

SPILL-AI – AI-driven causal inference of behavioral spillovers in epidemic systems

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Context and rationale

Epidemic control policies are typically evaluated under the assumption that populations respond primarily after interventions are implemented. Yet empirical evidence from COVID-19 and other crises shows that individuals adapt behavior before, beyond, and sometimes independently of formal policies. These endogenous adaptations—triggered by perceived risk, social influence, media exposure, and spatial proximity to outbreaks—can propagate across territories through mobility and communication networks. Such dynamics constitute behavioral spillovers: interventions or epidemic signals in one area inducing behavioral change in connected regions. They are grounded in mechanisms of risk perception, social norm diffusion, and collective adaptation extensively studied in the social sciences.

Despite their importance, spillovers remain poorly quantified and are often confounded with policy effects in standard evaluation frameworks. This limits our ability to accurately estimate intervention impact and to design coordinated public health responses.

Understanding these processes requires a new paradigm: treating collective behavior as a dynamic, latent, networked system interacting with epidemic spread. Focusing on the COVID-19 pandemic in France, the project positions behavioral spillovers at the intersection of artificial intelligence, epidemiology, and social sciences. It aims to develop AI-driven methods capable of inferring endogenous adaptation processes and their propagation across spatial and social networks.

Objectives

SPILL-AI pursues two interrelated objectives:

Objective 1 – Causal identification of endogenous behavioral adaptation. Develop causal inference frameworks to distinguish policy-induced mobility changes from spontaneous behavioral responses driven by epidemic signals.

Objective 2 – AI-based modeling of latent behavioral dynamics and spatial spillovers. Design interpretable machine learning and graph-based models to infer hidden collective adaptation regimes and quantify how behavioral changes propagate across territorial networks.

Together, these objectives reframe epidemic systems as coupled transmission–behavior processes, where adaptation is endogenous and predictive.

Description of work

SPILL-AI combines causal inference, statistical and mathematical modeling with machine learning and network-based AI methods to investigate endogenous behavioral adaptation and spatial spillovers in epidemic contexts. By integrating digital mobility data with epidemiological indicators and social science theory, the project aims to develop interpretable AI frameworks capable of identifying, quantifying, and predicting collective behavioral responses beyond formal policy interventions.

Data. SPILL-AI will use:

- Daily COVID-19 indicators at the departmental level (new cases, hospitalizations, ICU admissions) from SI-DEP and SIVIC datasets.
- High-resolution mobility data derived from anonymized mobile phone origin-destination matrices through a partnership with Orange Flux Vision, capturing inbound, outbound, and internal flows across French departments from March 2020 to July 2021.
- Contextual variables including intervention timing, meteorological conditions, and territorial characteristics.

These datasets allow reconstruction of time-varying spatial interaction networks and epidemic trajectories under asynchronous intervention regimes.

Ethics Statement. The mobile phone data are previously anonymised by the company in compliance with strict privacy requirements, presented to and audited by the French data protection authority (Commission Nationale de l'Informatique et des Libertés). All analyses will be conducted on aggregated data, ensuring no individual re-identification.

Task 1: Causal inference of endogenous behavioral adaptation. The first task will develop causal inference strategies to disentangle policy-induced mobility changes from spontaneous collective adaptation. Using staggered intervention designs, counterfactual modeling, difference-in-differences frameworks, and Inverse Reinforcement Learning¹ the project will estimate the magnitude and timing of anticipatory behavioral responses across territories.

Task 2: AI-based modeling of spatial behavioral spillovers. The second task will model how behavioral adaptation propagates across territorial networks. Time-varying mobility networks will be reconstructed from origin-destination matrices, with nodes representing territories and edges capturing spatial connectivity. Spatio-temporal Graph Neural Networks² and network autoregressive models will be developed to quantify spillover effects, identifying whether adaptation in one region induces anticipatory responses in connected areas. The objective is to measure the spatial reach, temporal lag, and amplification of behavioral spillovers, and to assess how these dynamics interact with epidemic growth.

Interdisciplinary framework and partnerships. The PhD will be supervised within a genuinely interdisciplinary framework integrating mathematical and statistical modeling, artificial intelligence, and social sciences:

- **Vittoria Colizza** (INSERM, Sorbonne Université): PhD supervisor; expertise in mathematical modeling, of infectious diseases spatial transmission, and mobility data analysis.
- **Giulia De Masi** (Sorbonne Université Abu Dhabi, SCAI member): PhD co-supervisor; expertise in network science, complex systems, and graph-based machine learning.
- **Jocelyn Raude** (EHESP): PhD co-supervisor; expertise in risk perception, social norms, and behavioral adaptation, providing theoretical grounding in SHS.
- **Pierre-Yves Boëlle** (Sorbonne Université, SCAI member): collaborator; expertise in statistical inference and epidemic modeling.

This supervisory and collaborative structure integrates AI, epidemiology, and SHS expertise, ensuring genuine interdisciplinary co-encadrement aligned with SCAI mission.

Positioning within SCAI. The project aligns with SCAI objective of fostering interdisciplinary AI research in the social sciences. By combining graph learning, causal inference, and social theory, it addresses a core challenge in AI for society: modeling adaptive collective behavior in complex systems. The proposed co-supervision structure ensures methodological innovation in AI while maintaining strong theoretical grounding in SHS.

Impact and contribution to SCAI. SPILL-AI advances AI research at the interface with social sciences and health by developing interpretable models of collective behavioral adaptation. It contributes to SCAI mission by: (i) designing graph-based and causal learning frameworks to model endogenous social dynamics; (ii) integrating theories of risk perception and norm diffusion into machine learning architectures; (iii) developing AI tools that disentangle policy effects from spontaneous behaviors. The methodological framework is transferable to other domains involving collective behavior, strengthening SCAI leadership in AI research on adaptive social systems.

References

1. Song, Y., et al. A state-based inverse reinforcement learning approach to model activity-travel choices behavior with reward function recovery. *Transp. Res. Part C Emerg. Technol.* **158**, 104454 (2024).
2. Gao, J. et al. STAN: spatio-temporal attention network for pandemic prediction using real-world evidence. *J. Am. Med. Inform. Assoc.* **28**, 733–743 (2021).