Toward Modeling the Emergence of Symbolic Communication

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***Abstract*— We quantitatively study the emergence of symbolic communication in humans with a communication game that attempts to recapitulate an essential step in the development of human language: the emergence of shared abstract symbols in order to accomplish complex tasks. A teacher must communicate an abstract notion, a formula in first order logic rendered to them in natural language, to a student. Subjects do so through a narrow channel that deprives them of common shared symbols: they cannot see or speak to one another and must only communicate via the motions of cars in a computer game. We observe that subjects spontaneously develop a shared symbolic vocabulary of car motions for task-specific concepts, such as "square" and "forall", as well as for task-agnostic concepts such as "I'm confused". Today, no agent can take part in this task, even though recognizing intentional motions and using those motions effectively are core competencies that we expect of social robots. As we scale up this task, we hope to shed light on how symbols are learned by humans and open up a rich new world of tasks for robots.**

I. INTRODUCTION

As Artificial Intelligence agents become an increasing part of our daily lives, there is a growing need for these agents to communicate with humans in human terms, that is, using sign systems that are fundamentally symbolic [1, 2]. Symbolic communication operates with signs whose mapping from form to meaning is arbitrary and governs numerous forms of human communication from body language to writing systems [3]. However, the spontaneous emergence and development of symbolic communication is rarely observed in nature, so the conditions required for it to develop are not fully understood.

A number of studies in cognitive science have investigated the spontaneous development of a shared code in human communication after removing existing communicative conventions [4–7]. In these studies, subjects play a cooperative communication game, such as a referential task, without being able to speak, see, or write to each other. Through the shared task, subjects are motivated to develop their own communicative codes, such as sequences of discrete spatial movements on a 2D grid, thereby producing novel symbolic communication systems [6].

Our experiment, a cooperative two-player game, similarly probes how humans spontaneously develop a shared symbolic vocabulary and reveals the emergence of a symbolic sign system. Like previous studies, we remove familiar modes of symbolic communication such as writing or speaking from the game. A teacher must communicate a task, encoded in a natural language utterance, to a student through continuous spatial movements in a teaching environment. The student then carries out that task in novel test maps. The players' communicative behavior is embodied in their movements in the game world, which implicitly tasks the players to create their own communication channel and detect communicative intent.

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Our experiment is novel in two ways. First, the space of communication is greatly expanded from that of previous studies: it occurs over a channel of continuous rather than discrete spatial movements, and operates over a larger and more abstract task space specified by FOL propositions that is unknown to the student. This allows us to attempt to explain sign development over a broad range of task and movement complexity. Second, it is believed that increased feedback and interaction between interlocutors results in more effective communication [4, 5]. Therefore, we introduce the possibility of unlimited reteaches of any given task by the teacher, removing restrictions in the amount of feedback and interaction between teacher and student.

The game environment and incentives are designed to communicate abstract notions, encoded in first order logic, through motions which have no existing shared symbolic lexicon, encouraging the development of new abstractions (section II). We have conducted a pilot experiment with two teacher-student pairs (section III). Our initial results show that the signs developed in the game not only include symbols but also exhibit some degree of compositionality. We conclude with a discussion of future directions including extending to artificial agents (section IV).

II. COMMUNICATION GAME

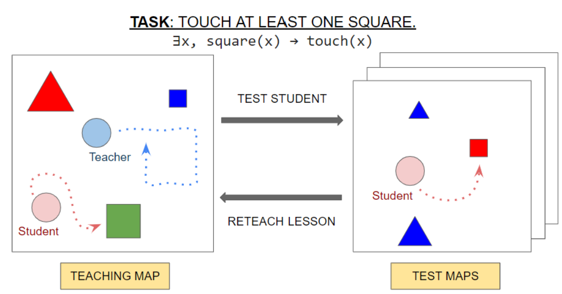


Fig. 1: The game flow for one task. The teacher (light blue circle) and the student (light red circle) start in a teaching map containing several objects (left). The teacher is given the task expressed in natural language but the student does not have access to this knowledge. The teacher must communicate the task to the student via car movements only. When the teacher is finished teaching, the student is moved to a new set of test maps to perform the task alone (right) while the teacher watches how the student performs the task. At any point during testing, the teacher may choose to move the student back to the teaching map to reteach the task. At the last test map, the teacher may advance the pair to the next task.

We have designed a communication game that incentivizes the emergence of meaningful communication between players (see Fig. 1). This communication is grounded in the game environment and its quality can be measured quantitatively by performance on tasks.

