

1 **Older adults sacrifice response speed to preserve multisensory integration performance**

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Abstract

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Ageing has been shown to impact multisensory perception, but the underlying computational mechanisms are unclear. For effective interactions with the environment, observers should integrate signals that share a common source, weighted by their reliabilities, and segregate those from separate sources. Observers are thought to accumulate evidence about the world's causal structure over time until a decisional threshold is reached.

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Combining psychophysics and Bayesian modelling, we investigated how ageing affects audiovisual perception of spatial signals. Older and younger adults were comparable in their final localisation and common-source judgement responses under both speeded and unspeeded conditions, but were disproportionately slower for audiovisually incongruent trials.

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Bayesian modelling showed that ageing did not affect the ability to arbitrate between integration and segregation under either unspeeded or speeded conditions. However, modelling the within-trial dynamics of evidence accumulation under speeded conditions revealed that older observers accumulate noisier auditory representations for longer, set higher decisional thresholds, and have impaired motor speed. Older observers preserve audiovisual localisation performance, despite noisier sensory representations, by sacrificing response speed.

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1. Introduction

41 Throughout life we are continually exposed to a barrage of sensory signals. Our ability
42 to effectively navigate through and respond to the world requires us to merge information from
43 multiple sensory modalities into a coherent percept. We may, for example, more easily locate a
44 predator in thick foliage by combining the sight of its movement with the sound of footsteps.

45 Accumulating evidence suggests that ageing affects how observers integrate sensory
46 signals into perceptual decisions. In speeded target detection paradigms older adults show
47 greater multisensory response facilitation (i.e. redundant target effect; Laurienti et al., 2006;
48 Mahoney et al., 2011). Further, older participants have been shown to integrate multisensory
49 stimuli differently in illusionary settings such as the sound-induced flash illusion (DeLoss et al.,
50 2013; McGovern et al., 2014; Setti et al., 2011) and the McGurk-MacDonald effect (Sekiyama
51 et al., 2014; Setti et al., 2013). Yet, the computational mechanisms underlying these age
52 differences in multisensory integration remain unclear.

53 Two key mechanisms need to be distinguished: First, ageing is known to reduce the
54 reliability of auditory and visual representations (Dobrevá et al., 2011; Lindenberger & Baltes,
55 1994; Otte et al., 2013; Salthouse et al., 1996). Differences in the reliability of sensory
56 representations may in turn alter the weights that are assigned to the sensory signals during the
57 integration process, thereby changing the final percept. Further, less reliable sensory
58 representations will also reduce observers' ability to determine whether sensory signals come
59 from a common source and thereby influence how they arbitrate between sensory integration
60 and segregation. In short, age-related increases in noise in the unisensory representations may
61 alter the perceptual outcome of multisensory integration, even if the integration processes are
62 intact.

63 Second, ageing may genuinely impact how observers arbitrate between sensory
64 integration and segregation depending on temporal, spatial or higher-order statistical
65 correspondence cues or how they weight sensory signals in the integration process. As a
66 consequence, even if unisensory processing were preserved, we would observe differences in
67 multisensory perception.

68 In short, both changes in unisensory representations and multisensory integration can

69 alter perceptual outcomes in a similar fashion. We thus need to apply models that allow us to
70 dissociate between those two mechanisms.

71 In the laboratory, the computational principles of multisensory integration have been
72 studied extensively in spatial ventriloquist paradigms where observers need to report their
73 perceived sound (or visual) location when presented with synchronous, yet spatially disparate,
74 auditory and visual signals. For small spatial disparities, observers' perceived sound location is
75 shifted (or biased) towards the location of the visual signal and vice versa depending on the
76 relative auditory and visual reliabilities—a phenomenon known as the spatial ventriloquist
77 effect. Yet, for large audiovisual spatial disparities where it is unlikely that signals come from a
78 common source, audiovisual interactions and crossmodal biases are attenuated. Recent
79 psychophysics and neuroimaging studies have shown that younger observers arbitrate between
80 sensory integration and segregation in a way that is consistent with the predictions of
81 hierarchical Bayesian Causal Inference (BCI; Aller & Noppeney, 2019; Koerding et al., 2007;
82 Rohe, Ehrlis, & Noppeney, 2019; Rohe & Noppeney, 2015a, 2015b; Shams & Beierholm, 2010;
83 Wozny et al., 2010). Bayesian Causal Inference enables arbitration between sensory integration
84 and segregation by explicitly modelling the two causal structures (i.e. common or independent
85 causes) that could have generated the sensory signals. If signals are caused by the same source
86 they are integrated, weighted in proportion to their relative sensory reliabilities; if they are
87 caused by different sources they are treated separately. To account for observers' uncertainty
88 about the world's causal structure, a final estimate (e.g. an object's location) is obtained by
89 averaging the estimates under the assumptions of common and independent sources weighted by
90 their respective posterior probabilities, a decision strategy referred to as model averaging (for
91 other decision functions see Wozny et al., 2010). Spatial ventriloquism, together with Bayesian
92 Causal Inference, may thus allow us to tease apart whether ageing affects only sensory
93 reliabilities (i.e. sensory variance) or also observers' multisensory binding (as quantified by the
94 model's causal prior), and to test whether older adults still respond in a way that is consistent
95 with the predictions of BCI.

96 However, current models of Bayesian Causal Inference do not account for temporal
97 constraints imposed by our natural world and the dynamics of observers' perceptual inference;

98 BCI enables predictions only for an observer's response choices (e.g. spatial localisation) but
99 not for his or her response times. In our natural environment we often need to trade off accuracy
100 for speed: a faster, less accurate estimate of the location of a predator may prove far more useful
101 than a highly accurate but slow one. Indeed, recent studies have shown that putatively
102 suboptimal multisensory behaviour can be considered optimal when the dynamics of perceptual
103 decision making, based on both response choices and times, are taken into account
104 (Drugowitsch et al., 2014). Considering response choices and times together is particularly
105 relevant for understanding the impact of ageing on multisensory integration, as older adults have
106 previously been shown to favour accuracy over speed to a greater degree than younger observers
107 (Smith & Brewer, 1995; Starns and Ratcliff, 2010).

108 Combining psychophysics and computational modelling, the current study was thus
109 designed to investigate how ageing impacts the computational parameters governing
110 multisensory decision making in both unspeeded and speeded contexts (Koerding et al., 2007;
111 Rohe & Noppeney, 2015a, 2015b; Wozny et al., 2010).

112 First, in an unspeeded spatial ventriloquist paradigm younger and older observers located
113 the source of a sound (which *implicitly* relies on causal inference; see above) or judged whether
114 the auditory and visual signal originated from the same source (which *explicitly* requires the
115 observer to infer the causal structure underlying the audiovisual signals). We assessed how
116 ageing affects observers' auditory and visual reliabilities (i.e. sensory noise), spatial prior (i.e.
117 spatial expectations), and causal prior (i.e. multisensory binding tendency), as key parameters of
118 the Bayesian Causal Inference model.

119 Second, in a speeded spatial ventriloquist paradigm observers were presented with
120 spatially congruent or incongruent audiovisual signals and rapidly discriminated whether the
121 auditory (or visual) stimulus was presented in their left or right hemifield. We used a modified
122 version of the Bayesian compatibility bias model (Noppeney, Ostwald, & Werner, 2010; Yu et
123 al., 2009) to characterise how observers accumulate evidence concurrently about signal location
124 and audiovisual spatial congruency (i.e. causal structure), and to make predictions jointly for
125 response choices and times. The age groups were compared in terms of auditory and visual
126 reliabilities, prior binding tendency, and final response threshold.

127 If older observers differ from younger observers only in sensory reliabilities in
128 unspeeded and speeded contexts, age-related changes in perceptual outcomes are a consequence
129 of their noiser sensory representations. However, if older observers' behaviour is inconsistent
130 with principles of Bayesian Causal Inference or explained by increases or decreases in their
131 multisensory binding tendencies (as quantified by the causal prior), then ageing genuinely
132 impacts multisensory interactions.

133 2. Methods

134 2.1. Participants

135 Twenty-three younger adults (eleven male, mean age = 19.5, $SD = 1.6$, range = 18 – 26
136 years) and twenty-three older adults (seven male, mean age = 72, $SD = 5.2$, range = 63 – 80
137 years) were included in the study. One older adult was excluded before testing was completed as
138 she was unable to perform unisensory auditory localisation (approximately the same response
139 was given to all auditory stimuli, regardless of source location). The younger adults were
140 undergraduate psychology students at the University of Birmingham, and were compensated in
141 cash or course credits for their time. Older adults were recruited to the study from a database of
142 local participants maintained by the University of Birmingham's School of Psychology, and
143 were compensated in cash. These community-living older adults had a diverse range of
144 backgrounds; 39% reported education at degree level or above. All participants reported normal
145 hearing and normal or corrected-to-normal vision, and were screened for basic auditory and
146 visual localisation ability using a forced left/right discrimination task (see Supplementary S1).
147 Participants gave informed consent prior to the commencement of testing. The research was
148 approved by the University of Birmingham Ethical Review Committee.

149 2.2. Experimental Setup

150 Participants were seated at a chin rest 130 cm from a sound-transparent projector screen.
151 Behind the screen, at the vertical centre, a shelf held an array of nine studio monitors (Fostex
152 PM04n) spaced horizontally by 7° of visual angle, including a speaker in the middle of the
153 screen. Auditory stimuli were presented via these speakers at approximately 75 dB SPL. The
154 locations of the speakers were not known to participants. Images were displayed using a BENQ

155 MP782ST multimedia projector at a total resolution of 1280 x 800. All stimuli were presented
156 using The Psychophysics Toolbox 3 (Kleiner, Brainard, & Pelli, 2007) in MATLAB R2010b
157 running on a Windows 7 PC.

