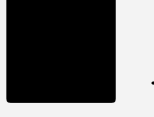



Bridging robot and human communication

Understanding human communication helps us train robots that engage with humans. Human communication is a mix of non-symbolic and **symbolic communication**.

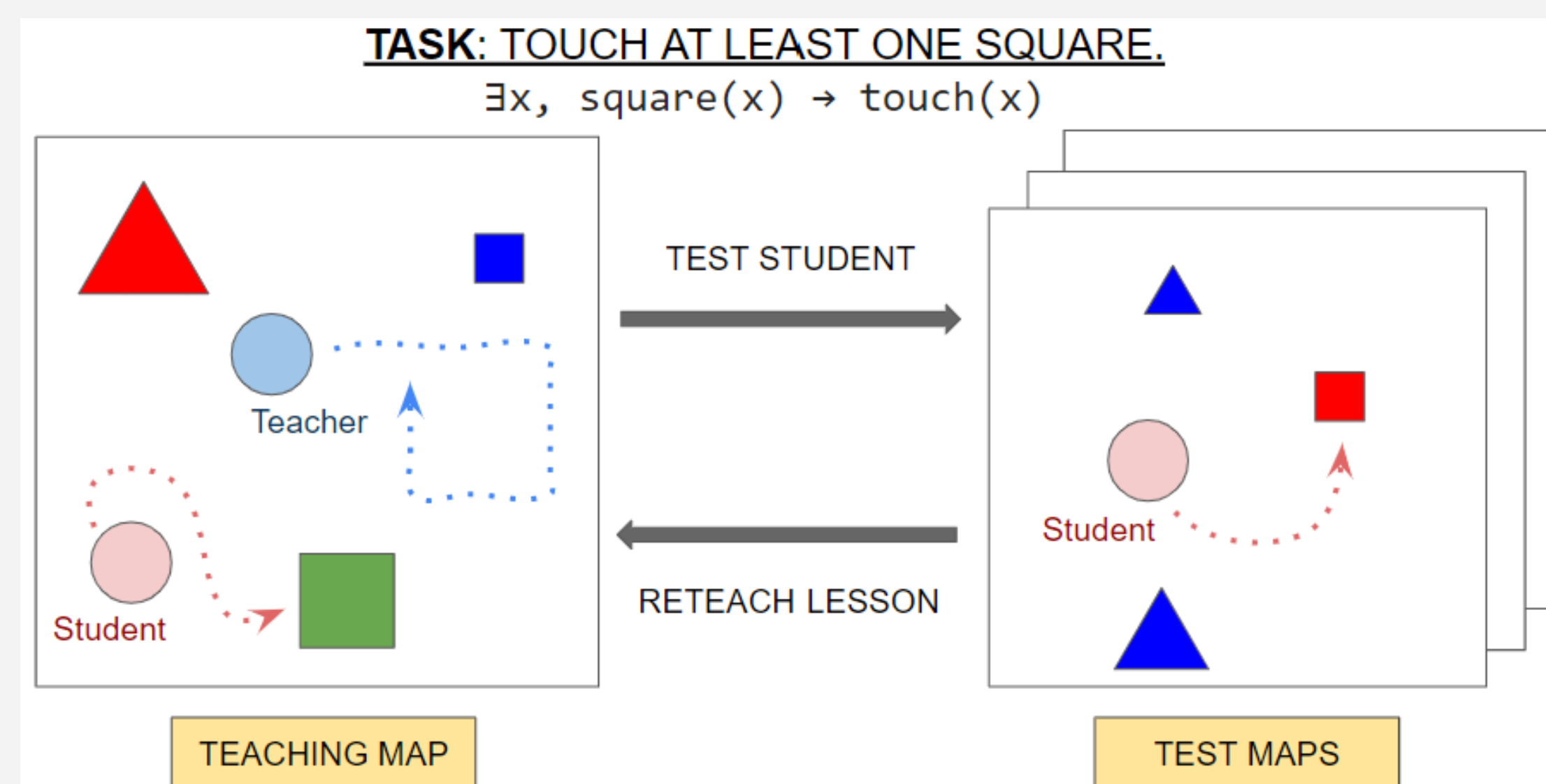
Type of Sign (Form, Meaning)	Non-symbolic Non-arbitrary	Symbolic Arbitrary
Example	 \rightarrow <i>square</i>	 \rightarrow <i>stop</i>

We need a method to study how humans develop and use symbolic systems:

- What processes and conditions give rise to symbols?
- What do symbols enable in communication?

Embodied two-player communication game

Cooperative game where a **teacher** teaches tasks to a **student** using only spatial movements. Remove familiar modes of symbolic communication to witness symbols re-develop.



