The effects of rapidity of fading on communication systems

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Although rapidity of fading has been long identified as one of the crucial design features of language, little is known about its effects on the design of communication systems. To investigate such effects, we performed an experiment in which pairs of participants developed novel communication systems using media that had different degrees of rapidity of fading. The results of the experiment suggest that rapidity of fading does not affect the pace with which communication systems emerge or the communicative efficacy of the emerged systems. However, rapidity of fading seems to affect the design of these systems. In particular, communication systems implemented in the more rapidly fading medium exhibited a higher degree of combinatorial reuse of their forms than systems implemented in the medium that faded more slowly. These results suggest that the design of language might be constrained by subtle relations the presence of which can be ascertained only through direct experimental manipulation. Human communication systems crafted today in the laboratory can provide new insights into the design of natural languages.

Spoken language rapidly fades in its natural medium.[1] Although this property has been long identified as one of the crucial design features of language (Hockett, 1960), we know very little about the effects that rapidity of fading might have on the design of language. This lack of knowledge is most likely due to the fact that, in terms of rapidity of fading, all spoken languages evolved under identical circumstances and, when a circumstance never changes, it is difficult for us to appreciate its potential effects. 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 (Morey-Holton, 2003).

In a similar vein, one might attempt to uncover the effects of different levels of rapidity of fading on the design of human communication systems by

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comparing scripts, the forms of which do not rapidly fade, to spoken languages. However, this is a problematic comparison. On the one hand, most scripts inherit their core features directly from spoken language. On the other hand, the rapidity of fading of forms is not the only difference between spoken and written communication, there are many others. To name just a few, written communication typically occurs across space and time; spoken communication typically occurs in the here and now.[2] Written communication is typically planned and unidirectional; spoken communication is typically spontaneous and bidirectional (Pickering & Garrod, 2004). Written communication requires schooling, spoken communication does not. Clearly, the comparison between spoken language and scripts does not allow an assessment of the exclusive effects of rapidity of fading on the design of communication systems. Such assessment requires minimally two conditions. First, we need to study communication systems that emerge independently from each other and are as independent as possible from pre-established forms of communication such as speech. Second, we need to selectively manipulate the rapidity of fading of the medium in which communicative forms are implemented. In this paper, we report the results of an experimental study that satisfies these requirements.

The study was conducted with a method that has been recently developed to investigate the emergence of human communication systems under controlled laboratory conditions (Galantucci, 2005). As we shall see, the method is well suited for the purposes of studying the effects of rapidity of fading. On the one hand, it enables us to observe the emergence of novel communication systems that are independent from each other and relatively independent from pre-established forms of communication (Galantucci, 2005). On the other hand, the method affords complete experimental control.

The main goal of the present study was that of determining how rapidity of fading affects emerging communication systems. To do this, we compared communication systems that emerged in identical conditions but for the rapidity of fading of the medium in which they were implemented. We looked for three possible effects of rapidity of fading. First, we analyzed how readily communication systems emerged, testing whether rapidity of fading affected the ease with which communication systems were established. Second, we compared the functionality of the emerged communication systems, testing whether rapidity of fading affected their communicative power. Finally, we compared the design of the emerged communication systems, testing the hypothesis that, the more rapidly communicative forms fade, the more likely it is that they are reused in combination with one another, following a design that closely resembles the core design of spoken language (Hockett, 1960; Martinet, 1960).

1. Method

Pairs of participants played a cooperative videogame with interconnected computers. The game required players to communicate about the location of the agents they controlled in the videogame (see section below – The game), but players played in different rooms and could not see or hear each other. Instead, they could send messages to each other by using a magnetic stylus on a small digitizing pad. The resultant tracings were relayed to the computer screens of both players. In particular, the horizontal location of the stylus on the pad controlled the horizontal location of a tracing on the screen. The vertical location of the stylus on the pad was irrelevant. Depending on experimental condition, the tracings generated when the stylus touched the pad were displayed in one of two ways (Figure 1A). In the *Fast fading* (FF) condition, the tracing appeared at a fixed height on the screen and disappeared as soon as the stylus was lifted from the pad. In the *Slow fading* (SF) condition, the tracing appeared at the top of the screen and then scrolled down the screen at a constant speed for 2.5 s, until it reached the end of the screen and disappeared. In both conditions, the use of standard graphic forms such as letters or numbers was practically impossible (Figure 1B). This constraint forced players to develop communication systems from their very foundations, minimizing the chances that the systems adopted their structure directly from speech (Galantucci, 2005).

