Supporting Information

Zaidel et al. 10.1073/pnas.1506582112

SI Text

Bayesian Prior Simulation (In Conjunction with Fig. S3). Individuals with ASD and controls performed differently when multisensory integration was tested with complete visual noise (0% coherence). Although those with ASD seemed to perform better initially, controls started out worse and improved over time (Fig. 4). Here, good performance required correct estimation that the visual cue was completely noisy. It seems that individuals with ASD could sense this situation better from the outset, whereas controls initially integrated more visual noise. This finding seems to be in line with the Bayesian hypothesis of ASD individuals being more attuned to the external signal, whereas controls are more affected by priors (here, their prior was to use the visual cue, as they had done till now). This prior initially perturbed their behavior, but also allowed for flexibility and changes over time. We present here a simulation to describe how different priors can lead to the results observed in Fig. 4.

The simulation is presented in Fig. S3. In accordance with previous studies, we assume a model in which visual and vestibular integration weights (w_{vis} and w_{ves}, respectively) sum to 1 (1). Therefore, it is enough to present a simulation for the visual weight (w_{vis}) only. This simulation serves as a tool to explain our hypothesis of reduced (and inflexible) Bayesian priors in ASD. For simplicity, we used Gaussian distributions, which were cut off at the bounds (w_{vis} is bound by [0, 1]). A more complex depiction could use distributions that take into account boundary effects. However, the general principles are conveyed with this simple simulation, which indeed shows that our data are consistent with the Bayesian prior hypothesis.

Fig. S3*A* presents simulated likelihood distributions for w_{vis}, given a 0% coherence visual stimulus. Identical likelihoods were used for controls and individuals with ASD. The likelihoods are simply one-tailed Gaussians with $\mu = 0$ and $\sigma = 0.1$ (and therefore maximum likelihood at $w_{\mathrm{vis}} = 0$). Because all participants had experienced only nonzero coherence multisensory sessions (with appropriate visual–vestibular integration) before exposure to their first 0% coherence block, we assume that their initial priors represented midrange values for w_{vis}. We therefore chose prior means to reflect equal visual and vestibular weighting (Gaussians with mean: $\mu = 0.5$) for both individuals with ASD and controls (Fig. S3*B*; repeat 1). This method led to nonzero maximum aposteriori (MAP) estimates for w_{vis} (Fig. S3 *C* and *D*). The simulated noise effect (Fig. S3*E*) was calculated in the same way as in Fig. 4 (ratio of combined to vestibular thresholds), using a representative vestibular threshold of $\sigma = 4°$ (Fig. S1) and the MAP estimates of w_{vis} for visual–vestibular weighting. This calculation demonstrates overweighting of the visual noise for both ASD and controls (Fig. S3*E*; as observed in the actual data, Fig. 4).

However, we introduced two differences between control and ASD priors. (*i*) We set the controls' prior to be narrower vs. ASD ($\sigma = 0.2$ and 0.5 for controls and ASD, respectively). This narrower prior led initially to greater overweighting of the visual noise in controls vs. ASD (Fig. S3*E*; as observed in the actual data, Fig. 4). (*ii*) The controls' prior had some flexibility (i.e., its mean shifted closer to zero by a factor of 0.5 for each block repeat: $\mu = 0.5, 0.25$, etc.). This flexibility led to a reduction of the noise effect in controls (Fig. S3*E*, *Left*; as observed in the actual control data, Fig. 4). In contrast, the ASD prior was wider and did not shift. It led to better initial performance than controls (being a wider and less influential prior), but no change over time (Fig. S3*E*, *Right*; as seen in the actual ASD data, Fig. 4). This simulation of wider (i.e., less influential) and nonflexible priors in ASD is in line with our results in Fig. 4.

Motion System. Participants were seated comfortably in a cockpit-style chair and restrained safely with a five-point racing harness. Each participant wore a custom-made thermoplastic mask, which was attached to the back of the chair for head stabilization. The chair, a projector, and a large projection screen were all mounted on a motion platform (6DOF2000E; Moog) to provide synchronized visual and vestibular input. Because of a technical malfunction of one of our motion systems, part of the experiments was performed on a second system, designed in the same way as the first, with only minor differences. Both systems used digital light-processing projectors (Galaxy 6, Barco in system 1; LV-8235UST, Canon in system 2) front projected onto a screen, ~65 cm from the eyes in system 1 and ~43 cm from the eyes in system 2. Active 3D glasses (CrystalEyes 3; RealD) provided stereoscopic vision in both systems, such that motion and task parameters (heading angles, motion profile, etc.) were kept the same. We confirmed that there was no difference in behavioral performance between the two systems by comparing control-group data gathered in the one vs. the other, using a two-way ANOVA (factors: coherence and motion-system). There was no significant effect of which motion system was used—neither on the vestibular ($P = 0.4$) nor visual ($P = 0.9$) thresholds.