158 Responses were made using a two-button response pad or optical mouse, and in all cases
159 this was effectively self-speeded; the next trial would not begin until a valid response was made.
160 However, for the speeded ventriloquist task it was emphasised to participants that they should
161 respond as quickly as possible while maintaining accuracy. See Figure 1A for an outline of the
162 setup.

163 **2.3. Stimuli**

164 Visual stimuli consisted of a 50 ms flash of 15 white (88 cd/m²) dots, each 0.44° of
165 visual angle in diameter, against a dark grey (4 cd/m²) background. Dot locations were sampled
166 uniquely for each trial from a bivariate Gaussian distribution, with a constant vertical standard
167 deviation of 5.4°. The horizontal standard deviation of this dot cloud was varied to manipulate
168 the reliability of spatial information, with a wider cloud (expressed in degrees of visual angle)
169 resulting in less reliable stimuli (Rohe & Noppeney, 2015). We define the specific horizontal
170 standard deviations used for each paradigm below.

171 The auditory stimulus was a burst of white noise (duration: 50 ms) played from one
172 speaker in the array in synchrony with the visual stimulus. Sounds were generated individually
173 for each trial and ramped on/off over 5ms. Across all tasks participants fixated a central cross
174 (0.22° radius) that was constantly presented throughout the entire experiment.

175 **2.4. Unspeeded audiovisual spatial ventriloquist paradigm**

176 *2.4.1. Design and procedure*

177 In a spatial ventriloquist paradigm observers were presented with synchronous auditory
178 and visual stimuli at variable audiovisual spatial disparities and performed implicit or explicit
179 causal inference tasks in separate blocks. First, in an auditory selective attention task, observers
180 reported their perceived sound location. As highlighted in the introduction, spatial localisation
181 implicitly relies on solving the causal inference problem. Second, they explicitly inferred and
182 reported the causal structure (i.e. common vs. independent sources) that could have generated

183 the audiovisual signals in common source judgements.

184 Irrespective of task context, on each trial auditory and visual stimuli were independently
185 sampled from five possible locations (-14° , -7° , 0° , 7° , or 14°), and could therefore be spatially
186 congruent or incongruent with varying degrees of disparity (0° , 7° , 14° , 21° , or 28°). Visual
187 stimuli had three levels of reliability (horizontal *SD* of 2° , 6° or 16°) (n.b. a fourth level of visual
188 reliability was excluded from the analysis because the dots were erroneously sampled). The
189 paradigm thus conformed to a 5 (A locations) x 5 (V locations) x 3 (V reliabilities) factorial
190 design.

191 In the sound localisation task participants reported the perceived sound location as
192 accurately as possible, after a 500 ms post-stimulus delay, by moving a mouse-controlled cursor
193 (white, subtending 9° in height and 0.5° wide) whose movement was constrained to the
194 horizontal plane. The next trial was started one second after observers had indicated their
195 perceived auditory location by clicking the mouse button. Trials were presented randomly in
196 200-trial blocks. In total, participants completed 600 trials (8 [repetitions] x 5 [A locations] x 5
197 [V locations] x 3 [V reliabilities])) of this task.

198 In the common-source judgement task participants reported whether they perceived the
199 auditory and visual signals to have originated from the same location. 500ms after the
200 presentation of the flash and beep, the words “same” and “different” appeared respectively
201 above and below the fixation cross. Participants indicated with a button press whether the sound
202 and flash were generated by a common source. Participants again completed 600 trials (8
203 [repetitions] x 5 [A locations] x 5 [V locations] x 3 [V reliabilities])) of this task, delivered in
204 three blocks of 200 trials.

205 Unisensory auditory or visual localisation blocks were also included to improve
206 estimation of sensory reliabilities. In unisensory auditory blocks, observers were presented with
207 sounds randomly at one of the five locations and indicated their perceived sound location with
208 the mouse cursor, as above. 80 trials of this task (16 per location) were completed in one block.
209 In unisensory visual blocks, stimuli from the three reliability levels indicated above (horizontal
210 *SD* of 2° , 6° or 16°) were presented randomly in one of the five locations and participants
211 instructed to locate the centre of the dot cloud with the mouse cursor. 120 trials of this task (8

212 per location, per reliability level) were completed in one block.

213 **2.4.2. Bayesian Causal Inference model**

214 We use Bayesian Causal Inference (BCI; Aller & Noppeney, 2019; Koerding et al.,
215 2007; Rohe, Ehrlis, & Noppeney, 2019; Rohe & Noppeney, 2015a, 2015b; Shams & Beierholm,
216 2010; Wozny et al., 2010) to investigate how younger and older observers arbitrate between
217 sensory integration and segregation. In the following we briefly describe the BCI model; for
218 further details see Koerding et al. (2007).

219 The BCI generative model assumes that common ($C = 1$) or independent ($C = 2$) sources
220 are determined by sampling from a binomial distribution with the causal prior $P(C = 1) =$
221 p_{common} . For a common source, the “true” location S_{AV} is drawn from the spatial prior distribution
222 $N(\mu_P, \sigma_P)$. For two independent causes, the “true” auditory (S_A) and visual (S_V) locations are
223 drawn independently from this spatial prior distribution. For the spatial prior distribution, we
224 assumed a central bias (i.e. $\mu_P = 0$). We introduced sensory noise by drawing x_A and x_V
225 independently from normal distributions centered on the true auditory (respectively visual)
226 locations with parameters σ_A (respectively σ_V for each visual reliability level).

227 Thus, the generative model included the following free parameters: the causal prior
228 p_{common} , the spatial prior standard deviation σ_P , the auditory standard deviation σ_A , and visual
229 standard deviations corresponding to the three visual reliability levels σ_{V1} , σ_{V2} , and σ_{V3} .

230 During perceptual inference the observer is assumed to invert this generative model. The
231 probability of the underlying causal structure can be inferred by combining the causal prior with
232 the sensory evidence according to Bayes’ rule:

$$233 \quad (1) \quad p(C = 1|x_A, x_V) = \frac{p(x_A, x_V|C = 1)p_{\text{common}}}{p(x_A, x_V)}$$

234 We assumed that subjects report ‘common source’ (i.e. explicit causal inference) when
235 the posterior probability of a common source is greater than the threshold of 0.5:

$$236 \quad (2) \quad \hat{C} = \begin{cases} 1 & \text{if } p(C = 1|x_A, x_V) > 0.5 \\ 2 & \text{if } p(C = 1|x_A, x_V) \leq 0.5 \end{cases}$$

237 In the case of a common source ($C = 1$; Figure 1B left), the maximum a posteriori
238 probability estimate of the auditory location is a reliability-weighted average of the auditory and
239 visual estimates and the prior.

$$(3) \quad \hat{S}_{A,C=1} = \frac{\frac{x_A}{\sigma_A^2} + \frac{x_V}{\sigma_V^2} + \frac{\mu_P}{\sigma_P^2}}{\frac{1}{\sigma_A^2} + \frac{1}{\sigma_V^2} + \frac{1}{\sigma_P^2}}$$

241 In the case of a separate-source inference ($C = 2$; Figure 1B right), the estimate of the
242 auditory signal location is independent from the visual spatial signal.

$$(4) \quad \hat{S}_{A,C=2} = \frac{\frac{x_A}{\sigma_A^2} + \frac{\mu_P}{\sigma_P^2}}{\frac{1}{\sigma_A^2} + \frac{1}{\sigma_P^2}}$$

244 Given the decisional strategy of model averaging (for other decisional strategies see
245 Wozny et al., 2010) the observer will compute a final auditory localisation estimate by
246 averaging the spatial estimates under common and independent source assumptions, weighted in
247 proportion to their posterior probabilities (i.e. implicit causal inference).

$$(5) \quad \hat{S}_A = p(C = 1|x_A, x_V)\hat{S}_{AV,C=1} + (1 - p(C = 1|x_A, x_V))\hat{S}_{A,C=2}$$

249 The predicted distributions of the auditory spatial estimates, $p(\hat{S}_A|S_A, S_V)$, and the
250 common source estimates, $p(\hat{C}|S_A, S_V)$, were obtained by marginalising over the internal
251 variables x_A and x_V . For the unisensory auditory and visual localisation tasks, we used the
252 predicted distributions $p(\hat{S}_{A,C=2}|S_A)$ for auditory blocks and $p(\hat{S}_{V,C=2}|S_V)$ respectively.

253 These distributions were generated by simulating x_A and x_V 10000 times for each of the
254 conditions and inferring \hat{S}_A , $\hat{S}_{A,C=2}$, $\hat{S}_{V,C=2}$, and \hat{C} from the equations above. Based on these
255 predicted distributions (given an additional noise kernel with a fixed $\sigma_{motor} = 1$), we computed
256 the log-likelihood of participants' auditory localisation and common-source judgement
257 responses.

