EMERGENCE OF LINGUISTIC COMMUNICATION FROM REFERENTIAL GAMES WITH SYMBOLIC AND PIXEL INPUT

Anonymous authors
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ABSTRACT

Emergent communication problems can be used to study the ability of algorithms to evolve or learn communication protocols. In this work, we study the properties of protocols emerging when reinforcement learning agents are trained end-to-end on referential communication games. We extend previous work using symbolic representations to using raw pixel input data, a more challenging and realistic input representation. We find that the degree of structure found in the input data affects the nature of the emerged protocols, and thereby corroborate the hypothesis that structured language is most likely to emerge when agents perceive the world as being structured.

1 INTRODUCTION

Research on emergent communication is influenced by the view that language derives meaning from its use (Wittgenstein, 1953).[1] This perspective especially motivates the study of language emergence through problems where co-operative agents try to achieve shared goals in games (Steels, 2003; Brighton & Kirby, 2006; Mordatch & Abbeel, 2017). This is also related to the study of multi-agent and self-play methods that have found great success in other areas of machine learning (Bansal et al., 2017; Silver et al., 2017).

The study of emergent communication is important for two related problems in language development, both human and artificial: language evolution, the development of communication protocols from scratch (Nowak & Krakauer, 1999); and language acquisition, the ability of an embodied agent to learn an existing language. In this paper we focus on the problem of how environmental or pre-linguistic conditions affect the nature of the communication protocol that an agent learns. Considering the realism and complexity of environments used for grounded language learning today (Brockman et al., 2016; Hermann et al., 2017), it is important to analyse these effects in detail.

One of the most important properties of natural language is that it is compositional. Smaller building blocks (words, morphemes, . . .) are used to generate infinite numbers of more complex forms (sentences, multi-word expressions, . . .), with the semantic meaning of the larger form being a function of the meaning of its parts (Frege, 1892). Compositionality is an advantage in both language and other communication protocols as it allows infinite expression through a finite dictionary. In emergent communication research, work has shown that agents can produce (somewhat) compositional protocols when engaging in language games (Steels, 2003). However, in those cases the computational agents were placed in artificial worlds containing just a handful of objects represented as disentangled, structured, and sometimes even atomic symbols, e.g., attribute-based vectors or one-hot vectors (Batali, 1998; Brighton, 2002; Franke, 2015; Andreas & Klein, 2017; Mordatch & Abbeel, 2017). However, humans do not receive symbolic but rather raw sensorimotor input. Hence, while these results are impressive, they can potentially produce misleading conclusions about human language (both from an applied and a scientific perspective). To date, little work has tested to what

[1] See Wagner et al. (2003) for a review of earlier work on emergent communication.

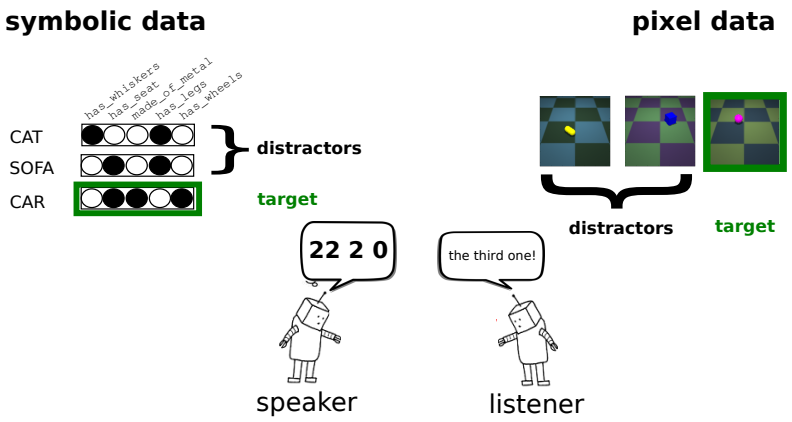

Figure 1: High-level overview of the referential game.

degree (if at all) these findings carry over when agents exist in less perfect and more realistic worlds that bear more similarity to the kind of entangled and noisy signals that humans are exposed to.[2]

