pair 7's sign system followed a distinctively different route. In Game 2, as a comparison of Figs. 5 and 8 illustrates, Pair 7 left unaltered the relation between the signs developed for Game 1 and the rooms in Game 2 marked by the same icons as in Game 1. In other words, as in Game 1, one horizontal line indicated the triangle room, two lines the flower room, three lines the circle room, and four lines the hexagon room. As for the signs for the new rooms, the signs for the star and bird rooms were composed from the Game 1 signs for the rooms above them. In particular, the sign for the room above, three or four lines, was preceded by a vertical line (Fig. 8) that roughly indicated "below-ness" (e.g., the star room was "below circle room"). The signs for the rightmost column were developed anew, again with reference to a numbering scheme. A short horizontal line indicated the uppermost room. Two short horizontal lines indicated the room below. Three horizontal lines indicated the lowest room.[21]

In Game 3, as Fig. 8 illustrates, the signs for the nine rooms in Game 2 remained unaltered, and the pair steadily converged on the method begun in Game 2: New signs were created by composing old signs with new bits, to modify their meaning. Thus, for example, the sign for the leftmost lowest room (Fig. 8) was composed of two vertical dashes, recursively signifying below–below, and three horizontal lines that had been the sign for the circle room in the coding scheme of Game 1. Similarly, the sign for the rightmost, topmost room was composed of a long horizontal line, meaning "over to the right," and one horizontal dash, the sign for the spade room in Game 2. A comparison between the Game 2 sign for the bird room and the sign for the hash mark room developed during Game 3 further illustrates the compositional nature of the pair's signs. In fact, for the hash mark room the pair used a sign composed of the vertical line to indicate "below-ness" and the sign for the room above it, four short horizontal lines. In other words, the vertical line was used with a new type of line—the short line type—but preserved its function, that of indicating "below-ness." Finally, the sign for the rightmost, lowest room was an example of multiple composition. The sign was composed of a horizontal line indicating "over," a vertical dash indicating "below," and four horizontal dashes indicating the umbrella room. The sign had a double reading. It could be read either as meaning "below the room above it" or as meaning "over the room to its left." Player A seemed to prefer the latter reading, producing the vertical dash for "below" first. Player B seemed to prefer the former reading, producing the horizontal line for "over" first. The players easily understood each other's versions of the sign.

3.2.5.2. Sign systems can integrate new mappings with old ones. A comparison between the sign systems developed by Pair 2 and those developed by Pairs 3 and 4 illustrates a second main observation about the development of sign systems: Depending on circumstances, sign systems can either rely on the repeated exploitation of the same mapping or rely on the integration of old and new mappings.

A first example of a pair that developed the sign system by the repeated exploitation of the same mapping was that of Pair 1, described previously. A second example is provided by Pairs 3 and 4, the pairs that used longitude sign systems. As shown in Fig. 8, during Game 2, Pairs 3 and 4 simply added a third location for the drawing of the line that indicated the longitude: A line in the middle of the communication panel indicated the central column in the 3×3 grid of the game map. During Game 3, the line in the middle was drawn slightly to the left to indicate the left-center column in the 4×4 grid of the game map and slightly to the right to indicate the right-center column.