The game works as follows:

- In the teaching map, the **teacher** teaches a task to the **student** using spatial movements.
- The **student** performs the task in three test maps while the **teacher** watches. The **teacher** can choose to reteach the lesson at any point during testing.
- Players fill out reflection forms after each task, where they draw and describe actions they used for communication. The **student** submits a guess of the task.

Tasks and maps

Tasks are specified using first order logic (FOL) .

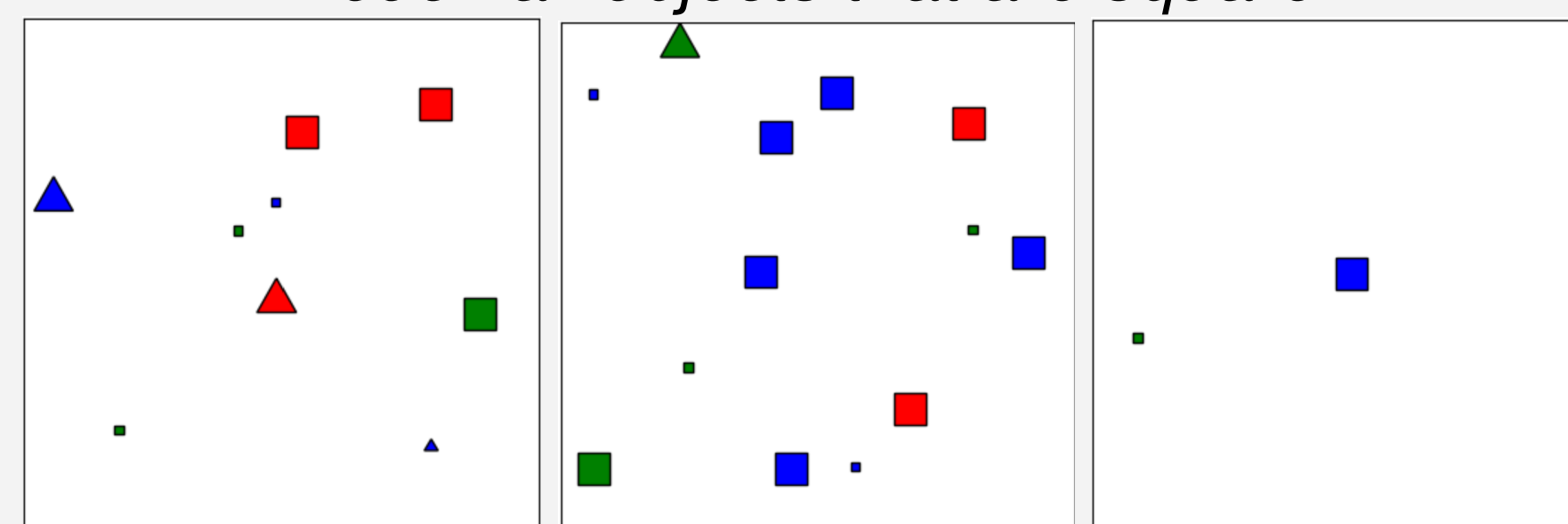
Predicates	Color: red, blue Shape: square, triangle Size: big, small
Actions	touch, touch going forwards, touch going backwards, avoid
Quantifiers	all (\forall), at least one (\exists)
Logical Connectives	and (\wedge), or (\vee), not (\neg)

Example tasks:

- (Easier) *Touch all objects that are red.*
- (Harder) *Touch at least one object that is not [red and square], and avoid all objects that are triangular.*

We generate teaching and test maps for each task. We include maps that are hard to teach by demonstration (**inconvenient** and **ambiguous** maps), but easy to teach using symbols.

Example game maps:
Touch all objects that are square



Pilot experiments

Two pairs (four volunteers) were recruited for the pilot study.