In this work and in the context of referential communication games (see Figure 1), we contrast the results of two studies that lie at extremes in terms of how much structure is provided by their environments. The first study (Section 3) focuses on symbolic representations, where objects are represented as bags-of-attributes. This representation is inherently disentangled since dimensions encode individual properties. The second study (Section 4) considers raw perceptual input, hence data that more closely resembles what humans are exposed to. Clearly, the latter is a more challenging scenario as computational agents should operate on entangled inputs with no pre-coded semantics. Crucially, both studies use the same referential game setup, the same learning procedure (policy learning methods) and the same neural network agent architectures.

We show that reinforcement learning agents can communicate not only when presented with symbolic and highly structured input data, but—more importantly—even when presented with raw pixel input. This opens up avenues to more realistic simulations of language emergence. From an applied perspective, we successfully use the learning signal from the referential game to train agents end-to-end, including in cases where they need to perform visual processing of images with a convolutional neural network. On a more theoretical note, we find that the agents struggle to produce structured messages when presented with entangled input data (Bengio et al., 2013) due to the difficulty of uncovering the true factors of variation, corroborating the hypothesis of Smith et al. (2003) that structured (compositional) language is most likely to emerge when agents perceive the world as structured.

2 Referential Games as Multi-agent co-operative Reinforcement Learning

The referential game is implemented as an instance of multi-agent co-operative reinforcement learning; two agents take discrete actions in their environment in order to maximize a shared reward.

2.1 Game

The agents engage in referential games, a variant of the Lewis signaling game (Lewis, 1969), which have been extensively used in linguistic and cognitive studies in the context of language evolution (e.g., Briscoe, 2002; Cangelosi & Parisi, 2002; Steels & Loetzsch, 2012; Spike et al., 2016; Lazaridou et al., 2017). See Figure 1 for a schematic description of our setup. First, a *speaker* is presented with a target object (highlighted *CAR* or right image) and sends a message describing that object

[2] An exception to that is the recent work by Havrylov & Titov (2017), Evtimova et al. (2017) and Lazaridou et al. (2017). However the authors consider pre-trained visual input which already encode semantics of the world in the form of presence of objects and their properties.

(here: "22 2 0"). Then the *listener* is presented with the target and a set of distractor objects, and—by making use of the speaker's message—has to identify the target object from the set of candidate objects. *Communicative success* is defined as the correct identification of the target by the listening agent.

Formally, the attribute-based object vectors (disentangled) or the pixel-based images (entangled) are the set of *pre-linguistic* items $W = \{o_1, \ldots, o_N\}$. From this set we draw a target $t \in W$ and subsequently $K-1$ distractors $D = \{d_1, \ldots, d_{K-1}\} \subset W$ s.t. $\forall_j t \neq d_j$. The speaker has only access to the target t, while the listener receives candidate set $C = t \cup D$, not knowing which of the set elements is target t.

2.2 Agents

The speaker encodes t to a dense representation u with $f^S(t, \theta_f^S)$. The function of this encoder depends on the type of pre-linguistic data used and is discussed separately for each study. Given a vocabulary V of discrete unit symbols (akin to words) and u, the speaker next generates a discrete, variable-length, bounded message $\mathbf{m}$ by sampling symbols from a recurrent policy π^S derived by a decoder $g^S(u, \theta_g^S)$. The sequence generation is terminated either by the production of a stop symbol or when maximum length L has been reached. We implement the decoder as a single-layer LSTM Hochreiter & Schmidhuber (1997). Note that the symbols in the agents' vocabulary V have no *a priori* meaning. Instead, these symbols get grounded during the game.

The listening agent uses a similar encoder as the speaker but has independent network weights (θ_{enc}^L). Applying this encoder to all candidates results in a set $\mathbf{v} = f^L(C, \theta_f^L)$. We use a single-layer LSTM to encode the message $\mathbf{m}$, s.t. $z = h^S(\mathbf{m}, \theta_h^L)$.

