Perceiving the arrow of time in autoregressive motion

Kristof Meding, Dominik Janzing, Bernhard Schölkopf*, Felix A. Wichmann*
* joint senior authors

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 observers, dependency algorithm and humans all use different strategies.

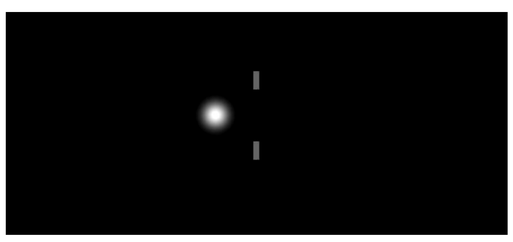
Causal Inference within the Additive Noise Framework

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

- The direction of a time series is identifiable for a linear non-gaussian time series (Peters et al., 2009)
- The future cannot influence the past, see Figure 1
- Residual dependence algorithm is successful for synthetic data and real

Experimental Paradigm

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



$$x_t = 0.05 \cdot x_{t-4} + 0.1 \cdot x_{t-3} + 0.2 \cdot x_{t-2} + 0.4 \cdot x_{t-1} + \epsilon_t$$
$$\epsilon_t \sim sgn(Y) \cdot |Y|^r, \quad Y \sim \mathcal{N}$$

- Experiment 1: 10 observers, 15 noise distributions (7 bimodal, 1 gaussian, 7 supergaussian), 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, 1600 trials in total

Data Analysis

Compare human performance to four algorithms:

- Ecological valid heuristic
- Residual dependence based, Figure 1 (Peters et al., 2009)
- Neurally inspired network, Figure 2 (Gorris et al., 2014)
- Bayesian ideal observer (Geisler, 2003): $\frac{p(x_t|x_{t-1})}{p(x_t|x_{t+1})}$

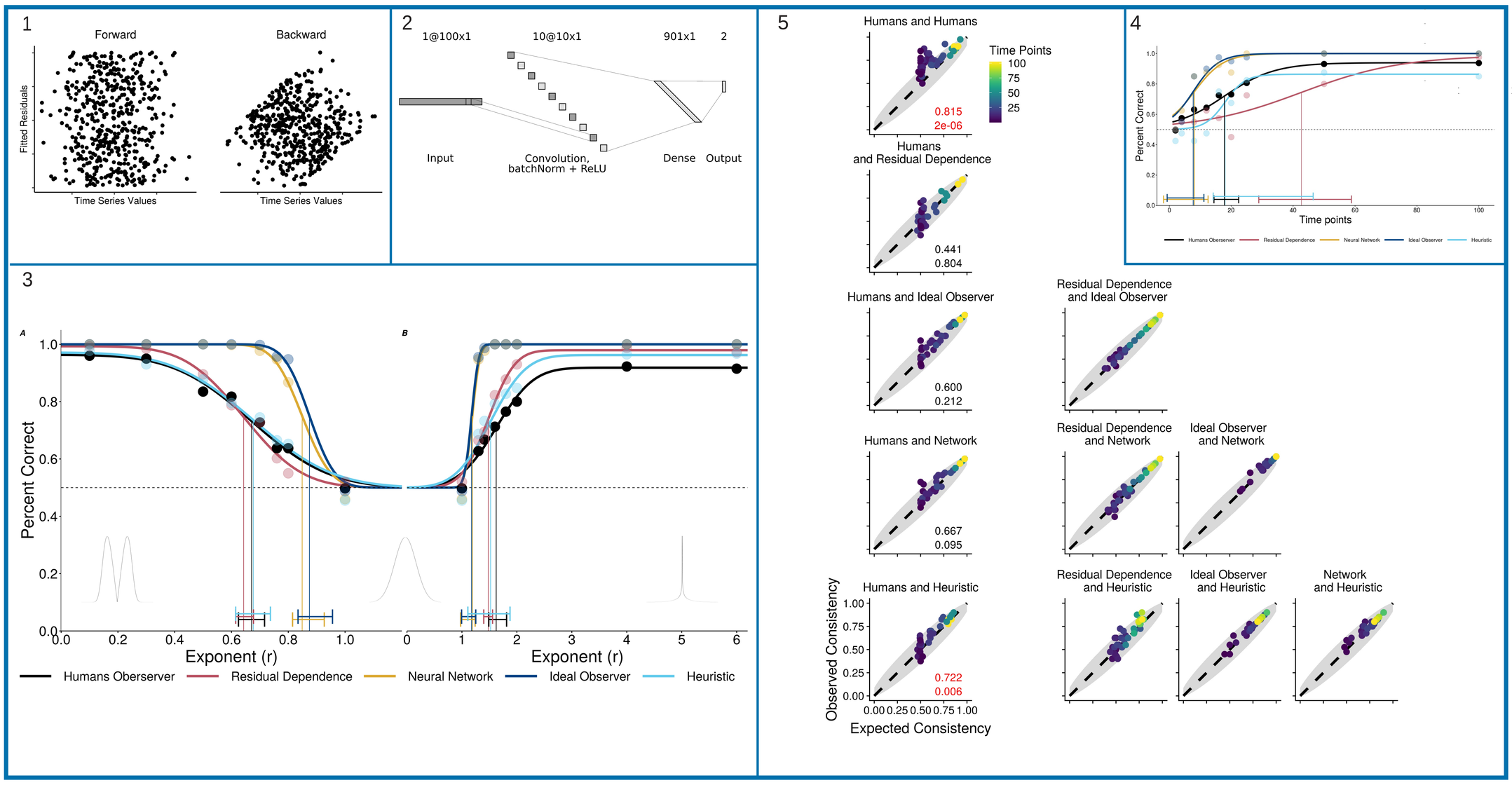
Results Experiment 1

- Human observers 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 appear sensitive to subtle asymmetries of noise distributions and that they use similar strategy to solve the arrow of time motion discrimination task. The human algorithm is unique and significantly different from the three machine algorithms we compared it to. However humans might use a strategy very similar to our simple heuristic. In addition we constructed two suboptimal Bayesian observers using early or late internal noise. But both manipulations did not yield higher similarity between humans and algorithms.



1 Fitted residuals for a forward and a backward time series

2 Neural Network structure

3 Psychometric Functions for human observers and algorithms in experiment 1

4 Psychometric Functions for human observers and algorithms in experiment 2

5 Expected consistency vs. observed consistency for human observers and algorithms in experiment 2 (Frozen noise analysis)

References:

Geisler, W. S. "Ideal observer analysis." The visual neurosciences 10.7 (2003).
Goris, R., et al. "A neural population model for visual pattern detection." Psychological Review 120.3 (2013).
Peters, J., et al. "Detecting the direction of causal time series." Proceedings of the 26th annual international conference on machine learning. ACM (2009).
Pickup, L. C., et al. "Seeing the arrow of time." Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (2014).

Affiliations:

University of Tübingen, Neural Information Processing Group, Germany [KM], [FAW]
Amazon Research Tübingen, Germany [DJ]
Max Planck Institute for Intelligent Systems, Department for Empirical Inference, Tübingen, Germany [KM], [BS]

Acknowledgements:

Funding was provided, in part, by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – projectnumber 276693517 – SFB 1233, TP 4 Causal inference strategies in human vision.