A. Game Mechanics

On separate computers, a teacher and a student each control a 2D car avatar that navigates a set of maps containing several objects. Players control the velocity and angle of their cars using their keyboard arrow keys. Their avatar movements are their only form of communication in the game. The players need to recognize the start and end of the signs (if any) and understand their meanings through gameplay. The game works as follows:

1) The teacher and student begin in a teaching map containing several objects, where the teacher communicates the task to the student via spatial movements only.
2) Once the teacher is done teaching, the student goes on to three test maps for the same task to execute the actions while the teacher watches. At any point in testing, the teacher may choose to reteach, returning the pair to the teaching map. At the last test map for the task, the teacher may choose between reteaching the lesson and moving onto the next task.
3) The teacher and student are rewarded a point for each successfully completed test map. The teacher sees the total score throughout the game, and the student sees the total score once per two tasks.
4) After each task (one teaching map + three test maps), each player fills out a reflection form where they draw and describe the actions they used to communicate and select whether previously registered actions are used, answering the questions "What does this action mean? When was it used? Who used it?". To avoid biasing players, we use the word *action* instead of *sign* or *symbol* (however, we post-interpret all registered *actions* as *signs*). Both players also submit a description of the overall communication in this round, detailing e.g. whether the player was confused, or the teaching strategy if the player was a teacher. In addition, the student submits a guess of the task description they were just asked to perform. Players do not have access to each others' reflections nor registered actions.

A game session repeats these steps with multiple tasks so the players develop a shared set of signs over time. The game motivates cooperative sign development in the following ways: (i) players cannot communicate with the sole exception of moving the cars on a shared 2D map, requiring new modes of communication; (ii) players are equally incentivized by student performance on test maps, which implicitly rewards good communication; (iii) players play through numerous tasks and reflections with the same partner, which reinforces sign meaning and offers continued opportunity to evolve the shared sign sets.

Prior to the game start, the student is not privy to the task space. The players are only given instructions about their roles– the teacher is told that they must communicate a set of natural language tasks to the student, and the student is told that they must learn a set of natural language tasks from the teacher and perform these tasks on a set of test maps. Both players are shown a practice round where they individually complete a task on one practice map in order to test game controls.

B. Task Space

A task in the game is a first-order logic (FOL) formula expressed in natural language. Our task space greatly expands the space of tasks of prior referential games by introducing actions and quantifiers. An atomic FOL task takes the form

$$\text{for } \mathtt{\textbf{quantifier}}\ x,\ \mathtt{\textbf{predicate}}(x) \rightarrow \mathtt{\textbf{action}}(x).$$

More complex tasks can be constructed using logical connectives **and** ($\wedge$), **or** ($\vee$), or **not** ($\neg$). We use connectives to combine multiple predicates to describe objects or construct complex tasks from atomic formulas. The task space is described in Table I.

Predicates	Color: red, blue Shape: square, triangle Size: big, small
Actions	touch, touch going forwards, touch going backwards, avoid
Quantifiers	all ($\forall$), at least one ($\exists$)
Logical Connectives	and ($\wedge$), or ($\vee$), not ($\neg$)

TABLE I: The first-order logic task space of the game

Tasks are sampled from a probabilistic grammar and are classified into four levels of complexity. Level 1 consists of touching **all** objects with single predicates; for example *Touch all objects that are red*. Level 2 adds one modification to an action or a quantifier; for example *Touch at least one object that is red*, or introduces one predicate composition such as *Touch all objects that are red and square*. Level 3 introduces multiple such modifications, and Level 4 uses logical connectives at the task level. The levels of the tasks are approximately distributed as 10% level 1, 30% level 2, 50% level 3, and 10% level 4.

C. Map Generation

Given a task, we generate a teaching map and three test maps, all measuring 450×450 pixels. Each object on a map is defined by its shape, size, color, and position. The space of object attributes is the predicate space in Table I.

So that the task is satisfiable in the generated map, we extract the set of predicates required to satisfy the formula and accordingly place N objects with these attributes on the map at random. We also place M objects of random attributes on the map as distractors. Distractors are important especially for test maps to measure student comprehension. For example, if the task is *Touch at least one square* and there are only squares on the test map, the student trivially succeeds and we gain no information about their level of understanding.

For both teaching and test maps, we sample $N \sim \mathcal{D}^{\text{required}}$ and $M \sim \mathcal{D}^{\text{distractor}}$. In the *base* case, both distributions are $\text{Unif}[1, 3]$.