Given encoded message z and candidates $\mathbf{v}$ the listener predicts a target object $u \in C$ following a policy π^L implemented using a non-parametric pointing module which samples the predicted object from a Gibbs distribution computed via the dot product between vectors z and all candidates $c \in C$. See Appendix B for information regarding the agents' architecture.

2.3 Learning

All weights of speaker and listener agent $\theta = \langle \theta_f^S, \theta_g^S, \theta_f^L, \theta_h^L \rangle$ are jointly optimized while playing the game. We emphasize that no weights are shared between the speaker and the listener, and that the only supervision used is communication success, i.e., whether the listener identified the correct target. The objective function that the two agents maximize for one training instance is $R\left(\sum^L \log p(m_t^l | m_t^{<l}, u) + \log p(u_{t'} | \mathbf{m}, C)\right)$ where R is the reward function returning 1 if $t = u_{t'}$ (if the listener pointed to the correct target) and 0 otherwise. To maintain exploration in the speaker's policy π^S of generating a message and the listener's policy π^L of pointing to the target, we add to the loss an entropy regularization term (Mnih et al., 2016). The parameters are estimated using the REINFORCE update rule (Williams, 1992). See Appendix B for information regarding learning.

3 Study 1: Referential game with symbolic data

We first present experiments where agents are learning to communicate when presented with structured and disentangled input. We use the dataset of Visual Attributes for Concepts Dataset (ViSA) of Silberer et al. (2013), which contains human-generated per-concept attribute annotations for 500 concrete concepts (e.g., *cat*, *sofa*, *car*) spanning across different categories (e.g., *mammals*, *furniture*, *vehicles*), annotated with 636 general attributes (e.g., *has_tail*, *is_black*, *has_wheels*). We disregarded homonym concepts (e.g., *bat*), thus reducing our working set of concepts to 463 and the number of attributes to 573 (after eliminating any attribute that did not occur with working concepts). On average, each concept has 11 attributes. All pre-linguistic objects are represented in terms of 1-hot vectors $o \in \{0, 1\}^{573}$. Note that these representations do care some inherent structure; the dimensions in the object vectors are disentangled and so each object can be seen as a conjunction of properties. Speaker and listener convert the pre-linguistic representations to dense representations u by using a feed-forward linear encoder followed by a sigmoid activation function.

Max Length	Vocabulary Size	Protocol Size	Training Accuracy	-1*topographic ρ
2	10	31	92.0%	0.13
5	17	293	98.2%	0.16
10	40	355	98.5%	0.26

Table 1: Commumicative success (**training accuracy** in percentage) with varying maximum message length. **vocabulary size** denotes the effective size of symbols used from a maximum number of 100. **protocol size** is the effective number of unique messages used. -1***topographic** ρ reports the structural similarity in terms of Spearman ρ correlation between the message and the object vector space. All Spearman ρ correlations throughout the paper are significant with $p < 0.01$.

In all our experiments, we set the number of candidate objects K to five, meaning there were four wrong choices per correct one (resulting in a 20% random baseline). Inspired by Kottur et al. (2017), who show that non-compositional language emerges in the case of overcomplete vocabularies, we set the size of vocabulary V to a number smaller than the set of objects (i.e., V has 100 symbols). Note that symbols in V have no pre-defined semantics and are getting grounded through the game.

3.1 Agent Performance and Ambiguity

We first report model performance on the training data, comparing different settings for the maximal allowed message length (2, 5 or 10 symbols). Results are presented in Table 1.

In the case of the shortest message settings (maximum length set to 2), our trained agents on average only develop a protocol of 31 unique messages used to describe 363 training concepts. This means there is a lot of ambiguity, with on average each message used to denote 11 concepts. Interestingly, recent findings suggest that ambiguity is a design feature of language that prevents the inefficient use of redundant codes, since some the message content can be extracted from context: "the most efficient communication system will not convey information already provided by the context" (Piantadosi et al., 2012). In our case, we do no explicitly encode any bias towards ambiguity. We hypothesize that ambiguity arises due to the hard exploration problem that agents are faced with, in combination with the fact that ambiguous protocols present a good "local optimum" that is over-represented in the hypothesis search space. As a result, in the absence of environmental pressures (e.g., a high number of carefully constructed distractors) a suboptimal policy can still achieve a reasonably high accuracy (92%), making it even harder during training to escape from such a solution.

