Perceiving the arrow of time in autoregressive motion

Processing causal information is a crucial ingredient for intelligent behavior. Here we show that human observers can discriminate forward and backward autoregressive motion with non-Gaussian independent additive noise similar to recent causal inference algorithms. Our powerful frozen noise approach shows that the neural network, Bayesian ideal observer, dependency algorithm and humans use all different cues.

Causal Inference within the Additive Noise Framework

\[ x_t = \alpha \cdot x_{t-1} + \epsilon_t, \quad \epsilon_t \not\sim \mathcal{N}, \quad x_{t-1} \perp \perp \epsilon_t \]

- The direction of a time series is identifiable for a linear non-Gaussian time series (Peters, 2009)
- The future cannot influence the past, see Figure 1
- Successful for synthetic data and real data (Pickup, 2014)

Experimental Paradigm
- Are humans able to perceive the arrow of time?
- Observers classify dot movement into forward and reversed time series

\[ x_t = 0.05 \cdot x_{t-1} + 0.1 \cdot x_{t-2} + 0.2 \cdot x_{t-3} + 0.4 \cdot x_{t-4} + \epsilon_t \]

\[ \epsilon_t \sim \text{sgn}(Y) \cdot |Y|^r, \quad Y \sim \mathcal{N} \]

- Experiment 1: 10 observers, 15 noise distributions (7 bimodal, 1 Gaussian, 7 super-Gaussian), 40 trials per noise distribution, 6400 trials in total
- Experiment 2: Frozen noise paradigm; bimodal noise distribution but shorter time series of variable length, 4 observers, 400 trials in total

Data Analysis

- Compare human performance to 4 algorithms:
  - Ecological valid heuristic
  - Residual dependence based, Figure 1 (Peters, 2009)
  - Neurally inspired network, Figure 2 (Gerrits, 2011)
  - Bayesian ideal observer (Geisler, 2001): \[ \frac{1}{\mathbb{P}(x_t | x_{t-1})} \]

Results Experiment 1
- Humans are able to discriminate forward and backward motion
- Humans show similar performance to the dependence algorithm and the heuristic
- Bayesian ideal observer and neural network have similar performance
- Do they use similar strategies?

Results Experiment 2
- Humans use similar strategies but have superior performance compared to the Residual dependence algorithm
- Humans might use the ecological valid heuristic
- Neurally inspired network and Bayesian ideal observer also use different strategies

Our results suggest that all human observers use similar cues to solve the arrow of time motion discrimination task, they appear sensitive to subtle asymmetries of noise distributions. The human algorithm is unique and significantly different from the three machine algorithms we compared it to. However they might use a strategy very similar to our simple heuristic. Additionally, we can show that the neural network also does not “learn” a full Bayesian representation.