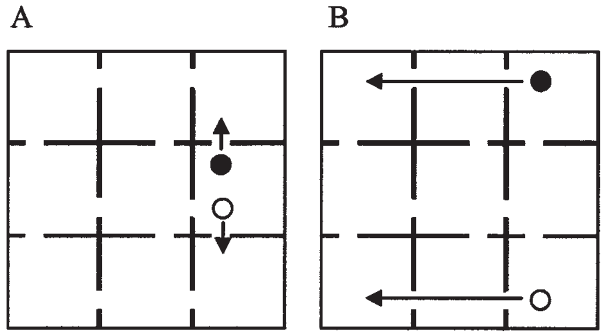
Pair 2, on the other side, provides a clear example of integration of different mappings. As described in Section 3.1.4.2, during Game 1, Pair 2 used a sign system whereby the number of dashes drawn on the communication panel corresponded to the number of vertices of the icons on the floor of the rooms. In Game 2, the mapping could no longer work: Not only were there rooms whose icons had the same number of vertices (e.g., the flower and the star room, see Fig. 6A), but there were icons that were very difficult to describe in terms of number of vertices, including an umbrella, a crown, and a bird. Pair 2 solved part of these problems in the following manner. First, the pair kept the Game 1 signs for the triangle, the circle, and the hexagon rooms. Second, Game 1's sign for the flower room—five dashes—became the sign for the star room. Pair 2 also converged on the use of a new sign. A short vertical line followed by a long tilde-like horizontal line was used to indicate the umbrella room (Fig. 8). For this sign the pair abandoned the icon–vertices system and adopted the icon–shape system: The sign looks like an umbrella. The players did not converge on the signs for the remaining four rooms. Player B often used the signs in Fig. 8, but Player A never adopted them. Player B's sign for the flower room was particularly noteworthy. The sign was composed of five dashes and a tilde. The sign followed a precise compositional logic: The five dashes indicated the five extremities of the icon, and the tilde expressed the fact that the extremities were curved. During Game 3, Pair 2 decidedly opted for multiple mappings. The icon–vertices system was extensively used: Eight of the 14 signs on which there was convergence were based on this system. The pair also converged on two signs that used the dashes as well as the tilde: the sign for the flower room developed by Player B during Game 2 and the sign for the leftmost room on the bottom row. The icon–shape system gave rise to the remaining six signs.

3.2.6. *Results IV: Efficient communication systems rely on silent behavior-coordinating procedures as well as on signs*

A comparison between Pairs 8 and 9 reiterates a point already illustrated previously (see Section 3.1.5): Signs are not the only ingredients of successful behavioral coordination. In Game 2, Pair 8 converged on the signs for 7 rooms out of 9, Pair 9 on 4 signs; in Game 3, Pair 8 converged on the signs for 14 rooms out of 16, Pair 9 on 7 signs (Fig. 8). Moreover, Pair 8 developed a specific sign for the prey in Game 2 and a sign for the chasing enemy in Game 3 (Fig. 8). Clearly, Pair 8 had a more complete and refined sign system than Pair 9. However, the performance of Pair 9 in both games was better than that of Pair 8. As for Game 2, Pair 9 completed it in 14 min, Pair 8 in 45 min. As for Game 3, Pair 9 completed it in 62 min, whereas Pair 8, after 150 min of playing, was still hovering around a zero score, at which point the study was terminated (Fig. 7). Clearly, despite the less developed sign system, Pair 9 was more efficient at playing Games 2 and 3 than Pair 8. How was this possible? The difference between the pairs was primarily a difference in balance between the use of signs and of silent behavior-coordinating procedures. Pair 8 relied heavily on signs; Pair 9 used signs only when they critically enhanced performance in the game (e.g., when a player found the prey) but developed very efficient silent behavior-coordinating procedures. In what follows, two of such silent behavior-coordinating procedures are illustrated in some detail.

The most common silent behavior-coordinating procedure in Games 2 and 3 was one that can be termed the *split-search* strategy. The strategy minimized the risk of accidental meetings during the search for the prey and is illustrated in Box 3.

Another procedure commonly used during Game 3 was one that most pairs used to handle an enemy attack. If the attack occurred immediately after capture of the prey, the chased player



When players have their agents in the same room (most often because they just found a prey) they make their agents leave the room through different doors (A). At that point, the search is organized around the initial door choice. For example, if Player A (black dot) exited from the door at the top of the room and Player B (white dot) from the door at the bottom, Player A would explore the rooms at the top of the map first and Player B would explore the rooms at the bottom first (B). In this manner each player has three rooms that can be visited without the risk of bumping into the other player's agent. In other words, players can explore 6/9 of the map with no risks of penalties. As soon as a player found the prey, the player stopped moving the agent and signaled the current location to the partner. (When playing without the communication medium, the player simply waited for the partner to show up.)

