Advances in Complex Systems
Vol. 15, Nos. 3 & 4 (2012) 1150026 (13 pages)

DOI: 10.1142/S0219525911500263

World Scientific
www.worldscientific.com

# EXPERIMENTAL SEMIOTICS: AN ENGINE OF DISCOVERY FOR UNDERSTANDING HUMAN COMMUNICATION

BRUNO GALANTUCCI*,†,‡ and GARETH ROBERTS*

*Department of Psychology, Yeshiva University,
2495 Amsterdam Avenue, New York, NY 10033, USA

†Haskins Laboratories, 300 George Street,
New Haven, CT 06511, USA

‡bruno.galantucci@yu.edu

Received 25 June 2011
Accepted 24 December 2011
Published 14 March 2012

The recent growth of Experimental Semiotics (ES) offers us a new option to investigate human communication. We briefly introduce ES, presenting results from three themes of research which emerged within it. Then we illustrate the contribution ES can make to the investigation of human communication systems, particularly in comparison with the other existing options. This comparison highlights how ES can provide an engine of discovery for understanding human communication. In fact, in complementing the other options, ES offers us unique opportunities to test assumptions about communicative behavior, both through the experimenters' planned manipulations and through the unexpected behaviors humans exhibit in experimental settings. We provide three examples of such opportunities, one from each of the three research themes we present.

*Keywords*: Human communication; experimental semiotics.

## 1. Introduction

Human communication systems are complex systems which organize the behaviors of many individuals into a culturally shared set of conventions [46, 74, 76]. Investigating experimentally such complex systems as they emerge and evolve within human communities is challenging and, in consequence, researchers typically opt for simulations with artificial agents (e.g., [2]). In the last few years a new option has become available [11, 70]. Researchers who take up this option — which will here be referred to as *Experimental Semiotics* (henceforth ES) — conduct controlled studies with human adults in which communication systems emerge *de novo* in the laboratory (e.g., [7, 11, 19, 27, 62]) or novel structure emerges in systems provided to participants (e.g., [37, 57, 64]). Experimental semioticians typically ask people to play collaborative games in virtual environments. While these games

usually require communication ([37] is a notable exception), players cannot use pre-established forms of communication such as existing spoken or written languages. The novel communication systems which players develop to play these games, as well as the communication failures which sometimes occur, provide new opportunities of investigation for students of human communication [13, 14, 63].

This paper has two goals. The first is that of briefly introducing ES. To this end, we describe three themes of research which emerged within it. The second goal is that of illustrating the contribution ES can make to the investigation of human communication systems, particularly in comparison to the other existing options. To this end, we will argue that ES provides a new engine of discovery for understanding human communication.

## 2. Three Themes of Research in ES

ES has offered a number of insights into the processes which govern human communication [13, 14, 63]. We focus on three specific research themes which emerged within ES. These themes will be here illustrated through three core questions.[a]

### 2.1. *Linguistic properties as the consequence of communication*

The first core question is this: Do key properties of natural language require explanations specific to natural language, or can they be explained in terms of general principles of human communication or cultural transmission? ES has a unique potential to answer this question. This potential will be discussed in Sec. 3.3; for the moment we will focus on a finding in ES which is of particular relevance to the question. Novel communication systems developed in the laboratory manifest, from very early on, linguistic properties such as *combinatoriality* (i.e., meaningless units are combined to form meaningful units [15]) and *compositionality* (i.e., meaningful units are combined in a structured way to form richer meaningful units [37, 64, 73]). Considering that, together, these two properties are sufficient conditions for one of the key hallmarks of human language, *duality of patterning* [29, 45], this finding suggests two conclusions. First, it suggests an answer to the question above, as key linguistic properties seem to arise as a consequence of communication or cultural transmission. Second, the finding suggests that the communication systems studied by experimental semioticians exhibit core properties of natural languages. In this sense, these systems may be considered as laboratory approximations of natural language. Of course a proper assessment of these conclusions requires further investigation, as we cannot exclude the possibility that the linguistic properties observed in the studies cited above were not caused by pre-existing biases originating from natural language. The presence of such a causal link is difficult to test with human

[a]What follows is not intended to be an exhaustive review of ES, nor of these themes (for such a review, see [14]). Rather, we have included a selection of studies which exemplify the themes well.

adults,[b] highlighting the important role of computational simulations and research with animals in complementing ES. Indeed, the two key elements of duality of patterning have been observed in communication systems developed by artificial agents (see [49, 66, 75] for compositionality and [48, 52, 77] for combinatoriality), as well as in the natural communication systems of animals (see [1] for compositionality and [44] for combinatoriality).

