Additional file 2

Beyond the Romberg Ratio: Direction-Resolved Modeling Reveals Reduced Visual Stabilization on Compliant Surfaces in Aging

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Supplementary Figures

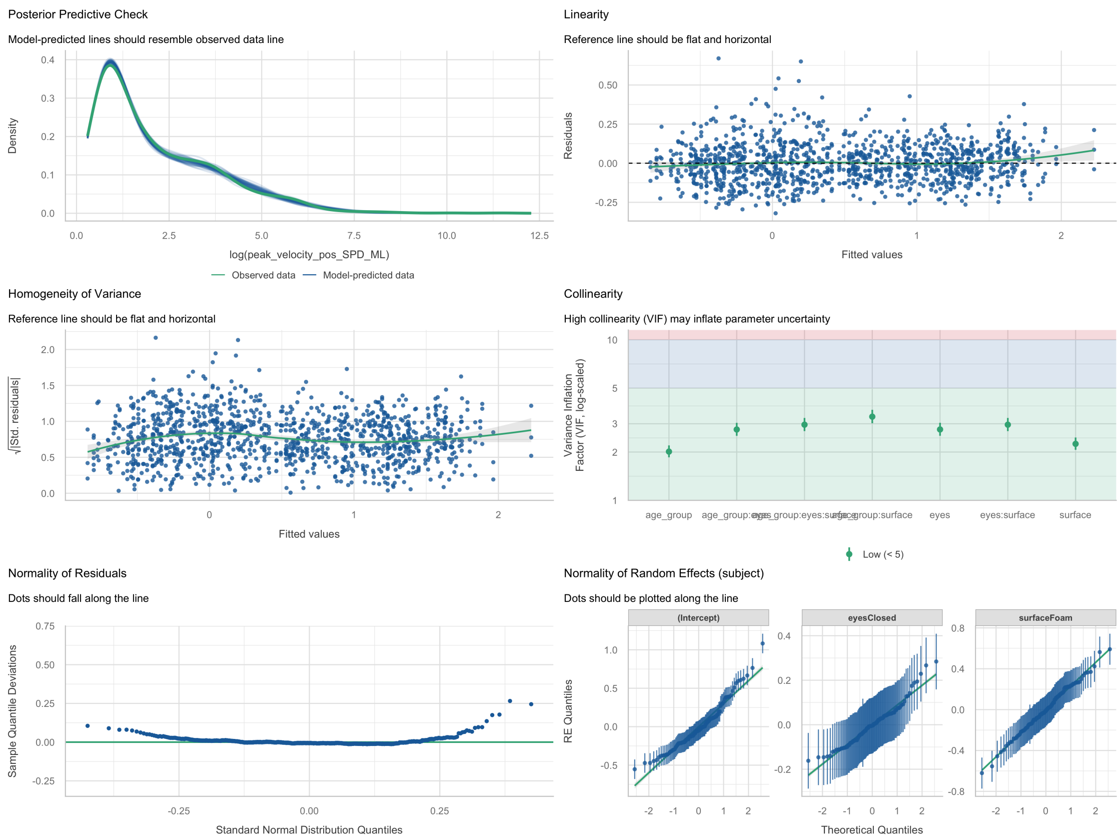

Figure S1: Diagnostic checks for the mediolateral linear mixed-effects model. Model assumptions for the trial-level model of log-transformed mediolateral peak sway velocity (1173 observations from 98 participants). **Posterior predictive check:** the distribution of model-predicted values closely tracks the observed distribution. **Linearity:** residuals show no systematic trend across fitted values. **Homogeneity of variance:** the spread of standardized residuals is approximately constant across fitted values. **Collinearity:** variance inflation factors for all fixed-effect terms are low (< 5). **Normality of residuals:** residual quantiles fall close to the reference line, with a mild departure in the upper tail reflecting the residual right-skew of sway velocity. **Normality of random effects:** the by-subject random intercept and the random slopes for vision and surface are approximately normally distributed. Together these checks indicate that the model assumptions are adequately met on the log scale. The influential-observations panel is omitted; a separate check confirmed that no observation exceeded conventional leverage or Cook's-distance thresholds.