Box 3. The split-search strategy.

rarely communicated the location of the attack via signs. The chased player either made the sign for the enemy alone, relying on the fact that the partner knew where the attack had to be taking place, or simply reached the partner's agent, without communicating at all. Similarly, if the attack happened when the pair had explored most of the rooms, and hence a meeting for capturing the prey was imminent, communication rarely occurred. It was only when the attack happened at a point in the game that was in between these two scenarios that pairs that had a sign for the enemy used it along with signs for location.

In other words, Study 1 B reiterates one of the main results of Study 1A (see Section 3.1.5). Pairs' solutions to the games did not consist of the mere exchanging of signs, but were multi-level behavioral processes whereby the information received via the communication medium was constantly integrated with other kinds of information and used in behaviorally efficient ways (cf. H. H. Clark, 1996).

3.2.7. Discussion

Study 1B provides ground for two general conclusions. The first conclusion concerns the development of established sign systems, and it is that novel signs are introduced into a sign system in a rather parsimonious way. The second conclusion concerns the forms of the signs used by the pairs in the study, and it is that the forms that best facilitate convergence are perceptually distinct, produced by simple motor sequences, and tolerant of individual variations. In what follows, the two conclusions are discussed in detail.

3.2.7.1. Sign systems develop parsimoniously. Overall, the development of the Game 1 sign systems that took place in Study 1B reflected a simple *principle of parsimony:* Once a sign system had emerged, new signs were rarely developed that were completely unrelated to the signs already in use. In other words, most pairs maintained, as the basic scaffolding for the development of their communication systems, the system that was generated for solving Game 1.[22] The principle of parsimony can also be thought of as an inertial constraint: The state of a communication system at time t_i depended on the state of the system at time t_{i-n}. This was true at two time scales. At a short time scale, the sign used by a player at time t_i was often constrained by the sign the partner used at time t_{i-n} (cf. Garrod & Pickering, 2004). For example, Player B in Pair 7 converged on some signs because Player A had produced them "before." At a larger time scale, the communication systems developed by the pairs in the past provide constraints on what could or could not be developed next. For example, in Games 2 and 3 many pairs did not use the signs for locations as a way to avoid bumping into each other. This happened because the signs for location had acquired, in the course of Game 2, a duplex semantic role, meaning not only locations on the map but also, roughly, "Hey, come here, I found the prey" (Fig. 8). Once this duplex role for the sign was established, the location sign could not be used without causing costly false alarms, in which a player mistakenly thought that a prey had been found. Another example comes from Pair 1, which persevered with a system of signs for the rooms that relied on counting the number of lines on the panels. Although it became obvious to the players during Game 3 that the system had become impractical, the pair did not modify it. For this pair, the history of the communication system had heavily constrained its future.

3.2.7.2. Some remarks on the forms of signs. From Fig. 8, it is apparent that most signs are composed of lines or dots; very few signs rely on complicated drawing movements. This pattern makes perfect sense if one assumes that the most important shaping force for sign forms is the ease with which they can be reliably copied (cf. Millikan, 2004). Moreover, the pattern suggests two very basic principles:

a. The forms that best facilitate convergence on a sign are easy to distinguish perceptually and yet are produced by simple motor sequences.
b. The forms that best facilitate convergence on a sign are tolerant of individual variations.

As for (a), it is interesting to note that when forms were easy to distinguish perceptually but not easy to produce (e.g., Pair 9), pair members failed to converge on many signs. At the same time, forms that were easy to produce but did not afford immediate, unambiguous perceptual identification, such as the sine wave form (Fig. 8), were often broadcast redundantly (i.e., more than one period of the sine wave was produced).