Staircase Procedure. Within each block, a staircase procedure (2) was run for each stimulus independently, but interleaved. Possible stimulus heading values were spaced logarithmically around straight ahead (±16°, 8°, 4°, 2°, 1°, 0.5°) with heading sign (positive or negative, for right or left of straight ahead, respectively) selected randomly for each trial. Each staircase began with the easiest heading (±16°). After a correct response, heading eccentricity was reduced (i.e., the task became more difficult) 30% of the time, and after an incorrect response, it was increased (i.e., became easier) 80% of the time. This staircase rule converges to the 73% point of the psychometric function (3). Each block comprised 300 trials (100 for visual-only, vestibular-only, and combined cues, each) and lasted ~30 min; 0% coherence blocks comprised 200 trials (no visual-only cues).

1. Fetsch CR, Turner AH, DeAngelis GC, Angelaki DE (2009) Dynamic reweighting of visual and vestibular cues during self-motion perception. *J Neurosci* 29(49):15601–15612.
2. Cornsweet TN (1962) The staircase-method in psychophysics. *Am J Psychol* 75:485–491.
3. MacNeilage PR, Banks MS, DeAngelis GC, Angelaki DE (2010) Vestibular heading discrimination and sensitivity to linear acceleration in head and world coordinates. *J Neurosci* 30(27):9084–9094.

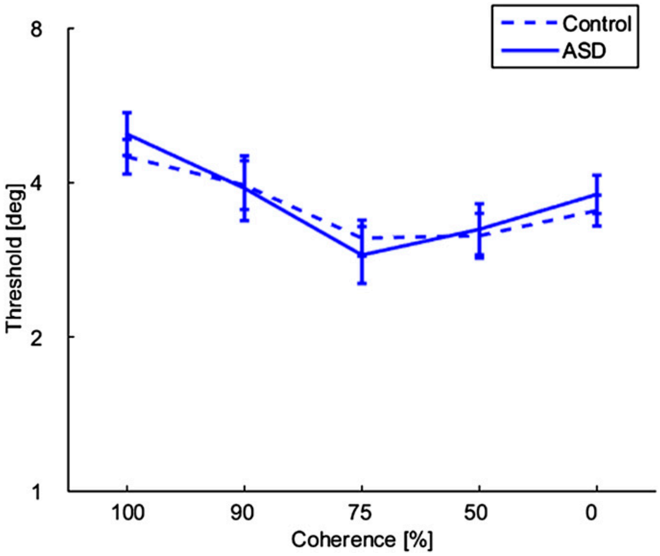

Fig. S1. Vestibular thresholds, related to Fig. 2. Mean ± SEM (log-scale) vestibular psychometric thresholds are presented as a function of visual coherence for controls (dashed line) and participants with ASD (solid line).

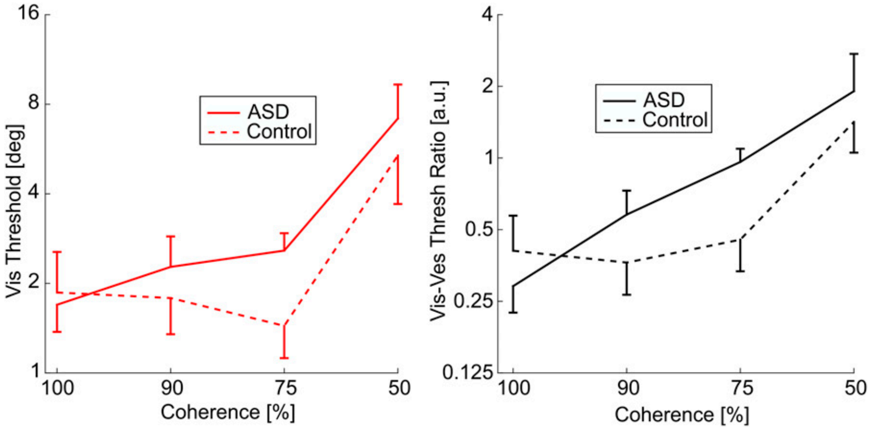

Fig. S2. Data subset with narrow age range (15–17 y), related to Fig. 2. The same analysis was performed as in Fig. 2*B* (all conventions the same), but on a subset of participants with narrower age range (ages 15–17 y old) centered on the age range used in this study (*n* = 7 ASD and *n* = 6 controls).