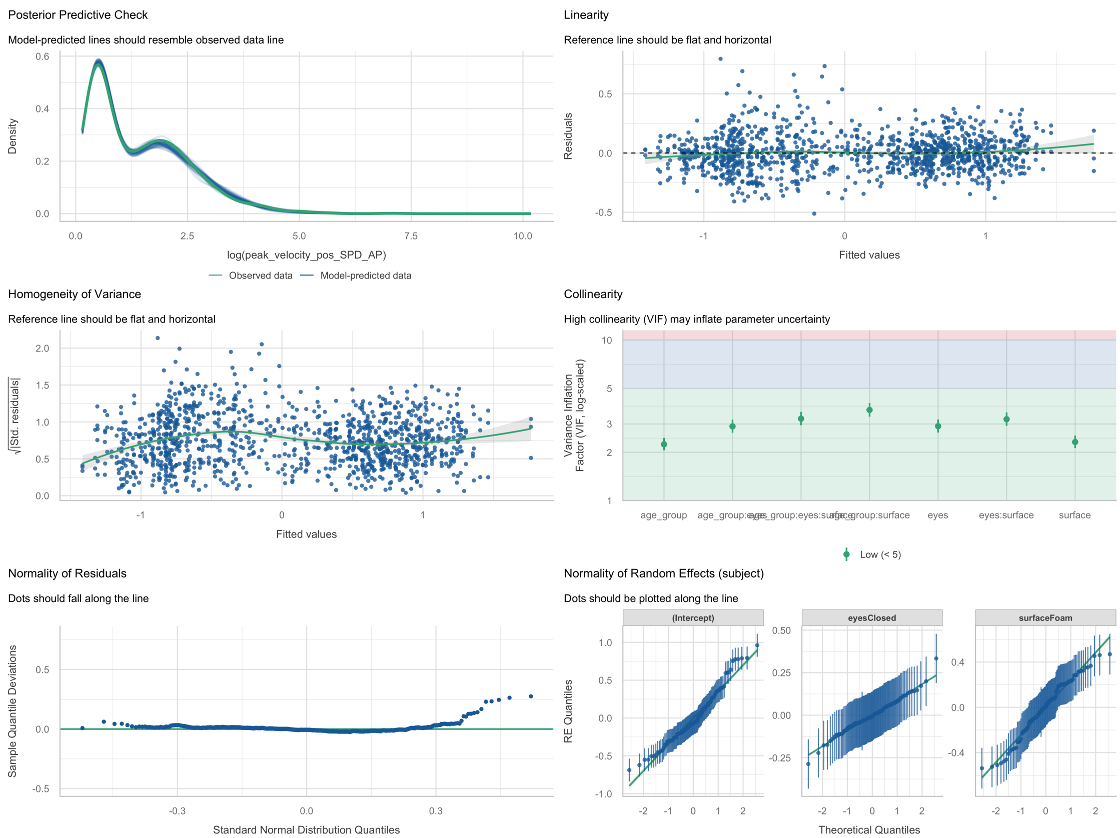

Figure S2: Diagnostic checks for the anteroposterior linear mixed-effects model. Model assumptions for the trial-level model of log-transformed anteroposterior peak sway velocity (1173 observations from 98 participants). Panels are as described for Figure S1: the posterior predictive check, residual linearity, homogeneity of variance, collinearity (variance inflation factors < 5), normality of residuals, and normality of the by-subject random effects. Residual quantiles fall close to the reference line through the central range, with a departure in the upper tail reflecting the residual right-skew of sway velocity; given the large sample, this does not materially affect the fixed-effect inference. The remaining checks indicate that the model assumptions are adequately met on the log scale. The influential-observations panel is omitted; a separate check confirmed that no observation exceeded conventional leverage or Cook's-distance thresholds.