As for (b), it is interesting to note that most signs in Fig. 8 are remarkably robust to individual variations. For example, the lines used by Pairs 2 and 7 in Game 1 could have been a bit shorter or a bit longer, more on the right side of the panel or more on the left, with a greater or lesser slant, thicker or thinner, and so on. The only thing that mattered for the system was how many of them were there. Similarly, the lines used by Pairs 3 and 4 in Game 1 could have been a bit thicker or thinner, more or less close to the sides, fully continuous or with some interruptions, and so on. The only thing that mattered for the sign system was the longitude of the lines, expressed in binary terms (i.e., on the right side versus on the left side).

Notes

1. This problem has been recognized since antiquity, and attempts have been made to overcome it. For example, Herodotus (2444 BP) tells us that the pharaoh Psammetichus (ca. 2600 BP) had two children raised together in severe cultural and linguistic isolation to discover which language they would speak. Similarly cruel experiments were conceived and implemented by Frederick II (700 BP) and by James IV (500 BP).
2. The round was also lost if a player made more than one move.
3. A score of 100 points was practically impossible to reach with a random level performance.
4. Wacom Graphire digitizing pad, 93 mm in height × 127 mm in width, with accuracy of ± 0.25 mm and an operating sampling rate of 50 Hz.
5. Throughout the article a distinction is made between *signal,* intended as the visual output of the communication medium, and *sign,* intended as the abstract unit of the communication system.
6. The thickness of the tracings on the communication panel varied, depending on the amount of pressure exerted by the stylus on the digitizing pad (the more the pressure, the thicker the line).
7. Players were recruited via flyers at a university library and were randomly matched in pairs. Once in the study, players were referred to as Player A or Player B by the experimenters and were separately escorted in and out of the building where the study took place.
8. Participants were told that they would receive an additional $2/hr over their $8/hr participation fee if the pair reached the score the experimenter set as the goal for the session. The reward was nominal. At the end of the study all participants were paid at the rate of $10/hr.
9. Player A began to show overt signs of not cooperating. For example, on losing a game Player A would move the agent into the closest reset square, ignoring any attempt of the partner to establish contact. This behavior was accompanied by orienting the face of the agent in the direction opposite to Player B's agent. Player B interpreted these signs (correctly) as signs of irritation, to the point that Player B overtly lamented that the partner's personality, or perhaps the partner's identity, had changed.
10. These pairs managed to obtain a positive score by tacitly adopting consistent moving schemes. For example, Pair 9's Player A typically moved the agent downward. If the agent was on the lower half of the grid, Player A moved it rightward. If the agent was in the lower right corner, Player A would wait a reasonable time for Player B to move, then moved it upward. In other words, Player A never moved the agent leftward. This sys-

tematic behavior enabled Player B to make sophisticated guesses about which move to make, enhancing the chances of winning the round.

11. Notice that even if Player A does not find the partner in room Y, the player can still gather some information about the partner's signing behavior, namely that the probability that the partner uses sign *S,* given that the partner's agent is either not in room Y or has just moved away from it, is greater than zero.
12. Notice that players were not explicitly aware of the dynamics described here and, most often, proceeded by trial and error.
13. Although they did not lead to successful communication, the signs most often used by Pair 5 are included in Fig. 5 for completeness.
14. As illustrated in Fig. 3C, when players drew a circle they generated a sine-wave-like signal.
15. The longitude systems inherited the key feature of the communication medium: The medium coded the horizontal component, but not the vertical component, of the players' drawing movements; players coded the horizontal location, but not the vertical location, of the agents on the map.
16. If the chase was interrupted before the end of the first minute, there was no loss of points.
17. As in Study 1A, success in the game was defined by reaching a score of 100 points, starting from an initial score of 50 points.
18. Again defined as reaching a score of 100 points starting from an initial score of 50 points.
19. Only 2 pairs had a negative NCS and one of them, Pair 3, had a negative score because Player B decided not to move, with the explicit intention of limiting the losses to the 5 points lost because of the passing of time.
20. For a detailed pair-by-pair description of the sign systems, see Galantucci (2004).
21. These new signs were not fully stable within the pair. Player B, in fact, had a slightly inconsistent count of the rooms: He coded the lowest room with four lines and the topmost with one. As a consequence, sometimes the middle room was signed with two lines, sometime with three. This confused Player A, who was never sure how to use the signs for the rightmost column. However, the sign system as a whole was efficient for, in the end, the new signs indicated with enough precision the location they were meant to indicate.
22. Pair 2, as illustrated in Section 3.2.5.2, provides an exception to this generalization. The exception is explained by the simple fact that the icon–vertices system developed by the pair for Game 1 could not be successfully used for most of the icons in the new games.