258 We fitted the Bayesian Causal Inference model jointly to observers' localisation
259 responses in the audiovisual and the unisensory visual and auditory stimulation conditions. We
260 modelled the sensory noise and spatial prior parameters separately for unisensory and bisensory
261 trials, as this was found to fit the data best overall (see Supplementary S5 for a formal
262 comparison with models that did not separate parameters based on unisensory or audiovisual
263 context). Therefore, a total of eleven free parameters was fitted for each participant: the causal
264 prior p_{common} , the spatial prior standard deviations $\sigma_{P uni}$ and $\sigma_{P bi}$, the auditory standard deviations
265 $\sigma_{A uni}$ and $\sigma_{A bi}$, and visual standard deviations corresponding to the three visual reliability levels

266 $\sigma_{V1\ uni}$, $\sigma_{V2\ uni}$, $\sigma_{V3\ uni}$, $\sigma_{V1\ bi}$, $\sigma_{V2\ bi}$, $\sigma_{V3\ bi}$ (indices *uni* and *bi* correspond to unisensory and bisensory
267 trials respectively). Assuming independence of conditions and responses, we summed the log-
268 likelihoods across conditions and across localisation and common-source judgement responses
269 to obtain a single log-likelihood for each subject. To obtain maximum likelihood estimates for
270 each subject's model parameters we used a Bayesian adaptive search algorithm (BADS; Acerbi
271 & Ma, 2017) with the parameters for initialisation determined by a prior grid search.

272 The parameters (causal prior, spatial prior[s], and sensory variances) obtained from the
273 winning model were compared between age groups using separate non-parametric Mann-
274 Whitney *U* tests. We also calculated Bayes factors using the Bayesian Mann-Whitney test as
275 implemented in JASP (JASP Team, 2018; van Doorn et al., 2018) using the default Cauchy
276 prior (scale = 0.707).

277 **2.5. Speeded ventriloquist paradigm**

278 **2.5.1. Design and procedure**

279 To assess participants' audiovisual integration of spatial cues under speeded conditions,
280 taking into account both final responses and reaction times, we used a simpler 2 (auditory
281 location: left vs. right) x 2 (visual location: left vs. right) x 2 (relevant and reported sensory
282 modality: auditory vs. visual) ventriloquist paradigm. On each trial, a visual stimulus with
283 horizontal $SD = 5.4^\circ$ was displayed simultaneously with a burst of white noise. The centre of the
284 visual cloud and the white noise were presented at 14° either left or right of a central fixation
285 cross. These audiovisual stimuli were spatially congruent on half of the trials, and incongruent
286 on the other half. In an auditory or visual selective attention paradigm, participants indicated
287 either the location of the sound (respond-auditory task) or the cloud (respond-visual task) as
288 quickly and accurately as possible via a two-choice key press, while ignoring the other modality.
289 The task was self-speeded in this way (i.e. no response deadline) as any imposed incentives or
290 timing criteria may have affected the groups differently; we rely on the compatibility bias model
291 (Yu et al., 2009; described below) to separate age differences in motor speed and
292 speed/accuracy trade-off from potential differences in sensory reliability/evidence accumulation.
293 The tasks were performed in two blocks of 160 trials. The order of these tasks was
294 counterbalanced between participants. In total the experiment included 320 trials: 40

295 (repetitions) x 2 (visual location) x 2 (auditory location) x 2 (reported sensory modality).

296 **2.5.2. Compatibility bias model**

297 To assess age differences in responses to multisensory stimuli under temporal
 298 constraints, we analysed the respond-auditory data by adapting the “compatibility bias” model
 299 to an audiovisual context (Noppeney, Ostwald, & Werner, 2010; Yu et al., 2009). This models
 300 the within-trial dynamics of audiovisual evidence accumulation, leading to predictions for both
 301 response choice and response times.

302 See Yu et al. (2009) for full details about the compatibility bias model. Briefly, this
 303 generative model assumes that congruent ($C = 1$) or incongruent ($C = 2$) sources are determined
 304 by sampling from a binomial distribution with the compatibility or congruency prior $P(C = 1) =$
 305 $p_{congruency}$. The visual S_V and auditory S_A sources can either be left (-1) or right ($+1$). For a
 306 congruent trial, the auditory and visual locations are identical, i.e. $S_A = S_V$ (S_A and S_V are either
 307 both left or both right). For an incongruent trial, the auditory and visual locations are in opposite
 308 hemifields, i.e. $S_A = -S_V$ (two possibilities: $S_A = -1$ and $S_V = 1$, or $S_A = 1$ and $S_V = -1$). Hence we
 309 obtain a total of four possible stimulus combinations. We then sample noisy sensory inputs
 310 successively for each time point within a trial by drawing $\mathbf{x}_t = [x_A(t) \ x_V(t)]$ independently from
 311 normal distributions centred on S_A (or S_V) with parameters σ_A (or σ_V respectively). This thereby
 312 models that the brain receives progressively more information about the location of the auditory
 313 and visual sources and thus, indirectly, about whether or not they are congruent (n.b. though in
 314 our experiment auditory and visual inputs are brief, we model evidence accumulation via
 315 feedback loops as a series of sensory inputs). Based on a stream of audiovisual inputs $\mathbf{X}_t = [\mathbf{x}_1,$
 316 $\mathbf{x}_2, \mathbf{x}_3 \dots \mathbf{x}_t]$ the observer is then assumed to compute the posterior probability over congruency C
 317 and auditory (or visual) source location iteratively according to Bayes’ rule (initialised with the
 318 prior $P(C) = \beta$):

$$319 \quad (6) \quad P(S_A, C | \mathbf{X}_t) = \frac{p(\mathbf{x}_t | S_A, C) P(S_A, C | \mathbf{X}_{t-1})}{\sum_{C' S'_A} p(\mathbf{x}_t | S'_A, C') P(S'_A, C' | \mathbf{X}_{t-1})}$$

320 A left/right decision is then made when the evolving trajectory of the marginal

$$321 \quad (7) \quad P(S_A = 1 | \mathbf{X}_t) = P(S_A = 1, C = 1 | \mathbf{X}_t) + P(S_A = 1, C = 2 | \mathbf{X}_t)$$

322 reaches a threshold q .

323 Thus, incongruent visual information should be most influential on perceived auditory
 324 location at the onset of the trial, when the initial compatibility prior dominates, but this
 325 influence decreases as information about the location of each stimulus is accumulated. The
 326 process is terminated when sufficient evidence is accumulated about the location of the auditory
 327 stimulus for a decisional threshold to be reached, after which a left/right spatial response is
 328 made. To accommodate that older adults have slower motor speed than younger adults (as
 329 confirmed by a separate finger tapping task reported in Supplementary S2), we included an
 330 additional non-decision-time parameter t_{nd} to account for motor delays.

331 The model therefore has five free parameters in total: the compatibility prior (i.e. prior
 332 probability of audiovisual signals coming from a common cause) β ; the standard deviations of
 333 the auditory and visual signals, σ_A and σ_V respectively; the response threshold q ; and a non-
 334 decision-time parameter t_{nd} that allows for a variable motor delay between the threshold being
 335 reached and a response being given.

336 As in the Bayesian Causal Inference model we obtained the predicted distributions of the
 337 auditory spatial estimates, $P(\hat{S}_A | S_A, S_V)$, and response times, $P(\widehat{RT}_A | S_A, S_V)$, by marginalising
 338 over the internal variables x_A and x_V . These distributions were generated by simulating x_A and x_V
 339 for 300 time steps (of 10 ms length) 10000 times for each of the conditions. For each simulated
 340 trial with a series of 300 x_A and x_V , we then computed the response time and choice when
 341 $P(S_A = -1 | \mathbf{X}_t)$ first crossed the decisional threshold q using Equations 5 and 6 above. Based
 342 on these predicted response choice and response time distributions, we computed the log-
 343 likelihood of participants' auditory (or visual) localisation responses and the response times
 344 (after adding the non-decision time t_{nd}). Assuming independence of conditions as well as
 345 independence of the log-likelihoods for response times and choices, we summed the log-
 346 likelihoods across conditions and across response times and choices for a particular subject. To
 347 obtain maximum likelihood estimates for the model parameters for each subject ($\beta, \sigma_A, \sigma_V, q, t_{nd}$)
 348 we used a Bayesian Adaptive Search optimisation algorithm (BADS; Acerbi & Ma, 2017) with
 349 parameters initialised based on a grid search.

