

## How to Create Shared Symbols

Nicolas Fay<sup>1</sup>, Bradley Walker<sup>1</sup>, Nik Swoboda<sup>2</sup> & Simon Garrod<sup>3</sup>

<sup>1</sup>School of Psychological Science, University of Western Australia, 35 Stirling Highway, Crawley WA  
6009, Australia

<sup>2</sup>Department of Artificial Intelligence, Universidad Politecnica de Madrid, 28040 Madrid, Spain

<sup>3</sup>Institute of Neuroscience and Psychology, University of Glasgow, Glasgow G12 8QB,  
United Kingdom

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Corresponding author:

Nicolas Fay, School of Psychological Science, University of Western Australia

35 Stirling Highway, Crawley, WA 6009 Australia

Email: nicolas.fay@gmail.com; Tel: +61 (0)8 6488 2688; Fax: +61 (0)8 6488 1006

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26 **Abstract**

27 Human cognition and behaviour is dominated by symbol use. This paper examines the  
28 social learning strategies that give rise to symbolic communication. Experiment 1 contrasts  
29 an individual-level account, based on observational learning and cognitive bias, with an  
30 inter-individual account, based on social coordinative learning. Participants played a  
31 referential communication game in which they tried to communicate a range of recurring  
32 meanings to a partner by drawing, but without using their conventional language.  
33 Individual-level learning, via observation and cognitive bias, was sufficient to produce signs  
34 that became increasingly effective, efficient and shared over games. However, breaking a  
35 referential precedent eliminated these benefits. The most effective, most efficient and  
36 most shared signs arose when participants could directly interact with their partner,  
37 indicating that social coordinative learning is important to the creation of shared symbols.  
38 Experiment 2 investigated the contribution of two distinct aspects of social interaction:  
39 behaviour alignment and concurrent partner feedback. Each played a complementary role  
40 in the creation of shared symbols: behaviour alignment primarily drove communication  
41 effectiveness, and partner feedback primarily drove the efficiency of the evolved signs. In  
42 conclusion, inter-individual social coordinative learning is important to the evolution of  
43 effective, efficient and shared symbols.

## 44      **1. Introduction**

45      Humans are a symbolic species (Deacon, 1997). Human cognition and behaviour is  
46      dominated by symbol use, evident from our everyday use of numeric and linguistic systems.  
47      But where do these symbols come from? This question is presented by Harnad (1990) as  
48      the symbol grounding problem; how shared meanings can arise from arbitrary symbols in  
49      the absence of a pre-established shared symbol system. A solution to the symbol grounding  
50      problem was offered by Peirce (1931), who suggested that symbols evolved from motivated  
51      signs that share a non-arbitrary correspondence between the sign and its meaning, i.e.,  
52      iconic signs that resemble their meaning (e.g., a portrait of van Gogh that brings the Dutch  
53      painter to mind), or indexical signs that share a natural association between the sign and its  
54      meaning (e.g., the smell of smoke is an index of fire). This paper examines the social  
55      learning strategies through which shared symbols might arise from motivated signs.

56              Human communication systems, such as language, are socially learned. We have a  
57      range of social learning strategies at our disposal, from individual-level strategies to more  
58      complex inter-individual strategies (Tomasello, Kruger, & Ratner, 1993). Social learning  
59      research has tended to focus on observational learning (an individual-level strategy), where  
60      an agent learns from observing the behaviour of a model (Bandura, 1977). To be successful,  
61      the agent must use perspective-taking to infer the observed model's intentions.  
62      Experimental simulations of language evolution are often based on individual-level  
63      observation plus the cognitive biases that guide human inference (e.g., Kirby, Cornish, &  
64      Smith, 2008). Whereas individual-level strategies may be sufficient for simpler forms of  
65      social learning, inter-individual strategies may be important to more complex social learning  
66      (Morgan, Laland, & Harris, 2015). Social coordinative learning is an inter-individual strategy,

67 as opposed to an individual-level strategy, because social learning arises when agents  
68 coordinate and integrate their perspectives. Contemporary theories of dialogue stress the  
69 importance of social coordinative processes to successful interpersonal communication  
70 (Clark, 1996; Pickering & Garrod, 2004).

71         Using an innovative experimental paradigm, Experiment 1 contrasts the contribution  
72 of observational learning (an individual-level strategy) with social coordinative learning (an  
73 inter-individual strategy) to the evolution of shared symbols. Experiment 1 demonstrates  
74 the importance of social coordinative learning to the evolution of effective, efficient and  
75 shared symbols. In Experiment 2 we identify two important aspects of social coordinative  
76 learning – behaviour alignment and concurrent partner feedback – and isolate the influence  
77 of each to examine their contribution to the evolution of shared symbols. The Experiment 2  
78 results indicate that behaviour alignment improved communication success and concurrent  
79 partner feedback improved sign efficiency. Together, these complementary processes  
80 drove the interactive evolution of shared symbols.

81         We begin by reviewing the evidence suggesting that social interactive processes are  
82 important to the evolution of shared symbols. Next, we highlight some problems with the  
83 experimental paradigms used, and how they might limit the conclusions reached. We then  
84 explain the present experiments, report their findings, and discuss their significance.

85

### 86 **1.1. Evidence that social interaction is important to the evolution of shared** 87 **symbols**

88 Naturalistic studies indicate that motivated signs are important to establishing shared sign-  
89 to-meaning mappings. For example, when sign language users lack a label for something  
90 they tend to use an iconic sign for it (Klima & Bellugi, 1979). However, communication

91 systems tend not to remain iconic; whereas early sign languages and writing systems made  
92 extensive use of motivated signs, both have evolved in the direction of arbitrariness  
93 (Frishberg, 1975; Vaccari & Vaccari, 1961). Following Wescott (1971), we consider signs to  
94 lie on a continuum that ranges from absolutely motivated to absolutely arbitrary, with icons  
95 at one end and symbols at the other (with indices somewhere in-between) (see also  
96 Bronowski, 1967). We propose that social interaction is a key mechanism that drives the  
97 evolution of signs along this continuum, from (more) iconic to (more) symbolic.

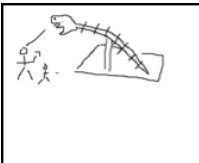
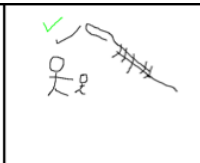
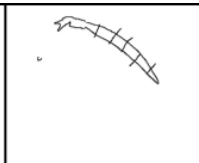
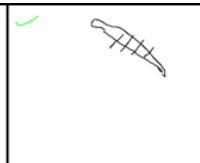
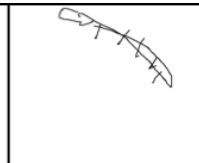
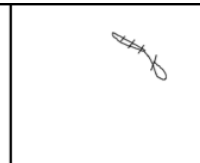
98         Social interaction plays a key role in contemporary theories of dialogue (Clark, 1996;  
99 Pickering & Garrod, 2004). Actively participating in dialogue ensures that meanings are  
100 mutually agreed, or grounded, between pairs of interlocutors (Clark & Schaefer, 1987) and  
101 across laboratory ‘generations’ of interlocutors (Tan & Fay, 2011). Grounding is an  
102 opportunistic process, where interlocutors try to find commonalities that allow them to  
103 coordinate, or align, their perspectives. For example, if person B accepts person A’s object  
104 description they can adopt that description, otherwise they can search out alternatives until  
105 a mutually acceptable description is identified. By contrast, if a passive observer does not  
106 understand person A’s description the communication is likely to fail because there is no  
107 opportunity for the observer to negotiate a mutually acceptable alternative with person A.

108         Social interaction also plays an important role in experimental-semiotic simulations  
109 of sign evolution. Experimental-semiotic studies examine the creation of novel human  
110 communication systems under controlled laboratory conditions (for reviews see Fay, Ellison,  
111 & Garrod, 2014; Galantucci, 2017; Tamariz, 2017). They do this by using a paradigm in  
112 which human participants must communicate without using their existing shared language.  
113 Typically, participants communicate in a novel modality, for example, through drawing  
114 (Galantucci, 2005; Garrod, Fay, Lee, Oberlander, & MacLeod, 2007; Healy, Swoboda, Umata,

115 & King, 2007; Roberts, Lewandowski, & Galantucci, 2015) or by gesture (Christensen,  
 116 Fusaroli, & Tylén, 2016; Fay, Arbib, & Garrod, 2013; Schouwstra & de Swart, 2014; Stolk,  
 117 Verhagen, & Toni, 2016), and the experimenters study how the communication systems  
 118 arise and evolve over repeated interactions between the participants.

119 A key finding is the importance of motivated signs and social interaction to the  
 120 creation of shared symbols (Garrod et al., 2007). In Garrod et al. (2007), participants tried  
 121 to communicate a set of recurring meanings to a partner by drawing on a shared  
 122 whiteboard. Like the game Pictionary®, participants were not allowed to speak or use  
 123 letters or numbers in their drawings. This procedure forced participants to create a novel  
 124 communication system from scratch. When participants played the game with an  
 125 interacting partner three things happened: their communication success improved as they  
 126 repeatedly communicated the same meanings, the signs they used evolved from complex  
 127 motivated signs to simpler, more symbolic signs, and over repeated interactions they  
 128 increasingly used the same signs to communicate the same meanings (i.e., their behaviour  
 129 aligned; see **Fig. 1**). This pattern, the creation of an effective inventory of shared symbols,  
 130 has been widely replicated (Caldwell & Smith, 2012; Fay, Garrod, Roberts, & Swoboda,  
 131 2010; Garrod, Fay, Rogers, Walker, & Swoboda, 2010; Theisen, Oberlander, & Kirby, 2010).  
 132 Analogous findings are observed in verbal referential communication experiments (Clark &  
 133 Wilkes-Gibbs, 1986; Garrod & Anderson, 1987).

134

					
<b>Game 1 Participant 1</b>	<b>Game 2 Participant 2</b>	<b>Game 3 Participant 1</b>	<b>Game 4 Participant 2</b>	<b>Game 5 Participant 1</b>	<b>Game 6 Participant 2</b>

135

136 **Fig. 1.** Sign refinement and alignment for the meaning ‘Museum’ over 6-games between a  
137 pair of participants in the Interaction condition from Experiment 1 of the present study.  
138 Participants alternated directing and matching roles from game to game. At Game 1  
139 Museum was communicated using a complex motivated sign that included a dinosaur, an  
140 exhibit space and two viewers. By Game 6 the sign has lost much of its initial motivation,  
141 evolving into a simpler, more symbolic representation, communicated by only the  
142 dinosaur’s spine. In addition to this symbolization process, the interacting partners’ signs  
143 became increasingly similar, or aligned, across games.

144

145 Experiments that manipulate the opportunity for interaction with a partner suggest  
146 that social coordinative processes are crucial to communication success and sign  
147 symbolization. Garrod et al. (2007) asked a group of passive observers to pick out the  
148 meaning associated with each of the signs produced by interacting pairs. Identification  
149 accuracy was lower among non-interacting observers compared to participants actively  
150 involved in the social coordinative process, indicating that social interaction was important  
151 to communication success. Furthermore, sign comprehension was lower among passive  
152 observers who were shown the later, simplified signs (games 4-6) compared to passive  
153 observers who were shown the more complex signs produced in the earlier games (see also  
154 Fay & Ellison, 2013; Fay, Garrod, & Roberts, 2008). This indicates that the signs became  
155 more abstract and symbolic, and their meaning became less accessible to observers, across  
156 repeated interactions. Note, the later signs were identified at higher than chance levels,  
157 indicating that they had not become absolute symbols, but they had become more  
158 symbolic, or less motivated, relative to the initial signs. Analogous results are returned by a  
159 verbal referential communication study (Schober & Clark, 1989). Furthermore, when

160 interactive partner feedback was unavailable, participants' signs became more complex  
161 across repeated productions, as opposed to simpler and more symbolic. This pattern is seen  
162 in experimental-semiotic studies (Garrod et al., 2007, 2010) and verbal referential  
163 communication studies (Hupet & Chantraine, 1992; Krauss & Weinheimer, 1966).

164

## 165 **1.2. Experimental paradigms limit the conclusions that can be drawn**

166 The experimental studies reviewed indicate that social coordinative learning enhances  
167 communication success and sign symbolization. However, the evidence is inconclusive. This  
168 is because the interactive and the non-interactive conditions they are contrasted with are  
169 not comparable. The interactive conditions engaged (repeated) production and (repeated)  
170 comprehension processes, whereas the non-interactive conditions engaged either  
171 (repeated) production (e.g., Garrod et al., 2007) or repeated comprehension processes (e.g.,  
172 Schober & Clark, 1989), but not both processes. It is therefore unclear if the benefits of  
173 social coordinative learning arise because social interaction engages production and  
174 comprehension processes, or because of the opportunity it affords for interactive  
175 grounding. An additional confound is that participants in the non-interactive conditions  
176 may have been less attentive, compared to interacting participants, given that they were  
177 not required to respond to the communicator.