### 2.2. *Social factors in communication*

The second core question addressed by experimental semioticians is this: What role do social factors play in the emergence and evolution of human communication systems? Experimental semioticians have tackled this question at two different levels. At the level of dyads, they have shown that the development of symbols (i.e., communication forms the meaning of which is purely conventional) depends on the degree of interaction in the dyads. In particular, the more interdependent the interaction, the higher the degree of symbolicity of the communication systems developed by the dyads [19, 27]. Symbolicity is another key feature of human languages and so this result strengthens the parallel drawn above between communication systems studied by experimental semioticians and natural language.

At the level of small communities, experimental semioticians have obtained a number of results. First, they have shown that small communities of interacting dyads will globally converge on simplified and symbolic communication systems [10]. These systems are different for different communities and are easier to learn than systems developed by isolated pairs [9]. Second, experimental semioticians have addressed an interesting theoretical difference which has arisen within the community of researchers who study language as a product of cultural evolution. Some researchers focus on intergenerational transmission processes (e.g., [36]); other researchers focus on intragenerational communicative processes [54, 69]. This difference reverberates in ES where some researchers study diffusion chains [4, 37] and others interacting dyads or small communities (e.g., [11, 19, 62, 64]). Garrod and his colleagues [20] directly contrasted diffusion chains and interactive dyads, concluding that the latter but not the former lead to systematic simplification and increasing symbolicity. Independently of whether this conclusion will withstand future tests, the study by Garrod *et al.* illustrates the potential of ES for empirically addressing theoretical issues. Finally, a study in ES has shown how frequency of interaction and group conflict affect linguistic divergence in groups of interacting individuals [57]. Specifically, teams of players used an artificial language in order to negotiate transactions in a game. Through frequent interaction, players became able to identify one another on the basis of linguistic cues, and this led to substantial linguistic divergence between players when the negotiations

[b]This problem might be solved by carrying out ES studies with pre-linguistic children. However, this has not yet been done, most likely because of the challenges of performing such studies.

occurred in the context of a competitive version of the game. Considering that the game lasted only a few tens of minutes, this study suggests that, when human interactions are *both* conflictive and frequent, linguistic divergence occurs at a very fast pace.

### 2.3. *The bootstrapping of communication*

The third core question addressed by experimental semioticians is this: How do humans bootstrap a communication system? Experimental semioticians have tackled this question examining successes and failures in their studies. This has provided a number of insights. The first one is that the fundamental mechanism people use to bootstrap communication [11] is similar to the mechanism of interactive alignment described by Garrod and colleagues in the context of conversations using natural language [18, 21]. In other words, the bootstrapping of communication might rely on a mechanism that is not different in kind from the mechanism that facilitates convergence on the fine details of how to use pre-established forms of communication [11]. The similarity between novel and pre-established communication systems is not confined to the fundamental mechanisms for alignment. Galantucci observed that the behavior of the players in his study reflected the efficient integration of explicit communicative acts (the use of signs) with information implicitly available to players and silent behavior-coordinating procedures [11]. Such efficient integration is typical of natural language use [3, 25, 72]. Together, these results strengthen once more the parallel drawn above between communication systems studied by experimental semioticians and natural language. Another conclusion concerning the bootstrapping of communication is that it relies on implicit coordination mechanisms. In particular, Galantucci found that explicit negotiations about the meaning of specific signs were not necessarily beneficial for bootstrapping communication systems in his game [12], a finding which again parallels a finding with natural language [18]. Indeed, unless players had a keen ability to coordinate their joint attention and actions — in which case they typically engaged in explicit negotiations sparingly and greatly benefited from them — players were easily led to utter confusion by such negotiations [12; see also 16] Consistent with this conclusion, Scott-Phillips and his colleagues found that when default implicit coordination procedures were made more difficult to establish, failures in bootstrapping a communication system occurred much more frequently than when such procedures were easier to establish [62].

In sum, despite its brief existence, ES has already flourished in different directions, providing new opportunities to address a set of very diverse issues. In the next section we focus on the opportunities offered by ES which make it act as an engine of discovery for understanding human communication. In particular, we will illustrate three such opportunities, one from each of the themes presented above.