In addition, we introduce two pressures in the teaching map to motivate sign development by the teacher.

- *Ambiguity*: We consider two forms of ambiguity by modifying distributions to sample objects. (1) Ambiguity in the quantifier: we place one target object ($N = 1$) so that it is more difficult to teach **all** vs. **at least one**. (2) Ambiguity in the predicate: we place no distractors ($M = 0$) so that the teacher cannot use them as negative examples to discriminate the solution set.
- *Inconvenience*: We set $\mathcal{D}^{\text{required}} = \text{Unif}[9, 11]$ to have a large number of target objects on the map. In maps with inconveniently many target objects, rather than touch all target objects the teacher may use a sign for brevity.

Teaching maps are sampled from *base*, *ambiguous in the quantifier*, *ambiguous in the predicate*, and *inconvenient* distributions with equal probability. Test maps are sampled from the *base* distribution only.

III. EXPERIMENTS

We have run two pilot experiments with four graduate student volunteers. We did not provide financial compensation for the game. Participants completed the game over a period of three or four days, playing approximately 10-15 tasks per day and taking breaks whenever they chose. Among the two pairs, Pair A finished 50 tasks in 10 hours and Pair B did 30 tasks in 3 hours. When rejoining the game, participants were able to pick up where they left off.

Player reflection forms evidence the development of signs for both pairs. Sign data registered in reflection forms consists of the player's drawing and description, where the description includes what the sign means, who used it, and how it was used. Our accounts of sign meaning in this section are taken directly from player reflection forms without further interpretation.

Pair A developed 12 mutually understood (non-symbolic and symbolic) signs, receiving a raw score of 150/150, while Pair B developed only one mutually understood non-symbolic sign, receiving a raw score of 70/90. However, because pairs are allowed as many reteaches as necessary to complete a task, raw score is not necessarily indicative of communication quality. Instead, since we observe that more reteaches corresponds to a lesser understanding of the task, we evaluate communication by weighting the score on each task by number of attempts. Pair A's weighted score was 0.82 (123.5/150) and Pair B's was 0.55 (49.5/90).

On average, Pair A retaught each task 1.4 ± 0.8 times, and took 3.1 ± 1.6 minutes per task. In contrast, Pair B retaught tasks 3.0 ± 4.4 times, and took 2.7 ± 2.2 minutes per task. In general, the average time taken per task decreased over the course of the game from 3.6 minutes in the first half to 2.7 minutes in the latter half for Pair A, and from 3.4 minutes to 2.0 minutes for Pair B. Player reflection forms qualitatively indicate that the tasks grew easier throughout the game, despite the stationary distribution of task levels, teaching maps, and test maps.

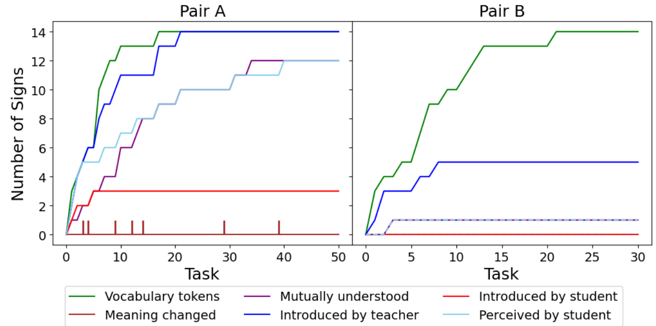


Fig. 2: Evolution of player lexicon over task index.
We consider a sign to be *introduced* by task t if a player uses a sign and registers it in the reflection form at some $t' \leq t$; The set of *vocabulary tokens* in a task description are those in Table I; A sign is *mutually understood* by task t if that sign has been registered in the student's reflection form (indicating understanding) at some $t' \leq t$, and similarly for the teacher; A sign is *perceived* by the student by task t if the sign has been registered as a new teacher-introduced sign (with any degree of uncertainty) in the student's reflection form at some $t' \leq t$; A sign's meaning is *changed* at task t if in either player's reflection form for t, the player updates the sign's description. We consider two registered actions sufficiently similar to be the same sign if their natural language descriptions have the same meaning and the drawings are similar. All plots except for *meaning changed* are cumulative.