178         These problems open the door to individual-level explanations of the observed  
179 phenomena. A simplicity bias captures the systematic preference to choose the simplest  
180 solution to a problem (Chater & Vitányi, 2003). It follows that a simplicity bias may drive  
181 sign simplification and, therefore, explain how the initially motivated signs became  
182 increasingly arbitrary and symbolic over repeated use. This individual-level explanation is  
183 consistent with a principle of least effort (Piantadosi, Tily, & Gibson, 2011; Zipf, 1949).



184 Without contrasting an interactive condition against a comparable non-interactive  
185 condition, it is unclear if sign symbolization arises through social coordinative learning or  
186 through observational learning that is guided by a simplicity bias.

187         Other research indicates that behaviour alignment can occur in the absence of direct  
188 social interaction. Verbal referential communication studies, in which participants describe  
189 events pictured on cards, show that interlocutors align their lexical choices and syntax, and  
190 this occurs with or without direct social interaction with a partner (Branigan, Pickering,  
191 McLean, & Cleland, 2007; Branigan, Pickering, Pearson, McLean, & Brown, 2011). These  
192 findings suggest that a cognitive bias toward behaviour alignment may be sufficient for the  
193 creation of a shared inventory of sign-to-meaning mappings. However, lexical priming can  
194 only occur when participants already share a lexicon, just as syntactic priming can only occur  
195 when participants already share a grammar. This is not the case in experimental-semiotic  
196 studies, where participants are tasked with creating a shared inventory of signs and  
197 combinatorial rules from scratch. Under these circumstances, social coordinative processes  
198 may be important to referential alignment.

199         Experiment 1 demonstrates the importance of social interaction to the creation of  
200 shared symbols. It does this by isolating the role of social coordinative learning from the  
201 role of observational learning and cognitive bias.

202

## 203 **2. Experiment 1. How to create shared symbols: Social Interaction,** 204 **observation and cognitive bias**

205 Experiment 1 tests the contribution of social interaction to three outcomes: communication  
206 success (or cognitive alignment), sign symbolization (operationalized using an information

207 theoretic measure of sign complexity) and behaviour alignment (human ratings of the  
208 extent to which interlocutors used the same signs to communicate the same meanings).  
209 These outcomes are important because any functional communication system should be  
210 effective, efficient and shared. Interacting pairs of participants were compared against  
211 participants allocated to a 'Pseudo-Interaction' condition that eliminated the opportunity  
212 for social coordinative learning.

213         The Interaction condition is similar to that used in other experimental-semiotic  
214 studies (Caldwell & Smith, 2012; Fay et al., 2010; Garrod et al., 2007, 2010; Theisen et al.,  
215 2010). Participants communicated by drawing a range of experimenter-specified meanings  
216 to a co-present partner across a virtual whiteboard tool (Healy, Swoboda, & King, 2002).  
217 Their partner tried to identify the intended meaning from a list of competitors, but could  
218 also interact graphically by drawing on the virtual whiteboard. Participants alternated  
219 directing and matching roles from game to game (1-6).

220         Two Pseudo-Interaction conditions were created that included (repeated)  
221 production and (repeated) comprehension processes but eliminated social interaction. In  
222 each Pseudo-Interaction condition participants believed they were directly interacting with  
223 a co-present partner, but they were not. Instead, the drawings produced by participants in  
224 the Interaction condition were played back to them across the virtual whiteboard tool.  
225 When it was their turn to communicate each meaning they were told their drawings would  
226 be sent to their partner, but they were not. Thus, in the Pseudo-Interaction conditions  
227 participants could be influenced by their partner but could not influence their partner, i.e.,  
228 communication was one-way as opposed to two-way (as was the case in the Interaction  
229 condition).

230 Two Pseudo-Interaction conditions were tested: Pseudo-Interaction: Precedent and  
231 Pseudo-Interaction: Broken Precedent. In the Pseudo-Interaction: Precedent condition, at  
232 Game 1 participants tried to identify the meaning associated with each of the drawings  
233 produced by their partner (a participant from the Interaction condition). In this condition  
234 their partner set the referential precedent by producing the first drawing for each meaning  
235 at Game 1. In the Pseudo-Interaction: Broken Precedent condition the participant drew first  
236 (at Game 1) and therefore set the referential precedent. Because there are a variety of  
237 ways that participants can communicate the different meanings (**Fig. 7** illustrates four  
238 different ways that participants communicated the meaning 'Parliament'), it is likely that  
239 the referential precedent set by the participant in this condition will be broken by their  
240 partner. Because referential precedents (or conceptual pacts; Brennan & Clark, 1996) set an  
241 expectation that a particular sign will be consistently used to pick out a particular meaning,  
242 they reduce uncertainty and aid partner comprehension (Keysar & Barr, 2002; Kronmüller &  
243 Barr, 2015; see also Relevance Theory; Sperber & Wilson, 1987). So, breaking a referential  
244 precedent is likely to negatively impact interpersonal communication.

245 Comparing the Interaction condition to the Pseudo-Interaction conditions allowed us  
246 to determine the contribution of social coordinative processes above and beyond the  
247 contribution of observational learning and cognitive biases. In the context of the present  
248 study, a simplicity bias may be sufficient to drive sign symbolization, and an alignment bias  
249 may be sufficient for interlocutors to create a shared inventory of sign-to-meaning  
250 mappings. However, if communication success, sign symbolization and sign alignment are  
251 stronger in the Interaction condition this would support the view that inter-individual social  
252 coordinative learning is important to the creation of shared symbols.

253           We predict that communication success, sign efficiency and sign alignment will be  
254 lower in the Pseudo-Interaction: Broken Precedent condition compared to the Pseudo-  
255 Interaction: Precedent condition. Our key prediction is that social interaction is important  
256 to each of these outcomes. If correct, communication success, sign efficiency and sign  
257 alignment will be highest in the Interaction condition compared to the Pseudo-Interaction  
258 conditions.

259

## 260 **3. Method**

261 Experiments 1 and 2 received approval from the University of Western Australia Ethics  
262 Committee. Participants viewed an information sheet before giving written consent to take  
263 part in the study. The information sheet and consent form were both approved by the  
264 Ethics Committee. All methods were performed in accordance with the guidelines from the  
265 NHMRC/ARC/University Australia's National Statement on Ethical Conduct in Human  
266 Research.

267

### 268 **3.1. Participants**

269 A convenience sample of sixty undergraduate students (42 self-reported females and 18  
270 self-reported males) participated in exchange for partial course credit or payment (A\$10).  
271 The sample size was based upon prior studies using the same experimental paradigm (Fay et  
272 al., 2010; Garrod et al., 2007, 2010). No statistical analyses were run prior to collecting the  
273 full sample. Participants were tested in unacquainted pairs, or individually, in testing  
274 sessions lasting up to 1-hour. All participants reported being free of any uncorrected visual  
275 impairment.

276

### 277 **3.2. Task and procedure**

278 The goal for each participant was to graphically communicate 16 confusable meanings (e.g.,  
279 ‘Arnold Schwarzenegger’, ‘Brad Pitt’, ‘Russell Crowe’) in such a way that their partner could  
280 identify their intended meaning. Like the game Pictionary©, participants were prohibited  
281 from using letters or numbers in their drawings. A review of the drawings produced by  
282 participants indicated they had followed the experimental instructions. The Director drew  
283 each meaning from their ordered list (16 targets plus 4 distractors; see **Table 1** for a  
284 complete listing) and their partner, the Matcher, tried to identify each meaning from their  
285 randomly ordered list of the same meanings.

286 The task was administered using a virtual whiteboard tool (Healy et al., 2002), which  
287 recorded all drawing activity. This tool has been used in a range of graphical communication  
288 studies (Fay et al., 2010; Garrod et al., 2010; Healy et al., 2007; Theisen et al., 2010). Each  
289 participant sat at a computer terminal where drawing input and meaning selection was  
290 made via a standard mouse. For the Director, each to-be-depicted meaning was highlighted  
291 in white text on a dark background at the top of the interface. Holding down the left mouse  
292 button initiated drawing. Director drawing was restricted to black ink and Matcher drawing  
293 was restricted to green ink (to distinguish between participants). By clicking an erase  
294 button on the interface participants were able to erase parts of their own drawing and their  
295 partner’s drawing. All drawing and erasing activity was displayed simultaneously on the  
296 Director and Matcher’s shared virtual whiteboards. When the matcher believed they had  
297 identified the director’s intended meaning they clicked the relevant button at the top of  
298 their interface, where there was a list of buttons corresponding to the competing meanings.  
299 Meaning selection brought the current trial to an end and initiated the next trial. No time

300 limit was imposed, and participants were given no explicit feedback with regard to their  
301 communication success. Having participants communicate remotely across networked  
302 computers meant they were unaware of their partner's identity.

303

### 304 3.3. Conditions

305 Participants were randomly allocated to one of three conditions: Interaction (N= 30, or 15  
306 interacting dyads), Pseudo-Interaction: Precedent (N= 15 individuals) or Pseudo-Interaction:  
307 Broken Precedent (N= 15 individuals). In the Interaction condition pairs of participants  
308 played 6 consecutive games of the task with the same partner, using the same meaning set  
309 on each game. For the Director, the first 16 meanings were always the target meanings  
310 (presented in a different random order on each game). The final 4 meanings were always  
311 the distractor meanings (presented in a different random order on each game). The 4  
312 distractor meanings were the same on each game and for each pair of participants. The  
313 distractor meanings were never communicated. Distractor meanings were included to  
314 ensure that Matchers could not use a process of elimination to identify the final target  
315 meaning. However, over the course of the experiment participants may have realized the  
316 distractor meanings were never communicated, and may have used a process of elimination  
317 to identify the final target meaning on the later games. For the Matchers, all 20 meanings  
318 were presented in a different random order on each game. In the Interaction condition  
319 participants alternated between directing and matching roles from game to game (i.e.,  
320 Participant 1 was the Director on games 1, 3 and 5 and the Matcher on games 2, 4 and 6,  
321 and Participant 2 was the Director on games 2, 4 and 6 and the Matcher on games 1, 3 and  
322 5). Irrespective of directing or matching role, participants were able to graphically interact  
323 within a trial. Thus, a Matcher might provide graphical feedback to the Director by

324 annotating part of their drawing or by offering a graphical alternative. This occurred on  
 325 11.60% of trials (23.33%, 11.25%, 13.75%, 8.33%, 7.50%, 5.42% of trials at game 1 to game 6  
 326 respectively).

327 The drawings produced by participants in the Interaction condition seeded the  
 328 Pseudo-Interaction conditions. The Pseudo-Interaction conditions provided participants  
 329 with exactly the same informational experience as participants in the Interaction condition,  
 330 but without the opportunity for social interaction. Participants in each Pseudo-Interaction  
 331 condition were told they would observe the interaction between two people playing the  
 332 Pictionary-type task (the Director and Matcher from the Interaction condition) and would  
 333 interact with one of them (the Director) when it was their turn to communicate the target  
 334 meanings. Because the virtual whiteboard tool (Healy et al., 2002) makes pixel-by-pixel  
 335 recordings of participants' drawings, we were able to dynamically play back the drawings  
 336 from the Interaction condition to participants in the Pseudo-Interaction conditions exactly  
 337 as they were produced.

338

339 **Table 1.** The set of meanings that Directors communicated to Matchers (distractor  
 340 meanings given in italic). Target and distractor meanings were fixed across conditions and  
 341 throughout the experiment.

Places	People	Entertainment	Objects	Abstract
Art Gallery	Arnold Schwarzenegger	Cartoon	Computer Monitor	Homesick
Parliament	Brad Pitt	Drama	Microwave	Loud
Museum	<i>Hugh Grant</i>	<i>Sci-Fi</i>	<i>Refrigerator</i>	Poverty
Theatre	Russell Crowe	Soap Opera	Television	<i>Sadness</i>

342

343           In the Pseudo-Interaction: Precedent condition the participant acted as the Matcher  
344 on games 1, 3 and 5 and the Director on games 2, 4 and 6 (see **Fig. 2**). In this condition,  
345 participants received the drawings produced by Participant 1 (Director trials) from the  
346 Interaction condition, plus any associated Matcher feedback. Matcher feedback was  
347 included in the playback from the Interaction condition to ensure that participants in the  
348 Pseudo-Interaction conditions received the same information as the Matchers in the  
349 Interaction condition. Participant 1 from each interacting dyad (15 in total) seeded a  
350 Pseudo-Interaction: Precedent participant.