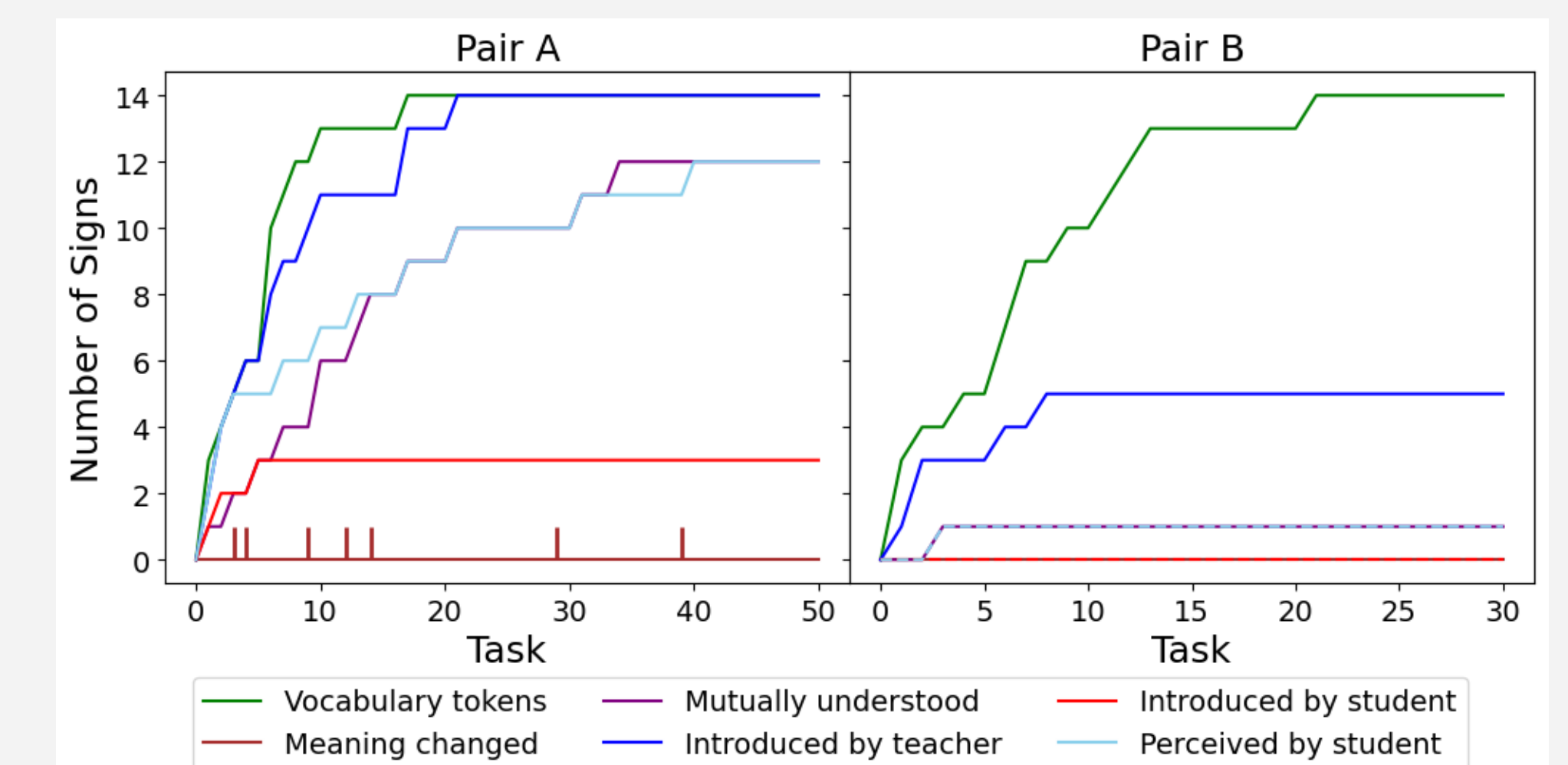
	Pair A	Pair B
# Tasks	50	30
Time	10h	3h
Raw Score	150/150	70/90
Weighted Score*	0.82	0.55
# Reteaches	1.4 ± 0.8	3.0 ± 4.4
# Signs	12	1
# Symbols	6	0
% Correct Task Guesses	60%	23%

* Weighted Score = Raw Score / # Reteaches

Pair A generalized better than Pair B. For Pair A, weighted score and number of reteaches were robust across harder tasks and inconvenient and ambiguous teaching maps, but not for Pair B.

Results: Emergence and development of signs

Sign sets converge over the sequence of tasks.






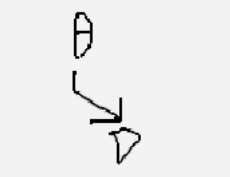
The total vocabulary size is 15. The mapping from sign sets to vocabulary tokens is not one-to-one:

- Student misses teacher signs
- Teacher A introduces compositional signs

Results: Symbolic vs. non-symbolic signs

It was harder to perceive and understand symbols than non-symbols. Symbols allow generalization to harder tasks and ambiguous environments.

Example signs:

Symbolic: ALL		Non-symbolic: TOUCH THIS	
			
Teacher A	Student A	Teacher B	Student B

Observations and next steps

We are expanding the study to more pairs and designing RL agents to play the game. With the human study, we would like to verify preliminary observations:

- Hard to develop mutually-understood symbols compared to non-symbols.
- Symbolic communication permits generalization.
- Linguistic structure such as compositionality develops early on in the task sequence.