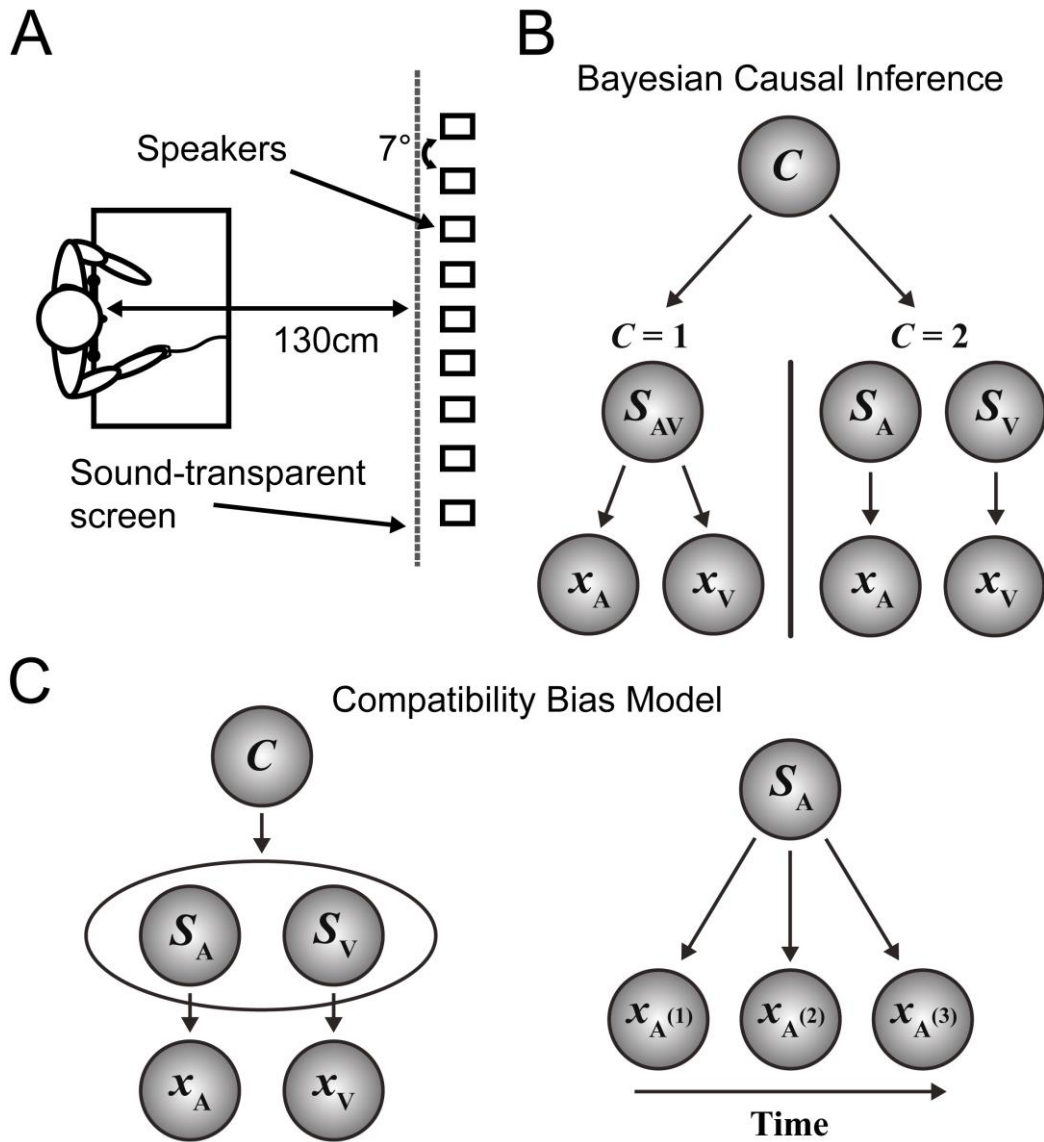
350 To investigate whether any of the parameters of these two Bayesian models were
 351 significantly different between older and younger adults the fitted parameters were entered into

352 separate non-parametric Mann-Whitney U tests. We also calculated Bayes factors using the
353 Bayesian Mann-Whitney test as implemented in JASP (JASP Team, 2018; van Doorn et al.,
354 2018) using the default Cauchy prior (scale = 0.707).

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359 *Figure 1.* Experimental setup and generative models. (A) Participants were presented with
 360 visual stimuli on a sound-transparent projector screen. Sounds were produced by individual
 361 speakers concealed behind this screen, which were separated by 7° of visual angle. Responses
 362 were given via a mouse or a two-button response pad. (B) Bayesian Causal Inference (BCI)
 363 model, based on Koerding et al. (2007). Auditory (x_A) and visual (x_V) signals may be generated
 364 by one common ($C = 1$) audiovisual source (S_{AV}), or by separate ($C = 2$) auditory (S_A) and visual
 365 (S_V) sources. (C) Compatibility bias model, adapted from Yu et al. (2009). Left: Auditory (S_A)
 366 and visual (S_V) sources can either be congruent ($C = 1$, i.e. in same hemifield) or incongruent (C
 367 = 2, i.e. in opposite hemifields). Right: Across time, the auditory source generates a series of
 368 auditory inputs, and the visual source (not shown) a series of visual inputs, in an independent
 369 and identical fashion.

3. Results

3.1. Unisensory screening tests and the Montreal Cognitive Assessment

Prior to the main unspeeded and speeded ventriloquist experiments, all observers were screened for basic auditory and visual localisation ability with a binary left/right forced-choice spatial classification task. Individuals were characterised in terms of the slope and threshold of psychometric functions fitted to these responses. Older and younger adults were closely matched: no significant age differences in threshold or bias were observed for auditory or visual spatial processing, suggesting that sensory spatial reliability was approximately similar between age groups. No participants were excluded as a result of poor performance on this task. See Supplementary S1 for full details.

Older participants were also screened using the Montreal Cognitive Assessment with a cut-off score of 23 (Coen et al., 2011; Roalf et al., 2013; Luis et al., 2009); none of our older participants scored below 25.

3.2. Unspeeded ventriloquist paradigm: Localisation and common source judgement

3.2.1. Descriptive and GLM-based analysis

An unspeeded spatial ventriloquist paradigm was used to compare younger and older adults' responses to audiovisual spatial stimuli in the absence of temporal constraints. Figure 2 shows participants' auditory localisation (presented in terms of the magnitude of ventriloquist effect, $VE = [A_{resp} - A_{loc}] / [V_{loc} - A_{loc}]$) and common-source judgement responses (characterised as the probability of responding "same-source") as a function of visual reliability level and audiovisual disparity. As predicted by Bayesian Causal Inference, the ventriloquist effect was strongest when visual reliability was high and the audiovisual disparity small. The age groups performed remarkably similarly on both measures, with standard GLM analyses revealing no significant effects of age on final response choices. However, older observers were significantly slower than younger adults when localising sounds in the spatial ventriloquist paradigm. Further, we observed significant age effects on the common-source judgement reaction times (Figure 2D), including significant interactions between age, visual reliability, and audiovisual disparity. See Supplementary S3 for full GLM analyses of these results.

398 **3.2.2. Bayesian modelling**

399 Table 1 summarises the fitted parameters (within-group mean and *SD*) of the Bayesian
 400 Causal Inference model for younger and older participants. Table 1 also reports the results of the
 401 nonparametric tests comparing the parameters between the older and younger groups together
 402 with the Bayes factors associated with each statistical comparison. We observed small but
 403 significant group differences in auditory and visual variance parameters that were estimated
 404 based on unisensory localisation tasks alone, suggesting that older adults were slightly less
 405 precise when locating both auditory and particularly unreliable visual stimuli. These group
 406 differences were not significant when the sensory variance parameters were estimated based on
 407 responses to audiovisual stimuli, probably because these parameters were less precisely
 408 estimated in this case: in the audiovisual context the visual variance parameter is only estimated
 409 indirectly from auditory responses, and the auditory variance is always estimated in the presence
 410 of interfering visual signals (and so may be influenced by factors other than peripheral sensory
 411 noise).

412 Crucially, however, no significant group differences were observed for the P_{common} or σ_P
 413 parameters. This suggests that the two age groups had similar central spatial priors and causal
 414 priors, suggesting that older and younger adults showed similar tendencies to bind audiovisual
 415 signals (in an unspedded context) consistent with Bayesian Causal Inference.

416 To verify that these results were not confounded by possible age differences in motor
 417 noise (i.e. noisier mouse localisation responses), we also fitted a version of the model that
 418 allowed the parameter σ_{motor} to vary freely (σ_{motor} was fixed at 1° for all participants in the main
 419 analysis). The pattern of results remained similar, though the group difference in $\sigma_{A\ uni}$ became
 420 marginally non-significant ($p = .052$). Further, there were no significant group differences in the
 421 σ_{motor} parameter ($p > .05$, $BF_{01} = 3.15$). See Supplementary S6 for details.

422 In summary, age did not influence observer's implicit (auditory localisation) or explicit
 423 (common-source judgement) causal inference in terms of response choices. Our Bayesian
 424 modelling analysis revealed that older adults had slightly noisier auditory and visual
 425 representations when estimated separately for the unisensory conditions. Importantly, though,
 426 the comparable causal prior (and central prior), and similar mean response choices, indicate that

427 older observers combined audiovisual spatial signals according to the same computational
428 principles as younger adults.

429 Yet, ageing was associated with complex changes in reaction times to multisensory
430 stimuli. The profile of these age differences suggests that older adults took more time to respond
431 when the causal structure of the stimuli was more ambiguous and the task therefore more
432 challenging, such as when the visual stimulus was less reliable and/or the audiovisual disparity
433 of intermediate size. These response time findings were followed up in a speeded ventriloquist
434 task, where observers were explicitly instructed to respond as quickly as possible while
435 maintaining accuracy.