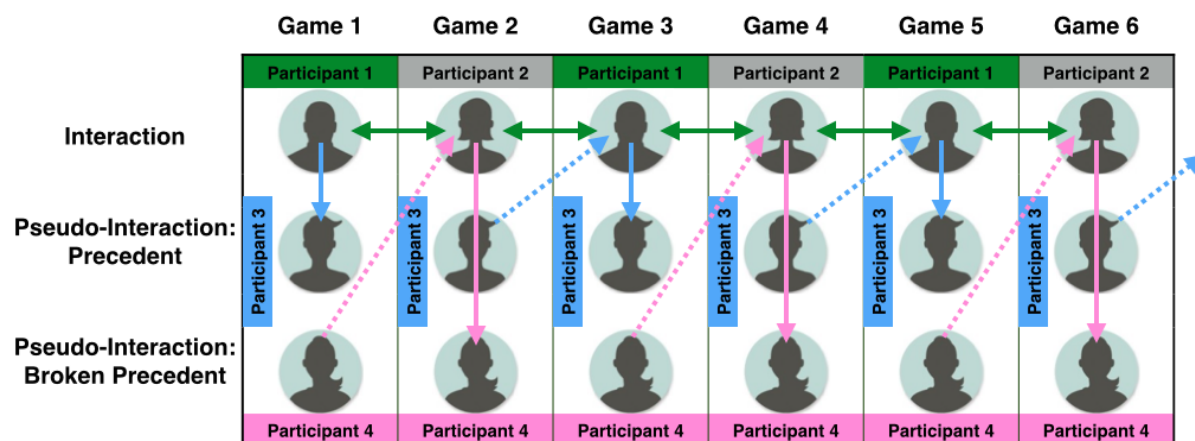
351           In the Pseudo-Interaction: Broken Precedent condition the participant acted as the  
352 Director on games 1, 3 and 5 and the Matcher on games 2, 4 and 6 (see **Fig. 2**). In this  
353 condition, participants received the drawings produced by Participant 2 (Director trials)  
354 from the Interaction condition, plus any associated Matcher feedback. Participant 2 from  
355 each interacting dyad seeded a Pseudo-Interaction: Broken Precedent participant. While  
356 observing the drawing playback from their partner, participants in the Pseudo-Interaction  
357 conditions were not permitted to produce graphical feedback. Whereas the drawing  
358 activity of Directors in the Interaction condition ended when the Matcher selected a  
359 meaning, the drawing activity of Directors in the Pseudo-Interaction conditions ended when  
360 they clicked a send button. They were told that doing so sent their drawing to their partner,  
361 who would then try to pick out their intended meaning.

362           Unlike the non-interactive conditions of prior studies, that contained either repeated  
363 production-only processes (Garrod et al., 2007; Hupet & Chantraine, 1992; Krauss &  
364 Weinheimer, 1964) or repeated comprehension-only processes (Garrod et al., 2007;  
365 Schober & Clark, 1989), the Pseudo-Interaction conditions in the present study included



366 both processes. Like the Interaction condition, communication in the Pseudo-Interaction  
 367 conditions involved regularly interchanging between production and comprehension  
 368 processes (see Fig. 2).

369



370

371 **Fig. 2.** Experiment 1 design. Pairs of participants in the Interaction condition took turns  
 372 directing and matching across Games 1-6. In this condition both participants (Director,  
 373 Matcher) could communicate during a trial, hence the bidirectional green arrows. Pseudo-  
 374 Interaction: Precedent participants tried to identify the drawings produced by Participant 1  
 375 (Interaction condition) at Games 1, 3 and 5 (solid blue arrow) and communicated each  
 376 meaning by drawing at Games 2, 4 and 6 (dashed blue arrow). Pseudo-Interaction: Broken  
 377 Precedent participants drew each meaning for Participant 2 (Interaction condition) at  
 378 Games 1, 3 and 5 (dashed pink arrow) and tried to identify the drawings produced by  
 379 Participant 2 at Games 2, 4 and 6 (solid pink arrow). In the Pseudo-Interaction conditions  
 380 only the Director could communicate during a trial, hence the unidirectional arrows.

381

### 382 3.4. Measures

383 *Communication Success* was measured by determining if the Matcher correctly identified  
384 the Director's intended meaning on each trial. Correct guesses were given a score of 1 and  
385 incorrect guesses a score of 0.

386 *Sign Symbolization.* Following Garrod et al. (2007), less complex signs were  
387 considered to be more symbolic. Sign complexity was measured using Pelli et al.'s (2006)  
388 information theoretic measure of perimetric complexity [Perimetric complexity = (inside +  
389 outside perimeter)<sup>2</sup>/ink area]. Previous work indicates this to be an effective scale-free  
390 measure of drawing complexity (Fay et al., 2010; Garrod et al., 2007; Tamariz & Kirby, 2014).

391 *Behaviour Alignment.* To measure behaviour alignment, pairs of drawings from each  
392 dyad (at Game 1-2, 2-3, 3-4, 4-5 or 5-6) were presented side-by-side on a computer screen  
393 and were rated for similarity (author BW). The drawings were rated on a Likert scale from  
394 0-9, where 0= very dissimilar and 9= very similar. In total 3600 pairs of drawings were rated  
395 for similarity (16 meanings x 5 pairs of adjacent games x 15 dyads x 3 conditions). A subset  
396 of drawings (240 pairs of drawings; 80 randomly sampled from each condition) were rated  
397 for similarity by a second judge (author NF). The raters were blind to the condition the  
398 drawings were sampled from. Comparison of the two sets of ratings showed strong inter-  
399 coder agreement ( $r = .834, p < .001$ ).

400

## 401 4. Experiment 1 results

402 The data was analysed using logistic and linear mixed effects modelling, with crossed  
403 random effects for dyads and for items. All the analyses were performed and all the figures

404 were created in R (R Core Team, 2013). Statistical models were estimated using the `glmer()`  
405 and `lmer()` function of `lme4` (Bates, Maechler, Bolker, & Walker, 2013). We tested all effects  
406 using model comparison, comparing models with identical random effects, but with the  
407 fixed effect(s) of interest removed from one of the models. The maximal random effects  
408 structure justified by the experiment design was specified where possible (Barr, Levy,  
409 Scheepers, & Tily, 2013).

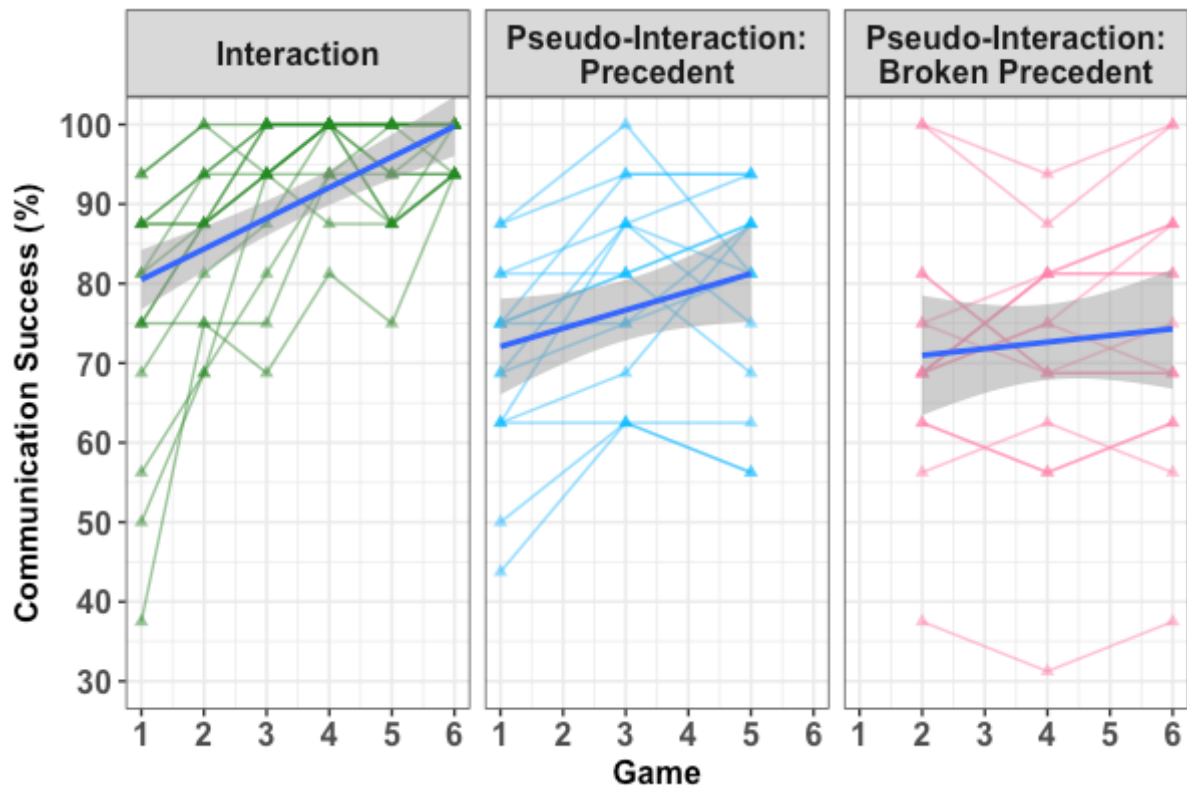
410

#### 411 **4.1. Communication success**

412 We first compared communication success in the Interaction condition to the Pseudo-  
413 Interaction: Precedent condition at Games 1, 3 and 5. The data was analyzed using a logistic  
414 mixed effects model. Condition and Game were entered as fixed effects with interaction.  
415 Both fixed effects were centered. The random effects structure included by-Dyad and by-  
416 Item random intercepts, as well as by-Item random slopes for Condition. This was the  
417 maximal random effects structure that would converge. The best fitting model specified  
418 Condition and Game as fixed effects with interaction ( $\chi^2(1) = 12.751, p < .001$ ). In both  
419 conditions communication success improved over games, but the improvement was  
420 stronger in the Interaction condition ( $\beta = 1.196, SE = 0.281, \chi^2(1) = 18.789, p < .001$ )  
421 compared to the Pseudo-Interaction: Precedent condition ( $\beta = 0.413, SE = 0.151, \chi^2(1) =$   
422  $8.962, p = .003$ ).

423 Next, the Interaction condition was compared to the Pseudo-Interaction: Broken  
424 Precedent Condition at Games 2, 4 and 6. Again, the best fitting model specified Condition  
425 and Game with interaction ( $\chi^2(1) = 17.846, p < .001$ ). Whereas communication success  
426 improved across games in the Interaction condition ( $\beta = 1.827, SE = 0.579, \chi^2(1) = 16.612,$   
427  $p < .001$ ), there was no statistical evidence of an improvement in communication success

428 across games in the Pseudo-Interaction: Broken Precedent condition ( $\beta= 0.174, SE= 0.143,$   
 429  $\chi^2(1) = 1.489, p = .222$ ). See **Fig. 3** for data visualisation.  
 430















431  
 432 **Fig. 3.** Change in communication success (plotted for each dyad) across Games 1-6 in the  
 433 Interaction condition and each of the Pseudo-Interaction conditions. The blue straight line  
 434 is the linear model fit and the grey shaded area is the 95% confidence interval.

435  
 436 **4.2. Sign symbolization**

437 Examples of sign symbolization and sign alignment from the different experimental  
 438 conditions are given in **Fig. 4**. Strong sign symbolization is observed in the Interaction  
 439 condition. At game 1 the sign used to communicate ‘Museum’ is highly motivated; it uses  
 440 icons (of a dinosaur, an exhibit space and two viewers) that structure-map (i.e., visually

441 resemble) features of the objects that are typically seen in a museum. By Game 6 a much  
 442 simpler sign is used, where the structure-mapping between the sign and its meaning is  
 443 mostly absent; only the dinosaur’s spine is retained from the earlier game 1 sign. At game 6  
 444 the mapping between the sign and its meaning has become more arbitrary, and therefore  
 445 more symbolic. Strong behaviour alignment is also observed in this condition: over games,  
 446 members of the interacting dyad increasingly used the same sign to communicate the same  
 447 meaning. Sign symbolization and sign alignment are observed in the Pseudo-Interaction:  
 448 Precedent condition, but they are weaker compared to the Interaction condition. By  
 449 contrast, sign symbolization is minimal in the Pseudo-Interaction: Broken Precedent  
 450 condition, and sign alignment is absent.

451

<b>Interaction</b>						
<b>Pseudo-Interacton: Precedent</b>						
<b>Pseudo-Interacton: Broken Precedent</b>						
	<b>Game 1</b>	<b>Game 2</b>	<b>Game 3</b>	<b>Game 4</b>	<b>Game 5</b>	<b>Game 6</b>

452

453 **Fig. 4.** Example drawings of the meaning ‘Museum’ from the different experimental  
 454 conditions across Game 1-6 from Experiment 1.