A. Emergence and Development of Signs

The players' shared sign sets appear to converge over the course of the game — see Fig. 2 for the trajectories of the used and perceived signs. Pair A stops introducing new signs by task 21, changing sign meaning by task 30, and perceiving new signs by task 40. Similarly, Pair B stops introducing new signs by task 8 and perceiving new signs by task 3.

The type and quantity of signs introduced by players mirrored their directional relationship. Most of the time, the teacher initiated communicating task meaning to the student and the student tried to decipher task meaning from the teacher. Indeed, Teacher A introduced 14 out of the 17 signs. All but one sign introduced by the teacher were for the purpose of communicating the *vocabulary tokens* in Table I. In addition, three "meta-linguistic signs" were developed to reinforce player understanding: the teacher-introduced sign to `CONFIRM UNDERSTANDING` and the student-introduced signs for `DO I TOUCH THIS?` and `I'M CONFUSED`. Similarly, Teacher B introduced two signs for `TOUCH` and `BACKWARDS`, as well as three meta-linguistic signs `DONE TEACHING`, `YOU'RE MISSING THIS`, and `CONFIRM UNDERSTANDING`. Because the game periodically shows players their scores as reinforcement, it is not required that players develop meta-linguistic signs. The fact that both pairs organically developed these signs indicates the importance of social rewards or dense feedback for more efficiently learning to communicate.

As shown in Fig. 2, Pair A was shown 14 vocabulary tokens but only used 12 signs to achieve a perfect score.

They managed this by composing signs (see section III-C) and collapsing the task space. For example, both pairs merged `TOUCH` with `TOUCH GOING FORWARDS`, and the teacher taught `TOUCH GOING FORWARDS` by default.

Not all teacher-introduced signs were understood by the student; see the gap between the dark blue and purple lines in Fig. 2. Twenty-three percent of signs introduced by Teacher A and 80% of signs introduced by Teacher B were never understood by their students. This happened conceptually at two levels. First, oftentimes the student did not perceive teacher-introduced signs as meaningful, missing 54% of signs upon introduction in Pair A and 80% in Pair B. Second, in Pair A, the student correctly perceived two signs as meaningful, but revised their meanings multiple times over the game.

B. *Non-symbolic vs. Symbolic Signs*

We acknowledge there are many ways to differentiate between symbolic and non-symbolic signs. In our analysis, we define a *symbol* as a sign that is not purely iconic or indexical, otherwise the sign is *non-symbolic*.

Among the teacher-introduced signs, 9 were symbols and 5 were non-symbolic for Pair A, and 2 were symbols and 3 were non-symbolic for Pair B. For example, the teacher in Pair A introduced a sign for `NOT` by rotating the avatar 45^o repeatedly facing right. As these arbitrary movements have no inherent connection to the meaning of `NOT`, this sign is a symbol. In contrast, Pair B's mutually understood sign consisted of the teacher tapping a target object, which directly points to the referent. Such signs are non-arbitrary and non-symbolic.

In general, it took a longer time for students to perceive and understand symbols than non-symbolic signs. For Pair A, all non-symbolic signs were perceived by the student after 1.6 uses on average and understood immediately once perceived. The symbolic signs took the student one usage to perceive and 2.5 uses to understand on average. Three of the symbolic signs introduced were never perceived nor understood. For Pair B, the student perceived and understood one of the sub-symbols after three uses and none of the symbols.

We hypothesize that once perceived, symbols are harder to understand than non-symbolic signs. This may be due to the arbitrary mapping between form and meaning in symbols, which require time to hypothesize and confirm meaning. This arbitrary mapping also explains the three missed symbols by Student A. These symbols were extremely similar to either common car motions or to pre-existing, mutually-understood signs. As the space of mappings from meaning to form is so large for symbols, from the student's point of view, why would the teacher propose a symbol similar to pre-existing car motions over something more differentiable? With more data, we can explore the conditions and difficulties to segment intentional symbols from motions, which may inform us on how to create parsers for e.g. human body language.

C. *Compositionality*

Signs introduced by Teacher A exhibit linguistic compositionality. Most commonly, the teacher combined size and direction with pre-existing signs for `ALL` and `TRIANGLE`. For example, the sign for `ALL` consisted of drawing a circle. Then, in *While going backwards, touch all big objects*, the teacher drew a big circle moving backwards (see Fig. 3).