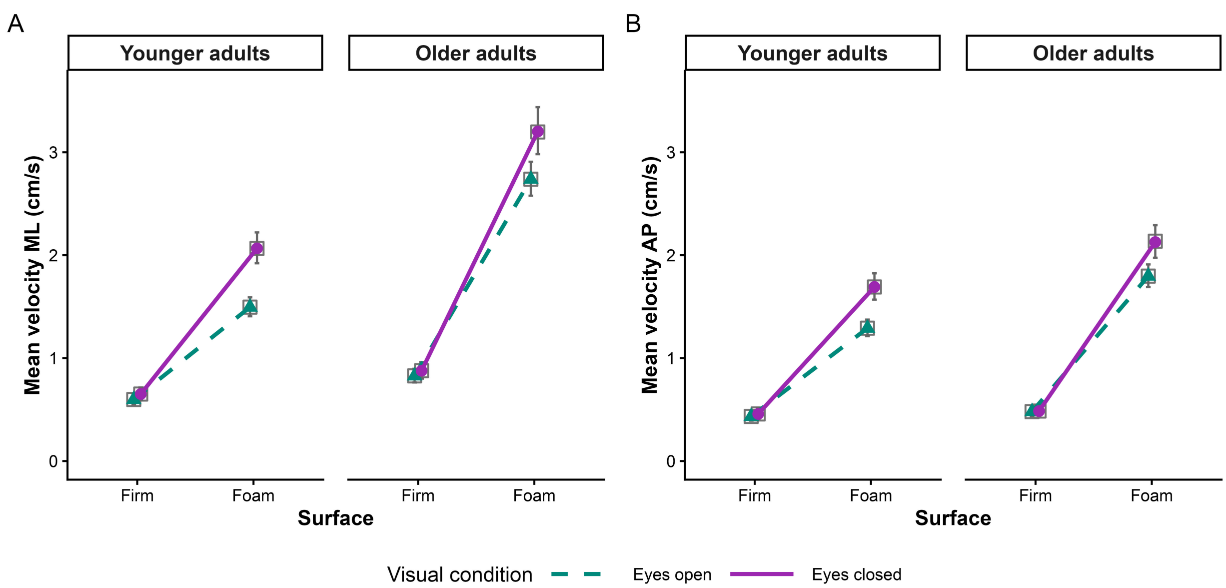

Figure S3: Model-based predicted mean sway velocity. Predicted mean sway velocity in the mediolateral (A) and anteroposterior (B) directions as a function of surface and visual condition, shown separately for older and younger adults. This figure uses the same conventions as Fig. 2 but with mean velocity in place of peak velocity as the outcome. Solid and dashed lines denote model-predicted values for eyes closed and eyes open, respectively; whiskers indicate 95% confidence intervals. Empty grey squares denote observed geometric condition means. As with peak velocity, the amplified and age-asymmetric effect of vision on foam—younger adults reducing sway more than older adults upon eye opening—is pronounced in the ML direction (A) but not the AP direction (B), corroborating the peak-velocity analysis (Fig. 2, Table 3) with an independent velocity measure.

Supplementary Tables

Table S1: Fixed effects from the linear mixed models (REML) of log-transformed peak sway velocity in the mediolateral (ML) and anteroposterior (AP) directions. Reference levels: young adults, eyes open, firm surface; coefficients represent increments from that baseline. Degrees of freedom and p-values use the Satterthwaite approximation.

	ML				AP			
Effect	β	SE	t	p	β	SE	t	p
Intercept	-0.330	0.047	-7.04	$<$ .001	-0.704	0.055	-12.88	$<$ .001
Age (Older)	0.353	0.066	5.38	$<$ .001	0.085	0.077	1.11	.269
Vision (Closed)	0.070	0.023	3.02	.003	0.061	0.027	2.28	.024
Surface (Foam)	0.966	0.039	24.63	$<$ .001	1.180	0.043	27.39	$<$ .001
Age x Vision	-0.010	0.033	-0.31	.759	-0.034	0.037	-0.91	.365
Age x Surface	0.335	0.055	6.11	$<$ .001	0.251	0.060	4.16	$<$ .001
Vision x Surface	0.287	0.024	12.01	$<$ .001	0.229	0.029	7.88	$<$ .001
Age x Vision x Surface	-0.172	0.034	-5.13	$<$ .001	-0.070	0.041	-1.71	.087

Note. Number of subjects = 98. Number of observations = 1173. Models were estimated using restricted maximum likelihood (REML) with the BOBYQA optimizer.

Table S2: Random effects from the linear mixed models (REML) of log-transformed peak sway velocity in the mediolateral (ML) and anteroposterior (AP) directions. Reference levels: young adults, eyes open, firm surface. By-subject random slopes are for the Closed-vs-open (Vision) and Foam-vs-firm (Surface) contrasts.

