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Supplementary Table S1. Full Transition Probability Results in the Primary Five-State Model

Transition	BPPV (n=70)	HC (n=46)	Adjusted β (95% CI)	t(df)	*P* value	FDR *q* value	Cohen's d
State 1 → State 1	0.550 ± 0.084	0.605 ± 0.079	-0.050 (-0.083 to -0.018)	-3.04 (110)	0.003	0.017	-0.67
State 1 → State 2	0.123 ± 0.057	0.112 ± 0.059	0.011 (-0.012 to 0.034)	0.94 (110)	0.350	0.514	0.19
State 1 → State 3	0.123 ± 0.053	0.113 ± 0.045	0.008 (-0.012 to 0.028)	0.81 (110)	0.418	0.540	0.19
State 1 → State 4	0.049 ± 0.037	0.048 ± 0.038	0.000 (-0.015 to 0.015)	0.04 (110)	0.971	0.971	0.04
State 1 → State 5	0.155 ± 0.076	0.122 ± 0.061	0.031 (0.003 to 0.058)	2.20 (110)	0.030	0.082	0.47
State 2 → State 1	0.131 ± 0.055	0.125 ± 0.069	0.009 (-0.015 to 0.033)	0.72 (110)	0.471	0.540	0.10
State 2 → State 2	0.617 ± 0.060	0.637 ± 0.063	-0.022 (-0.047 to 0.002)	-1.82 (110)	0.072	0.164	-0.34
State 2 → State 3	0.114 ± 0.049	0.118 ± 0.047	-0.007 (-0.026 to 0.013)	-0.68 (110)	0.497	0.540	-0.09
State 2 → State 4	0.126 ± 0.047	0.114 ± 0.050	0.014 (-0.005 to 0.034)	1.46 (110)	0.148	0.265	0.25
State 2 → State 5	0.012 ± 0.019	0.006 ± 0.014	0.006 (-0.001 to 0.013)	1.77 (110)	0.079	0.165	0.37
State 3 → State 1	0.110 ± 0.053	0.101 ± 0.044	0.013 (-0.007 to 0.033)	1.25 (110)	0.215	0.336	0.19
State 3 → State 2	0.121 ± 0.051	0.085 ± 0.043	0.034 (0.015 to 0.053)	3.55 (110)	5.67×10^{-4}	0.005	0.74
State 3 → State 3	0.538 ± 0.086	0.631 ± 0.079	-0.091 (-0.124 to -0.058)	-5.44 (110)	3.25×10^{-7}	8.12×10^{-6}	-1.12
State 3 → State 4	0.116 ± 0.054	0.089 ± 0.037	0.029 (0.010 to 0.048)	2.99 (110)	0.003	0.017	0.56
State 3 → State 5	0.115 ± 0.059	0.094 ± 0.043	0.015 (-0.006 to 0.036)	1.41 (110)	0.160	0.267	0.39
State 4 → State 1	0.060 ± 0.038	0.046 ± 0.034	0.012 (-0.002 to 0.027)	1.69 (110)	0.094	0.182	0.39
State 4 → State 2	0.131 ± 0.063	0.119 ± 0.056	0.008 (-0.016 to 0.033)	0.69 (110)	0.491	0.540	0.21
State 4 → State 3	0.116 ± 0.047	0.112 ± 0.047	0.007 (-0.012 to 0.025)	0.73 (110)	0.468	0.540	0.09
State 4 → State 4	0.560 ± 0.074	0.617 ± 0.073	-0.053 (-0.083 to -0.023)	-3.55 (110)	5.64×10^{-4}	0.005	-0.77
State 4 → State 5	0.133 ± 0.066	0.107 ± 0.067	0.025 (-0.001 to 0.052)	1.88 (110)	0.062	0.156	0.38
State 5 → State 1	0.115 ± 0.055	0.128 ± 0.062	-0.009 (-0.033 to 0.014)	-0.81 (110)	0.418	0.540	-0.23
State 5 → State 2	0.012 ± 0.019	0.005 ± 0.012	0.008 (0.001 to 0.014)	2.30 (110)	0.023	0.073	0.43
State 5 → State 3	0.138 ± 0.045	0.110 ± 0.057	0.028 (0.008 to 0.048)	2.75 (110)	0.007	0.029	0.56
State 5 → State 4	0.135 ± 0.051	0.134 ± 0.067	0.002 (-0.021 to 0.025)	0.16 (110)	0.872	0.908	0.01
State 5 → State 5	0.601 ± 0.059	0.623 ± 0.052	-0.028 (-0.050 to -0.005)	-2.44 (110)	0.016	0.057	-0.40

Abbreviations: BPPV, benign paroxysmal positional vertigo; CI, confidence interval; FD, framewise displacement; HMM, hidden Markov model; HC, healthy control.