Acknowledgments

This project has been supported by funds from the University of Connecticut and NIH (Grant DC–03782).

Ramesh Balasubramaniam, Louis Goldstein, Andrea Scarantino, Michael Studdert-Kennedy and an anonymous reviewer provided helpful discussion and comments. Theo

Rhodes and Sean Hutchins helped me in collecting the data. Michael Richardson is the author of the program that runs the games used for the two studies. Carol Fowler, Ruth Millikan, Michael Richardson, and Michael Turvey contributed substantially to the dissertation that led to this manuscript.

References

Bickerton, D. (1981). *Roots of language.* Ann Arbor, MI: Karoma.

Briscoe, T. (2000). Grammatical acquisition: Inductive bias and coevolution of language and the language acquisition device. *Language, 76,* 245–296.

Cangelosi, A., & Parisi, D. (Eds.). (2001). *Simulating the evolution of language.* London: Springer-Verlag.

Christiansen, M. H. (2000). Using artificial language learning to study language evolution: Exploring the emergence of word order universals. In J. L. Dessalles & L. Ghadakpour (Eds.), *The evolution of language: 3rd international conference* (pp. 45–48). Paris: Ecole Nationale Supérieure des Télécommunications.

Clark, A. (1997). *Being there: Putting brain, body and world together again.* Cambridge, MA: MIT Press.

Clark, H. H. (1996). *Using language.* Cambridge, England: Cambridge University Press.

Clark, H. H., & Wilkes-Gibbs, D. (1986). Referring as a collaborative process. *Cognition, 22,* 1–39.

Clark, R., & Roberts, I. (1993). A computational model of language learnability and language change. *Linguistic Inquiry, 24,* 299–345.

de Boer, B., & Vogt, P. (1999). Emergence of speech sounds in changing populations. *Advances in Artificial Life, Proceedings, 1674,* 664–673.

de Saussure, F. (1983). *Course in general linguistics* (R. Harris, Trans.). London: Duckworth. (Original work published 1916)

Galantucci, B. (2004). Toward an experimental method for studying the emergence of human communication systems. *Dissertation Abstracts International, 65*(5), 2673B. (UMI No. 3134786)

Galantucci, B., Fowler, C. A., & Richardson, M. J. (2003). Experimental investigations of the emergence of communication procedures. In R. Sheena & J. Effken (Eds.), *Studies in perception and action VII* (pp. 120–124). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Garrod, S., & Anderson, A. (1987). Saying what you mean in dialog—A study in conceptual and semantic coordination. *Cognition, 27,* 181–218.

Garrod, S., & Doherty, G. (1994). Conversation, coordination and convention—An empirical-investigation of how groups establish linguistic conventions. *Cognition, 53,* 181–215.

Garrod, S., & Pickering, M. J. (2004). Why is conversation so easy? *Trends in Cognitive Sciences, 8*(1), 8–11.

Goldin-Meadow, S., & Feldman, H. (1977, July 22). Development of language-like communication without a language model. *Science, 197,* 401–403.

Goldin-Meadow, S., & Mylander, C. (1998). Spontaneous sign systems created by deaf children in two cultures. *Nature, 391,* 279–281.

Hare, M., & Elman, J. L. (1995). Learning and morphological change. *Cognition, 56,* 61–98.

Hazlehurst, B., & Hutchins, E. (1998). The emergence of propositions from the co-ordination of talk and action in a shared world. *Language and Cognitive Processes, 13,* 373–424.

