Causal reasoning in a prediction task with hidden causes

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Motivation

- Humans guide decisions using causal knowledge.
- Causal knowledge predicts what the world does when we interact with it.
- Processing of causal information deeply embedded in animal cognition [1].
- Children develop causal understanding early on [2].

[1] Sloman, 2005; Blaisdell et al., 2006
Motivation

Understanding how causal knowledge is
- represented,
- learned,
- and used

is currently not well understood.

[1] Sloman, 2005; Blaisdell et al., 2006
Causal theory of choice

- Humans infer **consequences** of their actions using **causal models** learned through experience [1].

- Causal knowledge is represented using **causal Bayes nets** [2].

Observations vs. Interventions

Common Cause Model

a) $S \rightarrow R \quad W$

Forward Model

b) $S \quad R \rightarrow W$

c) $S \rightarrow R \quad W$

d) $S \rightarrow R \quad W$

e) $S \rightarrow R \quad W$

Complex Model

information flow
Belief updates

• Observational:

\[ P(W|R) = \sum_s P(W|S = s, R)P(S = s|R) \]

• Interventional:

\[ P(W|\text{do}(R)) = \sum_s P(W|S = s, R)P(S = s) \]
Questions

• Can humans learn and use complex causal structures?

• Hypothesis: Subjects learn a complex causal dependency (i.e. cause-effect relation) when they experience both the observational and interventional regimes.
Experimental method

- **Betting game** with hidden causes:
  - Two boxes with red and white balls.
  - Contents are **hidden**.
  - Bet on colour of **randomly drawn** ball.

- The causal structure is a complex model.

- Subjects play sequence of betting trials which they can **intervene** half of the time.

- We measure their **beliefs** and compare them to the model predictions.
Betting game

Swap
\( P(S) \)

Right
\( P(R|S) \)

White
\( P(W|S, R) \)
Betting game

Place bet.
Betting game

Place bet. Choose left or right box.
Game structure

- Subjects must complete 40 blocks (levels) of 10 trials each.
- They are allocated an initial budget at the beginning of each block.
- Each bet reduces the budget.
- Their goal is to keep as much as possible of the initial budget.
- If they reach zero, they must repeat the block.
Game structure

Level 1

Level 2

... 

Level n

Trials

a)

b)

c)

bets bars
remaining budget

Game
Betting mechanism

- Log-loss scoring rule encourages reporting true beliefs [1].
- Allows measuring beliefs on a trial-by-trial basis.
- Confident bets are too risky.
- Initial budget prevents conservative guesses.

Training & test games

<table>
<thead>
<tr>
<th>Game</th>
<th>Levels</th>
<th>Transparent</th>
<th>Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training 1</td>
<td>10</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Training 2</td>
<td>10</td>
<td>yes</td>
<td>yes (50%)</td>
</tr>
<tr>
<td>Test</td>
<td>40</td>
<td>no</td>
<td>yes (50%)</td>
</tr>
</tbody>
</table>

- We trained subjects on two simplified games:
  - Training 1 familiarises subjects with betting scheme.
  - Training 2 teaches the causal structure.
Summary of experimental method

- **Betting** optimally requires:
  - **learning** the trial parameters (statistics and causal structure),
  - **marginalising** over then hidden causes,
  - and **distinguishing** between actions and observations.

- **To train** the subjects:
  - we let them play two short **training games**, 
  - where the **contents** of the boxes were **visible** at all times, 
  - and where we let them **experience each condition** half of the time.

- **To test** whether they use causal reasoning:
  - we measure their **predictive beliefs** about the ball's colour, 
  - and **compare** them to the **model** predictions.
Data collection

- Subjects: Five (UPenn) students (S1-S5).
- The training and test games were played in a single session (< 90 mins), totalling more than 600 trials.
- Were not told statistics nor causal structure.
- Were told that all trials had identical statistics & causal structure; and the differences between games.
- $10 for participation + $10 for completion.
Final prediction probabilities

- 4 out of 5 learned to predict correctly **right from the start**.
- Combines expected utility, Bayes, and causality.
- S3 treated every condition as interventional.

Low sample size!
Learning curves

- Cumulative regret = performance - optimal.
- Smaller slope = better; negative curvature = learning.
- Training games: learning is very quick (< 40 trials).
- Test game: little to no learning—but positive slope: noisy beliefs?
- Curiosity: $S_3$ performs pretty well during the training games: smaller hypothesis space?
Summary of results

• Excepting S3, all the subjects made bets that were **consistent** with the **causal model**'s predictions.

• Hence, they **induced** the causal model, **marginalised** over hidden causes, and **distinguished** between actions and observations.

• Crucially:
  – **absence** of learning during test game,
  – and **uselessness** of regime distinction during training games,

suggest that subjects could **spontaneously** supply “regime indicators” to their experience.
Conclusions

- Subjects can learn complex causal structures—it appears to be sufficient to let them experience both regimes.
- Subjects can use causal deductive reasoning.
- Subjects appear to spontaneously tag experience as either interventional or observational, even though they do not need to do so to perform well.