## 3. ES as an Engine of Discovery

In order to illustrate how ES provides an engine of discovery for understanding human communication, we will first situate ES in the context of other approaches for studying human communication. The most direct approaches to studying human communication involve studying samples of natural languages (e.g., [8, 43]) or the use of language in natural contexts (e.g., [24, 58]). These approaches — which, for convenience, will be here collectively referred to as the *Natural Approach* (henceforth NA) — have the clear advantage of getting their data from real agents (humans) interacting in real environments (the world). However, this advantage is also a major drawback. Focusing on real agents in real environments implies the lack of experimental control, which in turn implies scarce opportunities for uncovering causal relations. Moreover, considering that, with a few partial exceptions [23, 33, 60], humans do not develop natural communication systems de novo, the NA is not ideal for studying the emergence and evolution of human communication.

The most radical response to these limitations has been that of studying artificial simulations of the human world, where by artificial we mean created by the scientist so as to be fully manipulable (e.g., [6, 30, 31, 35, 42, 50, 65, 68]). This approach — which, for convenience, will be here referred to as the *Artificial Approach* (henceforth AA) — has offered us a number of insights concerning human communication, particularly regarding its emergence and evolution [2, 38, 67]. However, this radical response does not come without its own problems. Human communication is a complex phenomenon and, as such, it is governed by a dense network of hard-to-identify causal relations. Typically, investigators who adopt the AA dramatically reduce the complexity of this network by making a substantial number of simplifying assumptions. If the conclusions reached by the AA are to contribute to the scientific understanding of the natural phenomena the AA intends to model, such assumptions must be tested. One way in which this has been done is that of embodying artificial agents and situating their communicative interactions in real physical environments (e.g., [55, 69]). Indeed, this move has taught us a lot about the causal networks originating from physical interactions occurring in a realistic world (e.g., [71]). Another way to test the assumptions made by investigators who adopt the AA is that of studying the behavior of real humans interacting in artificial environments, that is, of performing ES studies.[c] These studies provide two kinds of opportunities for testing assumptions about human behavior. The first consists of the planned tests which experimental semioticians perform to verify computational models (e.g., [37]) or to contrast different theories (e.g., [20]). The second kind of opportunity consists of the *unplanned* tests which happen as a side result of studies which had a different intent. An example of the former kind of opportunity has

[c]Of course, experimental studies with humans can also be performed by allowing the use of pre-established forms of communication such as natural language (e.g., [39]). For reasons of space and focus, we will not consider these studies here.

been illustrated above in Sec. 2.2 [20]; here we focus on the latter kind. When faced with experimental tasks, human participants sometimes violate the experimenter's expectations about their behavior. Paradoxically, this can be a major strength of ES, as such unexpected violations offer us opportunities to discover what we *do not understand* about human behavior. A classic example of this is provided by the *Ultimatum Game* [26]. In the standard version of the game, two participants are paired up anonymously for a one-shot interaction in which one member (the proposer) is given a sum of money to divide between the pair. Any division of the sum is permitted but, if the other member (the responder) of the pair refuses the offer, neither member gets anything. If we assumed, following traditional economic theories, that both parties would act exclusively according to rational self-interest, we would expect the proposer to offer as little as possible and the responder to accept any nonzero amount. This is indeed the strategy of choice for chimpanzees [32], but not for humans. On average, human proposers offer 40% to the responder, and the responders reject 16% of offers [51]. In other words, participants apply rules of fairness (e.g., "do not offer too little"; "refuse offers that are too small") that are optimized for repeated and non-anonymous interactions, that is, the kind of interactions they most often encounter in their daily lives. The important point is that this kind of finding is not a drawback of experiments with humans, but an advantage, as these experiments offer opportunities to reveal fundamental human biases. In what follows we provide two further examples of such opportunities, this time from our own ES research.

