Coordination Dynamics meets Active Inference and Artificial Intelligence (CD + AI^2): A multi-pronged approach to understanding the dynamics of brain and the emergence of conscious agency.

Center for Complex Systems and Brain Sciences
FLORIDA ATLANTIC UNIVERSITY

wellcome centre human neuroimaging

A.T. Sloan, N.A. Jones, N. Boiten, K.J. Friston,
M. Khodadadzadeh, D. Coyle,
K. Guidibanda, V.K. Jirsa, J.A.S. Kelso

UNIVERSITY OF BATH

INSTITUT DE NEUROSCIENCES DES SYSTÈMES

Ulster University

How do humans discover their ability to act on the world?

By tethering a baby's foot to a mobile (Fig. 1) and measuring the motion of both in 3D, we explore how babies begin to make sense of their coordinative relationship with the world and realize their ability to make things happen (*N*= 16; mean age = 100.33 days).
Using **dynamics as a guide**[1,2], we have developed tools to identify the moment an infant switches from spontaneous to intentional action (Fig. 2).

CD Analysis: 'Aha!' detector

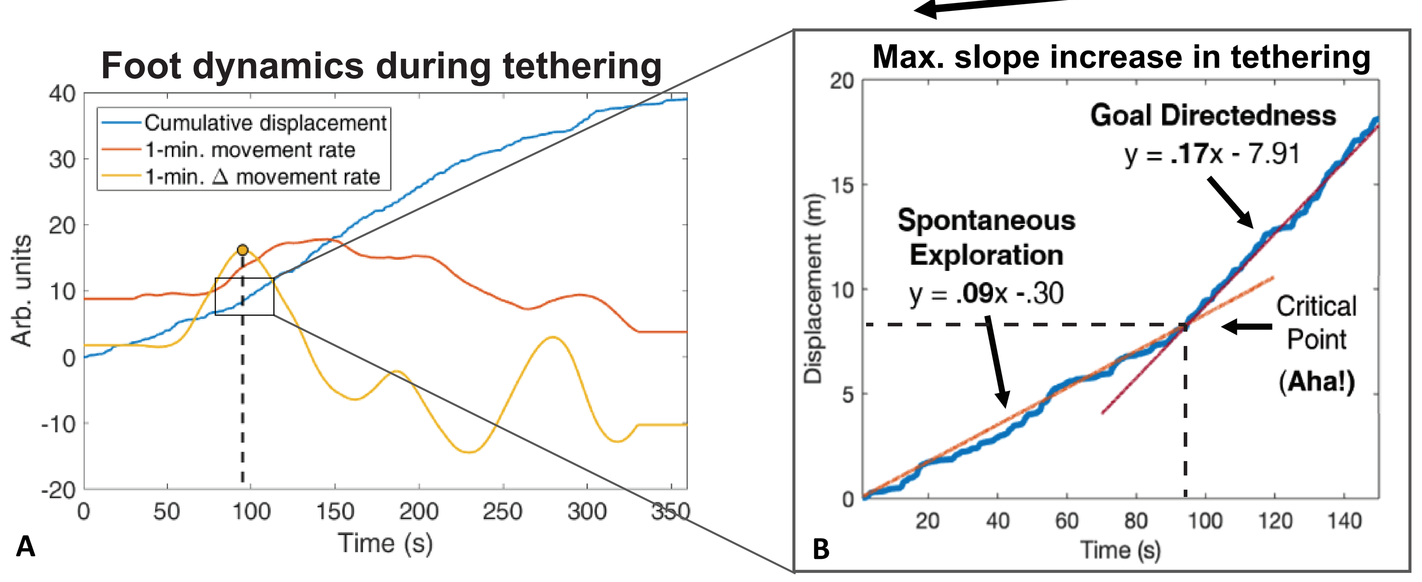


Fig. 2 Aha detector. (***A***) Tethered foot displacement (blue), movement rate (red), and change (Δ) in movement rate (yellow) for infant 104 (measures scaled to fit). To detect a moment of agentive discovery, we identified the peak Δ in movement rate (yellow dot). (***B***) A blow-up of (***A***) shows trigger foot cumulative displacement (blue) for infant 104 linearly modeled in the minute preceding and following peak Δ movement rate identified in (***A***) reveals a critical transition point at ~95 s. Slope of displacement nearly doubles as infant shifts from spontaneous exploration to goal-directed action, now purposefully triggering mobile movement[3].