	ML		AP	
	Variance	SD	Variance	SD
Subject-level				
Intercept	0.0987	0.3142	0.1333	0.3651
Vision (Closed)	0.0123	0.1109	0.0141	0.1186
Surface (Foam)	0.0602	0.2453	0.0688	0.2623
Residual				
	0.0205	0.1431	0.0303	0.1742

	ML	AP
Correlations among random effects		
Intercept–Vision (Closed)	+0.16	+0.20
Intercept–Surface (Foam)	−0.72	−0.76
Vision (Closed)–Surface (Foam)	−0.02	−0.12

Note. Number of subjects = 98. Number of observations = 1173.

Table S3: Simple effects of visual condition (closed minus open) at each surface × age-group combination, for the mediolateral (ML) and anteroposterior (AP) directions. Positive estimates indicate higher sway velocity with eyes closed. Values are on the log scale; $\exp(-\beta)$ is the proportional sway velocity with eyes open relative to eyes closed (values below 1 indicate a reduction). Degrees of freedom: Kenward–Roger. p-values: Holm–Bonferroni, corrected across the four contrasts within each direction.

Age group	Surface	β	SE	t	p	$\exp(-\beta)$
Mediolateral (ML)						
Older	Firm	0.060	0.023	2.64	.009	0.94
Older	Foam	0.175	0.023	7.61	$< .001$	0.84
Young	Firm	0.070	0.023	3.02	.006	0.93
Young	Foam	0.357	0.023	15.34	$< .001$	0.70
Anteroposterior (AP)						
Older	Firm	0.027	0.026	1.03	.306	0.97
Older	Foam	0.186	0.026	7.04	$< .001$	0.83
Young	Firm	0.061	0.027	2.28	.048	0.94
Young	Foam	0.290	0.027	10.83	$< .001$	0.75

Table S4: Simple effects of age group (old minus young) at each surface $\times$ visual condition combination in the mediolateral (ML) and anteroposterior (AP) directions. Positive estimates indicate higher sway velocity in older adults. Values are on the log scale. Degrees of freedom estimated via the Kenward–Roger method. Cohen's d was computed on the log-transformed scale using the pooled standard deviation weighted by degrees of freedom.

		ML					AP				
Surface	Eyes	β	SE	t	p	d	β	SE	t	p	d
Firm	Closed	0.343	0.073	4.72	$< .001$	0.96	0.051	0.084	0.61	.546	0.12
Firm	Open	0.353	0.066	5.38	$< .001$	1.06	0.085	0.077	1.11	.269	0.23
Foam	Closed	0.507	0.057	8.96	$< .001$	1.75	0.232	0.061	3.82	$< .001$	0.79
Foam	Open	0.689	0.048	14.48	$< .001$	3.06	0.336	0.052	6.45	$< .001$	1.34

Note. In the ML direction, the age difference was significant in all conditions, increasing from $d = 0.96$ (firm, eyes closed) to $d = 3.06$ (foam, eyes open). The very large effect size at foam/eyes open reflects both the divergence of group means and the convergence of within-group variability under this condition, consistent with younger adults achieving effective ML stabilization via visual input while older adults show a smaller velocity reduction. In the AP direction, the age difference emerged only under proprioceptive challenge (foam), with substantially smaller effect sizes ($d = 0.79$–1.34) than the corresponding ML contrasts.

Table S5: Estimated marginal means for peak sway velocity by direction. Means and 95% confidence intervals (CI) are back-transformed from the log scale. SE is computed via the delta method on the response scale. Degrees of freedom estimated via the Kenward–Roger method.

			Mediolateral (ML)			Anteroposterior (AP)		
Age Group	Vision	Surface	Mean (cm/s)	SE	95% CI	Mean (cm/s)	SE	95% CI
Older	Closed	Firm	1.09	0.06	[0.98, 1.20]	0.55	0.03	[0.49, 0.62]
Younger	Closed	Firm	0.77	0.04	[0.70, 0.85]	0.53	0.03	[0.47, 0.59]
Older	Open	Firm	1.02	0.05	[0.93, 1.12]	0.54	0.03	[0.48, 0.60]
Younger	Open	Firm	0.72	0.03	[0.66, 0.79]	0.49	0.03	[0.44, 0.55]
Older	Closed	Foam	4.48	0.18	[4.14, 4.84]	2.71	0.12	[2.49, 2.95]
Younger	Closed	Foam	2.70	0.11	[2.49, 2.92]	2.15	0.09	[1.97, 2.34]
Older	Open	Foam	3.76	0.13	[3.52, 4.02]	2.25	0.08	[2.09, 2.42]
Younger	Open	Foam	1.89	0.06	[1.77, 2.02]	1.61	0.06	[1.49, 1.73]

Note. Means and 95% confidence intervals (CI) are back-transformed from the log scale.