In classic signaling games, this polysemy phenomenon manifests itself as different states receiving the same signal and is termed *partial pooling equilibrium* (Skyrms, 2010). Perhaps rather counter-intuitively, Skyrms (p.131) suggests that a way to obtain communication protocols that are robust to this type of local communication minima is to allow the invention of new signals, essentially increasing the search space of signals. Motivated by this, we play variants of the game in which we allow the agents to produce messages of greater maximum length (5 and 10), which leads to improved communicative success (98.2% and 98.5% respectively). We observe that the number of messages in the protocol increases from 31 to 293 and 355 respectively, reducing the average number of concepts a message can denote from 11 concepts to (approximately) 1 concept.

3.2 Realistic context distribution

In the real world, when speakers refer to cats, listeners would more often be in a situation where they had to discriminate a cat in the context of a couch or a dog rather than in the context of a mirror or a cow.[3] Simply put, things in the world do not appear in random contexts, but rather there is regularity in the distribution of situational and visual co-occurrence. This property of the world is typically not captured in referential games studied in the language emergence literature, with distractors typically drawn from a uniform distribution. We address this issue and design an additional experiment with distractors sampled from a target-specific context distribution reflecting normalized object co-occurrence statistics. Co-occurrence data is extracted from the MSCOCO caption dataset (Lin et al., 2014). This leads to more plausible distractor sets, with for instance

[3]This example reflects real co-occurrences from caption data.

Data	Length 2 Protocol Size	Acc.	Length 5 Protocol Size	Acc.	Length 10 Protocol Size	Acc.
Training data	31	92.0	293	98.2	355	98.5
Test data	1	74.2	70	76.8	98	81.6
Unigram chimera	5	39.3	88	40.5	99	47.0
Uniform chimera	3	31.2	87	32.2	100	42.6

Table 2: Communicative success (**acc** in percentage) of agents evaluated on training (first row) and novel (last three rows) data. **protocol size** column reports the percentage of novel messages (i.e., messages that were not used in the training data).

the target GOAT more likely being mixed with SHEEP and COW as distractors than with BIKE or EGGPLANT.

Note that the distractor selection process (uniform vs context-dependent) affects the language learning dynamics. While the non-uniform distractor sampling of the context-dependent process can be exploited to learn a degenerate strategy—giving up to 40% communicative success shortly after the start of training—subsequently learning under this scenario takes longer. This effect is likely a combination of the local minimum achieved by the degenerate strategy above together with the fact that the co-occurrence statistics tend to align with the feature vectors, meaning that very similar objects are more likely to appear as distractors and the overall game thus becomes slightly more difficult.

We now consider the question of how objects, denoted by ambiguous words, i.e., objects obtained by the same message, are related. When the context is drawn uniformly, object similarity is a predictor of object *confusability*, as similar objects tend to be mapped onto the same message (0.26 and 0.43 median pairwise cosine similarities of objects that received the same message, for maximum message length 2 and 5, respectively). In the non-uniform case, we observe object confusability to be less influenced by object similarity (0.15 and 0.17 median pairwise cosine similarities of objects that received the same message, for maximum message length 2 and 5, respectively), but rather driven by the visual context co-occurrences. Thus, the choice of distractors, an experimental design decision that in existing language emergence literature has been neglected, has an effect on the organization (and potentially the naturalness) of the emerged language.

3.3 STRUCTURAL PROPERTIES OF EMERGED PROTOCOLS

Quantifying the degree of compositionality and structure found in the emerged language is a challenging task; to the best of our knowledge, there is no formal mathematical definition of compositionality that could allow for a definitive quantitative measure. Thus, research on this topic usually relies on defining *necessary requirements* that any language claiming to be compositional ought to adhere to, the ability to generalize to novel situations (Batali, 1998; Franke, 2015; Kottur et al., 2017). We adopt a similar strategy and report results (see Section 3.3.1) where we test the generalization ability of an emerged language to novel objects. Moreover, we also report results (see Section 3.3.2) on a quantitative measure of message structure proposed in the language evolution literature (Brighton & Kirby, 2006).