Supplementary Table S2. Motion-Related Sensitivity Analyses

Part A. Extended motion-adjusted models

Outcome	Primary β (95% CI)	Primary P	Primary q	Extended-motion β (95% CI)	t(df)	Extended-motion P	Extended-motion q
Switching rate	0.047 (0.035 to 0.060)	2.71×10^{-11}	3.61×10^{-11}	0.033 (0.015 to 0.050)	3.63 (108)	4.35×10^{-4}	5.80×10^{-4}
Mean dwell time, time points	-0.305 (-0.387 to -0.222)	4.05×10^{-11}	4.05×10^{-11}	-0.202 (-0.317 to -0.086)	-3.45 (108)	8.14×10^{-4}	8.14×10^{-4}
Number of visits	1.687 (1.236 to 2.138)	2.71×10^{-11}	3.61×10^{-11}	1.168 (0.530 to 1.806)	3.63 (108)	4.35×10^{-4}	5.80×10^{-4}
Mean self-transition probability	-0.049 (-0.061 to -0.037)	2.01×10^{-12}	8.04×10^{-12}	-0.033 (-0.050 to -0.016)	-3.83 (108)	2.16×10^{-4}	5.80×10^{-4}
State 1 fractional occupancy	-0.007 (-0.024 to 0.011)	0.445	0.556	-0.003 (-0.028 to 0.022)	-0.21 (108)	0.832	0.832
State 2 fractional occupancy	0.019 (0.004 to 0.035)	0.015	0.037	0.009 (-0.013 to 0.031)	0.78 (108)	0.435	0.832
State 3 fractional occupancy	-0.032 (-0.046 to -0.017)	4.46×10^{-5}	2.23×10^{-4}	-0.016 (-0.037 to 0.005)	-1.52 (108)	0.131	0.657
State 4 fractional occupancy	0.002 (-0.016 to 0.020)	0.840	0.840	0.004 (-0.022 to 0.030)	0.33 (108)	0.741	0.832
State 5 fractional occupancy	0.017 (0.001 to 0.033)	0.039	0.066	0.005 (-0.017 to 0.028)	0.48 (108)	0.634	0.832

Part B. Maximum-FD restricted sample

Outcome	Restricted BPPV n	Restricted HC n	Adjusted β (95% CI)	t(df)	P value	FDR q value
Switching rate	70	43	0.046 (0.033 to 0.059)	7.10 (107)	1.45×10^{-10}	1.94×10^{-10}
Mean dwell time, time points	70	43	-0.300 (-0.385 to -0.216)	-7.02 (107)	2.14×10^{-10}	2.14×10^{-10}
Number of visits	70	43	1.664 (1.199 to 2.129)	7.10 (107)	1.45×10^{-10}	1.94×10^{-10}
Mean self-transition probability	70	43	-0.049 (-0.061 to -0.036)	-7.69 (107)	7.57×10^{-12}	3.03×10^{-11}
State 1 fractional occupancy	70	43	-0.006 (-0.024 to 0.012)	-0.67 (107)	0.501	0.584
State 2 fractional occupancy	70	43	0.017 (0.002 to 0.033)	2.17 (107)	0.032	0.080
State 3 fractional occupancy	70	43	-0.030 (-0.045 to -0.015)	-3.95 (107)	1.39×10^{-4}	6.97×10^{-4}
State 4 fractional occupancy	70	43	0.005 (-0.013 to 0.024)	0.55 (107)	0.584	0.584
State 5 fractional occupancy	70	43	0.014 (-0.002 to 0.030)	1.68 (107)	0.096	0.159

Abbreviations: BPPV, benign paroxysmal positional vertigo; CI, confidence interval; FD, framewise displacement; HMM, hidden Markov model; HC, healthy control.