### 3.1. *Egocentric failures*

The first example relates to the theme discussed in Sec. 2.3 and comes from two studies performed by Galantucci and his colleagues with dyads of participants [11, 15]. One of the consistent results in the two studies was that some players failed in developing even a minimal communication system, in 2–3 hours of playing. Such failures persisted when people played the game in teams of three [17]. Indeed, in half of the triads studied by Galantucci and colleagues there was a player who, in six hours of playing, did not learn any of the signs produced by the other two players in the team. Most of these stark failures were due to an unexpected factor: communicative egocentrism [12]. For example, some players did not make any use of the one device they had at their disposal to communicate with their partners (a small digitizing pad) for as long as two consecutive hours, often while the partner tried repeatedly to initiate some form of communication. These players sometimes made use of the signs generated by the partner, demonstrating an understanding of the basic dynamics of the game. However, the idea of reciprocating the communicative acts initiated by the partner was not obvious to them, suggesting a severe egocentric limitation. This conclusion is consistent with the behavior of other players who were successful at the game but developed signs which had different meaning depending on something that they privately controlled — the vertical component

of the tracings they drew on a digitizing pad — but which was not publicly perceivable. For example, some players drew a vertical line on the pad from top to bottom to indicate that their agent was moving down in the environment and from bottom to top to indicate that their agent was moving up in the environment. Given the constraints of the communication medium, the two drawings led to *identical tracings* on the screen seen by the partner (as well as by the drawer). However, the drawings *felt different* to the tracer's hand and, for this reason, not only were they used as different signs but were also expected to be understood as such. Similar forms of communicative egocentrism have been documented before in the context of spoken conversation [34], but it seems that communicative egocentrism becomes stronger in the context of the semiotic games used by Galantucci and colleagues. In conclusion, Galantucci and colleagues learned something unexpected from their experiments: The bootstrapping of communication implies the overcoming of potent egocentric biases. This conclusion is fairly surprising if we consider that all of the participants in the studies by Galantucci and colleagues were adults who regularly used sophisticated forms of communication in their lives (e.g., spoken and written language).

### 3.2. *Identification strategies*

The second example relates to the theme discussed in Sec. 2.2 and comes from a study performed by Roberts [56]. In that study, groups of four participants played a social game consisting of a series of rounds. In each of the rounds, every player was paired anonymously with one of the others and had to negotiate resource exchanges by typing messages in an artificial "alien language." In one of the conditions of the game, the four participants were divided into two teams of two. Over different rounds, participants played half the time with their teammate and half with their opponents. Since it was beneficial to give resources to teammates and to receive them from anyone, but detrimental to give resources to opponents, identifying one's anonymous interlocutor was important. However, players were told whether they had been paired with an opponent or a teammate only at the end of the round, after any resource exchange had taken place. Under such conditions, there was a significant tendency for team "dialects" to evolve in the initially uniform alien language — that is, a given participant's language became more like their teammate's language than their opponents' language. For example, both members of one team might prefer to refer to a resource with the alien word *lale* — the form given to participants at the start of the game — while the other team might prefer the form *lele* — a variant that initially arose through error.

However, if we assume that participants were employing strategies optimized to the game, it is not clear that we should have expected the development of team dialects. Indeed, given that the primary goal was to be identifiable to one's teammate, participants would have done better by developing distinctive *idiolects*, that is, individual variants of the alien language that their teammates would recognize.

But this is not what the majority of participants did. Instead they interpreted a pressure for greater identifiability as a pressure for *greater alignment*: They aligned their language more to that of their teammates than to that of their opponents, and this led to dialect formation [56, 57]. Alignment is not an optimal strategy in two ways. First, it takes more effort, as it involves at least three steps: (a) identifying one's teammate; (b) observing the teammate's language; and (c) adjusting one's own language. The idiolect strategy, in contrast, involves only the first and the third step. The second reason the alignment strategy is less good is that it is open to everyone. Since it is no harder for one's opponents to align themselves to one's teammate, alignment should not make anyone more identifiable.

Why did participants choose a suboptimal strategy? The answer recalls the lesson offered by the Ultimatum Game: We cannot assume that participants will employ strategies optimized to the game we engage them in. In this case participants were biased toward aligning preferentially to those with whom they interacted the most [53, 59] or identified the most [40, 41]. In the real world, where cooperative networks are large and learning to recognize the idiolects of all members is impractical, this strategy is clearly more efficient.

### 3.3. *Novel manipulations*

There is another sense in which ES provides an engine of discovery for understanding human communication. ES is not only useful as a means of testing the assumptions of the AA but it also offers the possibility of uncovering phenomena which would be hard to uncover through the NA. In fact, experimental semioticians can manipulate factors the effects of which might not be appreciated via the NA because, in the natural world, such factors have little, if any, variation. Such *novel manipulations* can lead to important insights. For instance, the role that gravity plays in determining the forms of life on earth was not fully appreciated until we had opportunities to run experiments in environments with gravity levels different from those typical of our planet [47]. Through the use of artificial environments, ES offers similar opportunities. This will be illustrated with an example relating to the theme discussed in Sec. 2.1.