3.3.1 GENERALIZATION TO NOVEL OBJECTS

We perform experiments where trained agents from Section 3.1 are exposed to different types of unseen objects, each of them differing to the degree to which the unseen objects resemble the objects found in the training data. In the **test** scenario, objects come from the same data distribution as the training data, but were not presented to the agents during training (e.g., a mouse); in the **unigram chimeras** scenario, the novel objects are constructed by sampling properties from a property-based distribution inferred from the training data, thus breaking any feature correlation (e.g., a mouse-like animal with wheels); in the **uniform chimeras** scenario, the novel objects are constructed by uniformly sampling properties (e.g., a square red furry metallic object).

Table 2 reports the communicative success. While there is a drop in performance for unseen objects, agents are performing above random chance (i.e., 20%). The emerged language is indeed able to generalize to unseen objects; however, the degree of generalization is a function of similarity be-

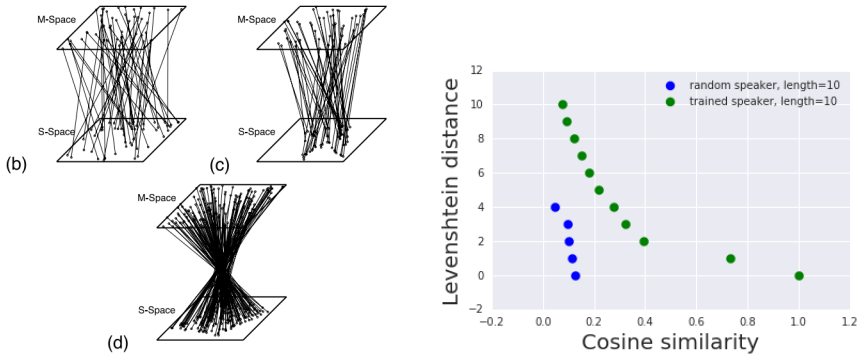

Figure 2: **left**: Three languages with different properties, taken from Brighton & Kirby (2006). The mapping between states and signals shown in (b) is random; there is no relationship between points in the meaning and signal space. In (c) and (d), similar meanings map to similar signals, i.e., there is a topographic relation between meanings and signals. **right**: Relation between objects' cosine similarity and their message Levenstein distance for trained and random agents.

tween the training and unseen objects, thus resulting in the **uniform chimeras** obtaining the lowest performance.

Moreover, we observe examples of *productivity*, a key feature of compositionality. At test time, speakers are able to come up with novel messages on-the-fly (i.e., messages that are not part of their lexicon inferred during training) to describe unseen objects. See Table 2 last 3 rows and **protocol size** column for the percentage of novel messages. Even though listeners were not trained to associate the novel messages with the novel objects, they are still able comprehend them and correctly identify the target object. In the **test data** and **length 10** cases, the novel messages account for almost all generated messages with performance being at 81.6%, providing evidence of the structure found in the messages.

3.3.2 TOPOGRAPHIC SIMILARITY

Given a set of objects, their meanings and the associated signals, Brighton & Kirby (2006) define *topographic similarity* to be the correlation of the distances between all the possible pairs of meanings and the corresponding pairs of signals. Figure 2 shows mappings between states and signals for examples of holistic (b) and compositional (c,d) languages (the topographic similarity of language (b) is low while for languages (c,d)). The intuition behind this measure is that, given the definition of compositionality under which "the meaning of the whole is a function of the meaning of its parts", semantically similar objects should have similar messages.