Table S6: Omnibus tests of fixed effects from the four-way combined linear mixed-effects model (REML) of log-transformed peak sway velocity, with direction included as a fourth fixed factor. Type III F-tests; degrees of freedom estimated via the Satterthwaite approximation. Reference levels: young adults, eyes open, firm surface, AP direction. The four-way Age × Vision × Surface × Direction interaction tests whether the three-way Age × Vision × Surface pattern differs between the ML and AP directions.

Effect	*df*	*F*	*p*
Age	1, 96.0	36.56	$< .001$
Vision	1, 96.2	137.62	$< .001$
Surface	1, 96.1	2973.48	$< .001$
Direction	1, 95.8	507.63	$< .001$
Age × Vision	1, 96.2	9.95	.002
Age × Surface	1, 96.1	23.19	$< .001$
Vision × Surface	1, 1953.7	195.56	$< .001$
Age × Direction	1, 95.8	59.18	$< .001$
Vision × Direction	1, 1946.2	3.08	.079
Surface × Direction	1, 1946.2	142.18	$< .001$
Age × Vision × Surface	1, 1953.7	18.30	$< .001$
Age × Vision × Direction	1, 1946.2	0.92	.337
Age × Surface × Direction	1, 1946.2	1.42	.234
Vision × Surface × Direction	1, 1946.2	0.06	.807
Age × Vision × Surface × Direction	1, 1946.2	3.27	.071

Note. Number of subjects = 98; number of observations = 2346 (each of the 1173 trials contributes one ML and one AP row). The model converged without singularity, with all variance components substantively non-zero. The four-way interaction point estimate was $\beta = -0.102$ (SE = 0.056, $p = .071$), indicating a larger three-way deficit in ML than in AP but not sufficiently precise to formally distinguish the two directional patterns. The directional asymmetry is therefore best characterised as quantitative rather than categorical.

Table S7: Table S7: Omnibus tests of fixed effects from the mean-velocity linear mixed models. Type III F-tests of log-transformed mean sway velocity in the mediolateral (ML) and anteroposterior (AP) directions, fitted to trial-level data. Degrees of freedom were estimated using the Satterthwaite approximation. This table corroborates the primary peak-velocity analysis (Table 3 in the main text): the three-way Age × Vision × Surface interaction is significant in ML but not AP.

	ML			AP		
Effect	*df*	F	p	*df*	F	p
Age	1, 96.0	75.25	$< .001$	1, 96.0	10.74	.001
Vision	1, 96.2	147.83	$< .001$	1, 96.3	69.94	$< .001$
Surface	1, 96.1	2510.17	$< .001$	1, 96.1	2842.95	$< .001$
Age × Vision	1, 96.2	14.14	$< .001$	1, 96.3	5.66	.019
Age × Surface	1, 96.1	21.26	$< .001$	1, 96.1	16.69	$< .001$
Vision × Surface	1, 881.2	124.55	$< .001$	1, 881.7	92.46	$< .001$
Age × Vision × Surface	1, 881.2	21.78	$< .001$	1, 881.7	2.27	.132

Table S8: Robustness of the Age × Vision × Surface interaction to adjustment for body size. Type III F-tests for the three-way interaction in log peak sway velocity, from the unadjusted model, a model adding height and BMI (z-scored) as covariates, and a model additionally allowing height and BMI to interact with vision and surface. Satterthwaite degrees of freedom. The interaction is essentially unchanged across adjustments, indicating it is not an artifact of the group difference in stature or BMI.

Direction	Model	*df*	F	p
ML	Unadjusted	1, 881	26.33	$< .001$
ML	Adj. height + BMI	1, 881.1	26.35	$< .001$
ML	Adj. + interactions	1, 881.1	26.38	$< .001$
AP	Unadjusted	1, 881.5	2.93	.087
AP	Adj. height + BMI	1, 881.6	2.94	.087
AP	Adj. + interactions	1, 881.7	2.97	.085