A Scientific Window

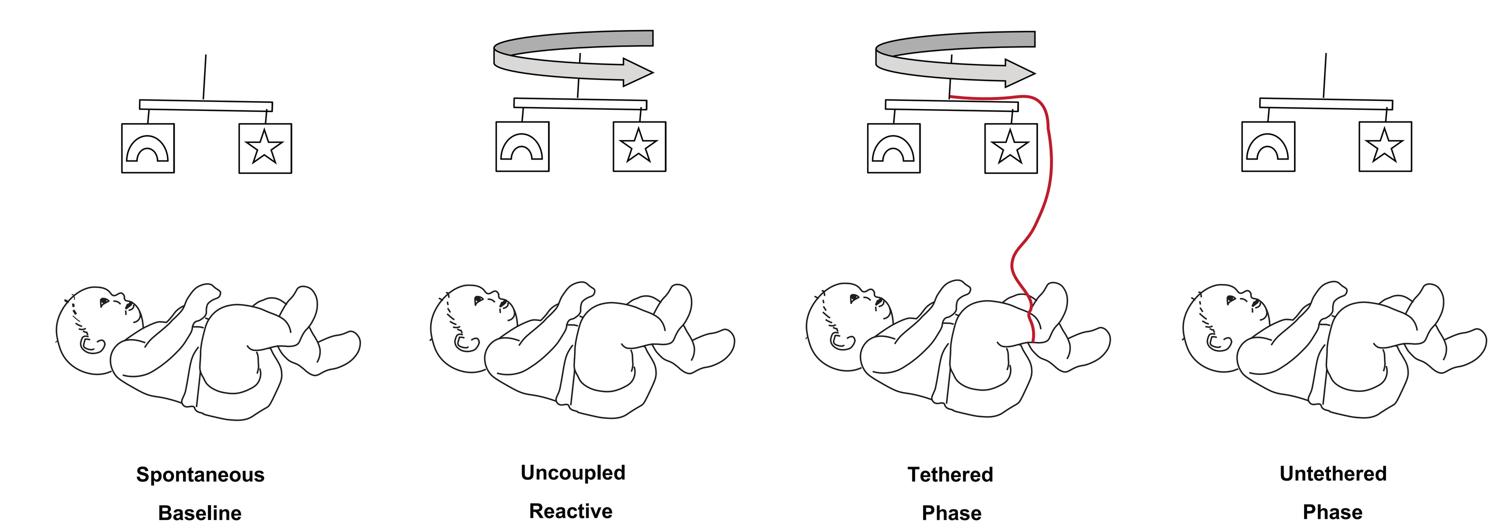


Fig. 1 Experimental Paradigm includes four experimental phases: 1) **Spontaneous baseline** with stationary mobile. In the absence of stimulus motion, infant activity is spontaneously generated; 2) **Uncoupled reactive phase** in which the experimenter triggers mobile motion to measure the infant's reaction to raw stimulation from a moving mobile; 3) **Tethered phase** - movements of the trigger foot (connected to a sensor by two ribbons) are translated into mobile rotation rate; and 4) **Untethered phase** - ribbons are detached, and the mobile is again stationary, as in the baseline phase When one of their feet is tethered to a mobile hanging above, infants may discover that they can make the mobile move. Can we catch this moment and uncover mechanisms underlying emergence of agency?

Active Inference Modeling

Preliminary **Coordination Dynamics (CD)** analysis and **Active Inference (AI)** generative modeling[4] indicate that moments of stillness hold important epistemic value for young infants discovering their ability to change the world around them (Fig. 3).