Healey, P. G. T., Garrod, S., Fay, N., Lee, J., & Oberlander, J. (2002). Interactional context in graphical communication. In B. Bel & I. Marlien (Eds.), *Proceedings of the 24th Annual Conference of the Cognitive Science Society* (pp. 441–446). Mahwah, NJ: Laurence Erlbaum Associates, Inc.

Healey, P. G. T., Swoboda, N., Umata, I., & Katagiri, Y. (2002). Graphical representation in graphical dialogue. *International Journal of Human–Computer Studies, 57,* 375–395.

Hudson, C. L., & Newport, E. L. (1999). Creolization: Could adults really have done it all? *Proceedings of the Boston University Conference on Language Development, 1,* 265–276.

Hurford, J. R. (1989). Biological evolution of the Saussurean sign as a component of the language acquisition device. *Lingua, 77,* 187–222.

Hutchins, E. (1995). *Cognition in the wild.* Cambridge, MA: MIT Press.
Kegl, J. (1994). The Nicaraguan sign language project: An overview. *Signpost, 7,* 24–31.
Kirby, S. (2002). Natural language from artificial life. *Artificial Life, 8,* 185–215.
Krauss, R. M., & Weinheimer, S. (1964). Changes in reference phrases as a function of frequency of usage in social-interaction—A preliminary study. *Psychonomic Science, 1,* 113–114.
Millikan, R. G. (1984). *Language, thought, and other biological categories.* Cambridge, MA: MIT Press.
Millikan, R. G. (2004). *Varieties of meaning.* Cambridge, MA: MIT Press.
Oudeyer, P-Y. (in press). The self-organization of speech sounds. *Journal of Theoretical Biology.*
Pickering, M. J., & Garrod, S. (in press). Toward a mechanistic psychology of dialogue. *Behavioral and Brain Sciences.*
Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996, December 13). Statistical learning by 8-month-old infants. *Science, 274,* 1926–1928.
Skyrms, B. (2002). Signals, evolution and the explanatory power of transient information. *Philosophy of Science, 69,* 407–428.
Steels, L. (1997). The synthetic modeling of language origins. *Evolution of Communication: An International Multidisciplinary Journal, 1,* 1–34.
Steels, L. (1998). The origins of syntax in visually grounded robotic agents. *Artificial Intelligence, 103,* 133–156.
Tanenhaus, M. K., Spivey-Knowlton, M. J., Eberhard, K. M., & Sedivy, J. E. (1995). Integration of visual and linguistic information in spoken language comprehension. *Science, 268,* 632–634.
Tomasello, M. (1999). *The cultural origins of human cognition.* Cambridge, MA: Harvard University Press.
Wittgenstein, L. (1953). *Philosophical investigations* (G. E. M. Anscombe, Trans.). Oxford, England: Basil Blackwell.
Yang, L. R., & Givon, T. (1997). Benefits and drawbacks of controlled laboratory studies of second language acquisition: The Keck second language learning project. *Studies in Second Language Acquisition, 19,* 173–193.

Appendix A

Game 1

- In this experiment you will be playing a video game with a partner. Here is how the game works:
- You control the movements of an agent on the screen with the four arrow keys (the experimenter reads the instructions while the game is on and makes demonstration moves).
- To change room, cross one of the doors of the room, and you will get into the adjacent room; if you cross the door back, you come back in the room you were in before.
- The layout of your environment does not change.
- Your partner plays in the same environment and moves like you.
- You always begin the game in different rooms at random, and your goal is to find each other without doing more than one room change per player.
- If you do two moves, it is an automatic loss.
- When the two moves are made you either win or lose: If you see four yellow squares at the corners of the room that means that the game is over and the score has been updated.
- At that point to start a new game both you and your partner have to be in a yellow square either in the same room or in different rooms.
- You and your partner can use the same yellow square.