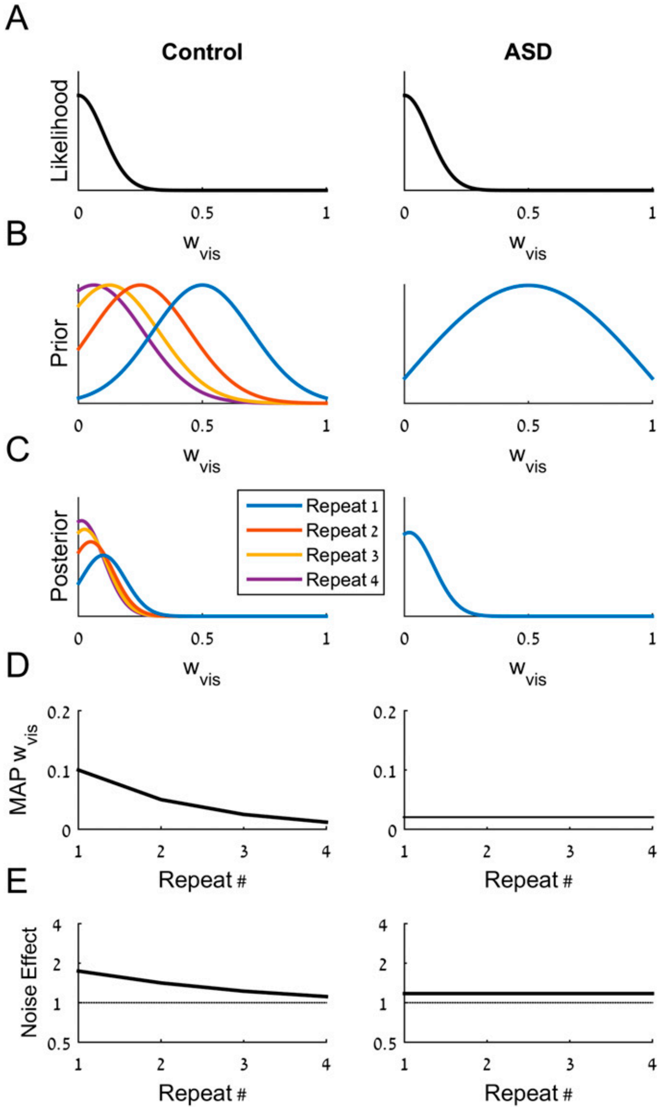

Fig. S3. Simulating the effect of cue weight priors, related to Fig. 4. (*A*) Simulated likelihood distribution for visual weights (w_{vis}) given a multisensory stimulus with 0% visual coherence. The same likelihood is used for both controls (*Left*) and ASD (*Right*). (*B*) Prior distributions for w_{vis} reflect a narrower prior for controls (*Left*) vs. ASD (*Right*), which shifts over block repeats for controls (no shift for ASD). For simple viewing of this shift, priors here were not renormalized after cropping at the bounds (this has no effect; posterior distributions were normalized). (*C–E*) Resulting posterior distributions shift leftward for the controls across block repeats (*C*, *Left*), resulting in a reduction of both the w_{vis} MAP estimate (*D*, *Left*) and noise effect (*E*, *Left*; like Fig. 4). A wider and static ASD prior (*B*, *Right*) results initially in better performance (lower noise effect), which does not change over time (*E*, *Right*).

Table S1. ASD participant data, related to *Materials and Methods*

	Participant details			ADOS			Vineland II*	IQ*		
ASD participant no.	Age	Sex	SCQ	Social affect	Communication and social interaction	Restricted and repetitive behavior	Composite standard score	Verbal	Nonverbal	Full scale
1	17	M	11				**66**			
2	15	M	11							
3	14	M	12					**104**	**119**	
4	18	M	15	7	8	2	76	92	110	104
5	14	M	16					**95**		**68**
6	15	M	16							
7	15	M	16	9	13	6	71	110	107	109
8	14	M	19	6	8	3	69	104	107	106
9	14	M	19	8	10	2	81	86	109	101
10	14	M	20							
11	15	M	26	9	11	2	63	120	102	118
12	15	M	15							
13	18	M	13				73			92
14	16	M	17	6	8	2	66	108	114	116
Average ± SD	15.3 ± 1.4	100% M	17.5 ± 4.0	7.5 ± 1.4	9.7 ± 2.1	2.8 ± 1.6	71.3 ± 5.9	102.1 ± 10.9	108.2 ± 5.5	101.8 ± 15.9

SCQ scores are current from the time of the study. Other scores are from within 2–5 y of the study.

*Bold type marks older scores (tested > 5 y before the study) that may not be representative of current performance.

Table S2. Control participant data, related to *Materials and Methods*

Control participant no.	Age	Sex	SCQ
1	16	M	3
2	15	M	3
3	16	M	4
4	13	M	5
5	14	M	6
6	18	M	7
7	18	M	5
8	18	M	1
9	16	M	1
10	18	M	6
11	13	M	5
12	14	M	4
13	13	M	3
14	18	M	6
15	18	M	1
16	13	M	1
17	15	M	3
18	14	M	9
19	14	M	10
20	19	M	4
21	19	M	8
22	15	M	7
Average ± SD	15.8 ± 2.1	100% M	4.6 ± 2.6

SCQ scores are current from the time of the study.