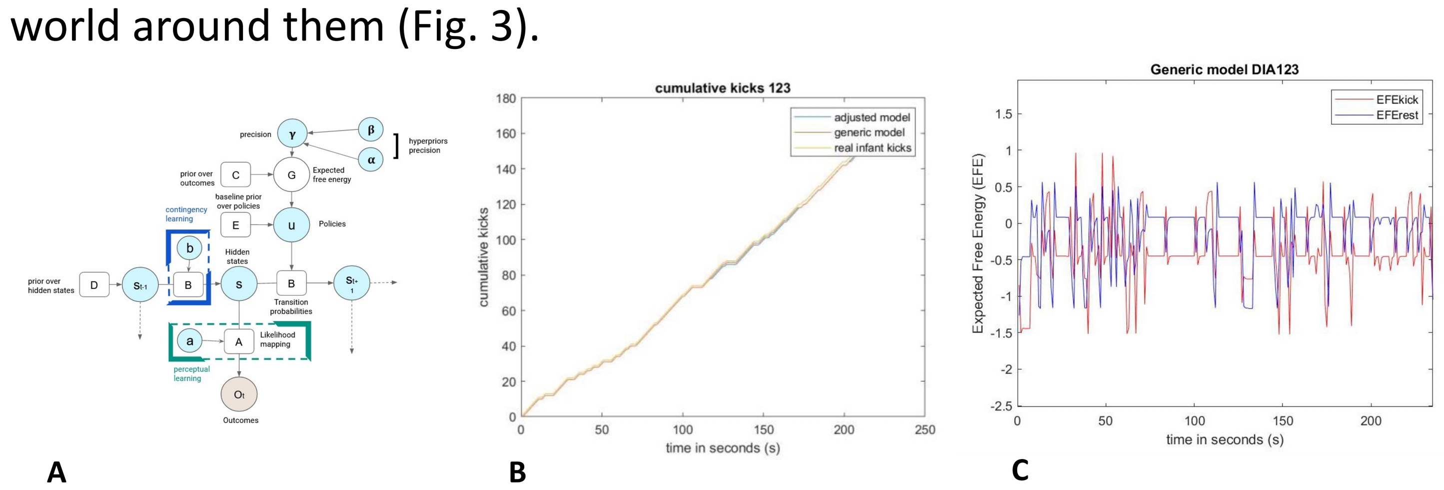


Fig. 3 Active inference modeling. (***A***) A Bayesian network representation of state estimation and policy selection for the active inference agent in the baby~mobile paradigm. To explore the cognitive mechanisms underlying infants' developing agency, we built an active inference model of kicking behavior during the baby~mobile paradigm, which incorporates two primitive aspects of agency: **perceptual learning** - associations between perceptions of self-movement and mobile-movement & **contingency learning** - associations between self actions and mobile movement. Inclusion of perceptual learning and contingency learning results in actions guided by the resolution of epistemic uncertainty about sensorimotor associations and control. (***B***) Tethered phase behavior was simulated after training the model using empiric observations from infant and mobile during baseline phases. Sample simulation results for Infant 123 show that this model can predict real infant actions in a one-step prediction task, <u>without assuming explicit rewards</u>. (***C***) In active inference, both exploratory (information seeking) and exploitative (reward-seeking) behaviors are explained in terms of expected free energy (**EFE**) minimization. EFE values track reward maximization and uncertainty reduction for a given action. <u>The lower the EFE value for an action, the higher the epistemic value of that action</u>. Whenever resting is preferable for the infant the EFE for the resting action (blue) drops below the EFE for the kicking action (red). EFE for both kick and rest actions of Infant 123 regularly reach minimal values, indicating the informational value of both movement and inactivity.

Artificial Intelligence Analysis

Artificial Intelligence (AI) classification architectures indicate that functionally connecting infants to a mobile via a tether influences the baby movement most where it matters, namely at the point of infant~world connection[5] (Table 1).