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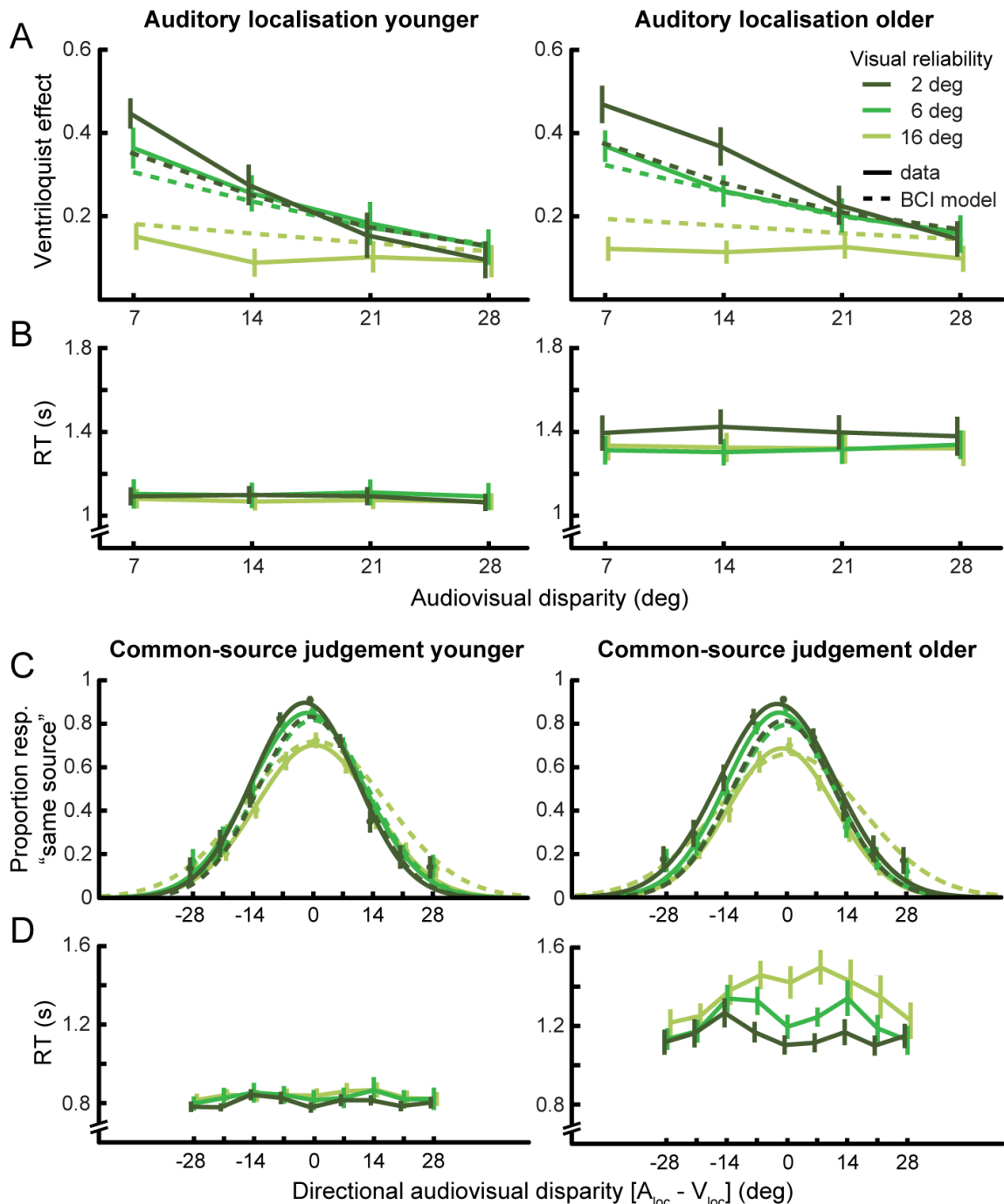
	Younger		Older		Mann-Whitney U			Bayes factors	
	Mean	SD	Mean	SD	W	p	η^2	BF_{10}	BF_{01}
Unisensory									
$\sigma_{P\ uni}$	37.20	35.69	24.79	28.63	299	.305	.02	0.46	2.16
$\sigma_{A\ uni}$	5.27	1.96	6.79	2.76	155	.026	.11	2.19	0.46
$\sigma_{V1\ uni}$	1.76	1.22	2.10	1.06	174	.075	.07	1.10	0.91
$\sigma_{V2\ uni}$	2.32	0.76	2.89	1.52	198	.218	.04	0.54	1.84
$\sigma_{V3\ uni}$	4.22	1.00	5.38	1.67	132	.005	.17	4.95	0.20
Bisensory									
P_{common}	0.42	0.13	0.43	0.13	245	.866	< .01	0.30	3.28
$\sigma_{P\ bi}$	38.71	25.88	32.20	27.37	303	.264	.03	0.40	2.49
$\sigma_{A\ bi}$	8.59	4.40	9.37	5.78	234	.677	< .01	0.35	2.84
$\sigma_{V1\ bi}$	3.19	4.08	3.08	3.13	241	.796	< .01	0.30	3.31
$\sigma_{V2\ bi}$	5.12	4.32	6.07	5.47	204	.274	.03	0.44	2.25
$\sigma_{V3\ bi}$	12.79	9.72	20.61	26.13	209	.327	.02	0.48	2.09

439 *Table 1.* Bayesian Causal Inference parameters (across-participants mean, SD) for younger ($n =$
440 23) and older ($n = 22$) participants. Mann-Whitney U tests with Bayes factors comparing the
441 BCI parameters between older and younger adults. The Bayesian Causal Inference model was
442 fitted jointly to unisensory and audiovisual conditions allowing for separate parameters for the
443 standard deviation of the spatial prior ($\sigma_{P,uni}$, $\sigma_{P,bi}$) and sensory noise ($\sigma_{A,uni}$, $\sigma_{A,bi}$, $\sigma_{V1,uni}$, $\sigma_{V1,bi}$, ...
444 $\sigma_{V3,uni}$, $\sigma_{V3,bi}$). BF_{10} quantifies degree of support for the alternative hypothesis that the groups
445 differ, relative to the null hypothesis; BF_{01} shows degree of support for the null hypothesis that
446 there is no difference between groups, relative to the alternative hypothesis.

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451 *Figure 2.* Behavioural responses, reaction times and BCI model predictions for younger and
 452 older adults. (A) Relative ventriloquist effect ($VE = [A_{resp} - A_{loc}] / [V_{loc} - A_{loc}]$) for auditory
 453 localisation, shown as a function of audiovisual disparity (x -axis, pooled over direction) and
 454 visual reliability (colour coded). Behavioural data (mean across subjects, solid lines) and the
 455 predictions of the Bayesian Causal Inference model (dashed lines) are shown. (B) Reaction
 456 times in auditory localisation task. (C) Proportion reported "same source" in common-source
 457 judgement task, as a function of audiovisual disparity and visual reliability. The panels show the
 458 Gaussians fitted to the behavioural response (mean across subjects, solid lines) and the
 459 predictions of the Bayesian Causal Inference model (dashed lines). (D) Reaction times (pooled
 460 over response; mean across subjects) in common-source judgement task. Error bars show ± 1
 461 *SEM*.

462 3.3. Speeded ventriloquist paradigm

463 3.3.1. Descriptive and GLM-based analysis

464 A simplified, speeded ventriloquist paradigm was used to assess younger and older
465 adults' responses to audiovisual spatial stimuli under speed instructions. Figure 3 summarises
466 response accuracy (panel B) and speed (panel C) for younger and older adults; trials are pooled
467 over left and right to characterise them in terms of spatial (in)congruence. Standard GLM
468 analysis of these results shows that older adults were significantly more accurate than younger
469 adults in the respond-visual task. Older adults were also significantly slower overall and,
470 importantly, age interacted with congruence in the respond-auditory tasks (see Section 3.2).
471 Mirroring the profile of the unspeeded common-source judgement responses, older adults again
472 took disproportionately longer to respond under the most challenging conditions where they
473 located the auditory signal in the presence of an incongruent visual distractor. See
474 Supplementary S4 for full GLM analysis.

475 3.3.2. Compatibility bias model

476 The compatibility bias model was fitted to participants' auditory spatial responses and
477 reaction times. This allowed us to characterise how younger and older observers accumulate
478 audiovisual evidence about spatial location and audiovisual congruency until a decisional
479 threshold is reached and a response given. Fitted parameters were compared using separate
480 Mann-Whitney U tests and the Bayesian version of the Mann-Whitney test (JASP Team, 2018;
481 van Doorn et al., 2018). See Table 2 for a summary of results.

482 Corroborating the findings of the BCI model, the age groups did not differ in their prior
483 tendency to integrate multisensory stimuli, quantified in this case by the compatibility prior β .
484 However, similar to the results from unspeeded localisation, the auditory signal (σ_{auditory}) was
485 significantly noisier in older than younger adults, leading to a slower accumulation of evidence
486 and thus (in combination with the motor slowing and higher decision threshold, see below)
487 slower response times. This indicates that it takes older participants longer than their younger
488 counterparts to reach any given level of evidence about the location of an auditory stimulus. The
489 groups did not differ in the variance of the visual input σ_{visual} . However, the remaining two
490 parameters were also significantly different between the groups. First the non-decision time t_{nd} ,

491 which captures the time between a decision is made and the response given, was significantly
 492 higher for the older age group. This is unsurprising; our older adults' impaired motor speed is
 493 confirmed by a separate finger-tapping task reported in Supplementary S2. Second, older adults
 494 also set their decision threshold q significantly higher, requiring more evidence before deciding
 495 on a response. See Figure 3A for an illustration of the model. Taken as a whole, our Bayesian
 496 modelling analysis confirms that older adults show a similar multisensory binding tendency and
 497 combine signals to the same computational principles as younger adults. However, older adults
 498 have noisier unisensory auditory spatial representations. As a result of i. those noisier auditory
 499 spatial representations, ii. a different speed-accuracy trade off (i.e. decision threshold q) and iii.
 500 slower motor speed (i.e. non-decision time t_{nd}) they have slower response times.