Supplementary Table S3. Within-Group Associations Between Censor-Aware HMM Measures and Motion Indices

Group	Censor-aware HMM measure	Motion index	n	Spearman ρ	P value	FDR q value
Healthy controls	Censor-aware switching rate	Mean framewise displacement	46	−0.262	0.079	0.310
		Maximum framewise displacement	46	−0.334	0.023	0.281
		Proportion of volumes with FD > 0.5 mm	46	−0.240	0.109	0.310
	Censor-aware mean empirical self-transition probability	Mean framewise displacement	46	0.150	0.321	0.481
		Maximum framewise displacement	46	0.227	0.129	0.310
		Proportion of volumes with FD > 0.5 mm	46	0.159	0.290	0.481
BPPV	Censor-aware switching rate	Mean framewise displacement	70	−0.215	0.073	0.310
		Maximum framewise displacement	70	−0.057	0.636	0.849
		Proportion of volumes with FD > 0.5 mm	70	−0.039	0.748	0.856
	Censor-aware mean empirical self-transition probability	Mean framewise displacement	70	0.152	0.209	0.418
		Maximum framewise displacement	70	0.033	0.784	0.856
		Proportion of volumes with FD > 0.5 mm	70	0.020	0.871	0.871

Abbreviations: BPPV, benign paroxysmal positional vertigo; CI, confidence interval; FD, framewise displacement; HMM, hidden Markov model; HC, healthy control.

Supplementary Table S4. Sensitivity of Global HMM Temporal Effects to Global Signal Regression

Outcome	Primary β (95% CI)	Primary *P*	Primary *q*	No-GSR β (95% CI)	t(df)	No-GSR *P*	No-GSR *q*
Switching rate	0.047 (0.035 to 0.060)	2.71×10^{-11}	3.61×10^{-11}	0.017 (0.001 to 0.033)	2.08 (110)	0.040	0.046
Mean dwell time, time points	-0.305 (-0.387 to -0.222)	4.05×10^{-11}	4.05×10^{-11}	-0.072 (-0.143 to -0.001)	-2.02 (110)	0.046	0.046
Number of visits	1.687 (1.236 to 2.138)	2.71×10^{-11}	3.61×10^{-11}	0.598 (0.028 to 1.167)	2.08 (110)	0.040	0.046
Mean self-transition probability	-0.049 (-0.061 to -0.037)	2.01×10^{-12}	8.04×10^{-12}	-0.070 (-0.092 to -0.048)	-6.41 (110)	3.67×10^{-9}	1.47×10^{-8}

Abbreviations: BPPV, benign paroxysmal positional vertigo; CI, confidence interval; FD, framewise displacement; HMM, hidden Markov model; HC, healthy control.

Supplementary Table S5. Associations Between Global HMM Temporal Metrics and Clinical Measures in BPPV

Clinical measure	HMM metric	Available BPPV n	Adjusted β (95% CI)	t(df)	*P* value	FDR *q* value
DHI	Switching rate	70	-0.095 (-0.333 to 0.143)	-0.80 (64)	0.428	0.833
DHI	Mean dwell time, time points	70	0.089 (-0.149 to 0.327)	0.75 (64)	0.459	0.833
DHI	Number of visits	70	-0.095 (-0.333 to 0.143)	-0.80 (64)	0.428	0.833
DHI	Mean self-transition probability	70	0.115 (-0.126 to 0.355)	0.95 (64)	0.344	0.833
ABC	Switching rate	70	-0.189 (-0.427 to 0.048)	-1.59 (64)	0.116	0.466
ABC	Mean dwell time, time points	70	0.189 (-0.048 to 0.426)	1.60 (64)	0.116	0.466
ABC	Number of visits	70	-0.189 (-0.427 to 0.048)	-1.59 (64)	0.116	0.466
ABC	Mean self-transition probability	70	0.193 (-0.048 to 0.433)	1.60 (64)	0.114	0.466
VVAS	Switching rate	70	0.065 (-0.187 to 0.316)	0.52 (64)	0.608	0.833
VVAS	Mean dwell time, time points	70	-0.066 (-0.317 to 0.185)	-0.53 (64)	0.599	0.833
VVAS	Number of visits	70	0.065 (-0.187 to 0.316)	0.52 (64)	0.608	0.833
VVAS	Mean self-transition probability	70	-0.063 (-0.317 to 0.192)	-0.49 (64)	0.625	0.833
PVAS	Switching rate	70	-0.011 (-0.251 to 0.229)	-0.09 (64)	0.927	0.928
PVAS	Mean dwell time, time points	70	0.011 (-0.229 to 0.251)	0.09 (64)	0.928	0.928
PVAS	Number of visits	70	-0.011 (-0.251 to 0.229)	-0.09 (64)	0.927	0.928
PVAS	Mean self-transition probability	70	-0.020 (-0.263 to 0.223)	-0.16 (64)	0.872	0.928

Abbreviations: BPPV, benign paroxysmal positional vertigo; CI, confidence interval; FD, framewise displacement; HMM, hidden Markov model; HC, healthy control.