Galantucci and colleagues manipulated the rapidity with which forms faded in the medium used by players to communicate in a ES game [15]. Rapidity of fading did not affect the pace with which sign systems were developed in the game, nor did it affect the efficacy with which these systems supported communication. In other words, rapidly fading forms afforded the same opportunities for communication as forms that faded more slowly. However, rapidity of fading had a profound effect on the type of sign systems developed by the players. In particular, in systems developed with rapidly fading forms, the individual forms were reused and combined much more frequently than in systems developed with more slowly fading forms. Considering that speech fades rapidly, Galantucci and colleagues argued that one of the core design principles of spoken language, combinatoriality, may be influenced

by a simple physical property of the medium in which speech is implemented. Independently from the validity of this argument, the study provides an important insight. Rapidity of fading had been long identified as one of the design features of natural language [29]. However, its potential effects on the design of natural language have never been appreciated before. This is most likely due to the fact that, in terms of rapidity of fading, all natural languages evolved under identical circumstances and thus we had no opportunities to learn about the effects of that factor. It is interesting to notice that the AA has a similar potential for novel manipulations as ES. However, we are not aware of any study within the AA which introduces such manipulations in an artificial environment. We believe that this is not by chance. Since everything in a fully artificial environment is under the control of the researcher, there is a strong pressure to justify the assumptions made in designing it, and this constrains the researcher's freedom to introduce manipulations that do not reflect reality.

## 4. Conclusions

In this paper we have briefly introduced a new field of research — Experimental Semiotics — and argued that it can provide an engine of discovery for understanding human communication. In particular, we have focused on three specific research themes within ES: linguistic properties as the consequence of communication; social factors in communication; and the bootstrapping of communication. With respect to the first of these, research has suggested that many features of human language may be due to the nature of communication itself, rather than language-specific biases. Research on the second theme has clearly indicated that the form and structure of communication systems cannot be understood without reference to a variety of social factors — such as inter- and intra-generational transmission, frequency of interaction, and competition (or cooperation) between speakers. Research on the third has shown that, while explicit negotiation may hinder the bootstrapping of new communication systems, the mechanisms that support such bootstrapping are likely the same as the mechanisms which support successful use of natural language.

We have also emphasized the contribution of ES in the context of other approaches to studying communication: the Natural Approach and the Artificial Approach. We have argued that ES complements these approaches by allowing us to test our assumptions about human behavior in two ways. Some of the tests are built into the experiments by the researchers; others originate in the unexpected behavior of participants. This capacity for experiments to challenge well-established scientific assumptions about human behavior has become clear in the field of economics. Cross-cultural experimental research has uncovered no society whose members behave according to the old-fashioned canonical model of *homo economicus* [28]. Indeed, by now it seems reasonable to say not only that experimental methods have changed the theoretical landscape of economics, but that the methodology has become part of the mainstream [5, 61]. It is our hope that, by following a similar

path, Experimental Semiotics will soon become part of the standard toolkit for research into language and communication.

## Acknowledgment

The support of the National Science Foundation (BCS-1026943) is gratefully acknowledged.