To compute this measure, we first compute two lists of numbers: (i) the Levenshtein distances between all pairs of objects' messages and (ii) the cosine similarity between all pairs of all objects' ViSA vectors. Given these two lists, the topographic similarity (see the topographic ρ in Table 1) is defined as the Spearman ρ correlation between the lists. Intuitively, if similar objects share much of the message structure (e.g., common prefixes or suffixes), and dissimilar objects have little common structure, then the topographic similarity should be high, the highest possible being 1. From these measurements, we find that similar objects get similar messages. As an example, a qualitative analysis of the messages generated in the **length 10** and **training data** cases showed that 32% of the *mammal* objects had as prefix the bigram *95#10*, 36% of *vehicle* objects had *68#95* and 11% of *tool* objects had *0#61*, suggesting that these prefix bigrams encode category-specific information.

Next, for each object pair, we calculate their Levenshtein message distance and respective cosine similarity, and plot in Figure 2 (**right**) for each distance the average cosine similarities of the pairs with that distance (this is done for the **length 10** and **training data** experiment). We observe that there is a clear relation between message similarity and meaning similarity. In Figure 2, we also plot a similar correlation curve for an emerged language obtained by producing messages with a randomly initialized and fixed speaker/listener architectures. This emerged language is at random

in terms of communicative success; however, it does show signs of structure since similar objects obtain similar messages. This seems to suggest that structured and disentangled pre-linguistic representations are, perhaps, a sufficient condition for the emergence of structured language, especially in neural network-based agents which, due to the nature of representation and information flow, favor similar inputs to trigger similar outputs.

4 STUDY 2: REFERENTIAL GAME WITH RAW PIXEL DATA

In this section, we present experiments in which agents receive as input entangled data in the form of raw pixel input and have to learn to perform visual conceptual processing guided from the communication signal.

We use a synthetic dataset of geometric objects generated using the MuJoCo physics engine (Todorov et al., 2012). We generate RGB images of resolution 124×124 depicting a single object. For each object we pick one of eight colors (*blue, red, white, black, yellow, green, cyan, magenta*) and five shapes (*box, sphere, cylinder, capsule, ellipsoid*) resulting in 40 combinations, for each of which we generate 100 variations, varying the floor color and the object location in the image. Moreover, we introduce different variants of the game: **game A** with 19 distractors; **game B** with 1 distractor; **game C** with 1 distractor and with speaker and listener having different viewpoints of the target object (thus the target object on the listener's side is in a different location); **game D** with 1 distractor, with speaker and listener having different viewpoints, and with balanced number of shapes and color (obtained by downsampling from 8 colors to 5 and removing any image containing objects of the 3 disregarded objects). For each game, we create train and test splits with proportions 75/25.

Pre-linguistic objects are presented in the form of pixel input, $o \in [0-255]^{3\times124\times124}$. Speaker and listener convert the images o to dense representations u, each of them using an 8-layer convolutional neural network (ConvNet). Crucially, we do not pre-train the ConvNets on an object classification task; the only learning signal is the communication-based reward. Despite this fact, we observe that the lower layers of the ConvNets are encoding similar information to ConvNet pre-trained on ImageNet (Deng et al., 2009).[4] Conceptually, we can think of the whole speaker/listener architecture as an encoder-decoder with a discrete bottleneck (the message). Given our initial positive findings, this reward-based learning signal induced from communication games could be used for class-agnostic large-scale ConvNet training. Moreover, we find that even though no weights were shared, the agents' conceptual spaces get aligned at different levels, reminiscent of theories of interactive conceptual alignment during dialogue (Garrod & Pickering, 2004) (see Appendix A).

4.1 COMMUNICATIVE SUCCESS AND EMERGENT PROTOCOLS

Unlike the experiments of Section 3 where agents start from disentangled representations, starting from raw perceptual input presents a greater challenge; the agents have to establish naming conventions about objects, while at the same time learning to process the input with their own visual conceptual system. Since we do not pre-train their ConvNets on an object recognition task, the dense representations u used to derive the message contain no bias towards any image- or object-specific information (e.g, color, shape, object location). The extraction of visual properties is thus driven entirely by the communication game. This contrasts with the cases of Havrylov & Titov (2017) and Lazaridou et al. (2017) who are using pre-trained visual vectors, and qualitatively observe that the induced communication protocols encode information about objects. Table 3 presents the results in terms of communicative **train** and **test** success. Despite the challenges posed in this setup due to the raw nature of data, overall performance is well above chance, indicating that reinforcement learning agents trained end-to-end can manage to establish a communication protocol in this grounded environment.