1.1 The game

Pairs played a videogame in which each player controlled one agent. The game was organized in rounds. In each round, the agents started in two different rooms at random in a four room virtual environment (2 × 2 grid, Figure 1C) and had to find each other, without making more than one room change each. Players could not see each other's agents when the agents were in different rooms. In other words, to win at the game consistently, players needed to communicate about the respective positions of their agents on the grid. The scoring mechanism of the game was such that, in the absence of effective communication, the score stably fluctuated around its initial value. If the pair reached a threshold score that indicated successful communication, players were invited to play a new version of the game: The game environment was enlarged (6 rooms, 2 × 3 grid) and an additional room change per round was allowed. For successful pairs, the size of the environment (and the number of room changes allowed) could grow three more times until the environment, at the fifth and final stage, was composed of 16 rooms (4 × 4 grid). Pairs were invited to play for three sessions of two hours each and were told that their goal in the game was to achieve as high a score as possible. For the entire duration of the game, the movements of the agents and the activity on the pads were recorded at approximately 32 Hz. On termination of the last experimental session, participants were interviewed for about thirty minutes during which they provided a detailed written description of the communication systems they developed for playing.

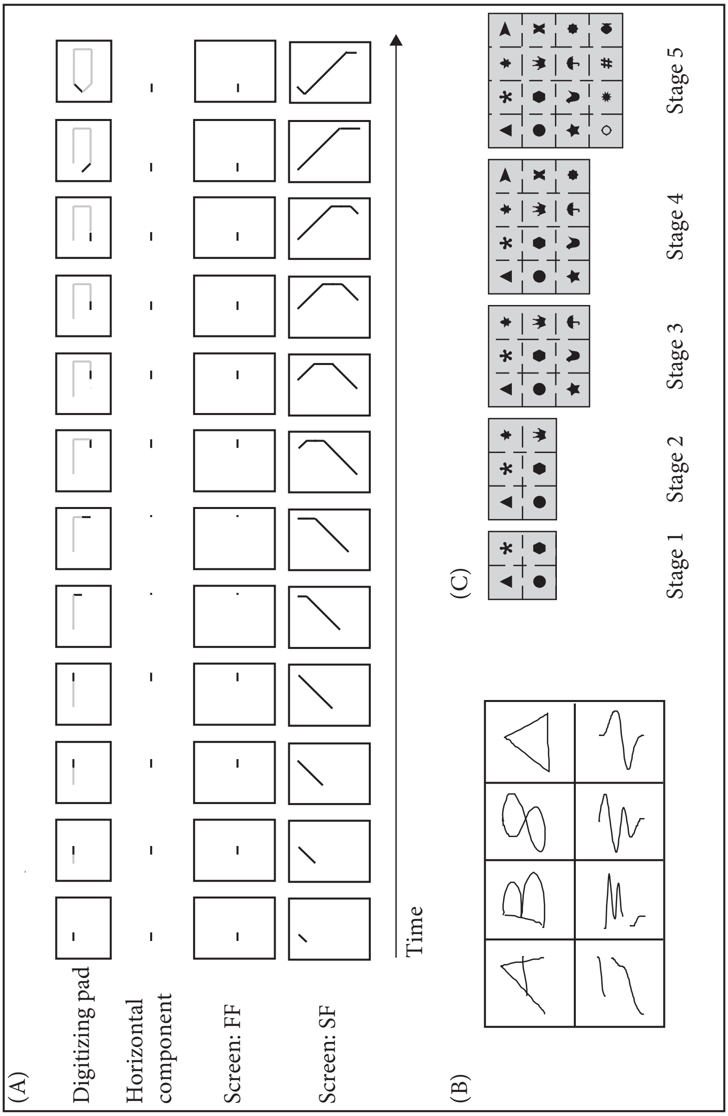

Figure 1. Methods: (A) How the tracings on the digitizing pad appeared on the screen in the two conditions; (B) How common graphic symbols appear on the screen (in the SF condition); (C) Maps of the game environment at different stages.

1.2 Participants

Sixteen pairs of participants were invited to participate in the experiment for a compensation of $10 per hour. Participants in a pair did not know each other and did not get to know each other until the end of the study. Two pairs were dropped from the study because, due to a lack of understanding of the requirements of the game, they had no functional communication system at the end of the first two experimental sessions.[3] Of the remaining fourteen pairs, seven pairs participated in the FF condition and seven in the SF condition.