## References

[1] Arnold, K. and Zuberbühler, K., Meaningful call combinations in a non-human primate, *Curr. Biol.* **18** (2008) R202–R203.
[2] Cangelosi, A. and Parisi, D. (eds.), *Simulating the Evolution of Language* (Springer-Verlag, London, 2002).
[3] Clark, H. H., Coordinating with each other in a material world, *Discourse Stud.* **7** (2005) 507–525.
[4] Cornish, H., Investigating how cultural transmission leads to the appearance of design without a designer in human communication systems, *Interact. Stud.* **11** (2010) 112–137.
[5] Croson, R. and Gächter, S., The science of experimental economics, *J. Econ. Behav. Organ.* **73** (2010) 122–131.
[6] Dall'Asta, L., Baronchelli, A., Barrat, A. and Loreto, V., Nonequilibrium dynamics of language games on complex networks, *Phys. Rev. E* **74** (2006), doi:10.1103/PhysRevE.74.036105.
[7] de Ruiter, J. P., Noordzij, M. L., Newman-Norlund, S., Newman-Norlund, R., Hagoort, P., Levinson, S. C. and Toni, I., Exploring the cognitive infrastructure of communication, *Interact. Stud.* **11** (2010) 51–77.
[8] Dunn, M., Greenhill, S. J., Levinson, S. C. and Gray, R. D., Evolved structure of language shows lineage-specific trends in word-order universals, *Nature* **473** (2011) 79–82.
[9] Fay, N., Garrod, S. and Roberts, L., The fitness and functionality of culturally evolved communication systems, *Philos. Trans. R. Soc. B: Biol. Sci.* **363** (2008) 3553–3561.
[10] Fay, N., Garrod, S., Roberts, L. and Swoboda, N., The interactive evolution of human communication systems, *Cogn. Sci.* **34** (2010) 1–36.
[11] Galantucci, B., An experimental study of the emergence of human communication systems, *Cogn. Sci.* **29** (2005) 737–767.
[12] Galantucci, B., Experimental Semiotics: A new approach for studying communication as a form of joint action, *Top. Cogn. Sci.* **1** (2009) 393–410.
[13] Galantucci, B. and Garrod, S., Experimental Semiotics: A new approach for studying the emergence and the evolution of human communication, *Interac. Stud.* **11** (2010) 1–13.
[14] Galantucci, B. and Garrod, S., Experimental Semiotics: A review, *Front. Hum. Neurosci.* **5** (2011), doi: 10.3389/fnhum.2011.00011.
[15] Galantucci, B., Kroos, C. and Rhodes, T., The effects of rapidity of fading on communication systems, *Interact. Stud.* **11** (2010) 100–111.
[16] Galantucci, B. and Steels, L., The emergence of embodied communication in artificial agents and humans, in *Embodied Communication in Humans and Machines*, eds. Wachsmuth, I., Lenzen, M. and Knoblich, G. (Oxford University Press, Oxford, 2008), pp. 229–256.

[17] Galantucci, B., Theisen, C. A., Gutierrez, E. D., Kroos, C. and Rhodes, T., The diffusion of novel signs beyond the dyad, to appear in *Lang. Sci.*
[18] Garrod, S. and Anderson, A., Saying what you mean in dialog — A study in conceptual and semantic coordination, *Cognition* **27** (1987) 181–218.
[19] Garrod, S., Fay, N., Oberlander, J. and MacLeod, T., Foundations of representation: Where might graphical symbol systems come from? *Cogn. Sci.* **31** (2007) 961–987.
[20] Garrod, S., Fay, N., Rogers, S., Walker, B. and Swoboda, N., Can iterated learning explain the emergence of graphical symbols, *Interact. Stud.* **11** (2010) 33–50.
[21] Garrod, S. and Pickering, M., Why is conversation so easy? *Trends Cogn. Sci.* **8** (2004) 8–11.
[22] Goldenfeld, N. and Kadanoff, L. P., Simple lessons from complexity, *Science* **284** (1999) 87–89.
[23] Goldin-Meadow, S. and Mylander, C., Spontaneous sign systems created by deaf children in two cultures, *Nature* **391** (1998) 279–281.
[24] Goodwin, C., *Conversational Organization: Interaction Between Speakers and Hearers* (Academic Press, New York, 1981).
[25] Goodwin, C., Action and embodiment within situated human interaction, *J. Pragmat.* **32** (2000) 1489–1522.
[26] Güth, W., Schmittberger, R. and Schwarze, B., An experimental analysis of ultimatum bargaining, *J. Econ. Behav. Organ.* **3** (1982) 367–388.
[27] Healey, P. G. T., Swoboda, N., Umata, I. and King, J., Graphical language games: Interactional constraints on representational form, *Cogn. Sci.* **31** (2007) 285–309.
[28] Henrich, J., Boys, R., Bowles, S., Camerer, C., Fehr, E., Gintis, H., McElreath, R., Alvard, M., Barr, A., Ensminger, J., Henrich, N. S., Hill, K., Gill-White, F., Gurven, M., Marlowe, F. W., Patton, J. Q. and Tracer, D., "Economic Man" in cross-cultural perspective: Behavioral experiments in 15 small-scaler societies, *Behav. Brain Sci.* **28** (2005) 795–855.
[29] Hockett, C. F., Logical considerations in the study of animal communication, in *Animal Sounds and Communications*, eds. Lanyon, W. and Tavolga, W. (American Institute of Biological Sciences, Washington, 1960), pp. 392–430.
[30] Hurford, J. R., Biological evolution of the Saussurean sign as a component of the language acquisition device, *Lingua* **77** (1989) 187–222.
[31] Hutchins, E. and Hazlehurst, B., How to invent a lexicon: The development of shared symbols in interaction, in *Artificial Societies: The Computer Simulation of Social Life*, eds. Gilbert, N. and Conte, R. (UCL Press, London, 1995).
[32] Jensen, K., Call, J. and Tomasello, M., Chimpanzees are rational maximizers in an ultimatum game, *Science* **318** (2007) 107–109.
[33] Kegl, J., Senghas, A. and Coppola, M., Creation through contact: Sign language emergence and sign language change in Nicaragua, in *Language Creation and Language Change: Creolization, Diachrony, and Development*, ed. DeGraff, M. (MIT Press, Cambridge, MA, 1999), pp. 179–237.
[34] Keysar, B., Communication and miscommunication: The role of egocentric processes, *Intercult. Pragmat.* **4** (2007) 71–84.
[35] Kirby, S., Syntax out of learning: The cultural evolution of structured communication in a population of induction algorithms, in *Advances in Artificial Life*, Lecture Notes in Computer Science, Vol. 1674 (Springer-Verlag, 1999), pp. 694–703.
[36] Kirby, S., Natural language from artificial life, *Artificial Life* **8** (2002) 185–215.
[37] Kirby, S., Cornish, H. and Smith, K., Cumulative cultural evolution in the laboratory: An experimental approach to the origins of structure in human language, *Proc. Nat. Acad. Sci.* **105** (2008) 10681–10686.