In **game A**, the agents reach 93.7% accuracy (with 5% random baseline) and their lexicon consists of 1068 messages to describe 3000 training objects. By examining their protocol (see Table 3), we

[4]Specifically, for all 4000 images we compute two sets of activations, one derived from the speaker's ConvNet and one from a pre-trained ResNet model (He et al., 2016). We then compute all pairwise cosines in the speaker's ConvNet and ResNet space and correlate these values. We find Spearman ρ to be in the range 0.6-0.7 between the first 3 layers of the speaker's ConvNet and the ResNet.

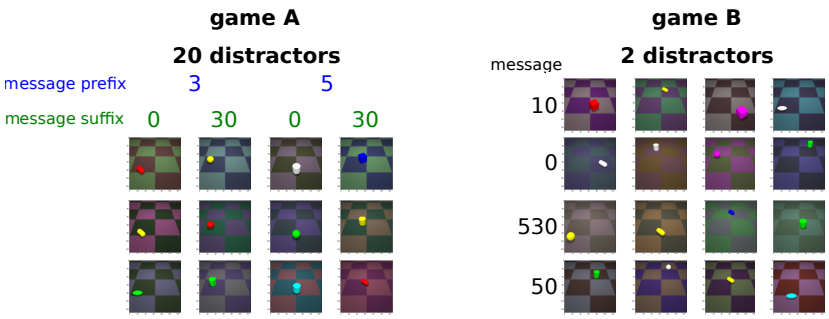

Figure 3: Target images and their associated messages from **game A** and **game B**.

Game	Distractors	Balanced	Viewpoints	Lexicon	Train Acc.	Test Acc.
A	20	No	No	1068	93.7	93.6
B	2	No	No	13	93.2	93.4
C	2	No	Yes	8	86	85
D	2	Yes	Yes	5	90	89

Table 3: Communicative success results (numbers are in percentage format).

find messages to encode information about absolute location of objects, i.e., x and y co-ordinates, a communication strategy that does not take into account properties of the object itself (e.g., color or shape); this is a strategy usually followed by human players of referential games (Kazemzadeh et al., 2014). Moreover, we observe some structure in the space with message prefix denoting x-coordinate information and message suffix denoting y-coordinate (see Figure 3).

However, we find the emerged protocols to be very unstable and too grounded in the specific game situation. Small modifications of the game setup, while having close to no negative impact on the communicative performance, can alter radically the form, semantics and interpretability of the communication protocol. In the **game B** (with 50% random baseline), performance remains at the same level (93.2%). We observe that the protocol consists of 13 messages and is harder to interpret (see Figure 3 for randomly sampled examples). When we change the viewpoint of the agents (**game C**), thus biasing them against communicating about absolute object location, the players derive a compact communication protocol consisting of 8 unique messages that describe primarily color. Finally, when color and shape are balanced (**game D**), we still observe a bias of agents towards the color of objects, with the five induced messages providing a perfect clustering of the objects according to their colors.

In an entangled world, agents do not possess *a priori* visual biases and knowledge of concepts. Since objects can be conceptualized in indefinitely many ways, the type of information encoded in the messages is tied to the environmental pressures; communication behaviour is a function of the environment, which also dictates what data structures can emerge. The implication of this observation is that protocols essentially overfit to the particular game situation, to the degree that they become specialized ad-hoc naming conventions.

Interestingly, the emergence of ad-hoc naming conventions has also been observed during human-human interaction; when participants engage in some specific game situation (e.g., communicating about abstract tangram shapes), they tend to form highly specialized naming conceptions (i.e., *conceptual pacts*) that allow them to communicate with maximum efficiency (Brennan & Clark, 1996). While in this study we do not address this issue of how a stable and general language could emerge in entangled worlds, we believe that to alleviate the formation of such ad-hoc communication protocols it is essential to increase the complexity of the games as well as introducing the notion of game multi-tasking.