2. Results

To detect differences between the communication systems developed in the two conditions we used four measures. The first two measures captured the *performance* of the pairs at the game and allowed us to test whether pairs in the two conditions developed communication systems with equal ease. The third measure captured the *communicative power* of the communication systems developed by the pairs and allowed us to test whether rapidity of fading affected the efficacy with which pairs in the two conditions were able to communicate in the game. Finally, a fourth measure captured the amount of *form recombination* that was present in the pairs' communication systems and allowed us to test whether pairs in the FF condition reused their communicative forms in combination more frequently than pairs in the SF condition.

2.1 Performance

The average latency before pairs were able to communicate successfully (measured as the moment in time at which the pair reached the threshold score for the first stage of the game) was 48.21 ± 37.24 SD min, with no significant difference between pairs in the two conditions [FF: 44.43 ± 35.65; SF: 52.00 ± 41.24; $t(12) = .37$, $p = .72$, $d = .2$]. The average stage of the game played successfully by the pairs at the end of the third session was 3.5 ± 1.45, with no significant difference between pairs in the two conditions [FF: 3.57 ± 1.61; SF: 3.43 ± 1.4; $t(12) = .18$, $p = .86$, $d = .09$]. Together, these results indicate that the pairs' game performance in the two conditions was about the same; rapidity of fading did not affect the ease with which communication systems were developed.

2.2 Communicative power

The communicative power of a communication system was determined by counting the number of locations in the game map that the system allowed to discriminate at the end of the last experimental session. In particular, for each pair, we

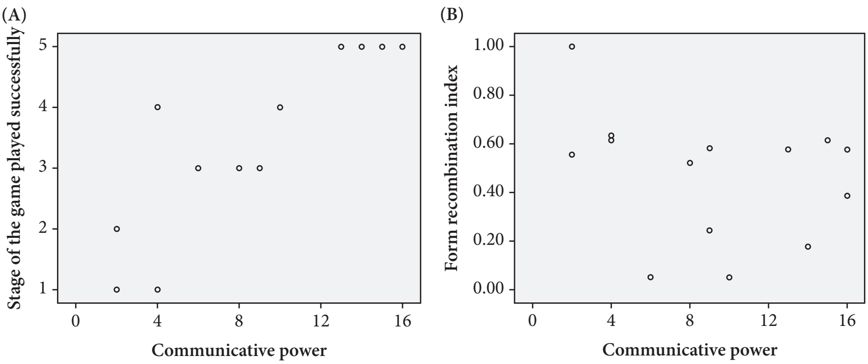

Figure 2. Results: Scatter plots across conditions of (A) Communicative power vs. performance in the game and (B) Communicative power vs. Form recombination index.

counted all the locations that (a) were consistently indicated as discriminable by both players in the descriptions provided after the end of the game, and (b) were consistently discriminated by both players during the game (this was determined by inspecting the recordings of the game).

Communication systems developed in the FF condition identified roughly the same number of locations as communication systems developed in the SF condition [FF: 8.86 ± 6.28; SF: 9.43 ± 3.99; $t(12) = .2$, $p = .84$, $d = .1$]. In other words, the systems developed in the two conditions had similar communicative power, a result that is consistent with the fact that the average performance of the pairs in the two conditions was about equal. Indeed, communicative power and performance in the game were strongly correlated across conditions [$r(14) = .88$ $p < .001$, Fig. 2 (A)], suggesting that the method worked as intended: Success in the game implied more powerful communication systems.

The results presented so far can be easily summarized. Not only rapidity of fading did not affect the pace with which communication systems emerged, but it also did not affect the communicative efficacy of the emerged systems. Once players were afforded the possibility to manipulate a mutually visible signal, they found a way to use it to communicate in an effective manner, regardless of its specific properties.

We now turn to the measure of form recombination that we used to detect differences in design between the communication systems developed by the pairs in the two conditions.

2.3 Form recombination

The description of the procedure to determine form recombination requires two preliminary steps. The first step illustrates how we organized into a database the signaling activity produced by the players. The second step illustrates how we detected the presence of equivalent forms across the database.

Sign database. For each pair, we inspected the recordings of the game and extracted the signaling activity (i.e., the horizontal movements of the stylus on the pad) that occurred contingently with successful moves in the game. These signaling activities, which we will refer to as the *signs* of the communication system used by the pair, were organized in a digital database according to the locations they indicated. The database was then reduced by selecting, for each location identified by each pair, only the last occurrence of the signs produced by the players during the game.[4] Finally, for each sign in the database, we identified its *forms* as the sequences of sample points during which the stylus was uninterruptedly in contact with the digitizing pad. That is, a form was a vector of contiguous stylus positions (sampled at approximately 32 Hz) which corresponded to a drawing stroke on the digitizing pad.