- The only means of contact you have with the other player is the pad: Whatever you trace on the pad will appear both on your computer screen and on the other player's screen, and vice versa.
- A win is worth 2 points, a loss is –4 points, and every minute you lose a point.
- When the game is over you can move around at no additional cost, but time will keep costing points.
- You start with 50 points, and the goal for the extra cash is 75 points.
- Now you will have 3 min of free play to explore how the agent and the pad work. After this we will restart the game and you will be playing it for real.
- Any questions?

Game 2

- Now you will be playing a new game:
- The environment is changed.
- The goal is changed: Now in one of the rooms there is a prey that you have to spot and capture.
- You spot the prey by simply entering its room; to capture it you and your partner must be in that room. The capture is worth 4 points; after capture there is no reset; the prey disappears and reappears in a random room.
- Whenever you and your partner end up in the same room and there is no prey in it you pay a penalty of 2 points.
- Time always costs 1 point a minute.
- Your goal for the extra cash is 75 points.
- Any question?

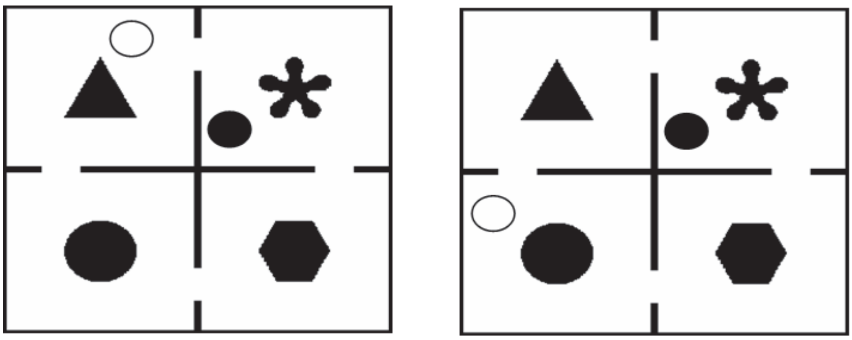
Game 3

- Now you will be playing a new game:
- The environment is changed.
- The goal is the same as before: Capture the prey (this time the prey is worth 4 points).
- Bumping into each other still costs 2 points, and time costs 1 point a minute.
- There will be two enemies: Enemy A and Enemy B. Enemy A attacks you, and Enemy B attacks your partner. Your enemy will jump on you as soon as you enter its room and will follow you wherever you go. When you are under attack, you lose 3 points a minute (instead of 1), but you will not see the score dropping on the computer screen until you put an end to the attack.
- The attack ends as soon as you and your partner get together in a room (in this case there is no penalty for the meeting).
- You start at 50 points, and your goal for the extra cash is 75 points.
- Any questions?

Appendix B

Game 1

- Suppose that you are not able to participate in the next session of the game and decide to have a friend of yours take your place in the game. Please describe in detail all that your friend will need to know to play the game as you would play it yourself.
- Please describe how you (black circle) and your partner (white circle) would go about solving the following two scenarios:



- Please describe the meaning of each of the signs you and your partner use and how that particular meaning has been established:

Game 2

- Suppose that you are not able to participate in the next session of the game and decide to have a friend of yours take your place in the game. Please describe in detail all that your friend will need to know to play the game as you would play it yourself.
- Please describe
  - how you and your partner manage to not bump into each other
  - how you manage to get your partner in the room where you have found the prey
  - how your partner manages to get you in the same room where he or she has found the prey
- Please describe the meaning of each of the signs you and your partner use and how that particular meaning has been established.

Game 3

- Suppose that you are not able to participate in the next session of the game and decide to have a friend of yours take your place in the game. Please describe in detail all that your friend will need to know to play the game as you would play it yourself.
- Please describe
  - how you and your partner manage to not bump into each other
  - how you manage to get your partner in the room where you have found the prey

  - how your partner manages to get you in the same room where he or she has found the prey
  - how you handle an enemy attack on you
  - how you handle an enemy attack on your partner
- Please describe the meaning of each of the signs you and your partner use and how that particular meaning has been established (focus on the changes between the communication procedures you had in Game 1 and Game 2 and the communication procedure you have now).