Theory of Mind and Movement Synchrony

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Abstract
We investigate relations between theory of mind (ToM) and movement synchrony observed during parent-child interaction. In our experiment children and parents engage in a simple cooperative game, and their performance is recorded on video. General movement statistics are extracted from the recordings. Our results show that scores obtained by children in standard first-order ToM tasks are related to specific patterns of movement coordination. Such relation is not observed with second-order ToM tasks.

Introduction

Theory of mind (ToM) is usually defined as understanding of other people's thoughts and beliefs. Most often it is studied in the context of children social development. It is also of potential interest to the field of developmental robotics when we consider robots operating in social environment.

There are numerous controversies regarding ToM:

- Is ToM an embodied ability or is it purely representational?
- Pragmatic context for ToM are social interactions yet it is usually measured through abstract tasks devoid of interaction.
- How much and how complex ToM do we really need in everyday interactions?

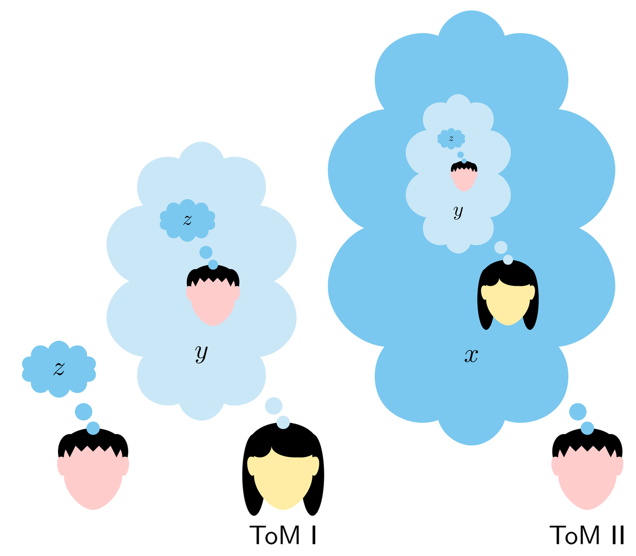

Figure 1: First-order and second-order theory of mind.

Research questions

1. Can movement synchrony in a cooperative game predict child's results in classic (representational) ToM tasks?
2. Does it provide additional information when executive functions are controlled for?
3. Are first-order ToM and second-order ToM different in this regard?

Experimental tasks

Coordination task: Cooperative game with a wooden labyrinth.

ToM I tasks: Diverse Beliefs task, Belief Emotion task, Contents False Belief task, Knowledge Access task, Unexpected Transfer task.

ToM II tasks: Ice Cream Seller task, Gift task.

Executive functions tasks: Children Card Sort task (**cognitive flexibility**), Simon task (**inhibitory control**), Children's Gambling task (**"hot" executive functions**), digit repetition task (**working memory**).

ToM I was measured when children were 42 months old, other tasks when children were 66 months old.

Figure 2: Mother and child playing the labyrinth game.

Quantifying movement synchrony

Step 1: Frame-difference method for extracting movement from video.

Movement may be roughly quantified by calculating number of pictures changing color between consecutive video frames. We split the video into different regions to obtain separate time series representing movement of parent and child.

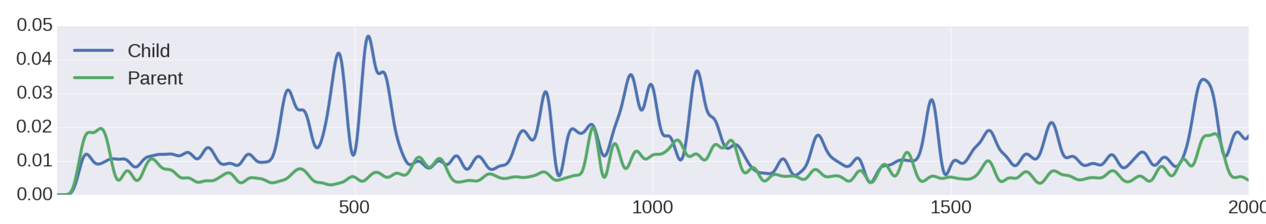

Figure 3: Time series representing overall amount of movement of both agents obtained through frame-difference method.