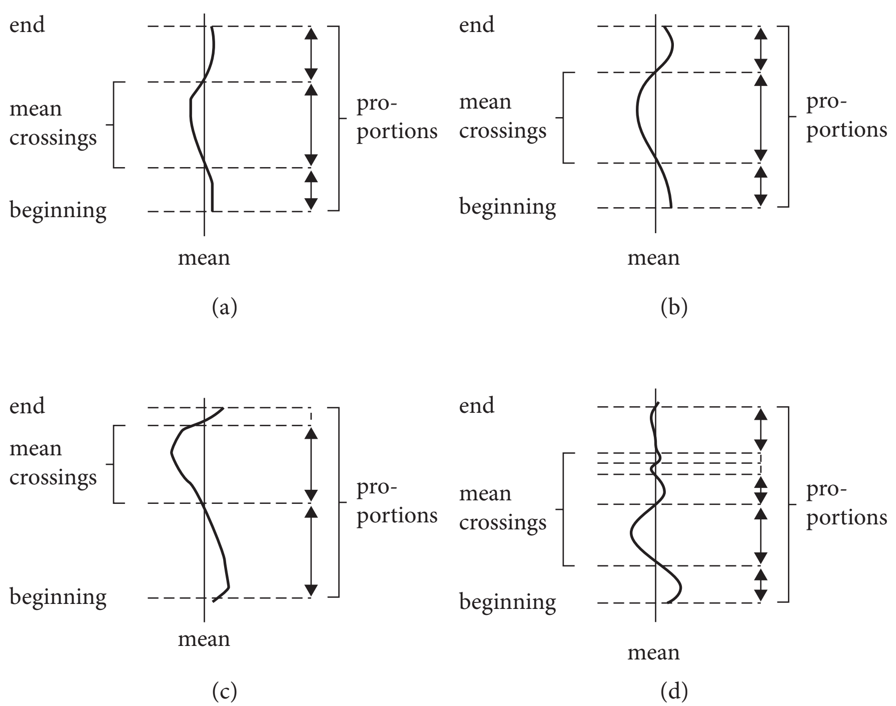

Figure 3. The form equivalence test. The forms in (A) and (B) pass the test because they have the same number of mean crossings and their form proportions are within the 10% from each other. The forms in (A) and (C), as well as the forms in (B) and (C), do not pass the test because their form proportions are not within 10% of each other. The form in (D) is not equivalent to any of the forms in (A)–(C) because it has a different number of mean crossings.

Signs		A		E	I		O			U		
	Forms	•	▬	•	•	•	▬	▬	▬	•	•	▬
A	•	IS	IS	1	1	1	0	0	0	1	1	0
	▬		IS	0	0	0	1	1	1	0	0	1
E	•			IS	1	1	0	0	0	1	1	0
I	•				IS	IS	0	0	0	1	1	0
	•					IS	0	0	0	1	1	0
O	▬						IS	IS	IS	0	0	1
	▬							IS	IS	0	0	1
	▬								IS	0	0	1
U	•									IS	IS	IS
	•										IS	IS
	•											IS

Figure 4. Exemplification of the procedure used for computing the Form recombination index. The procedure is here applied to a fictitious communication system that comprises five signs (indicated by the letters A, I, E, O, U) encoded with the two forms of the Morse code. The recurrence of a form across signs is indicated by a "1" in the table. Overall, there are 20 recurrences and 27 non recurrences, yielding a Form recombination index of about .43 [20/(20+27)]. Intra-sign recurrences and non-recurrences (both indicated as IS in the figure) are not considered for the computation of the index.

Form equivalence test. The equivalence of forms was tested with a procedure that relied exclusively on form shape. For each form, we computed its mean value and determined in how many places the form crossed the mean value (henceforth *mean crossings*). Then, we computed the proportion of the form that was comprised between each mean crossing (henceforth *form proportions*; see Fig. 3) and expressed the shape of the form as the ordered series of its form proportions. Two forms were considered equivalent if they had the same number of mean-crossings and their respective form proportions had values that were within ten percent of each other.[5]

Form recombination index. We applied the form equivalence test described above to each pair of forms in the database. This resulted in a matrix which indicated, for each form, how many times (if any) that form recurred in the whole database. To obtain an index of form recombination for each player, we then calculated how frequently forms recurred across the database, with the exclusion of recurrences that occurred within a sign (see Fig. 4 for an example). This exclusion guaranteed that we detected global recombination, that is, that the reuse of forms occurred across the signs and not within them. Finally, for each pair we computed form recombination as the average of the indices for the two players.