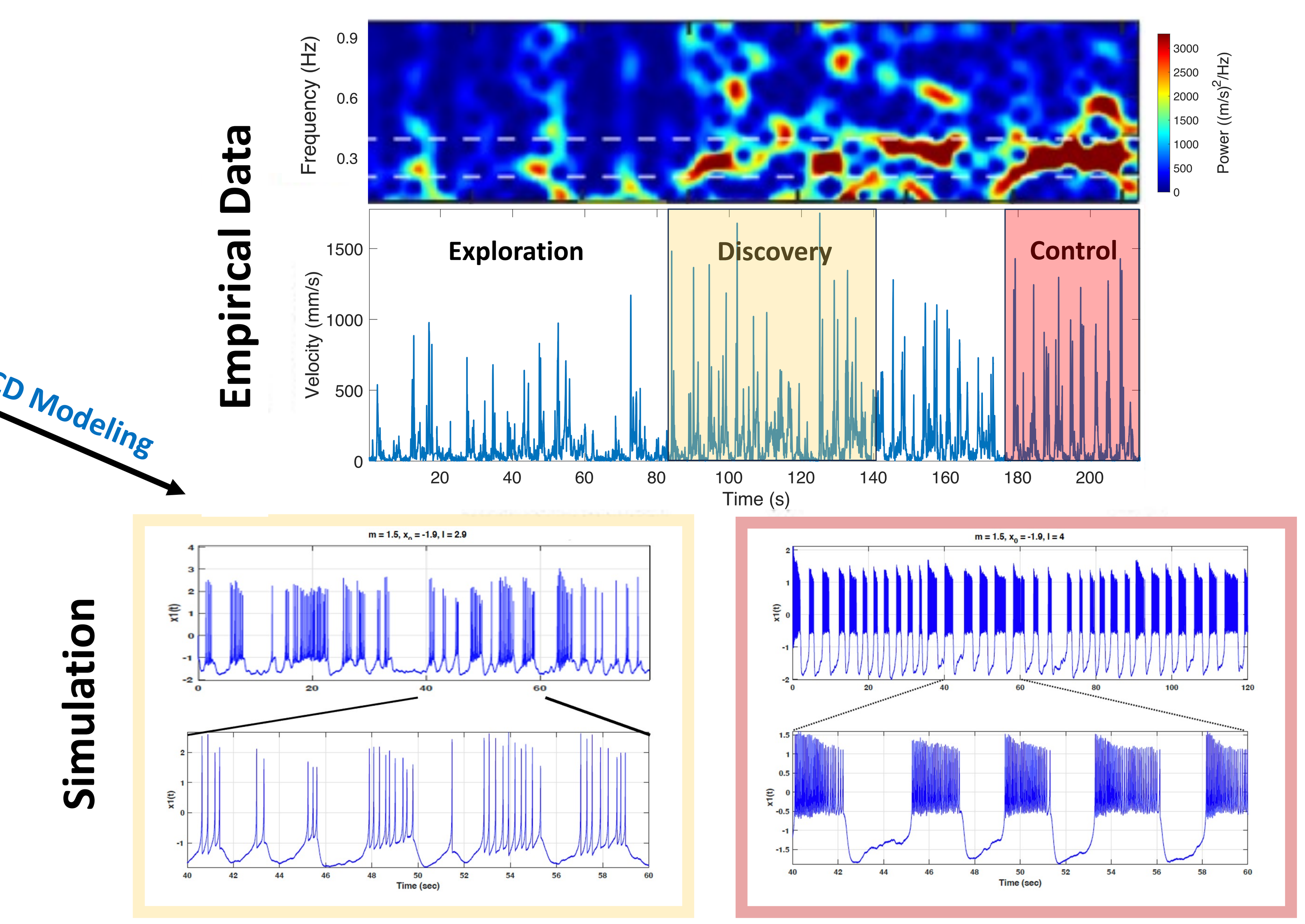
Table 1. Performance of all models: Average sliding window accuracy (%)

Joint-Type	Classification Accuracy							
	LDA	Knn	FCNet	1D-Conv	1D-CapsNet	2D-Conv	2D-CapsNet	MEAN Joint-Type accuracy
Left hand	**59.63%**	55.89%	50.15%	55.57%	55.12%	-	-	55.27%
Right hand	51.15%	**58.00%**	51.26%	57.84%	50.32%	-	-	53.72%
Hands	52.63%	54.89%	55.25%	59.19%	56.55%	**59.57%**	50.65%	55.53%
Left foot	**75.63%**	64.84%	71.63%	70.10%	60.89%	-	-	68.61%
Right foot	71.31%	62.68%	**77.78%**	61.21%	68.24%	-	-	68.24%
Feet	70.63%	63.34%	73.62%	78.15%	81.15%	65.65%	**86.25%**	74.11%
Left knee	39.05%	**61.63%**	53.05%	58.78%	58.25%	-	-	54.15%
Right knee	50.10%	**59.42%**	51.55%	59.26%	57.14%	-	-	55.49%
Knees	50.55%	33.60%	51.23%	59.78%	**61.22%**	59.66%	60.19%	53.75%
Full-body	39.63%	50.89%	57.88%	56.52%	60.60%	56.12%	**65.51%**	55.31%
MEAN Classifier accuracy	56.03%	56.52%	59.34%	61.64%	60.95%	60.25%	65.65%	-

* For each **joint-type**, the model with greatest classification accuracy is in **bold**.
** For each model, the joint-type with greatest classification accuracy is in red.

A model of slow~fast brain coordination dynamics based on a 3D extension of the Jirsa-Kelso Excitator[6] successfully simulated the evolution of tethered foot activity as infants transition from spontaneous to ordered action. By tuning a small number of parameters, this model captures patterns of emergent goal-directed action (Fig. 4).

CD Modeling



Discovery within Tethered interaction is characterized by **intermittent bursting**

Enhanced **Control** after discovery is characterized by **regular bursting @ ~0.3Hz**

Conclusion: Meshing concepts, methods and tools of **A**ctive **I**nference, **A**rtificial **I**ntelligence and **C**oordination **D**ynamics at multiple levels of description, the **CD + AI^2** program of research aims to identify key control parameters that shift the infant system from spontaneous to intentional behavior. This potent combination of mathematical modeling and quantitative analysis along with empirical study will allow us to <u>express the emergence of agency in quantifiable, lawful terms</u>.

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Scan me to watch a baby in action!