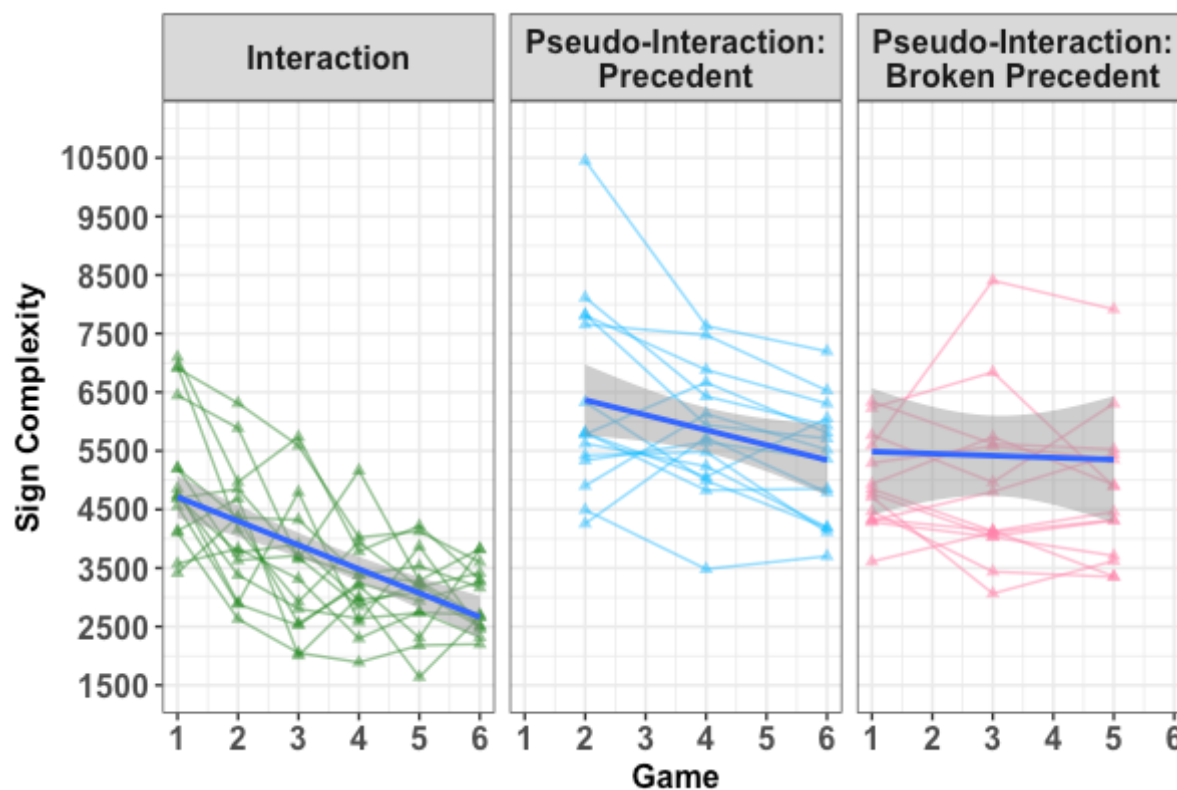
455

456 First, sign complexity in the Interaction condition was compared to the Pseudo-  
 457 Interaction: Precedent condition at Games 2, 4 and 6. The data was analyzed using a linear  
 458 mixed effects model. Condition and Game were entered as fixed effects with interaction.

459 Both fixed effects were centered. The maximal random effects structure was specified. This  
460 included by-Dyad and by-Item random intercepts, as well as by-Dyad random slopes for  
461 Game and by-Item random slopes for the Condition by Game interaction. The best fitting  
462 model specified Condition and Game as fixed effects without interaction ( $\chi^2(1) = 0.245$ ,  
463  $p = .621$ ). Sign complexity decreased over games in both conditions ( $\beta = -562.03$ ,  $SE =$   
464  $93.05$ ,  $\chi^2(1) = 23.433$ ,  $p < .001$ ), but overall sign complexity was lower in the Interaction  
465 condition compared to the Pseudo-Interaction: Precedent condition ( $\beta = 2505.94$ ,  $SE =$   
466  $292.02$ ,  $\chi^2(1) = 37.426$ ,  $p < .001$ ).

467         Next, sign complexity in the Interaction condition was compared to the Pseudo-  
468 Interaction: Broken Precedent condition at Games 1, 3 and 5 (same model). Here, the best  
469 fitting model specified Condition and Game as fixed effects with interaction ( $\chi^2(1) =$   
470  $20.023$ ,  $p < .001$ ). Whereas sign complexity decreased across games in the Interaction  
471 condition ( $\beta = -1007.76$ ,  $SE = 121.39$ ,  $\chi^2(1) = 29.448$ ,  $p < .001$ ), there was no statistical  
472 evidence of a decrease in sign complexity in the Pseudo-Interaction: Broken Precedent  
473 condition ( $\beta = -67.92$ ,  $SE = 131.93$ ,  $\chi^2(1) = 0.263$ ,  $p = .608$ ). See **Fig. 5** for data  
474 visualisation.

475



476

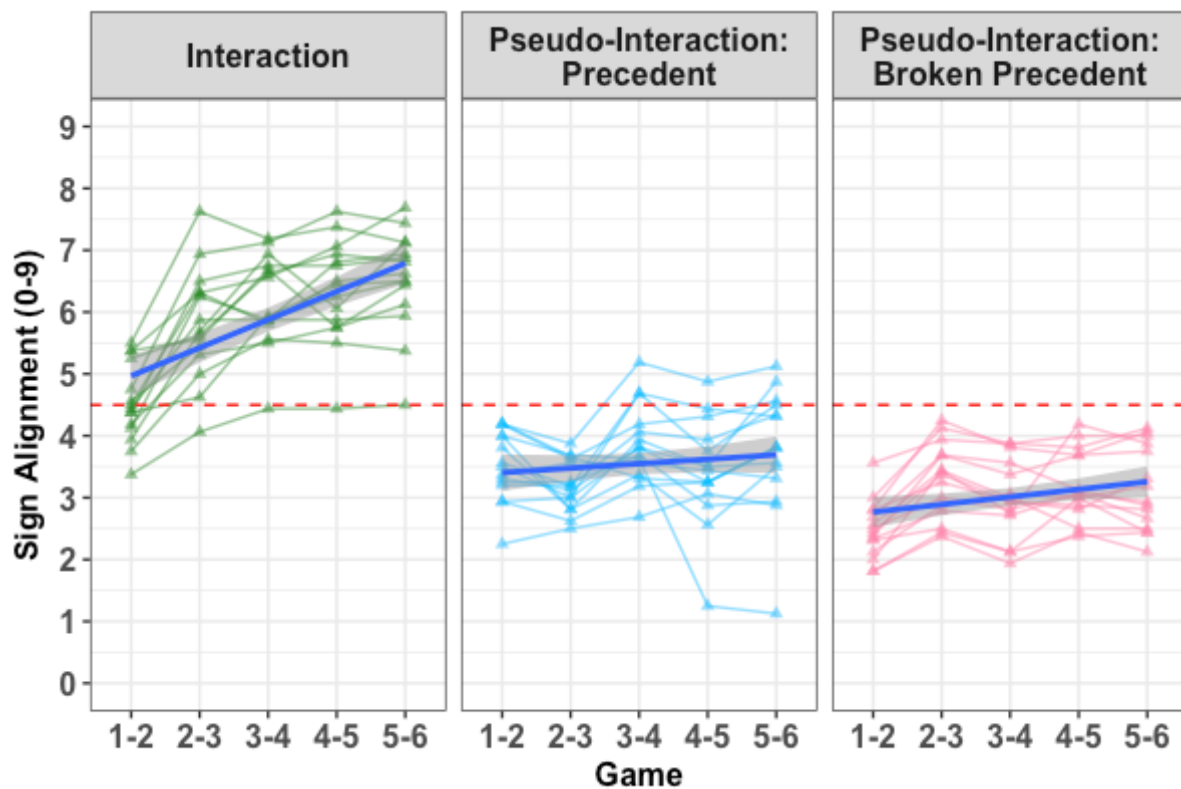
477 **Fig. 5.** Change in perimetric complexity of the signs (plotted for each dyad) across Games 1-  
 478 6 in the Interaction condition and each of the Pseudo-Interaction conditions. The blue  
 479 straight line is the linear model fit and the grey shaded area is the 95% confidence interval.

480

### 481 **4.3. Behaviour alignment**

482 The final analysis of Experiment 1 compared the change in behaviour alignment  
 483 (operationalized as the extent to which drawings of the same experimental meaning  
 484 became similar, i.e., sign alignment scores) over games in the different conditions. The sign  
 485 similarity data was analyzed using a linear mixed effects model (same model used in sign  
 486 complexity analysis, but with Condition factor coded). The best fitting model specified  
 487 Condition and Game as fixed effects with interaction ( $\chi^2(1) = 22.365, p < .001$ ). The  
 488 interaction effect is explained by the stronger increase in sign alignment scores across  
 489 games in the Interaction condition ( $\beta = 0.455, SE = 0.043$ ) compared to the Pseudo-

490 Interaction: Precedent condition ( $\beta= 0.071, SE= 0.073$ ) and the Pseudo-Interaction: Broken  
 491 Precedent condition ( $\beta= 0.121, SE= 0.043$ ). Comparison of the Pseudo-Interaction  
 492 conditions indicated that the sign alignment scores increased over games ( $\chi^2(1) =$   
 493  $4.131, p = .042$ ), and that overall sign alignment was higher in the Pseudo-Interaction  
 494 Precedent condition compared to the Pseudo-Interaction: Broken Precedent condition  
 495 ( $\chi^2(1) = 8.869, p = .002$ ). Note that sign alignment scores in both Pseudo-Interaction  
 496 conditions are lower than neutral alignment, indicating that participants tended not to align  
 497 their behaviour (see Fig. 6 for data visualisation).  
 498



499  
 500 **Fig. 6.** Change in rated sign alignment (plotted for each dyad) over Games in the Interaction  
 501 condition and each of the Pseudo-Interaction conditions. The horizontal dashed red line  
 502 indicates neutral sign alignment. The blue straight line is the linear model fit and the grey  
 503 shaded area is the 95% confidence interval.



504

## 505 **5. Experiment 1 discussion**

506 Experiment 1 tested the contribution of social interaction to the creation of shared symbols.  
507 Social interaction proved to be important to communication success. Participants in the  
508 Interaction condition showed the strongest improvement in communication success over  
509 games, replicating previous studies (Fay et al., 2010; Garrod et al., 2007, 2010; Schober &  
510 Clark, 1989). Crucially, the experimental paradigm ruled out alternative explanations of the  
511 enhanced communication success in the Interaction condition, such as the absence of  
512 interchanging production and comprehension processes in the non-interactive conditions,  
513 or lower attention among participants who passively observed the communication of active  
514 interlocutors (Garrod et al., 2007; Schober & Clark, 1989). Communication success  
515 improved over games among participants in the Pseudo-Interaction: Precedent condition.  
516 This indicates that observational learning is sufficient to improve communication success. In  
517 the Pseudo-Interaction: Broken Precedent condition there was no statistical evidence of an  
518 improvement in communication success. This highlights the importance of referential  
519 precedents to interpersonal communication.

520 The simplest, and most symbolic signs were produced by participants in the  
521 Interaction condition. This finding replicates previous studies (Fay et al., 2010; Garrod et al.,  
522 2007, 2010; Hupet & Chantraine, 1992; Krauss & Weinheimer, 1964), and supports an inter-  
523 individual principle of least collaborative effort (Clark, 1996; Clark & Wilkes-Gibbs, 1986).  
524 Sign simplification was observed in the Pseudo-Interaction: Precedent condition, indicating  
525 a role for a simplification bias in sign symbolization, and supporting the individual-level  
526 principle of least effort (Piantadosi et al., 2011; Zipf, 1949). In the Pseudo-Interaction:

527 Broken Precedent condition there was no evidence of a change in sign complexity. This  
528 again highlights the importance of referential precedents to interpersonal communication  
529 and demonstrates their effect on the expression of a simplification bias on sign  
530 symbolization.

531 Social interaction proved important to behaviour alignment. Participants in the  
532 Interaction condition showed a strong increase in their sign alignment scores across games,  
533 replicating previous studies (Branigan, Pickering, & Cleland, 2000; Fay et al., 2010; Garrod &  
534 Anderson, 1987; Garrod et al., 2007, 2010). Sign alignment was observed in the Pseudo-  
535 Interaction conditions, but was weaker compared to the Interaction condition. Consistent  
536 with prior studies (Branigan et al., 2007, 2011), and an alignment bias, sign alignment did  
537 not require social interaction, but it was stronger with it. In the Pseudo-Interaction: Broken  
538 Precedent condition sign alignment was lowest. This again highlights the importance of  
539 referential precedents to interpersonal communication, and demonstrates their effect on  
540 the expression of a behaviour alignment bias.

541 The Experiment 1 results supported our predictions. The most effective, most  
542 efficient and most shared communication systems were produced by participants in the  
543 Interaction condition. The results of the Pseudo-Interaction: Precedent condition suggest  
544 that observation and cognitive bias contributed to the evolution of shared symbols. In this  
545 condition communication success improved, the signs became more efficient and more  
546 aligned over games. This occurred despite the participants not being able to directly  
547 interact with their partner. However, breaking a referential precedent eliminated these  
548 effects (Pseudo-Interaction: Broken Precedent condition). When a referential precedent  
549 was broken, communication success did not improve, the signs did not become more  
550 efficient, and sign alignment was much lower. Participants in this condition may have

551 interpreted their partner's behaviour as uncooperative, and this may have reduced their  
552 motivation to align their behaviour, indicating that inferential processes were guiding  
553 communication behaviour.

554 Taken together, the Experiment 1 results demonstrate that inter-individual social  
555 coordinative learning is important to the creation of shared symbols.