On average, form recombination for pairs in the FF condition was substantially higher than for pairs in the SF condition [FF = .61 ± .19, SF = .33 ± .26; $t(12) = 2.38$, $p < .05$, $d = 1.23$]. Across conditions, form recombination was not correlated with communication power [$r(14) = -.3$, $p = .31$, Fig. 2 (B)].

3. Discussion

We set out to investigate the effects of rapidity of fading on the design of communication systems. In order to do this we studied novel communication systems that were developed in identical conditions but for the rapidity of fading of the medium in which the systems were implemented. The results of the study are fairly straightforward. On the one hand, we found the negative results that rapidity of fading does not seem to affect the ease with which communication systems emerge, or the communicative efficacy of the emerged systems. On the other hand, we found the positive results that rapidity of fading seems to favor the emergence of combinatorial designs. Systems that were developed with forms that more rapidly faded relied more often on form recombination.

These findings are relevant for currently standing hypotheses about the origin of combinatorial designs in human language. Studdert-Kennedy and Goldstein (2003) hypothesized that the properties of the articulatory system for the production of speech favored the emergence of a combinatorial design in spoken language. The current study suggests the new hypothesis that another possible reason why speech adopted a combinatorial design is the fact that its forms rapidly decay. The two hypotheses are not mutually exclusive and further research is needed to clarify the extent to which the constraints they propose interact with each other.

The findings of the study are also relevant to another hypothesis about the origins of combinatorial designs in human languages. According to this hypothesis, combinatorial designs represent a solution to the problem of compactly expressing a large number of meanings (Lindblom, MacNeilage, & Studdert-Kennedy, 1984; Nowak, Plotkin, & Jansen, 2000). Surprisingly, in our study the number of meaning does not seem, per se, to lead to more combinatorial designs. Indeed, we obtained a negative correlation between communication power and the index of form recombination. Perhaps the number of meanings comprised in the systems studied here is below the critical threshold at which the number of meanings begins to have an effect on the structure of communication systems. Or perhaps, such effect is overridden by other constraints during the early emergence of communication systems. The latter hypothesis would provide an explanation to the intriguing observation that animal communication systems with only three signals obtain one of the three from a combination of the other two (Arnold & Zuberbühler, 2006).

Of course, the hypotheses that we suggest here require more experimental testing. However, we believe that the relevance of this study for students of human communication goes beyond the specific hypotheses that it suggests. Typically, investigators interested in the effects of physical constraints on the design of communication systems have been focusing on the naturally occurring differences between signed and spoken language (Meier, Cormier, & Quinto-Pozos, 2002). This study demonstrates that today a new option exists. That is, the option to directly *manipulating* the properties of the environment into which a communication system emerges and develop (Galantucci, 2009). This option complements the options of *observing* the natural evolution of communication systems (e.g., Changizi, Zhang, Ye, & Shimojo, 2006; Kegl, Senghas, & Coppola, 1999; Sandler, Meir, Padden, & Aronoff, 2005) or that of *simulating* it (Cangelosi & Parisi, 2002). It is our hope that future investigations will continue to explore the intriguing opportunities afforded by studying in the laboratory the emergence of novel forms of human communication.

Notes

1. What we write about spoken language in this paper can be extended, mutatis mutandis, to signed language.

2. Of course devices that record and transmit voice have recently modified these constraints.

3. One of these pairs never developed a communication system; the other developed a rudimentary system that discriminated two locations in Stage 1. This system collapsed soon after the pair, after much struggle, reached Stage 2 of the game. The pair did not reestablish functional communication by the end of the second experimental session and, at that point, the experiment was interrupted because players were frustrated and no longer engaged in the game. The system that was temporarily used by this pair to reach Stage 2 is not considered in this study because it did not meet the criteria of consistency necessary for determining its communicative power (see the Results section).

4. The signs in the database were consistent with the written descriptions provided by the players at the end of the game.

5. To test equivalence between two forms—say form A and form B—we ran the test twice. The first time we computed the 10% margins from the proportions of form A, the second time

from the proportions of form B. In case the two tests had a different outcome, we considered the forms to be non equivalent. Also, if the range of variation for a form was less than 2.5% of the total pad range, we considered the form to be a vertical line, as variations of such small magnitude were most likely due to motor noise and imperceptible to the players' eye. All vertical lines were considered equivalent forms.

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