[38] Kirby, S. and Hurford, J. R., The emergence of linguistic structure: An overview of the iterated learning model, in *Simulating the Evolution of Language*, eds. Cangelosi, A. and Parisi, D. (Springer-Verlag, London, 2002), pp. 121–48.
[39] Krauss, R. M. and Weinheimer, S., Changes in reference phrases as a function of frequency of usage in social interaction — A preliminary study, *Psychonom. Sci.* **1** (1964) 113–114.
[40] Labov, W., The social motivation of a sound change, *Word* **19** (1963) 273–309.
[41] Lakin, J. L., Chartrand, T. L. and Arkin, R. M., I am too just like you: Nonconscious mimicry as an automatic behavioral response to social exclusion, *Psychol. Sci.* **19** (2008) 816–822.
[42] Liljencrants, J. and Lindblom, B., Numerical simulation of vowel quality systems — Role of perceptual contrast, *Language* **48** (1972) 839–862.
[43] Lupyan, G. and Dale, R., Language structure is partly determined by social structure, *PLoS ONE* **5** (2010), e8559. doi: 10.1371/journal.pone.0008559.
[44] Marler, P. (ed.), *The Structure of Animal Communication Sounds* (Dahlem Konferenzen, Berlin, 1977).
[45] Martinet, A., *Elements of General Linguistics* (University of Chicago Press, Chicago, 1960), Translated by E. Palmer.
[46] Millikan, R. G., *Varieties of Meaning* (MIT Press, Cambridge, MA, 2004).
[47] Morey-Holton, E., The impact of gravity on life, in *Evolution on Planet Earth: The Impact of the Physical Environment*, eds. Rothschild, L. and Lister, A. (Academic Press, London, 2003), pp. 143–59.
[48] Nowak, M. A., Krakauer, D. C. and Dress, A., An error limit for the evolution of language, *Proc. R. Soc. Lond. B — Biol. Sci.* **266** (1999) 2131–2136.
[49] Nowak, M. A., Plotkin, J. B. and Jansen, V. A. A., The evolution of syntactic communication, *Nature* **404** (2000) 495–498.
[50] Nowak, M. A., Plotkin, J. B. and Krakauer, D. C., The evolutionary language game, *J. Theor. Biol.* **200** (1999) 147–162.
[51] Oosterbeek, H., Sloof, R. and van de Kuilen, G., Cultural differences in ultimatum game experiments: Evidence from a meta-analysis, *Exper. Econ.* **7** (2004) 171–188.
[52] Oudeyer, P.-Y., The self-organization of combinatoriality and phonotactics in vocalization systems, *Connect. Sci.* **17** (2005) 325–341.
[53] Pickering, M. and Garrod, S., Towards a mechanistic psychology of dialogue, *Behav. Brain Sci.* **27** (2004) 169–226.
[54] Puglisi, A., Baronchelli, A. and Loreto, V., Cultural route to the emergence of linguistic categories, *Proc. Nat. Acad. Sci. USA* **105** (2008) 7936–7940.
[55] Quinn, M., Evolving communication without dedicated communication channels, in *Advances in Artificial Life: ECAL6 2001*, eds. Kelemen, J. and Sosik, P. (Springer-Verlag, Berlin, 2001), pp. 357–366.
[56] Roberts, G., *Cooperation, Social Selection, and Language Change: An Experimental Investigation of Language Divergence*, Unpublished doctoral dissertation, University of Edinburgh, UK (2010), http://bit.ly/kEFwVG.
[57] Roberts, G., An experimental study of social selection and frequency of interaction in linguistic diversity, *Interact. Stud.* **11** (2010) 138–159.
[58] Sacks, H., *Lectures on Conversation*, Ed. G. Jefferson with "Introduction" by E. A. Schegloff, Vols. 1–2 (Blackwell, Oxford, 1992).
[59] Sancier, M. L. and Fowler, C. A., Gestural drift in a bilingual speaker of Brazilian Portuguese and English, *J. Phon.* **25** (1997) 421–436.