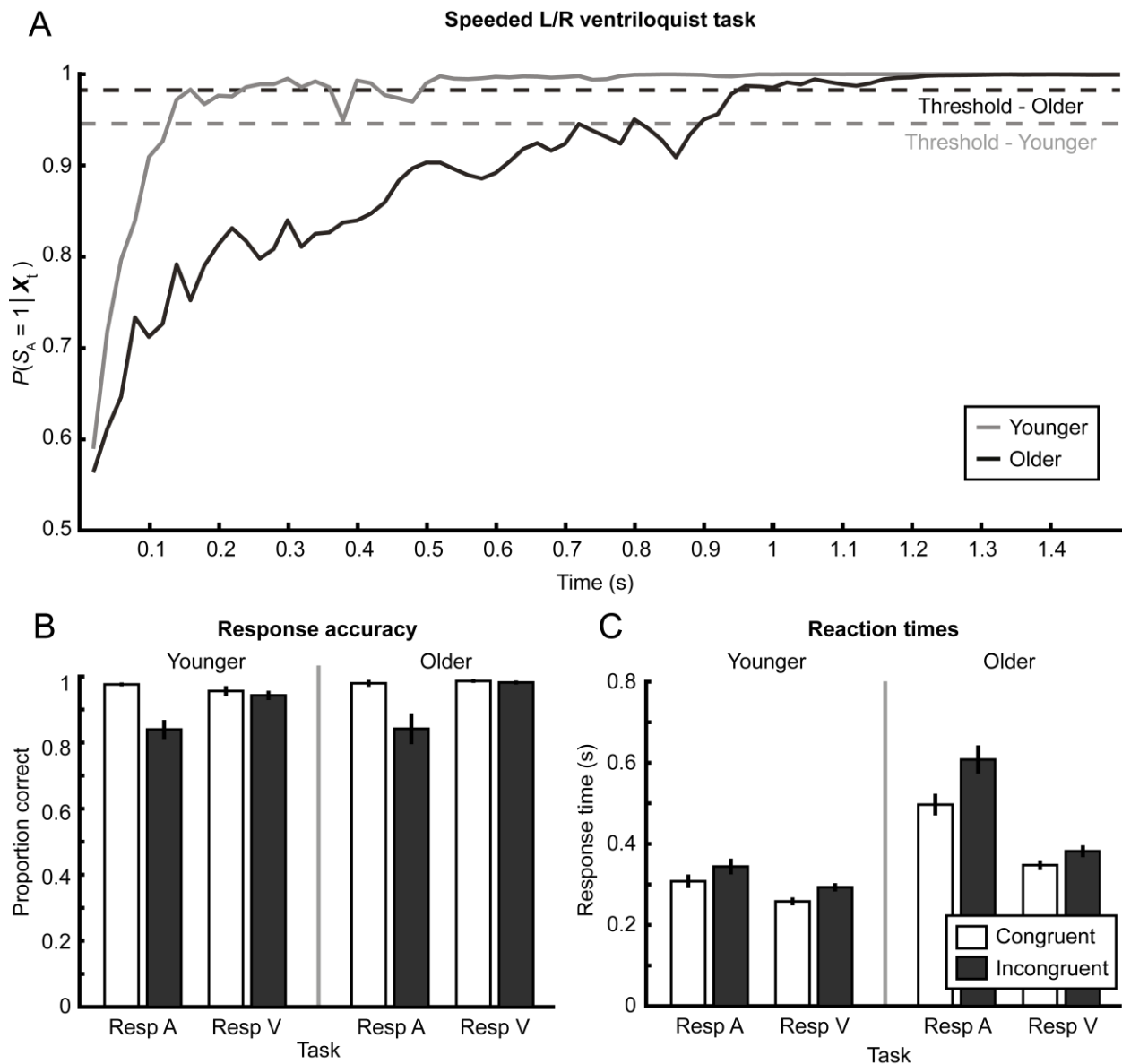
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	Younger		Older		Mann-Whitney U			Bayes factors	
	Mean	SD	Mean	SD	W	p	η^2	BF_{10}	BF_{01}
σ_A	1.53	0.54	2.93	4.01	164	.044	.09	3.11	0.32
σ_V	1.85	3.50	0.87	0.97	283	.507	.01	0.44	2.27
β	0.75	0.12	0.78	0.13	192	.169	.04	0.56	1.79
q	0.93	0.05	0.95	0.07	141	.010	.14	2.68	0.37
t_{nd}	0.22	0.05	0.33	0.07	54	< .001	.45	5101.52	< 0.01

502 *Table 2.* Compatibility bias parameters (across-participants mean, SD) for younger ($n = 23$) and
 503 older ($n = 22$) participants. Mann-Whitney U tests with Bayes factors comparing the
 504 compatibility bias parameters between older and younger adults: standard deviation of the
 505 auditory signal σ_A , standard deviation of the visual signal σ_V , compatibility prior β , response
 506 threshold q , and non-decision-time t_{nd} . BF_{10} quantifies degree of support for the alternative
 507 hypothesis that the groups differ, relative to the null hypothesis; BF_{01} shows degree of support
 508 for the null hypothesis that there is no difference between groups, relative to the alternative
 509 hypothesis.

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513 *Figure 3.* Speeded left/right ventriloquist paradigm and compatibility bias model. (A)

514 Accumulation of evidence traces for the compatibility bias model: for ‘respond auditory’ trials
 515 the observer is thought to accumulate audiovisual evidence about whether the auditory source is
 516 left = -1 or right = 1 within a trial until a decisional threshold is reached and a response elicited.
 517 Solid lines show the posterior probability $P(S_A = 1 | \mathbf{X}_t)$ as a function of within-trial time with
 518 auditory and visual inputs arriving every 10 ms. Each trace represents the mean across ten
 519 (incongruent, auditory right) simulated trials for a representative participant in each group, using
 520 these participant’s maximum likelihood parameters. Dashed lines indicate the participants’ fitted
 521 decisional thresholds. Older observers accumulate noisier evidence until a higher decisional
 522 threshold is reached. (B and C) Response accuracy and reaction times (across-participants mean
 523 ± 1 SEM) for respond-auditory and respond-visual tasks, separated by spatial congruence (i.e.
 524 pooled over left and right).

525

526

4. Discussion

527
528 This study investigated the effects of ageing on audiovisual integration for spatial
529 localisation under both speeded and unspeeded conditions. Our results demonstrate that ageing
530 does not fundamentally impact how observers integrate auditory and visual spatial signals into
531 representations of space: older adults showed the same audiovisual binding tendency as the
532 younger age group, and their behaviour conformed similarly to the predictions of the Bayesian
533 models. However, older adults showed noisier sensory, in particular auditory, representations.
534 Moreover, they used a higher decisional threshold, trading off speed for accuracy. This suggests
535 that older observers preserve audiovisual localisation performance, despite noisier sensory
536 representations, by sacrificing response speed.

537 These results may initially seem surprising in light of accumulating research showing
538 that ageing alters multisensory integration. For example, older adults have been shown to be
539 more susceptible to the sound-induced flash illusion (DeLoss et al., 2013; McGovern et al.,
540 2014; Setti et al., 2011) and to respond differently to McGurk-MacDonald stimuli (Sekiyama et
541 al., 2014; Setti et al., 2013). It is possible, however, for such effects to occur in the absence of
542 age differences in the actual computational processes underlying multisensory perception. Any
543 change that leads to an increase in sensory variances may make the arbitration between common
544 and separate sources more challenging, and/or change the relative weighting of the sensory
545 modalities in the final percept. Potentially, susceptibility to the sound-induced flash illusion is
546 changed with age because it relies on precise representations of stimulus timing that have been
547 shown to be impaired by ageing (Chan et al., 2014; Mazelová et al., 2003). Ng and Recanzone
548 (2017) provide a possible mechanism for this decline: a study of neural responses to simple
549 stimuli in macaque primary auditory cortex found that aged monkeys showed firing patterns that
550 were noisier (i.e. less temporally precise) and less selective than those seen in younger animals.
551 Age-related differences in perception of McGurk-MacDonald stimuli may also be due in part to
552 impaired temporal perception, as the fine temporal structure of speech signals is an important
553 cue for comprehension (especially in the context of competing noise; Moore, 2008). In this case
554 the effect is likely to be further compounded by reductions in speech comprehension, resulting
555 from presbycusis that particularly affects higher sound frequencies (Pichora-Fuller & Souza,

556 2003). These mechanisms are notably unisensory, and do not imply any change in the
557 computational process of multisensory integration itself.

558 The argument that older adults' changed multisensory perception results primarily from
559 differences in unisensory variances, and not from alterations in the computational mechanisms
560 *per se*, can also explain why we did not find significant age differences in the final responses to
561 our multisensory tasks: our unisensory results, and those of others (Dobrevá et al., 2011; Otte et
562 al., 2013), demonstrate only limited age differences in localisation ability. Based on screening
563 tests involving binary left/right judgements, younger and older adults were similar in their
564 ability to locate unisensory auditory and visual stimuli. The sensory variance parameters of a
565 Bayesian Causal Inference model fitted to multisensory localisation and common-source
566 judgement responses also did not differ between age groups. However, the same parameters
567 fitted using the more sensitive unisensory free-localisation responses did reveal small but
568 significant age differences in sensory variances, suggesting that older adults were less reliable in
569 their localisation of both auditory and (low-reliability) visual stimuli.

570 Existing literature is similarly ambiguous about age-related declines in (especially)
571 auditory localisation. Dobrevá et al. (2011) report limited but significant age differences in
572 observers' ability to freely localise transient broadband stimuli along the azimuth, while Otte et
573 al. (2013) found no such effects. It therefore seems that the effects of normal, healthy ageing on
574 auditory localisation ability may be subtle and difficult to detect.

575 In terms of visual localisation, we note that our older adults are likely to have had
576 impaired accommodation responses compared to the younger age group (Glasser & Campbell,
577 1997). Depending on the corrective lenses worn (participants were instructed to wear their
578 normal spectacles for testing), this may have led to the older group expending more effort to
579 keep the visual stimuli in focus and/or the stimuli appearing less focused. The small but
580 significant age differences we observed in unisensory visual localisation may be, in part, a
581 reflection of this reduced accommodation ability.

582 In light of these limited age differences in audiovisual localisation performance, it would
583 be interesting for future research to apply computational modelling to multisensory contexts
584 where strong age differences have been shown previously. The sound-induced flash illusion is a

585 strong candidate for this, as older adults are known to be significantly more susceptible (DeLoss
586 et al., 2013; McGovern et al., 2014; Setti et al., 2011) and young observers' perception of the
587 illusion has previously been successfully modelled using a BCI framework (Shams et al., 2005).
588 Fitting the BCI model to younger and older observers' responses would allow us to distinguish
589 whether age differences in perception of the sound-induced flash illusion result from changes in
590 unisensory variances (i.e. noise) or in observers' multisensory binding itself.