556

## 557 **6. Experiment 2. How to create shared symbols: The** 558 **complimentary roles of behaviour alignment and concurrent** 559 **partner feedback**

560 Experiment 1 demonstrated that inter-individual social-coordinative learning is important to  
561 the creation of shared symbols. Experiment 2 isolated two important aspects of social  
562 interaction – behaviour alignment and concurrent partner feedback – and investigated the  
563 contribution of each to the evolution of effective and efficient human communication  
564 systems.

565 Pickering and Garrod (2004) argue that interlocutors cognitively align by aligning  
566 their linguistic behaviour and this underlies successful communication (see Fusaroli & Tylén,  
567 2016 for a discussion of other factors that influence successful interpersonal  
568 communication). While a correlation between referential alignment and cognitive  
569 alignment has been observed (Fay, Lister, Ellison, & Goldin-Meadow, 2014; Fusaroli et al.,  
570 2012; Reitter & Moore, 2014), the causal role of referential alignment on cognitive  
571 alignment is unclear. If referential alignment directly influences cognitive alignment,

572 prohibiting interacting participants from imitating their partner's signs and aligning their  
573 behaviour will lower communication success. This was tested in Experiment 2.

574         Whereas referential alignment occurs across interaction episodes (i.e., as partners  
575 alternate directing and matching roles), concurrent partner feedback occurs within an  
576 interaction episode. Concurrent partner feedback can take a variety of forms. During  
577 conversation, listeners are co-narrators who provide verbal feedback (e.g., saying "mhm"  
578 while listening to a speaker) and visual feedback (e.g., frowning or nodding), that improves  
579 the flow of conversation (Bavelas, Coates, & Johnson, 2000; Clark & Krych, 2004; Mein, Fay,  
580 & Page, 2016). Like listeners in a conversation, Matchers in the present study can signal  
581 their attention and understanding by commenting on the Director's drawing, e.g., by adding  
582 a tick mark (see **Fig. 1**). During conversation listeners can indicate a communication  
583 breakdown and initiate a repair (e.g., by asking the speaker for clarification; Dingemanse et  
584 al., 2015; Schegloff, 2000). A similar repair mechanism was observed in Experiment 1 when  
585 a Matcher circled a part of the Director's drawing to request clarification. In addition to  
586 these information expansion requests, Matcher feedback can drive information contraction  
587 by bringing the trial to an end before the Director has completed their drawing (by clicking a  
588 meaning button, the equivalent of an interruption during conversation). So, we predict that  
589 Matcher feedback will contribute to communication success and to sign symbolization. This  
590 was tested in Experiment 2.

591         In addition to examining the effects of behaviour alignment and concurrent partner  
592 feedback, Experiment 2 also examined the interplay between behaviour alignment and  
593 concurrent partner feedback on communication success and sign symbolization to  
594 determine if they operate independently or if they interact. This was done by  
595 experimentally manipulating the opportunity for participants to imitate the signs produced

596 by their partner, and the opportunity for participants to receive concurrent partner  
597 feedback, in a full factorial design. We then examined the effect of this on communication  
598 success and sign symbolization.

599

## 600 **7. Method**

### 601 **7.1. Participants**

602 A convenience sample of 120 undergraduate students (84 self-reported females and 36 self-  
603 reported males) participated in exchange for partial course credit or payment (A\$10). The  
604 sample size was based upon prior studies using the same experimental paradigm (Fay et al.,  
605 2010; Garrod et al., 2007, 2010). No statistical analyses were run prior to collecting the full  
606 sample. Participants were tested in unacquainted pairs in testing sessions lasting 1 hour.  
607 All participants reported being free of any uncorrected visual impairment.

608

### 609 **7.2. Task and procedure**

610 The experimental paradigm is identical to that used in Experiment 1, including the meaning  
611 set (see **Table 1**). Like Experiment 1, Experiment 2 was administered using the virtual  
612 whiteboard tool developed by Healy et al. (2002).

613 Experiment 2 examined the influence of behaviour alignment and concurrent  
614 partner feedback on communication success and sign symbolization. Participants were  
615 assigned to one of four conditions that represented a combination of the factors of interest:  
616 Imitation (Allow Imitation, Forbid Imitation) and Feedback (Allow Feedback, No Feedback).  
617 Thirty participants (15 dyads) were randomly assigned to each condition. In the Forbid  
618 Imitation conditions (Allow Feedback or No Feedback) participants were instructed not to

619 imitate their partner's drawing for each meaning. They were told they would have to use a  
620 different sign to that used by their partner to communicate each meaning. So, in this  
621 condition, participants were unable to align their behaviour. In the No Feedback conditions  
622 (Allow Imitation or Forbid Imitation) participants were unable to produce within-trial  
623 feedback when acting as the Matcher. Specifically, they were unable to draw while acting  
624 as the Matcher (this functionality was removed from the virtual whiteboard tool). In this  
625 condition the Director clicked a send button when they had finished their drawing. Once  
626 done, the list of competing meanings became available for selection by the Matcher. Thus,  
627 Matchers were unable to interrupt the Director's communication and bring the trial to an  
628 end.

629






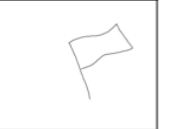
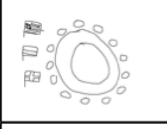
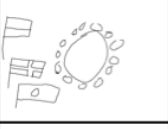
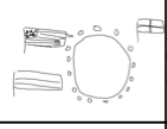

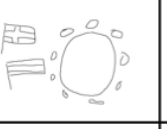


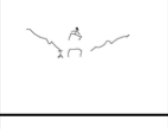

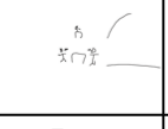








### 630 **7.3. Measures**

631 Like Experiment 1, Experiment 2 measured *Communication Success*, *Sign Symbolization* and  
632 *Behaviour Alignment*. Behaviour alignment was quantified by rating the similarity of pairs of  
633 drawings of the same meaning from each dyad (at Game 1-2, 2-3, 3-4, 4-5, 5-6) on a Likert  
634 scale from 0-9, where 0= very dissimilar and 9= very similar (author BW). In total 4800 pairs  
635 of drawings were rated for similarity (16 meanings x 5 pairs of adjacent games x 15 dyads x  
636 4 conditions). A subset of drawings (1200 pairs of drawings; 300 randomly sampled from  
637 each condition) were rated for similarity by a second judge (author NF). The raters were  
638 blind to the condition the drawings were sampled from. Comparison of the two sets of  
639 ratings showed strong inter-coder agreement ( $r = .710, p < .001$ ).

640

641 **8. Experiment 2 results**

642 Examples of sign symbolization and sign alignment from the different experimental  
 643 conditions are given in **Fig. 7**. Participants who were instructed not to imitate their  
 644 partner’s sign for each meaning followed the instructions: one participant drew a building  
 645 with a flag to communicate ‘Parliament’ and their partner drew a speaker at a podium  
 646 (Forbid Imitation, Allow Feedback); another drew a parliamentary speaker with a hammer,  
 647 and their partner drew a series of buildings (Forbid Imitation, No Feedback). When allowed  
 648 to imitate their partner’s signs, behaviour alignment was observed: onto a flag (Allow  
 649 Imitation, Allow Feedback), or people seated around a table (Allow Imitation, No Feedback).  
 650 These examples also highlight the diversity of signs used to communicate the same meaning  
 651 in the present study. Concurrent partner feedback had a strong effect on sign  
 652 symbolization: in the Allow Feedback conditions the signs were dramatically simplified  
 653 across games, and in the No Feedback conditions they retained considerable sign  
 654 complexity.

<b>Allow Imitation, Allow Feedback</b>						
<b>Allow Imitation, No Feedback</b>						
<b>Forbid Imitation, Allow Feedback</b>						
<b>Forbid Imitation, No Feedback</b>						
	<b>Game 1</b>	<b>Game 2</b>	<b>Game 3</b>	<b>Game 4</b>	<b>Game 5</b>	<b>Game 6</b>

655

656 **Fig. 7.** Example drawings of the meaning ‘Parliament’ from the different experimental  
657 conditions across Game 1-6 from Experiment 2.

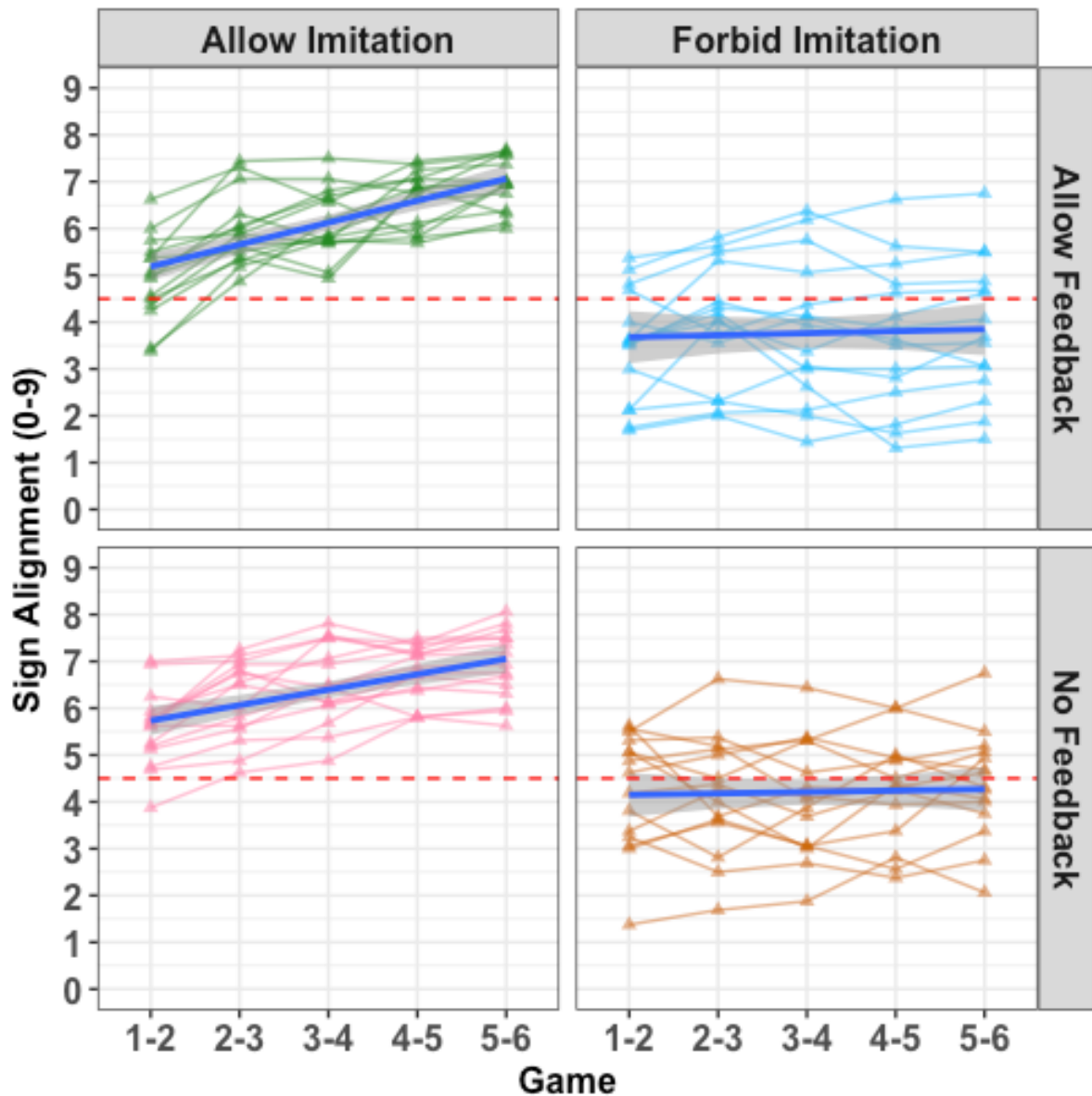
658

### 659 **8.1. Manipulation check: Behaviour alignment**

660 The first analysis tested whether participants who were forbidden from imitating the signs  
661 produced by their partner followed the instructions. The sign similarity data was analyzed  
662 using a linear mixed effects model. Imitation (Allow Imitation, Forbid Imitation), Feedback  
663 (Allow Feedback, No Feedback) and Game (1-6) were entered as fixed effects with  
664 interaction. All fixed effects were centered. The random effects structure included by-Dyad  
665 and by-Item random intercepts, as well as by-Dyad random slopes for Game and by-Item  
666 random slopes for the Imitation by Feedback interaction. This was the maximal random  
667 effects structure that would converge. The best fitting model specified Imitation and Game  
668 as fixed effects with interaction ( $\chi^2(1) = 36.649, p < .001$ ). The interaction effect is  
669 explained by the increase in sign alignment scores over games in the Allow Imitation  
670 conditions ( $\beta = 0.407, SE = 0.055, \chi^2(1) = 25.578, p < .001$ ) and the null effect of Game in  
671 the Forbid Imitation conditions ( $\beta = 0.035, SE = 0.039, \chi^2(1) = 0.822, p = .365$ ). See **Fig. 8**  
672 for data visualisation.

673





674

675 **Fig. 8.** Change in sign alignment scores (plotted for each dyad) for the different conditions  
 676 over Games. The horizontal dashed red line indicates neutral sign alignment. The blue  
 677 straight line is the linear model fit and the grey shaded area is the 95% confidence interval.

