The role of causal inference in audiovisual spatial recalibration

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Abstract

The brain recalibrates the senses to maintain their internal consistency. Crucially, the senses should only be recalibrated in response to inter-sensory conflicts that occur between two signals that come from a common cause. Thus, recalibration relies inherently on causal inference, i.e. determining whether signals come from a common source. To investigate the role of causal inference in recalibration we presented observers with synchronous audiovisual (AV) signals at variable spatial disparities followed by unisensory A or V signals. Observers judged whether AV signals came from common causes and located the unisensory signals. Psychophysics results show that recalibration of the less reliable A cue depends non-linearly on spatial disparity and is enhanced when observers perceive a common cause. These behavioural profiles cannot be accounted for by fixed ratio models of recalibration, but are consistent with Bayesian causal inference (BCI) models in which the spatial estimates are read out using the decisional strategy of model selection.

Keywords: Bayesian Causal inference; Audio-visual spatial recalibration; multisensory integration

Introduction

Our sensory systems continuously need to adapt to changing sensory statistics in our environment. For instance, entering a room with reverberatory properties brings A and V spatial cues into conflict. To maintain internal consistency and external accuracy with respect to the outside world, the observer needs to rapidly recalibrate the A and V senses. In the lab, exposure to synchronous, yet spatially misaligned, AV signals induces a bias in observer's perceived sound location towards the previously presented V stimulus even when presented alone – a phenomenon coined ventriloquist aftereffect (Radeau & Bertelson, 1974). Crucially, spatial recalibration can arise even after a brief exposure to an inter-sensory spatial conflict such as a single spatially disparate AV stimulus (Wozny & Shams, 2011; Park & Kayser, 2019).

Despite extensive research into AV spatial recalibration, the underlying computational principles remain controversial. Some research suggests that the senses are recalibrated according to a fixed ratio or reliability-weighted integration irrespective of their spatial disparity. By contrast, recent research suggests that audiovisual recalibration relies on the signals' causal structure and is enhanced when AV cues are perceived as originating from a common source(Wozny & Shams, 2011). Further, non-linear effects of visual reliability on recalibration were better explained by Bayesian causal inference than reliability weighted or fixed ratio integration in forced fusion models (Hong, Badde, & Landy, 2021).

We compared fixed ratio and Bayesian Causal inference models as explanatory accounts for AV spatial recalibration in a new psychophysics study that combined AV common source judgments with subsequent unisensory A (or V) localization.

Methods

Experiment Paradigm Each trial included an AV phase and a unisensory A (or V) phase (Wozny & Shams, 2011; Park & Kayser, 2019). In the AV phase, 35 healthy observers were presented with synchronous AV signals at variable spatial disparities and reported whether AV signals come from common or distinct sources via a two choice key press followed by a confidence rating (high/medium/low). In the unisensory phase, they located the A (or V) signal (see figure 1a). In both phases, A and/or V signals were independently sampled from four locations along the azimuth(-12, -4, 4, 12 deg), resulting in 7 AV spatial disparities $(0, \pm 8, \pm 16, \pm 24)$.

Statistical Analysis We quantified recalibration for A signals as the difference between observers' reported location on an A trial minus the average reported locations across all A trials for the same A location. We computed recalibration effects for each of the four absolute disparity levels (by flipping the sign of the recalibration for negative spatial disparities). Using Linear Mixed Effects (LME) models (with subject as a random intercept), we first assessed the linear and quadratic effects of spatial disparity, common source judgments and their interactions on observers' recalibration:
$Recalibration \sim absolute.disparity + common.judge + I(disparity^2) + I(disparity^2) : common.judge + I(disparity^2) : confidence + (1|sub\_id)$
Next, we quantified the recalibration effects for each absolute spatial disparity level separately for AV trials on which observers perceived common versus separate sources (shown in figure 1c): $Recalibration \sim 1 + com.8 + com.16 + com.24 + sep.0 + sep.8 + sep.16 + sep.24 + (1|sub\_id)$

Computational Models We compared the behavioural profiles with the predictions obtained from three computational models of recalibration (see Hong, Badde and Landy (2021)):
1) In the fixed-ratio model, the recalibration i.e. bias is proportional to the disparity between the noisy sensory signals $(x_V - x_A)$.
In the BCI model (Kording, et al. (2007)), the bias is proportional to the difference between observer's spatial estimate and the noisy auditory signal $(\hat{s}_A - x_A)$. The spatial estimate $\hat{s}_A$ was read out according to the decision strategy of
2) model selection (MS) i.e. $\hat{s}_A = \hat{s}_{A,C=1}$ if $P(C=1|x_A, x_V) > 0.5$ and otherwise $\hat{s}_{A,C=2}$
or 3) model averaging (MA) i.e. $\hat{s}_A = \hat{s}_{A,C=1} P(C=1|x_A, x_V) + \hat{s}_{A,C=2} P(C=2|x_A, x_V)$
Because the noisy sensory signals are internal (i.e. unknown to experimenter), we performed Monte Carlo simulations and generated 1000 x_V and x_A for each AV location combination ranging from -12 to 12 deg visual angle (increment: 1 deg). For the explanatory figure 1 b, we estimated $\hat{s}_A$ by simulating 300 x_A and artificially setting x_V to 0. All simulations were performed with parameters $(\sigma_A = 12, \sigma_V = 8, \sigma_P = 40, p_{common} = 0.4)$.