[60] Sandler, W., Meir, I., Padden, C. and Aronoff, M., The emergence of grammar: Systematic structure in a new language, *Proc. Natl. Acad. Sci. USA* **102** (2005) 2661–2665.
[61] Santos, A. C., Behavioral and experimental economics: Are they really transforming economics? *Cambridge J. Econ.* (2011), doi: 10.1093/cje/beq049.
[62] Scott-Phillips, T., Kirby, S. and Ritchie, G. R. S., Signalling signalhood and the emergence of communication, *Cognition* **113** (2009) 226–233.
[63] Scott-Phillips, T. C. and Kirby, S., Language evolution in the laboratory, *Trends Cogn. Sci.* **14** (2010) 411–417.
[64] Selten, R. and Warglien, M., The emergence of simple languages in an experimental coordination game, *Proc. Natl. Acad. Sci. USA* **104** (2007) 7361–7366.
[65] Skyrms, B., Signals, evolution and the explanatory power of transient information, *Philos. Sci.* **69** (2002) 407–428.
[66] Smith, K., Brighton, H. and Kirby, S., Complex systems in language evolution: The cultural emergence of compositional structure, *Adv. Complex Syst.* **6** (2003) 537–558.
[67] Steels, L., The synthetic modeling of language origins, *Evol. Commun.* **1** (1997) 1–34.
[68] Steels, L., The origins of syntax in visually grounded robotic agents, *Artif. Intell.* **103** (1998) 133–156.
[69] Steels, L., Evolving grounded communication for robots, *Trends Cogn. Sci.* **7** (2003) 308–312.
[70] Steels, L., Experiments on the emergence of human communication, *Trends Cogn. Sci.* **10** (2006) 347–349.
[71] Steels, L., Modeling the formation of language: Embodied experiments, in *Evolution of Communication and Language in Embodied Agents*, eds. Nolfi, S. and Mirolli, M. (Springer-Verlag, Berlin, 2010), pp. 235–262.
[72] Tanenhaus, M. K., Spivey-Knowlton, M. J., Eberhard, K. M. and Sedivy, J. E., Integration of visual and linguistic information in spoken language comprehension, *Science* **268** (1995) 632–634.
[73] Theisen, C. A., Oberlander, J. and Kirby, S., Systematicity and arbitrariness in novel communication systems, *Interact. Stud.* **11** (2010) 14–32.
[74] Tomasello, M., *The Cultural Origins of Human Cognition* (Harvard University Press, Cambridge, MA, 1999).
[75] Vogt, P., The emergence of compositional structures in perceptually grounded language games, *Artif. Intell.* **167** (2005) 206–242.
[76] Wittgenstein, L., *Philosophical Investigations* (Basil Blackwell, Oxford, 1953).
[77] Zuidema, W. and de Boer, B., The evolution of combinatorial phonology, *J. Phon.* **37** (2009) 125–144.