678

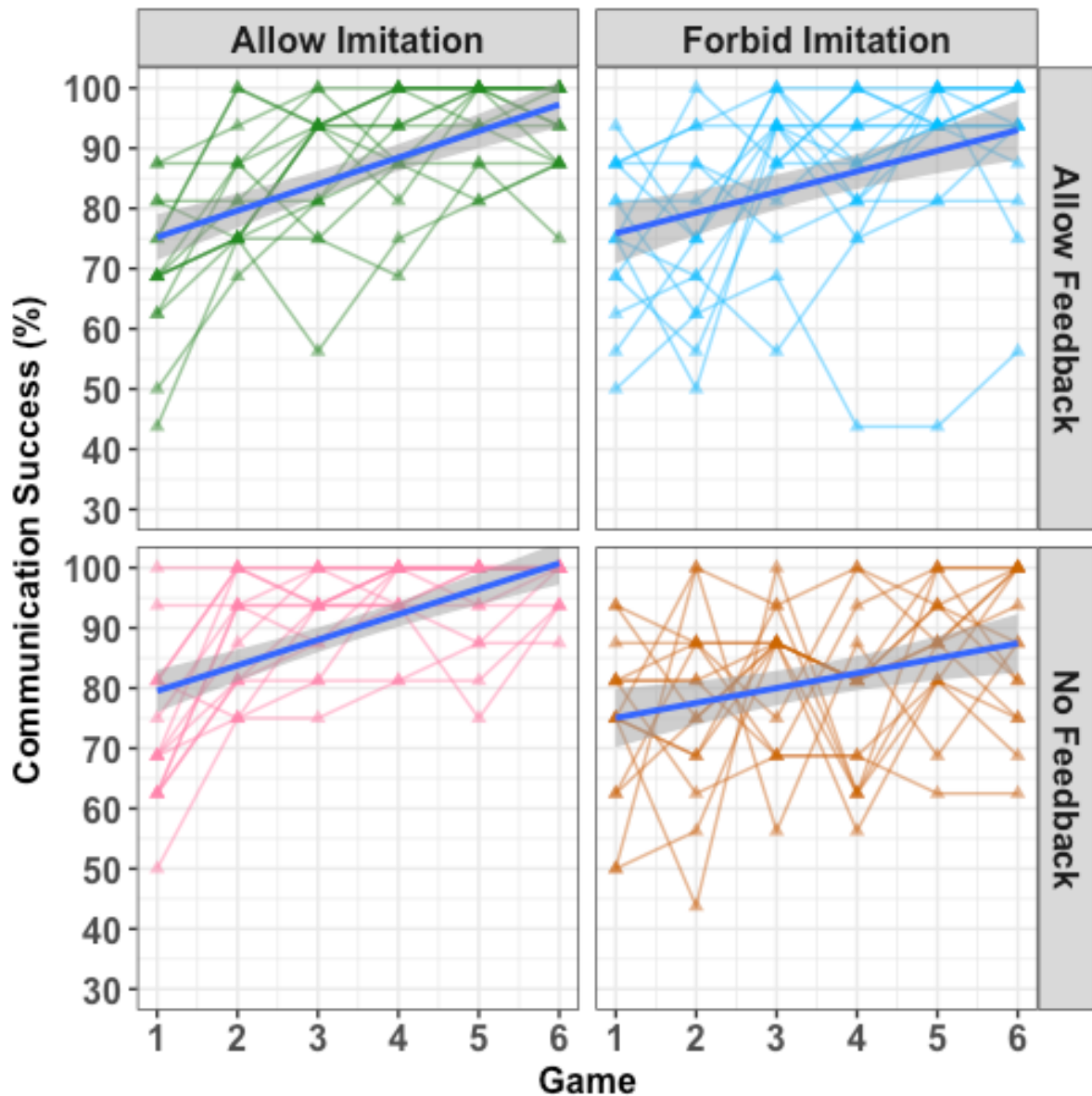
## 679 **8.2. Communication success**

680 Next we examined the change in communication success across Games 1-6 in the Imitation  
 681 (Allow Imitation, Forbid Imitation) and Feedback (Allow Feedback, No Feedback) conditions.

682 The data was analyzed using a logistic mixed effects model. Imitation, Feedback and Game  
683 were entered as fixed effects with interaction. All fixed effects were centered. Due to a  
684 technical error, item information was not recorded for the communication success data or  
685 the sign complexity data. The random effects structure included by-Dyad random  
686 intercepts. This was the maximal random effects structure that would converge. The best  
687 fitting model specified a three-way Imitation by Feedback by Game interaction ( $\chi^2(1) =$   
688  $6.919, p = .008$ ).

689         Comparison of the Allow Imitation conditions (Allow Feedback, No Feedback)  
690 indicated an improvement in communication success over games ( $\beta = 0.656, SE = 0.081,$   
691  $\chi^2(1) = 41.398, p < .001$ ), but there was no statistical evidence that partner feedback  
692 affected communication success ( $\chi^2(1) = 0.427, p = .513$ ). Comparison of the Forbid  
693 Imitation conditions (Allow Feedback, No Feedback) returned a Feedback by Game  
694 interaction ( $\chi^2(1) = 3.699, p = .054$ ). This reflected the stronger improvement in  
695 communication success over games when partner feedback was allowed ( $\beta = 0.292, SE =$   
696  $0.047, \chi^2(1) = 41.150, p < .001$ ) compared to when participants were unable to provide  
697 partner feedback ( $\beta = 0.169, SE = 0.041, \chi^2(1) = 17.509, p < .001$ ). We then compared  
698 the Allow Imitation conditions (collapsed) to each of the Forbid Imitation conditions (Allow  
699 Feedback, No Feedback). In each case, this returned a condition by Game interaction  
700 ( $\chi^2(1) = 4.906, p = .027$  and  $\chi^2(1) = 14.900, p < .001$ ). This is explained by the  
701 stronger improvement in communication success over games in the Allow Imitation  
702 conditions compared to each of the Forbid Imitation conditions. See **Fig. 9** for data  
703 visualisation.

704



705

706 **Fig. 9.** Change in communication success (plotted for each dyad) for the different conditions  
 707 across Games 1-6. The blue straight line is the linear model fit and the grey shaded area is  
 708 the 95% confidence interval.

709

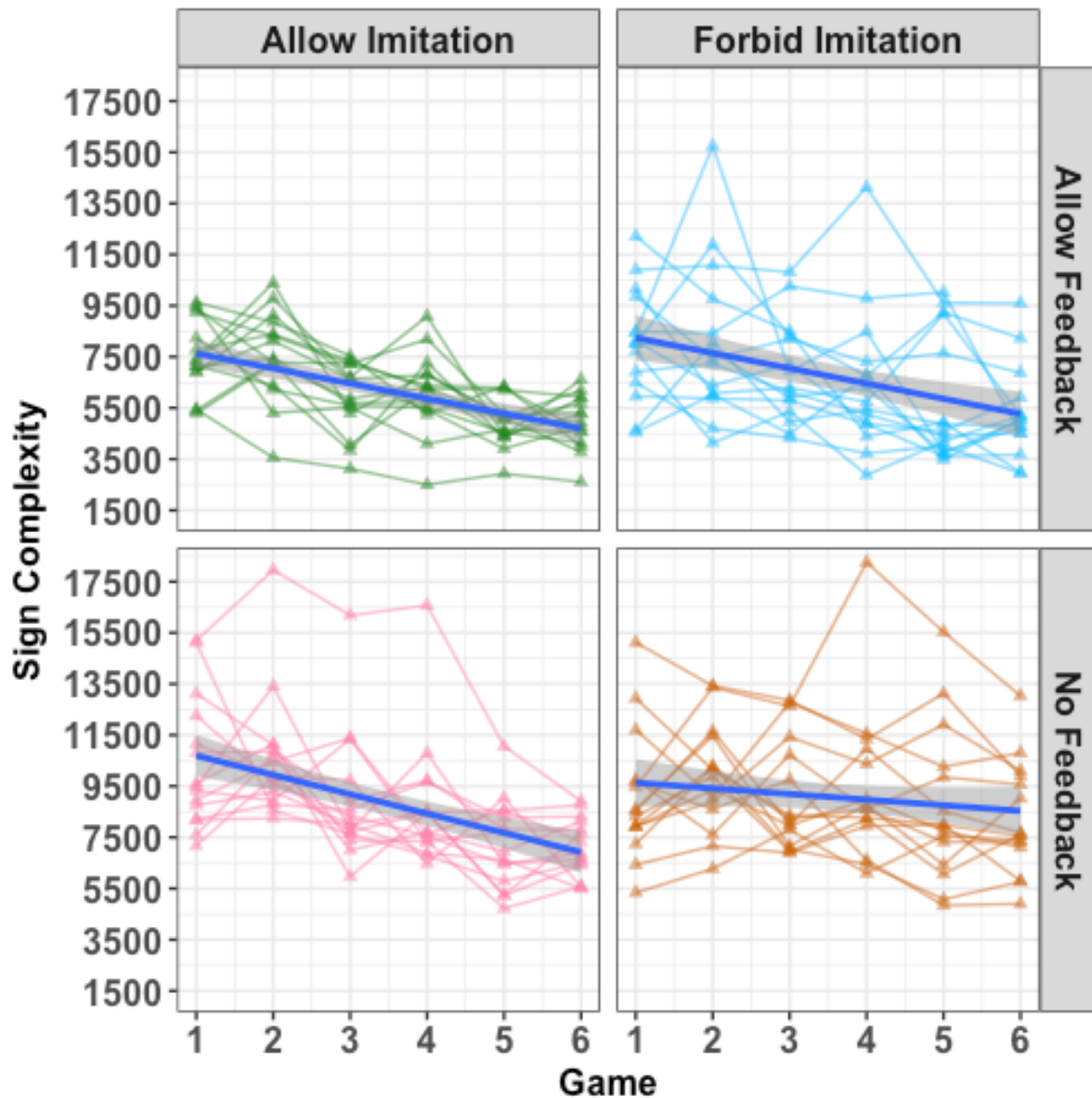
### 710 8.3. Sign symbolization

711 The final analysis compared the change in sign complexity over games in the different  
 712 conditions. As before, less complex signs were considered to be more symbolic (see Garrod  
 713 et al., 2007). Sign complexity was again measured using Pelli et al.'s (2006) information

714 theoretic measure of perimetric complexity [Perimetric complexity = (inside + outside  
715 perimeter)<sup>2</sup>/ink area]. The sign complexity data was analyzed using a linear mixed effects  
716 model. Imitation, Feedback and Game were entered as fixed effects with interaction. All  
717 fixed effects were centered. The random effects structure included by-Dyad random  
718 intercepts, as well as by-Dyad random slopes for Game. Like communication success, the  
719 best fitting model specified a three-way Imitation by Feedback by Game interaction  
720 ( $\chi^2(1) = 4.926, p = .026$ ).

721         Comparison of the Allow Feedback conditions (Allow Imitation, Forbid Imitation)  
722 indicated a reduction in sign complexity over games ( $\beta = -591.57, SE = 68.68, \chi^2(1) =$   
723  $37.353, p < .001$ ), but there was no statistical evidence that imitation reduced sign  
724 complexity ( $\chi^2(1) = 1.253, p = .263$ ). Comparison of the No Feedback conditions (Allow  
725 Imitation, Forbid Imitation) returned an Imitation by Game interaction ( $\chi^2(1) = 6.649, p =$   
726  $.009$ ). This reflected the reduction in sign complexity over games when sign imitation was  
727 allowed ( $\beta = -754.70, SE = 129.6, \chi^2(1) = 17.729, p < .001$ ), and a null effect of Game when  
728 sign imitation was forbidden ( $\beta = -220.1, SE = 147.00, \chi^2(1) = 2.090, p = .148$ ). We then  
729 compared the Allow Feedback conditions (collapsed) to the Allow Imitation but No  
730 Feedback condition. The best fitting model included a main effect of Game ( $\chi^2(1) =$   
731  $53.245, p < .001$ ), indicating that sign complexity decreased over games, and a main effect  
732 of condition ( $\chi^2(1) = 18.282, p < .001$ ), indicating that overall sign complexity was lower  
733 when participants could provide concurrent partner feedback. See **Fig. 10** for data  
734 visualisation.

735



736

737 **Fig. 10.** Change in perimetric complexity of the signs (plotted for each dyad) for the  
 738 different conditions across Games 1-6. The blue straight line is the linear model fit and the  
 739 grey shaded area is the 95% confidence interval.

740

## 741 9. Experiment 2 discussion

742 Experiment 2 isolated two distinct aspects of social interaction – behaviour alignment and  
 743 concurrent partner feedback – and examined the contribution of each, and their

744 combination, to the creation of shared symbols. To examine the role of behaviour  
745 alignment, participants in half of the dyads tested were instructed not to imitate the signs  
746 produced by their partner. The manipulation worked; participants who were allowed to  
747 imitate their partner's signs did so, and this led to increased sign alignment, via behaviour  
748 matching, over games. There was no evidence of sign alignment among participants for  
749 whom sign imitation was forbidden.