Step 2: Cross-recurrence quantification analysis (cRQA)

cRQA is a powerful framework for analyzing time series based on the idea of co-visitation of states in phase space. Popular recurrence measures are **recurrence rate (RR)**, which is an equivalent of correlation coefficient, and **determinism (DET)**, which measures how much the series synchronize consistently over longer chunks of time. Through shifting original time series we can obtain time-lagged profiles of both measures. The analysis is done over sliding window and profiles for maximal and average values of each measure are calculated.

Step 3: Non-linear feature aggregation

1. We extract features representing value of the central peak and the level of asymmetry between left and right side of the plot from each diagonal profile.
2. Random forest model is used to select important features and predict child ToM level based on them. Cross-validation scheme yields unbiased predictions.
3. Model predictions are used as **"movement synchrony"** aggregate.
4. Features are aggregated separately for ToM I and ToM II.

Results

Relations with ToM I

Sample size: N=110

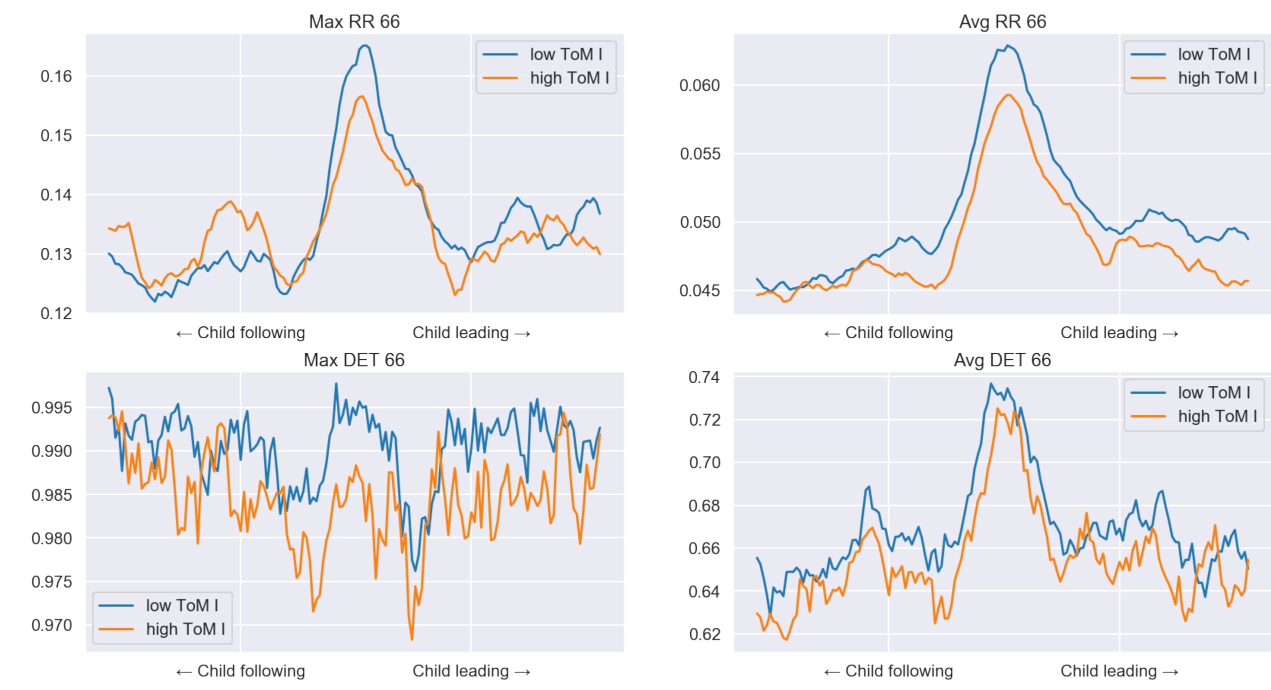

Figure 4: Time-lagged profiles for recurrence rate and determinism. ToM I scores were split evenly into low-high groups.

	coef	std err	t	P>|t|	[0.025	0.975]
Intercept	-0.1177	0.086	-1.364	0.175	-0.289	0.053
Movement synchrony ***	0.2962	0.083	3.581	0.001	0.132	0.460
Cognitive flexibility	0.1471	0.082	1.791	0.076	-0.016	0.310
"Hot" executive functions	-0.0702	0.089	-0.785	0.434	-0.247	0.107
Working memory **	0.2985	0.099	3.018	0.003	0.102	0.495
Inhibitory control *	-0.2105	0.095	-2.218	0.029	-0.399	-0.022