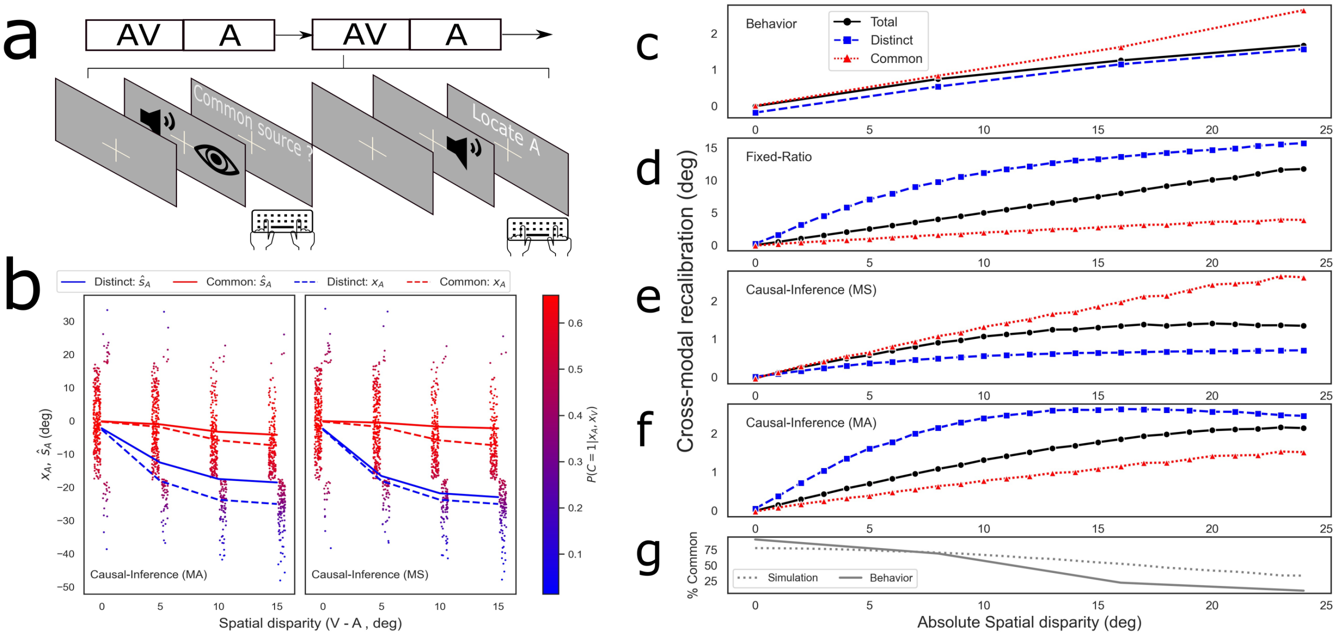

Figure 1: **a)** The experiment paradigm. **b)** x_A and $\hat{s}_A$ as a function of spatial disparity for the model averaging(left) and model selection(right) when artificially setting x_V to 0. The dots cloud showed the distribution of the auditory measurements x_A for common (left cloud) and distinct (right cloud) inferences. The color of the dots encoded the posterior probability $P(C=1|x_A, x_V)$. The solid lines illustrated the mean $\hat{s}_A$ for both common(red) and distinct(blue) dots. The dashed lines depicted the mean x_A. **c-f)** The recalibration as a function of the absolute spatial disparities from the behavior data(c) and from the simulation data with the fixed-ratio model(d), the causal-inference model with model selection(e) and with model averaging(f). **g)** The ratio of common cases as a function of absolute spatial disparities for behaviour data(solid) and simulated data(dashed).

Results

Psychophysics Results Observers' total recalibration depends non-linearly on spatial disparity (black line, figure 1c). It is enhanced for trials with common (red) relative to distinct (blue) cause judgments as expected under causal inference. Moreover, the total recalibration effect aligns more closely with the recalibration for common source judgment trials at small spatial disparities, but with separate source judgment trials at large spatial disparities, reflecting the decline in % perceived common source with greater spatial disparity (figure 1g). These effects were confirmed statistically with a significant linear effect of spatial disparity ($t = 4.197, p < 0.001$) and common source judgement ($t = 2.645, p = 0.008$), as well as a significant interaction term of quadratic disparities x common source judgement ($t = 2.270, p = 0.023$).

Model Simulation Results First, our model simulations show that the non-linear effect of spatial disparity on the total recalibration is captured by BCI with MS (e) and MA (f) but not by fixed ratio recalibration (d). Second, only the BCI with MS predicts a larger recalibration effect from common than independent source judgments, while the opposite profile is observed for the fixed ratio and the BCI with MA (with current parameter values). Figure 1b illustrates that the stronger recalibration effect for the distinct sources in MA and Fixed Ratio models arises from a selection bias of the noisy x_A (for explanatory purposes we set $x_V = 0$). Observers judge independent causes at small AV spatial disparities only when the noisy x_A is far apart from x_V and true s_A, resulting in a large discrepancy between x_A and $\hat{s}_A$ when computed via MA. By contrast, when computed via MS, $\hat{s}_A$ depends on distinct cause judgment only, resulting in a small difference between $\hat{s}_A$ and x_A , hence only limited recalibration. In short, complex non-linearities in the recalibration effect can arise from Bayesian Causal Inference and biased selection of x_A and x_V when trials are selected according to observers' common source judgements.

Conclusions

Our psychophysics results show that the total recalibration effect depends non-linearly on spatial disparity and is enhanced when observers perceive a common cause (Wozny & Shams, 2011; Kording et al., 2007). Bayesian Causal Inference with MS and MA - but not Fixed Ratio models- can both explain the non-linear effects of spatial disparity on AV recalibration, as this arises from the computations of Bayesian Causal Inference. However, only BCI with MS - but not BCI with MA or Fixed Ratio models - predicts stronger recalibration effects for trials on which observers perceived common than independent causes of the A and V signals.

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