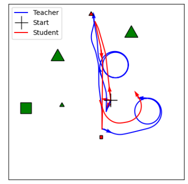
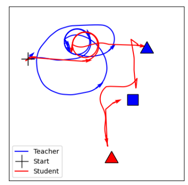
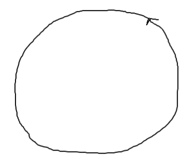
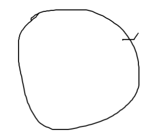
Teaching Map	Teacher Response	Student Response
		
Touch all objects that are red.	Circle movement anticlockwise to indicate ALL, used during the first task to indicate all possible objects.	I think the circle means touching all of these.
		
While going backwards, touch all objects that are big.	It is a BIG circle (indicating ALL), while executing the movement going BACKWARDS.	The teacher moves in a circle backwards to show I should move backwards while touching objects. I guess the big circle means big objects too.

Fig. 3: Several teaching map traces and corresponding signs registered by Pair A, where each row is (left to right) a teaching map, a sign registered by the teacher immediately thereafter, and the corresponding sign registered by the student.

When introduced, compositional signs consisted of one pre-existing, mutually understood sign whose form is modified by one or two new concepts. Compositional signs never combined only pre-existing signs, nor only new concepts. When concepts were previously mutually understood as stand-alone forms, such as `SMALL` (a very small circle) and `ALL`, the teacher did not modify them to be compositional when presented with the opportunity. Instead, they persisted as independent forms throughout the game. In addition, the choice of concepts to make compositional was influenced by the form of pre-existing signs. When it was difficult to compose two pre-existing sign forms, the teacher drew these two forms separately, for example, in the case of `ALL` and `TRIANGLE`. These two phenomena suggest an inertia in sign morphology even when opportunities to simplify the language present themselves. We believe that this is due to a tension at production time that tries to balance the potential utility of introducing new symbols with the potential disruption in communication.

D. *Evaluating Communication*

Although Pair A achieved a perfect score on all tasks, the student's reflection forms show that their sign set could only convey a subset of the task space corresponding to 10 out of 14 vocabulary tokens seen, with the student guessing the task correctly 60% of the time. However, even though the mapping from the players' final sign set to the task space is not surjective, the players' sign set was sufficient to succeed at the game. Moreover, the raw score and number of attempts per task are robust to teaching map distribution and task level, indicating that their sign set can generalize to harder tasks.

In contrast, with one non-symbolic sign for `TOUCH`, Pair B's language conveys propositional logic at best and fails to generalize in ambiguous situations. Indeed, Pair B's performance is not robust to ambiguous teaching maps. Their weighted score was 1.83 for base teaching maps and 1.75 for inconvenient teaching maps, compared to 0.70 for ambiguous predicate teaching maps and 0.00 for ambiguous quantifier teaching maps. As the task level increases, the number of attempts decreases while the raw score remains constant. The large proportion (77%) of incorrect student guesses together with teacher testimony indicate that this is due to the student coincidentally satisfying tasks with large solution sets. The poor generalization of Pair B's sign set compared to Pair A suggests that developing a diverse sign set is essential to succeed at the game.

IV. CONCLUSION & FUTURE WORK

Our pilot study demonstrates the emergence of symbols through spatial movements. Preliminary results suggest that a robust set of non-symbolic and symbolic signs lets players generalize to difficult tasks and ambiguous environments. Experimenting with more teacher-student pairs, we could more confidently comment on which factors, such as lexicon size or number of symbols, correlate with better performance and communication. As future teacher-student pairs will likely be recruited from outside the lab, we will financially compensate all future participants.

We are actively working on several extensions to the experiment. (1) Expanding the task space by introducing different types of predicates and logical forms such as temporal relationships. (2) Expanding the map space by imposing different physical constraints on players; for example, the target shapes on a teaching map cannot be physically reached by the teacher. (3) Investigating population dynamics by re-pairing participants.

Finally, many forms of human communication are non-verbal including body movements and negotiating for the right of way. To better understand how robots communicate with humans non-verbally, we can train artificial agents to develop symbols by interacting with humans. Indeed, studies bridging human and machine emergent communication demonstrate that social grounding of language through teacher-student imitation helps both humans and robotic agents learn word-concept mappings more quickly [8]. We are investigating training models in a multi-agent setting to determine which feature representations and reward functions can enable agents to acquire this knowledge. This way, we can compare human and robot performance in symbol production and segmentation, asking questions such as: to what extent can robots perceive human gestures as intentional and symbolic? Can robots similarly produce behavior that humans interpret as meaningful and symbolic? Perhaps by understanding human symbolic communication, we are one step closer to building robots that are able to communicate meaningfully with humans.

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