750 As predicted, sign alignment improved communication success, establishing a causal  
751 link between behaviour alignment and comprehension. When sign imitation was forbidden  
752 concurrent partner feedback improved communication success, but not as strongly as  
753 behaviour alignment. Concurrent partner feedback proved to be important to sign  
754 symbolization. Allowing the matcher to interrupt the director, and bring the trial to an end  
755 via meaning selection, drove progressive sign simplification and abstraction over games.  
756 When unable to provide concurrent partner feedback (the functionality was removed from  
757 the interface), behaviour alignment reduced sign complexity, but not to the extent of  
758 concurrent partner feedback. Without the opportunity for behaviour alignment or the  
759 opportunity to provide concurrent partner feedback, there was no evidence of sign  
760 symbolization.

761 Taken together, the Experiment 2 results demonstrate that each process played a  
762 complementary role in the creation of shared symbols: behaviour alignment drove  
763 communication success and concurrent partner feedback drove sign symbolization.

764

## 765 **10. General discussion**

766 Experiment 1 examined the importance of social interaction to the creation of shared  
767 symbols. Interaction proved to be important to the evolution of communication systems  
768 that were effective, efficient and shared. Compared to the conditions where the  
769 opportunity for social interaction was removed, in the Interaction condition communication  
770 success was higher, the signs became simpler and more symbolic, and interlocutors  
771 increasingly used the same signs to communicate the same meanings (i.e., their behaviour  
772 aligned). These findings support the results of pragmatic (e.g., Garrod & Anderson, 1987;  
773 Krauss & Weinheimer, 1964; Schober & Clark, 1989) and semiotic experiments (e.g., Garrod  
774 et al., 2007, 2010) by demonstrating that inter-individual coordinative social learning is  
775 important to the creation of shared symbols.

776         The Experiment 1 results also indicate that observation and cognitive bias may play a  
777 role in the creation of shared symbols. When denied the opportunity to directly interact  
778 with their partner, participants in the Pseudo-Interaction: Precedent condition showed  
779 increased communication success, sign symbolization and sign alignment across the  
780 communication games. Although lower on each measure compared to participants who  
781 could directly interact with their partner, this finding suggests that individual-level  
782 observational learning positively contributed to the creation of shared symbols. These  
783 findings support theoretical accounts and empirical studies in which observation plus  
784 cognitive biases guide language evolution (e.g., Kirby et al., 2008; Kirby, Griffiths, & Smith,  
785 2014; Thompson, Kirby, & Smith, 2016). Note that when a referential precedent was broken  
786 (Pseudo-Interaction: Broken Precedent) the influence of observation and cognitive bias was  
787 eliminated; there was no statistical evidence of a change in communication success, sign

788 symbolization or sign alignment across the communication games. Like experimental  
789 pragmatic studies, breaking a referential precedent negatively impacted interpersonal  
790 communication (Kronmüller & Barr, 2015).

791         Having established that social interaction is important to the creation of shared  
792 symbols, Experiment 2 investigated the precise role played by two distinct aspects of social  
793 interaction: behaviour alignment and feedback. By experimentally manipulating the  
794 opportunity for behaviour alignment and concurrent partner feedback in a full factorial  
795 design, Experiment 2 demonstrated that each process made a distinct contribution to the  
796 creation of shared symbols: behaviour alignment primarily drove improvements in  
797 communication success and concurrent partner feedback primarily drove improvements in  
798 sign efficiency. Together, these complementary processes drove the interactive evolution  
799 of shared symbols.

800         The Experiment 1 and 2 findings suggest a possible solution to the symbol grounding  
801 problem (Harnad, 1990). Complex iconic signs ground shared meanings. Once grounded,  
802 social interaction drives sign alignment and refinement, the mechanisms through which  
803 effective and efficient shared symbols arise. This explanation offers a convincing candidate  
804 process through which iconic signs evolve into symbols, as originally proposed by Charles  
805 Sanders Peirce over 100 years ago (Peirce, 1931).

806

### 807 **10.1. The interplay between cognitive bias & social interaction**

808 Smith and Wonnacott (2010) examined the effect of intergenerational transmission on the  
809 elimination of unpredictable variation in a miniature artificial language. They found that as  
810 the miniature language was transmitted from person to person across a transmission chain  
811 it became increasingly regularized and language-like, suggesting that a bias for regularity



812 was amplified across repeated transmission episodes, i.e., via unidirectional vertical  
813 transmission and without social interaction. Using an identical task, but one where  
814 participants were organized into interacting pairs as opposed to transmission chains, Smith,  
815 Fehér and Ritt (2014) showed that unpredictable variation was eliminated across  
816 participants' repeated social interactions with the same partner. This finding suggests that  
817 an individual-level bias for regularity may have been amplified by social interaction (see also  
818 Fehér, Wonnacott, & Smith, 2016). A key benefit of the interplay between cognitive bias  
819 and social interaction is the timescale on which it operates; when a cognitive bias is  
820 amplified via social interaction, rather than via intergenerational transmission, language  
821 change can be more rapid and responsive to environmental change.

822         The Experiment 1 findings support a role for cognitive biases in language evolution  
823 that is conditional on the communication context. In the absence of social interaction, a  
824 simplicity bias drives sign symbolization, and an alignment bias drives the evolution of a  
825 shared inventory of sign-to-meaning mappings among interlocutors. However, when a  
826 referential precedent was broken the influence of the cognitive biases was eliminated. By  
827 contrast, and similar to the aforementioned artificial language-learning studies, when  
828 participants could directly interact with their partner the cognitive biases were amplified,  
829 giving rise to a more powerful improvement in communication success, sign symbolization  
830 and sign alignment. This finding, that cognitive bias expression is conditional on the  
831 communication context, indicates that cognitive biases need not be deterministic, but can  
832 adapt to environmental change.

833

834 **10.2. Scaling up to larger populations**

835 Experiments 1 and 2 indicate that inter-individual social coordinative learning is important  
836 to the creation of shared symbols. How might our findings, based on dyadic interaction,  
837 scale-up to larger populations? Several experimental studies have examined the processes  
838 that operate when participants interact as part of a laboratory micro-society that includes  
839 between 8 and 24 members (Centola & Baronchelli, 2015; Fay et al., 2010; Garrod &  
840 Doherty, 1994). These studies, alongside agent-based computer simulations (Barr, 2004;  
841 Steels, 2003), indicate that the same social coordinative learning mechanisms identified in  
842 dyadic interaction experiments drive the evolution of referential conventions in larger  
843 populations. So, the processes identified in the present study are likely to be important to  
844 the creation of shared symbol systems in larger populations.

845         Using an identical task to that used in the present study, Fay et al. (2010) examined  
846 the evolution of shared symbol systems in 8-person micro-societies. Like the present study,  
847 participants interacted in pairs. After several games they switched partners, and continued  
848 in this way until they had interacted with each of the other members of their micro-society.  
849 Initially a diverse range of complex motivated signs was used to communicate each of the  
850 different meanings. Across interactions communication success improved and the initial  
851 sign variation was lost as participants aligned on a uniform inventory of single sign-to-  
852 meaning mappings. In addition, the signs used to communicate the different meanings  
853 became increasingly simplified and symbolic across repeated interactions in each micro-  
854 society. So, like the present study, social interaction improved communication success,  
855 behaviour alignment and sign symbolization, but at the population-level.

856         Increasing the population size also increased the diversity of signs that were used to  
857 communicate each meaning, and this increased competition between the different signs.

858 Tamariz et al. (2014) modelled the change in the frequency of the different communication  
859 variants used in each micro-society to communicate each meaning. They found that the  
860 data was best modelled by a combination of ‘egocentric bias’ and ‘content bias’. When  
861 participants encountered a new sign-to-meaning mapping, they tended to reuse the sign  
862 they had used previously (egocentric bias) unless the newly encountered sign was perceived  
863 to be superior (content bias). In a large population, this preference to adopt the most  
864 informative sign (see Rogers & Fay, 2016 for empirical support) led to the selection of a set  
865 of sign-to-meaning mappings that were better designed, relative to those developed in  
866 interacting dyads, for comprehension and production by naïve learners (Fay & Ellison, 2013;  
867 Fay et al., 2008).

868 The findings of the present study scale up to larger populations, but larger  
869 populations add a selection dynamic that improves the ease of acquisition, and the  
870 transmission fidelity of the evolved signs, an outcome consistent with cumulative cultural  
871 evolution (Tennie, Call, & Tomasello, 2009; Tomasello, 1999).

872

## 873 **11. Conclusion**

874 This paper examined the social learning strategies important to the creation of shared  
875 symbols. Experiment 1 demonstrated that individual-level processes, via observation and  
876 cognitive biases, contributed to the evolution of effective, efficient and shared symbols.  
877 However, when a referential precedent was broken the benefits of these individual-level  
878 processes were eliminated. Importantly, the addition of inter-individual processes, via  
879 social interaction, produced the most effective, most efficient, and most shared symbols.  
880 These findings demonstrate that social coordinative learning plays an important role in the

881 creation of shared symbols. Our findings also suggest that cognitive bias expression  
882 (simplicity and alignment bias) is conditional on the communication context, such that  
883 breaking a referential precedent eliminated the influence of the bias, and social interaction  
884 amplified the bias. Having established that social coordinative learning is important to the  
885 creation of shared symbols, Experiment 2 examined the precise contribution made by two  
886 distinct aspects of social interaction: behaviour alignment and concurrent partner feedback.  
887 Behaviour alignment primarily drove improvements in communication success and  
888 concurrent partner feedback primarily drove improvements in sign efficiency.

889 Social coordinative learning plays an important role in the evolution of shared  
890 symbols. The benefits of social coordinative learning arise through two complementary  
891 aspects of social interaction: behaviour alignment drives sign effectiveness, and concurrent  
892 partner feedback drives sign efficiency and symbolization.

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## 898 **References**

- 899 Bandura, A. (1977). *Social learning theory*. General Learning Press.
- 900 Barr, D. J. (2004). Establishing conventional communication systems: Is common knowledge  
901 necessary? *Cognitive Science*, 28(6), 937–962.
- 902 Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for  
903 confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*,  
904 68(3), 255–278. <https://doi.org/10.1016/j.jml.2012.11.001>
- 905 Bates, D., Maechler, M., Bolker, B., & Walker, S. (2013). lme4: Linear mixed-effects models  
906 using Eigen and S4. *R Package Version*, 1(4).
- 907 Bavelas, J. B., Coates, L., & Johnson, T. (2000). Listeners as co-narrators. *Journal of*  
908 *Personality and Social Psychology*, 79(6), 941–952.
- 909 Branigan, H. P., Pickering, M. J., & Cleland, A. A. (2000). Syntactic co-ordination in dialogue.  
910 *Cognition*, 75(2), B13–B25.
- 911 Branigan, H. P., Pickering, M. J., McLean, J. F., & Cleland, A. A. (2007). Syntactic alignment  
912 and participant role in dialogue. *Cognition*, 104(2), 163–197.
- 913 Branigan, H. P., Pickering, M. J., Pearson, J., McLean, J. F., & Brown, A. (2011). The role of  
914 beliefs in lexical alignment: Evidence from dialogs with humans and computers.  
915 *Cognition*, 121(1), 41–57. <https://doi.org/10.1016/j.cognition.2011.05.011>
- 916 Brennan, S. E., & Clark, H. H. (1996). Conceptual Pacts and Lexical Choice in Conversation.  
917 *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 22(6), 1482–  
918 1493.
- 919 Bronowski, J. (1967). *Human and animal languages*. The Hague: Mouton.

- 920 Caldwell, C. A., & Smith, K. (2012). Cultural Evolution and Perpetuation of Arbitrary  
921 Communicative Conventions in Experimental Microsocieties. *PLoS ONE*, 7(8),  
922 e43807. <https://doi.org/10.1371/journal.pone.0043807>
- 923 Centola, D., & Baronchelli, A. (2015). The spontaneous emergence of conventions: An  
924 experimental study of cultural evolution. *Proceedings of the National Academy of  
925 Sciences*. <https://doi.org/10.1073/pnas.1418838112>
- 926 Chater, N., & Vitányi, P. (2003). Simplicity: a unifying principle in cognitive science? *Trends in  
927 Cognitive Sciences*, 7(1), 19–22.
- 928 Christensen, P., Fusaroli, R., & Tylén, K. (2016). Environmental constraints shaping  
929 constituent order in emerging communication systems: Structural iconicity,  
930 interactive alignment and conventionalization. *Cognition*, 146, 67–80.  
931 <https://doi.org/10.1016/j.cognition.2015.09.004>
- 932 Clark, H. H. (1996). *Using language*. Cambridge: Cambridge University Press.
- 933 Clark, H. H., & Krych, M. A. (2004). Speaking while monitoring addressees for understanding.  
934 *Journal of Memory and Language*, 50(1), 62.
- 935 Clark, H. H., & Schaefer, E. F. (1987). Collaborating on contributions to conversation.  
936 *Language and Cognitive Processes*, 2, 19–41.
- 937 Clark, H. H., & Wilkes-Gibbs, D. (1986). Referring as a collaborative process. *Cognition*, 22,  
938 1–39.
- 939 Deacon, T. (1997). *The Symbolic Species: The co-evolution of language and the brain*. New  
940 York, NY: Norton.
- 941 Dingemanse, M., Roberts, S. G., Baranova, J., Blythe, J., Drew, P., Floyd, S., ... others. (2015).  
942 Universal principles in the repair of communication problems. *PLoS One*, 10(9),  
943 e0136100.