Relations with ToM II

Sample size: N=108

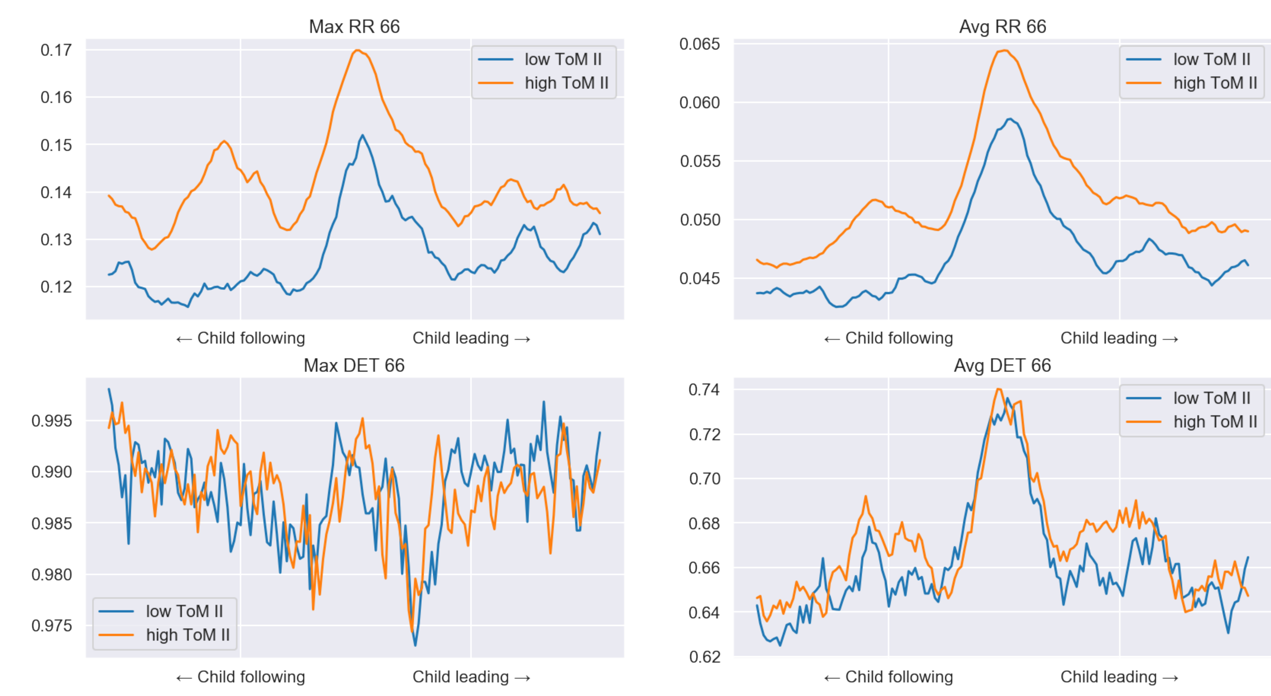

Figure 5: Time-lagged profiles for recurrence rate and determinism. ToM II scores were split evenly into low-high groups.

	coef	std err	t	P>|t|	[0.025	0.975]
Intercept	0.0626	0.100	0.629	0.531	-0.135	0.260
ToM I *	0.2700	0.104	2.586	0.011	0.063	0.477
Movement synchrony	0.0247	0.202	0.122	0.903	-0.376	0.426
Cognitive flexibility	0.0093	0.093	0.100	0.921	-0.175	0.193
"Hot" executive functions	0.1038	0.104	1.001	0.319	-0.102	0.310
Working memory *	0.2909	0.118	2.467	0.015	0.057	0.525
Inhibitory control	0.1018	0.109	0.936	0.352	-0.114	0.318

Conclusions

- We revealed non-trivial relation between movement synchrony and first-order ToM. Similar association was not observed for second-order ToM.
- Discovered relation suggests that first-order ToM is linked to embodied interaction taking place here-and-now. Precise form of this relation requires further studies.
- It is possible to quantify some aspects of social skills just by analyzing natural interactions.
- Social cognition skills are also important for future robots to interact with people in natural way. Functional equivalent of ToM may be helpful in regulating such interactions.
- Theories of how social skills may be acquired in bottom-up way during interactions may be further developed and tested.

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