591 Our discussion of age differences in multisensory integration has thus far addressed only
592 final response choices, ignoring reaction times, but our natural environment does not afford us
593 infinite time to react to multisensory stimuli. When we define and evaluate multisensory
594 integration performance, it is therefore also important to consider the time taken to respond. In
595 fact, GLM-based analyses of common-source judgement reaction times suggested that older
596 adults took disproportionately longer to respond to audiovisual signals at intermediate levels of
597 spatial disparity, where the underlying causal structure (i.e. common vs. independent sources)
598 was less certain. Such findings imply the presence of differences in the groups' evidence
599 accumulation and decision-making process, and/or in their speed/accuracy criteria, even in an
600 unsped context.

601 We thus applied a simplified, speeded ventriloquist paradigm to directly address the
602 question of age differences in response times to multisensory spatial stimuli. GLM analyses
603 again showed that older adults were disproportionately slower in the most challenging
604 condition, in this case locating a sound in the presence of an incongruent visual distractor. To
605 characterise the computational processes underlying these differences, it is necessary to move
606 beyond the static BCI model to a dynamical approach that can make predictions jointly about
607 observers' spatial choices and response times. We thus applied the compatibility bias model
608 (Noppeney, Ostwald, & Werner, 2010; Yu et al., 2009) to participants' auditory judgement
609 responses in this paradigm.

610 This model assumes that the observer accumulates auditory and visual evidence about
611 the location of the reported stimulus, and about the causal structure of the signals, until a
612 decisional threshold is reached and a response given. It thereby provides an important
613 perspective on the dynamics of decision making within a trial. Again in this case, the

614 fundamental computations were not affected by healthy ageing. Likewise, older adults' prior
615 binding tendency was not significantly different from the younger group. However, the
616 compatibility bias model also revealed that older adults responded more slowly than younger
617 adults for three reasons. First, older adults have impaired motor speed, as indexed by the non-
618 decision time variable (and confirmed by a supplementary finger-tapping task; see
619 Supplementary S2). Second, they use a higher response threshold, requiring a greater degree of
620 certainty before a response is given. This is consistent with previous studies of age differences
621 in speed/accuracy trade-off (Smith & Brewer, 1995; Starns and Ratcliff, 2010). Third, the
622 compatibility bias model analysis suggests that the auditory representations are less reliable (i.e.
623 greater auditory variance) in older participants, such that evidence accumulates more slowly (see
624 Figure 3). In other words, the initial auditory representation may be noisier and less reliable for
625 older adults, but older observers can achieve equal performance levels (in terms of final
626 response choices) to younger participants by accumulating this noisy evidence for longer via
627 internal feedback loops.

628 It is important to note that the Bayesian causal inference model, and other approaches
629 that consider only the observer's final response, may be less sensitive to these age-related
630 changes in internal sensory noise (though the unisensory localisation data do provide some
631 evidence of small reliability differences). This illustrates how dynamical models that
632 accommodate both reaction times and final response choices can provide critical new insights
633 into evidence accumulation and perceptual decision making.

634 In conclusion, our results demonstrate that multisensory causal inference is preserved in
635 older adults. However, older observers only maintain this performance by accumulating noisier
636 auditory information over a longer period of time. When combined with well-established
637 changes in motor speed and speed/accuracy trade-off, this leads to significant and nonlinear age
638 differences in reaction times to complex multisensory stimuli during spatial localisation.

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Supplementary Methods and Results

744 S1. Unisensory L/R discrimination

745 We administered simple left/right forced-choice tasks to compare age groups on basic
746 unisensory spatial discrimination ability, and to ensure all participants were able to locate
747 auditory and visual stimuli in space sufficiently well for inclusion in the study. We chose these
748 measures as more directly relevant than, for example, pure tone hearing thresholds (older
749 participants are likely to have some impairment at higher frequencies, but this may not result in
750 any substantial decrease in auditory localisation ability).

751 Participants' spatial hearing performance (i.e. bias and reliability/variance of auditory
752 spatial representations) was measured using a forced left/right spatial discrimination task.
753 Individual bursts of white noise were emitted from one of seven locations (-21° , -14° , -7° , 0° ,
754 7° , 14° , or 21°) in a random order. Participants indicated as accurately as possible via key press
755 whether the sound originated from the left or right half of the screen. This task involved one
756 block of 210 trials (30 per location).

757 Visual spatial perception (i.e. bias and variance/reliability of visual spatial
758 representations) was measured using a similar left/right spatial discrimination task. Visual
759 stimuli with horizontal $SD = 2^\circ$ or 25° were randomly presented centred at one of seven
760 locations (-21° , -14° , -7° , 0° , 7° , 14° , or 21°); participants indicated whether the centre of the dot
761 cloud originated from the left or right side of the screen. This task involved two blocks of 210
762 trials each (total 30 trials per condition).

763 For each participant and stimulus type, we used the Palamedes toolbox for MATLAB
764 (Prins & Kingdom, 2009) to calculate the slope α and threshold β of cumulative Gaussians fitted
765 to the proportion of "perceived right" responses as a function of true stimulus location. These
766 parameters were allowed to vary freely, while the lapse parameters γ and λ were constrained to
767 be the same and to fall between 0 and 0.05 (Wichmann & Hill, 2001).

768 Older and younger adults were closely matched on these tasks. For auditory spatial
769 discrimination, an independent-samples t -test revealed no significant effect of age on slope or
770 threshold values, $p > .05$.

771 For visual discrimination, a 2 (age) x 2 (reliability) mixed ANOVA of slope values

772 revealed a strong main effect of spatial reliability as expected, $F(1,43) = 20.186, p < .001, \eta^2 =$
773 $.32$, but no main effect of age or age x reliability interaction. A similar mixed ANOVA of
774 threshold values revealed no significant main effects of age or reliability, nor any interaction, p
775 $> .05$.

776 No participants were excluded based on their performance in this task. The lowest-
777 performing participant had a fitted slope (accuracy) parameter of 0.10 in the auditory task,
778 which still represents performance well above chance for sounds presented 7° left or right of
779 centre. Auditory threshold (i.e. left/right bias) values were all within 7° (i.e. speaker separation
780 distance) of centre. Similarly, the poorest high reliability visual slope was 0.22, with the most
781 extreme threshold value only 2.52° from centre.

782 **S2. Motor speed**

783 We used a finger tapping task to compare the age groups in terms of basic motor speed,
784 and to screen participants for significant motor impairment that may affect their ability to
785 respond to the tasks. Participants were instructed to ball their hand into a fist, extending their
786 index finger, and to repeatedly tap a key as quickly as possible for 20 seconds. An on-screen
787 progress bar and countdown provided feedback on performance and time remaining. The task
788 was repeated four times (twice per hand, not including a preceding 10-second practice with each
789 hand).

790 We analysed the data in terms of the median time between finger taps in seconds (pooled
791 across hands). A two-sample Welch's t -test confirmed that younger participants ($M = 0.175, SD$
792 $= 0.014$) were significantly faster than their older counterparts ($M = 0.189, SD = 0.024$), $t(43) =$
793 $2.459, p = .018, d = 0.73$. No participants were excluded based on their performance here, as the
794 slowest responders were within two standard deviations of their respective group means (a
795 conservative threshold).

796 **S3. GLM analysis of unspeeded ventriloquist paradigm**

797 As well as fitting the Bayesian Causal Inference model, we also performed classical
798 GLM-based analyses on final responses and response times in the unspeeded ventriloquist
799 paradigm. The results are summarised in Figure 2 of the main manuscript.

800 For auditory localisation responses, the magnitude of the ventriloquist effect was
 801 calculated as $VE = (A_{resp} - A_{loc}) / (V_{loc} - A_{loc})$ and the mean for each condition was
 802 entered into a 2 (age) x 4 (disparity [pooled over direction]) x 3 (visual reliability) mixed
 803 ANOVA. This revealed significant main effects of disparity, $F(3, 129) = 85.31, p < .001, \eta^2 =$
 804 $.67$, reliability, $F(2, 86) = 49.02, p < .001, \eta^2 = .53$, and a disparity*reliability interaction, $F(6,$
 805 $258) = 30.00, p < .001, \eta^2 = .41$. However, no main effect of, or interaction with, age was
 806 apparent, $p > .05$. See Figure 2A of the main manuscript.

807 For common-source judgement responses, we fitted three-parameter Gaussians (peak,
 808 mean, standard deviation) to the probability of perceiving a common source as a function of
 809 (signed) audiovisual disparity ($A_{loc} - V_{loc}$) and compared these parameters separately in 2
 810 (age) x 3 (visual reliability) mixed ANOVAs. The peak of the Gaussian varied with visual
 811 reliability level, $F(2, 84) = 49.24, p < .001, \eta^2 = .54$. The mean and width parameters were not
 812 significantly affected by visual reliability, and no main effect of (or interaction with) age was
 813 apparent for any of the parameters, $p > .05$. See Figure 2C of the main manuscript.

814 Median response times to the auditory localisation task were analysed in a 2 (age) x 4
 815 (disparity [pooled over direction]) x 3 (visual reliability) mixed ANOVA. Aside from a main
 816 effect of age, $F(1, 43) = 9.77, p = .003, \eta^2 = .19$, response times did not differ significantly
 817 between conditions, $p > .05$. This is unsurprising, as mouse movements are far more variable
 818 (and take much longer) than button presses, so any small effects of condition are likely to be
 819 lost. See Figure 2B of the main manuscript.