- 944 Fay, N., Arbib, M., & Garrod, S. (2013). How to Bootstrap a Human Communication System.  
945 *Cognitive Science*, 37(7), 1356–1367. <https://doi.org/10.1111/cogs.12048>
- 946 Fay, N., Ellison, M., & Garrod, S. (2014). Iconicity: From sign to system in human  
947 communication and language. *Pragmatics & Cognition*, 22(2), 244–263.
- 948 Fay, N., & Ellison, T. M. (2013). The Cultural Evolution of Human Communication Systems in  
949 Different Sized Populations: Usability Trumps Learnability. *PLoS ONE*, 8(8), e71781.  
950 <https://doi.org/10.1371/journal.pone.0071781>
- 951 Fay, N., Garrod, S., & Roberts, L. (2008). The fitness and functionality of culturally evolved  
952 communication systems. *Philosophical Transactions of the Royal Society B-Biological*  
953 *Sciences*, 363(1509), 3553–3561.
- 954 Fay, N., Garrod, S., Roberts, L., & Swoboda, N. (2010). The interactive evolution of human  
955 communication systems. *Cognitive Science*, 34(3), 351–386.
- 956 Fay, N., Lister, C. J., Ellison, T. M., & Goldin-Meadow, S. (2014). Creating a Communication  
957 System from Scratch: Gesture Beats Vocalization Hands Down. *Frontiers in*  
958 *Psychology*, 5:354.
- 959 Fehér, O., Wonnacott, E., & Smith, K. (2016). Structural priming in artificial languages and  
960 the regularisation of unpredictable variation. *Journal of Memory and Language*.  
961 <https://doi.org/10.1016/j.jml.2016.06.002>
- 962 Frishberg, N. (1975). Arbitrariness and iconicity: Historical change in American Sign  
963 Language. *Language*, 51, 696–719.
- 964 Fusaroli, R., Bahrami, B., Olsen, K., Roepstorff, A., Rees, G., Frith, C., & Tylén, K. (2012).  
965 Coming to Terms: Quantifying the Benefits of Linguistic Coordination. *Psychological*  
966 *Science*, 23(8), 931–939.



- 967 Fusaroli, R., & Tylén, K. (2016). Investigating Conversational Dynamics: Interactive  
968 Alignment, Interpersonal Synergy, and Collective Task Performance. *Cognitive*  
969 *Science*, 40(1), 145–171. <https://doi.org/10.1111/cogs.12251>
- 970 Galantucci, B. (2005). An experimental study of the emergence of human communication  
971 systems. *Cognitive Science*, 29(5), 737–767.
- 972 Galantucci, B. (2017). Experimental Semiotics. *Oxford Research Encyclopedia of Linguistics*,  
973 1–18. <https://doi.org/10.1093/acrefore/9780199384655.013.210>
- 974 Garrod, S., & Anderson, A. (1987). Saying what you mean in dialogue: A study in conceptual  
975 and semantic co-ordination. *Cognition*, 27(2), 181–218.
- 976 Garrod, S., & Doherty, G. (1994). Conversation, Coordination and Convention - an Empirical  
977 Investigation of How Groups Establish Linguistic Conventions. *Cognition*, 53(3), 181–  
978 215.
- 979 Garrod, S., Fay, N., Lee, J., Oberlander, J., & MacLeod, T. (2007). Foundations of  
980 Representation: Where Might Graphical Symbol Systems Come From? *Cognitive*  
981 *Science*, 31(6), 961–987.
- 982 Garrod, S., Fay, N., Rogers, S., Walker, B., & Swoboda, N. (2010). Can iterated learning  
983 explain the emergence of graphical symbols? *Interaction Studies*, 11(1), 33–50.
- 984 Harnad, S. (1990). The symbol grounding problem. *Physica D: Nonlinear Phenomena*, 42(1–  
985 3), 335–346.
- 986 Healy, P. G. T., Swoboda, N., & King, J. (2002). A tool for performing and analysing  
987 experiments on graphical communication. In X. Faulkner, J. Finlay, & F. Detienne  
988 (Eds.), *People and computers XVI: Proceedings of HCI2002: The 16th British HCI*  
989 *Group Annual Conference* (pp. 55–68). London: Springer-Verlag.

- 990 Healy, P. G. T., Swoboda, N., Umata, I., & King, J. (2007). Graphical language games:  
991 Interactional constraints on representational form. *Cognitive Science*, *31*, 285–309.
- 992 Hupet, M., & Chantraine, Y. (1992). Changes in repeated references: Collaboration or  
993 repetition effects? *Journal of Psycholinguistic Research*, *21*, 485–496.
- 994 Keysar, B., & Barr, D. J. (2002). Anchoring Comprehension in Linguistic Precedents. *Journal*  
995 *of Memory and Language*, *46*(2), 391–418. <https://doi.org/10.1006/jmla.2001.2815>
- 996 Kirby, S., Cornish, H., & Smith, K. (2008). Cumulative cultural evolution in the laboratory: An  
997 experimental approach to the origins of structure in human language. *Proceedings of*  
998 *the National Academy of Sciences*, *105*(31), 10681–10686.
- 999 Kirby, S., Griffiths, T., & Smith, K. (2014). Iterated learning and the evolution of language.  
1000 *Current Opinion in Neurobiology*, *28*(0), 108–114.  
1001 <https://doi.org/10.1016/j.conb.2014.07.014>
- 1002 Klima, E., & Bellugi, U. (1979). *The Signs of Language*. Cambridge MA: Harvard University  
1003 Press.
- 1004 Krauss, R. M., & Weinheimer, S. (1964). Changes in the length of reference phrases as a  
1005 function of social interaction: A preliminary study. *Psychonomic Science*, *1*, 113–114.
- 1006 Krauss, R. M., & Weinheimer, S. (1966). Concurrent feedback, confirmation and the  
1007 encoding of referents in verbal communication. *Journal of Personality and Social*  
1008 *Psychology*, *4*, 343–346.
- 1009 Kronmüller, E., & Barr, D. J. (2015). Referential precedents in spoken language  
1010 comprehension: A review and meta-analysis. *Journal of Memory and Language*, *83*,  
1011 1–19.

- 1012 Mein, C., Fay, N., & Page, A. C. (2016). Deficits in joint action explain why socially anxious  
1013 individuals are less well liked. *Journal of Behavior Therapy and Experimental*  
1014 *Psychiatry, 50*, 147–151. <https://doi.org/10.1016/j.jbtep.2015.07.001>
- 1015 Morgan, T. J. H., Laland, K. N., & Harris, P. L. (2015). The development of adaptive  
1016 conformity in young children: effects of uncertainty and consensus. *Developmental*  
1017 *Science, 18*(4), 511–524. <https://doi.org/10.1111/desc.12231>
- 1018 Peirce, C. S. (1931). *Collected Papers of Charles Sanders Peirce* (Vol. 1–8). Cambridge, MA:  
1019 Harvard University Press.
- 1020 Pelli, D. G., Burns, C. W., Farell, B., & Moore-Page, D. C. (2006). Feature detection and letter  
1021 identification. *Vision Research, 46*(28), 4646–4674.
- 1022 Piantadosi, S. T., Tily, H., & Gibson, E. (2011). Word lengths are optimized for efficient  
1023 communication. *Proceedings of the National Academy of Sciences, 108*(9), 3526–  
1024 3529. <https://doi.org/10.1073/pnas.1012551108>
- 1025 Pickering, M. J., & Garrod, S. (2004). Toward a mechanistic psychology of dialogue.  
1026 *Behavioral and Brain Sciences, 27*(2), 169–226.
- 1027 R Core Team. (2013). *R: A Language and Environment for Statistical Computing*. Vienna,  
1028 Austria: R Foundation for Statistical Computing. Retrieved from [http://www.R-](http://www.R-project.org/)  
1029 [project.org/](http://www.R-project.org/)
- 1030 Reitter, D., & Moore, J. D. (2014). Alignment and task success in spoken dialogue. *Journal of*  
1031 *Memory and Language, 76*, 29–46. <https://doi.org/10.1016/j.jml.2014.05.008>
- 1032 Roberts, G., Lewandowski, J., & Galantucci, B. (2015). How communication changes when  
1033 we cannot mime the world: Experimental evidence for the effect of iconicity on  
1034 combinatoriality. *Cognition, 141*, 52–66.

- 1035 Rogers, S. L., & Fay, N. (2016). Stick or Switch: A Selection Heuristic Predicts when People  
1036 Take the Perspective of Others or Communicate Egocentrically. *PloS One*, *11*(7),  
1037 e0159570.
- 1038 Schegloff, E. A. (2000). When 'others' initiate repair. *Applied Linguistics*, *21*(2), 205–243.
- 1039 Schober, M. F., & Clark, H. H. (1989). Understanding by Addressees and Overhearers.  
1040 *Cognitive Psychology*, *21*(2), 211–232.
- 1041 Schouwstra, M., & de Swart, H. (2014). The semantic origins of word order. *Cognition*,  
1042 *131*(3), 431–436.
- 1043 Smith, K., Feher, O., & Ritt, N. (2014). Eliminating Unpredictable Linguistic Variation through  
1044 Interaction. In *Proceedings of the 36th Annual Conference of the Cognitive Science*  
1045 *Society* (pp. 1461–1466). Cognitive Science Society.
- 1046 Smith, K., & Wonnacott, E. (2010). Eliminating unpredictable variation through iterated  
1047 learning. *Cognition*, *116*(3), 444–449.
- 1048 Sperber, D., & Wilson, D. (1987). *Precis of relevance: Communication and cognition*.  
1049 *Behavioral and Brain Sciences*, *10*(4), 697–710.
- 1050 Steels, L. (2003). Evolving grounded communication for robots. *Trends in Cognitive Sciences*,  
1051 *7*(7), 308–312.
- 1052 Stolk, A., Verhagen, L., & Toni, I. (2016). Conceptual Alignment: How Brains Achieve Mutual  
1053 Understanding. *Trends in Cognitive Sciences*, *20*(3), 180–191.
- 1054 Tamariz, M. (2017). Experimental Studies on the Cultural Evolution of Language. *Annual*  
1055 *Review of Linguistics*, *3*(1), 389–407. [https://doi.org/10.1146/annurev-linguistics-](https://doi.org/10.1146/annurev-linguistics-011516-033807)  
1056 [011516-033807](https://doi.org/10.1146/annurev-linguistics-011516-033807)

- 1057 Tamariz, M., Ellison, T. M., Barr, D. J., & Fay, N. (2014). Cultural selection drives the  
1058 evolution of human communication systems. *Proceedings of the Royal Society B:  
1059 Biological Sciences*, 281(1788), 1–6. <https://doi.org/10.1098/rspb.2014.0488>
- 1060 Tamariz, M., & Kirby, S. (2014). Culture: copying, compression, and conventionality.  
1061 *Cognitive Science*, 39(1), 171–183.
- 1062 Tan, R., & Fay, N. (2011). Cultural transmission in the laboratory: Agent interaction improves  
1063 the intergenerational transfer of information. *Evolution & Human Behavior*, 32(6),  
1064 399–406.
- 1065 Tennie, C., Call, J., & Tomasello, M. (2009). Ratcheting up the ratchet: on the evolution of  
1066 cumulative culture. *Philosophical Transactions of the Royal Society B: Biological  
1067 Sciences*, 364(1528), 2405–2415. <https://doi.org/10.1098/rstb.2009.0052>
- 1068 Theisen, C. A., Oberlander, J., & Kirby, S. (2010). Systematicity and arbitrariness in novel  
1069 communication systems. *Interaction Studies*, 11(1), 14–32.
- 1070 Thompson, B., Kirby, S., & Smith, K. (2016). Culture shapes the evolution of cognition.  
1071 *Proceedings of the National Academy of Sciences*, 113(16), 4530–4535.  
1072 <https://doi.org/10.1073/pnas.1523631113>
- 1073 Tomasello, M. (1999). *The cultural origins of human cognition*. Cambridge, MA: Harvard  
1074 University Press.
- 1075 Tomasello, M., Kruger, A. C., & Ratner, H. H. (1993). Cultural learning. *Behavioral and Brain  
1076 Sciences*, 16(3), 495–511.
- 1077 Vaccari, O., & Vaccari, E. E. (1961). *Pictorial Chinese-Japanese characters* (4th ed.). Vermont,  
1078 USA: Tokyo, Japan: Charles E. Tuttle.
- 1079 Wescott, R. W. (1971). Linguistic iconism. *Language*, 47, 416–428.

1080 Zipf, G. K. (1949). *Human Behavior and the Principle of Least Effort*. New York: Addison-

1081 Wesley.

1082