Did I do it? Causal Inference of Agency in goal-directed actions

Conference Paper - January 2011

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Introduction

The perception of own actions is affected by both visual information and predictions derived from internal forward models [1]. The integration of these sources depends critically on whether visual consequences are associated with one’s own action (sense of agency) or with changes in the external world unrelated to the act [2, 3] and the accuracy of integration-execution [4, 5]. Attribution of pretences to consequences of own actions should thus depend on the consistency between internally predicted and actual visual signals.

The goal of this work is to develop quantitative theories for the influence of the sense of agency on the fusion of visual cues and predictions derived from internal forward models. Our work exploits graphical models as a helpful theoretical framework.

Motive

Example: Archery.

1. Aim: hit bullseye.
2. Two possible outcomes: Hit or Miss.

Models given for two cases of attributed agency of visual stimulus to self-action (Fig. 2) or to external influence (Fig. 3).

Formulate causal inference model [22, 23, Fig. 4].

Reformulate and adapt Fig. 2 to the experiment to receive the graphical model in Fig. 8.

Experiment

To study the attribution of sensations to consequences of own actions, we investigated the effect of the consistency between internally predicted and actual sensory consequences using a virtual reality setup.

Tip of index finger of participant’s right hand positioned on a haptic driver (trial starting position) on horizontal board.

Hand movable from participant’s view.

Display fast (quasi-ballistic) pointing movements to fixed target amplitude.

Target points chosen uniformly by subject within the upper right quadrant of the circle.

1. Terminal visual feedback $x_{vis}$ of motion at target amplitude.
2. Visual feedback $x_{vis}$ calculated from tracked hand motion $x_{mot}$.
3. Visual feedback either true or rotated by offset angle (e.g. $\alpha = 30^\circ$, $45^\circ$, $60^\circ$).
4. Offset angle in random order to minimize effects of trial-by-trial adaptation.

Participants had to answer 2 questions.
1. Which direction did you point to? $X_e$
2. Did you cause the direction of $X_e$? $\text{De/ Definitely, No, Rather, Yes, Undecided}$

Graphical Model

Binary rating variable (agency) modeling sense of agency.

Fig. 8: Both visual feedback $x_{vis}$ and internal motor state $x_{mot}$ vary the target on a virtual and extended motor state $x_e$

For motor action assessed by the tracking system.

From subject’s perspective only observed variables $x_{vis}$ and $x_{mot}$.

Parameters to be estimated are the prior statistics for each variable: $p(x_{vis}) = \mathcal{N}(\mu_{vis}, \sigma_{vis}^2)$, $p(x_{mot}) = \mathcal{N}(\mu_{mot}, \sigma_{mot}^2)$ (1)

Parameters learned over dataset $p(\mu_{vis}, \sigma_{vis}^2)$, $p(\mu_{mot}, \sigma_{mot}^2)$.

Given these parameters, model predicts subject interprets visual stimulus as caused by own action.

Results

Fig. 9 shows components along which we expect data to fall for different strategies.

If subjects trust only their internal estimate, we expect data accumulate around $\mu \in (0, \alpha)$.

On the other hand, subjects trust only the visual feedback, the data is expected to accumulate around $\mu \in (\alpha, 0)$.

Values $x_{vis}$ $x_{mot}$ $\mu_{vis}$ $\mu_{mot}$ $\sigma_{vis}^2$ $\sigma_{mot}^2$

Other

0.2 0.8

1 1 0.0001 0.0001

Quantitative analysis of the prediction quality concerning the first visual impression.

Correct prediction of agency posterior.

References


Acknowledgements

This work was supported in part by the Dementias Benign for Computational Neuroscience, Tübingen, funded by the German Federal Ministry of Education and Research (BMBF: FKZ: 01EE1001X) and the DFG. The Center for Integrative Neuroscience (CIN), Tübingen, 2004 project (FP6-2001-215805 BAINES7, FP6-2004-5T3 TANGO, EPTT, FFP-FFP-2004-5T3 TANGO, FP6-2004-5T3 TANGO, the DFG, and the Hermann and Lilly Schilling Foundation.)

Discussion and Conclusion

Subjectively experienced consequence.

Small $\Delta \sigma$ (deviation b/w real and predicted visual consequences) – optimal fusion of internal estimate and visual feedback.

Large $\Delta \sigma$ – direction estimate being largely independent from visual feedback.

Good fit of model expectation to data, $x_{vis}$, though no bias.

Attribution of agency.

Systematic variation of agency posterior with the deviation size.

Small $\Delta \sigma$ – high probability.

Large $\Delta \sigma$ – less probability.

Correct prediction of agency (belief that observer caused the visual feedback) by this model (Fig. 8).

In conclusion.

Subjects attribute agency of sensory consequence to their own motor actions depending on individual parameters.

$\Delta \sigma$ affects attribution agency.

Optimal cue fusion is performed within region of self-attribution and not outside.

Bayesian Graphical Model suitable to capture underlying model selection.

The presented model correctly predicts the agency posterior.

Previous Exp. Results

To healthy subjects participated in the previous experiment, representative subjects are shown below.

- Different Manipulation angles (i.e. $\alpha = 30^\circ, 45^\circ, 60^\circ$).

- Only: Which direction did you point to? $X_e$

Empirical Data

- Subject to subject variations in agency attribution tendency.

- Large $\Delta \sigma$ – direction estimate being largely independent from visual feedback.

- Good fit of model expectation to data, $x_{vis}$, though no bias.

$\Delta \sigma$ (deg)

Did you cause the visual feedback?

Fig. 10: Experimentally observed
direction of action and feedback.

Which direction did you point to?

Fig. 11: Experimentally observed
direction of action and feedback.

- Subject to subject variations in agency attribution tendency.

$\Delta \sigma$ (deg)

Did you cause the visual feedback?

Fig. 12) Subject 1.

- Large $\Delta \sigma$ – direction estimate being largely independent from visual feedback.

- Good fit of model expectation to data, $x_{vis}$, though no bias.

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References