Game	Object Position	Object Shape	Object Color	Floor Color
A	0.95	0.90	0.24	0.36
B	0.88	0.35	0.65	0.45
C	0.93	0.68	0.77	0.43
D	0.90	0.52	0.85	0.55

Table 4: Accuracy of probe linear classifiers of speaker's induced visual representations.

4.2 PROBE MODELS

In order to investigate what information gets captured by the speaker's ConvNet, we probe the inferred visual representations u used to derive the message. Specifically, we design 4 probe classifiers for the **color** and **shape** of object, **object position** which is derived by discretizing each co-ordinate into 3 bins, and **floor color** which is obtained by clustering the RGB color representation of the floor. For each probe, we performed 5-fold cross validation with a linear classifier and report accuracy results in Table 4. Overall, different games result in visual representations with different predictive power. **object position** is almost always encoded in the speaker's visual representation, even in situations where location of the object is not a good strategy for communication. On the other hand, **object shape** seems to provide less salient information, despite the fact that it is relevant for communication, at least in the **game C&D**.

As expected, the structure and semantics of the emergent protocols are a function of the information captured in the visual representations. The degree to which the agents are able to pull apart the objects' factors of variation impacts their ability to communicate about those factors, with the most extreme case being **game D**, where the message ignores the shape entirely. Thus, disentanglement seems to be a necessary condition for communication, at least in the case of pixel input.

5 CONCLUSION

We presented a series of studies investigating the properties of protocols emerging when reinforcement learning agents are trained end-to-end on referential communication games. We found that when agents are presented with disentangled input data in the form of attribute vectors, this inherent compositional structure is successfully retained in the output. Moreover, we showed that communication can also be achieved in cases where agents are presented with raw pixel data, a type of input that aligns better with the raw sensorimotor data that humans are exposed to, opening avenues to more realistic (and large scale) simulations of language emergence. At the same time, we found that their ability to form compositional protocols is hampered by their ability to pull apart the objects' factors of variations.

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A CONCEPTUAL ALIGNMENT OF SPEAKER AND LISTENER

During conversation, communication allows interlocutors to achieve interactive conceptual alignment (Garrod & Pickering, 2004). We are able to communicate because we have established a common ground and our representations at different levels become aligned (e.g., participants mutually understand that "he" in the conversation refers to Bob). We investigated whether the agents' conceptual systems achieve a similar structural alignment. We measure the alignment in terms of Spearman ρ correlation of the intra-agent pairwise object cosine similarities as calculated via representing objects as activations from ConvNet layers.

Interestingly, we observe a gradual increase in the structural similarity as we represent the objects with layers activations closer to the pixel space. Simply put, conceptual spaces are more aligned the closer they are to the raw pixel input ($\rho = 0.97$-0.91, depending on the game) and become more dissimilar as the representations become more abstract. We can draw the analogy to language processing, as first ConvNet layers perform some low-level processing analogous to phoneme recognition or word segmentation (and are thus more objective) while higher layers perform more abstract processing vaguely analogous to semantics and pragmatics (thus, represent more subjective knowledge). In cases of successful communication, their conceptual spaces at closer to the communication point are structurally very similar ($\rho = 0.85$-0.62, depending on the game), however this similarity drops dramatically in cases of failure of communication ($\rho = 0.15$).

B HYPERPARAMETER DETAILS

All LSTM hidden states of the "speaking" and "listening" module as well and the "seeing" pre-linguistic feed-forward encoders (see Section 3), have dimension 50. The "seeing" pre-linguistic ConvNet encoders (see Section 4) has 8 layers, 32 filters with the kernel size 3 for every layer and with strides $[2, 1, 1, 2, 1, 2, 1, 2]$ for each layer. We use ReLU as activation function as well as batch normalization for every layer.

For learning, we used the Rmsprop optimizer, with learning rate 0.0001. We use a separate value of entropy regularization for each policy. For π^S we use 0.01 and for π^L we use 0.001. We use a mini-batch of 32.