820 Median response times to the common-source judgement task were analysed using a 2
 821 (age) x 9 (signed disparity) x 3 (visual reliability) mixed ANOVA. A main effect of age
 822 confirmed that older adults were slower overall, $F(1, 43) = 44.19, p < .001, \eta^2 = .51$.
 823 Furthermore, age interacted significantly with visual reliability, $F(2, 86) = 4.92, p = .009, \eta^2 =$
 824 $.09$, and audiovisual disparity, $F(8, 344) = 3.07, p = .002, \eta^2 = .06$, and the three-way interaction
 825 was also significant, $F(16, 688) = 2.63, p < .001, \eta^2 = .05$. Main effects of reliability, $F(2, 86) =$
 826 $9.41, p < .001, \eta^2 = .16$, and disparity, $F(8, 344) = 8.05, p < .001, \eta^2 = .15$, were also apparent, as
 827 was the interaction between these, $F(16, 688) = 3.55, p < .001, \eta^2 = .05$. See Figure 2C of the
 828 main manuscript.

829 **S4. GLM analysis of speeded ventriloquist paradigm**

830 We performed GLM-based analyses on response times and choices to supplement the
831 compatibility bias model in the speeded ventriloquist task. For these analyses, trials were pooled
832 over left and right locations and hence characterised as spatially congruent or incongruent.
833 Accuracy was quantified as the proportion of correct localisation responses per condition; reaction
834 times were per-condition medians within each participant. We performed four separate 2 (age) x
835 2 (congruence) mixed ANOVAs, analysing accuracy and reaction times for both the respond-
836 auditory and respond-visual tasks. These results are summarised in panels B and C of Figure 3 of
837 the main manuscript.

838 A mixed ANOVA of response accuracies in the respond-auditory task revealed a main
839 effect of congruence, $F(1, 43) = 26.46, p < .001, \eta^2 = .38$ (congruent > incongruent), but no
840 main effect of age or interaction, $p > .05$. Conversely, in the respond-visual task a main effect of
841 age showed that older adults were significantly more accurate, $F(1, 43) = 7.28, p = .010, \eta^2 =$
842 $.15$, possibly due to their higher response threshold (as revealed by the compatibility bias
843 model); a main effect of congruence was also present, $F(1, 43) = 5.01, p = .030, \eta^2 = .10$
844 (congruent > incongruent), but age and congruence did not significantly interact, $p > .05$.

845 A mixed ANOVA of response times to the respond-auditory task showed, through a
846 main effect of age, that older adults were significantly slower overall, $F(1, 43) = 45.01, p < .001,$
847 $\eta^2 = .51$. A main effect of congruence was also present, $F(1, 43) = 60.57, p < .001, \eta^2 = .51$
848 (congruent < incongruent). Importantly, these factors also interacted, $F(1, 43) = 15.60, p < .001,$
849 $\eta^2 = .13$, corroborating the finding from the unspeeded paradigm that older adults were
850 disproportionately slower when the task was more challenging (i.e. locating a sound in the
851 presence of an incongruent visual distractor). Main effects of age, $F(1, 43) = 38.52, p < .001, \eta^2$
852 $= .47$, and congruence, $F(1, 43) = 38.89, p < .001, \eta^2 = .48$, on response times were also revealed
853 for the respond-visual task, but these did not significantly interact, $p > .05$. See Figure 3B and
854 3C for a summary.

855 **S5. BCI model selection**

856 In Section 2.4.2 of the main text we describe a Bayesian Causal Inference model with
857 eleven free parameters, which fitted separate sensory noise and spatial prior parameters

858 depending on the trial type (observers were presented with auditory, visual, and audiovisual
 859 signals in separate blocks). However, it is also possible that sensory variances are shared across
 860 unisensory and audiovisual blocks, rather than independent. In such a case, the visual and
 861 auditory variances would depend only on the external sensory signals and noise imposed by
 862 peripheral sensory processing (irrespective of context and task), and the estimation of the
 863 auditory and visual variances jointly from all data would provide more precise parameter
 864 estimates. If sensory variances are *not* shared across unisensory and audiovisual blocks, treating
 865 them as though they are would lead to biased estimation. Likewise, the spatial priors may, or
 866 may not, depend on stimulus blocks/task context. To formally address these questions we
 867 compared the following three models, which differed in whether the sensory variances and
 868 spatial prior were allowed to vary across task context.

869 Model A (i.e. the standard Bayesian inference model with 6 parameters) assumed that
 870 sensory variances and priors were equal for unisensory and bisensory blocks. This model thus
 871 included six parameters: p_{common} , σ_P , σ_A , σ_{V1} , σ_{V2} , σ_{V3} .

872 Model B constrained the spatial prior to be equal for unisensory and audiovisual blocks,
 873 but allowed the sensory variances to differ between unisensory and audiovisual contexts,
 874 yielding ten parameters: p_{common} , σ_P , $\sigma_{A\ uni}$, $\sigma_{V1\ uni}$, $\sigma_{V2\ uni}$, $\sigma_{V3\ uni}$, $\sigma_{A\ bi}$, $\sigma_{V1\ bi}$, $\sigma_{V2\ bi}$, $\sigma_{V3\ bi}$ (with the
 875 indices *uni* and *bi* referring to unisensory and bisensory blocks respectively).

876 Model C allowed the sensory variances and spatial prior variances to differ between
 877 unisensory and audiovisual contexts. Hence, this model included 11 parameters: p_{common} , $\sigma_{P\ uni}$,
 878 $\sigma_{A\ uni}$, $\sigma_{V1\ uni}$, $\sigma_{V2\ uni}$, $\sigma_{V3\ uni}$, $\sigma_{P\ bi}$, $\sigma_{A\ bi}$, $\sigma_{V1\ bi}$, $\sigma_{V2\ bi}$, $\sigma_{V3\ bi}$.

879 We arbitrated between these three models using the Bayesian information criterion
 880 (BIC) as an approximation to the model evidence. We performed Bayesian model comparison
 881 (Rigoux et al., 2014) at the group (random effects) level as implemented in SPM12 (Stephan et
 882 al., 2009; Friston et al., 1994), pooled across age groups, to obtain the protected exceedance
 883 probability (the probability that a given model is more likely than any other model, beyond
 884 differences due to chance) for the candidate models.

885 Model C, that fitted sensory variance and spatial prior parameters separately for
 886 unisensory and bisensory contexts, outperformed the others at the group level with a protected

887 exceedance probability of 0.58 (compared with values of 0.18 for Model A and 0.24 for Model
 888 B). This suggests that the task and stimulus context influenced the estimates of sensory
 889 variances and spatial priors to some degree. We therefore report, and compare between groups,
 890 the parameters obtained from Model C.

891 S6. BCI analysis including motor noise

892 To account for the possibility of age differences in ability to use a mouse, we fitted a
 893 version of our winning BCI model that included σ_{motor} as an extra free parameter. A summary of
 894 the results is given below. It basically replicates the main findings from our main analysis and
 895 reveals no significant differences between age groups for motor noise.

896

	Younger		Older		Mann-Whitney U			Bayes factors	
	Mean	SD	Mean	SD	W	p	η^2	BF_{10}	BF_{01}
Unisensory									
$\sigma_{P\ uni}$	37.45	33.66	28.61	32.19	297	.327	.02	0.41	2.43
$\sigma_{A\ uni}$	4.66	1.75	6.17	2.82	167	.052	.09	1.90	0.53
$\sigma_{V1\ uni}$	0.69	0.71	1.19	1.40	226	.551	.01	0.74	1.35
$\sigma_{V2\ uni}$	1.21	0.97	1.71	1.62	230	.613	.01	0.56	1.79
$\sigma_{V3\ uni}$	3.45	1.27	4.56	2.34	137	.008	.15	1.40	0.71
Bisensory									
P_{common}	0.42	0.16	0.45	0.12	230	.613	.01	0.36	2.78
$\sigma_{P\ bi}$	41.07	27.89	30.77	26.81	304	.254	.03	0.56	1.79
$\sigma_{A\ bi}$	8.04	4.45	8.39	4.89	233	.661	.01	0.30	3.33
$\sigma_{V1\ bi}$	2.06	2.07	3.43	5.61	243	.831	< .01	0.48	2.08
$\sigma_{V2\ bi}$	4.48	3.13	5.30	5.06	229	.597	.01	0.35	2.86
$\sigma_{V3\ bi}$	13.93	18.11	18.91	24.70	223	.507	.01	0.38	2.63
σ_{motor}	2.13	1.41	1.97	1.12	264	0.813	< .01	0.32	3.15

897 *Table S1.* Bayesian Causal Inference parameters (across-participants mean, SD) for younger (n
 898 = 23) and older (n = 22) participants, including fitted motor kernel. Mann-Whitney U tests with
 899 Bayes factors comparing the BCI parameters between older and younger adults. The Bayesian
 900 Causal Inference model was fitted jointly to unisensory and audiovisual conditions allowing for
 901 separate parameters for the standard deviation of the spatial prior ($\sigma_{P,uni}$, $\sigma_{P,bi}$) and sensory noise
 902 ($\sigma_{A,uni}$, $\sigma_{A,bi}$, $\sigma_{V1\ uni}$, $\sigma_{V1\ bi}$...). The standard deviation of motor response σ_{motor} was constrained to
 903 be the same for unisensory and multisensory localisation responses. BF_{10} quantifies degree of
 904 support for the alternative hypothesis that the groups differ, relative to the null hypothesis; BF_{01}

905 shows degree of support for the null hypothesis that there is no difference between groups,
906 relative to the alternative hypothesis.
907

Supplementary References

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