

Supplementary Information: Differential Effects of Static and Illusory-Motion Stimuli on Implicit Visuomotor Adaptation

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S1 Subject-Averaged Repeated-Measures ANOVA Sensitivity Analyses

To assess whether the principal findings depended on the trial-level mixed-effects modelling framework, complementary subject-averaged repeated-measures analyses of variance (RM-ANOVAs) were conducted using the **afex** package. Trial-level observations were first averaged within participant for each combination of the relevant experimental factors. The resulting participant-level means were then analysed using Type III RM-ANOVAs. For omnibus analyses, Illusion Group was included as a between-subjects factor; for within-illusion analyses, each illusion group was analysed separately. Greenhouse–Geisser (GG) corrections were applied where required by violations of sphericity. Partial eta squared (η_p^2) was calculated as the effect-size measure.

These analyses were treated as sensitivity analyses rather than alternative primary tests. The primary linear mixed-effects (LME) models retained trial-level observations and explicitly accounted for participant-level clustering, whereas the RM-ANOVAs reduced the data to participant-level means. The RM-ANOVAs therefore tested whether the principal inferential pattern was preserved after aggregation, rather than providing an alternative estimate of the trial-level model. Their effect sizes are reported as complementary descriptions of the magnitude of the participant-level effects and were not used to derive post hoc estimates of statistical power. Prospective sensitivity to the primary higher-order interactions was assessed separately using Monte Carlo simulations that reproduced the trial-level experimental structure (Supplementary Section [S9](#)).

S1.1 Reach Planning Bias: Omnibus Analysis

The subject-averaged RM-ANOVA reproduced the critical Illusion Group $\times$ Orientation $\times$ Target Angle interaction observed in the primary LME analysis. The omnibus RM-ANOVA results are presented in Table 1.

Mauchly’s test indicated departures from sphericity for Target Angle, Illusion Group $\times$ Target Angle, Target Angle $\times$ Orientation, and the critical Illusion Group $\times$ Target Angle $\times$ Orientation interaction. Greenhouse–Geisser corrections were therefore applied to these effects. The critical three-way interaction remained highly significant after correction, $F(5.05, 219.89) = 23.62$, $p < .001$, with a large partial eta squared ($\eta_p^2 = .352$).

Table 1 Subject-averaged RM-ANOVA for the Reach Planning Bias omnibus model.

Effect	GG-adjusted df	F	η_p^2	p
Illusion	2, 87	8.92	.170	< .001
Target Angle	2.30, 199.88	1.72	.019	.177
Illusion $\times$ Target Angle	4.59, 199.88	2.96	.064	.016
Orientation	1, 87	20.69	.192	< .001
Illusion $\times$ Orientation	2, 87	2.32	.051	.104
Target Angle $\times$ Orientation	2.53, 219.89	0.30	.003	.792
Illusion $\times$ Target Angle $\times$ Orientation	5.05, 219.89	23.62	.352	< .001

Thus, aggregation to participant-level means did not alter the principal omnibus conclusion. The Illusion Group $\times$ Target Angle $\times$ Orientation interaction remained significant and was associated with a large participant-level effect size ($\eta_p^2 = .352$), providing convergent evidence for the critical interaction identified by the trial-level LME analysis.

S1.2 Reach Planning Bias: Within-Illusion Analyses

Within each illusion group, the subject-averaged RM-ANOVAs reproduced the inferential pattern of the primary LME analyses. Significant Orientation $\times$ Target Angle interactions were observed for Müller-Lyer and Ponzo, whereas the corresponding interaction was not significant for Rotating Snakes. The results are summarised in Table 2.

For Müller-Lyer, the Orientation $\times$ Target Angle interaction was significant, $F(2.43, 70.50) = 21.34$, $p < .001$, with a large effect size ($\eta_p^2 = .424$). For Ponzo, the corresponding interaction was also significant, $F(1.64, 47.49) = 24.32$, $p < .001$, with a large effect size ($\eta_p^2 = .456$). In contrast, Rotating Snakes showed no significant Orientation $\times$ Target Angle interaction, $F(1.99, 57.79) = 1.34$, $p = .270$, with a small effect size ($\eta_p^2 = .044$).

Table 2 Subject-averaged RM-ANOVA for Reach Planning Bias within illusion groups, with comparison to the primary LME analyses.

Illusion	Primary effect	LME	RM-ANOVA	η_p^2	p
Müller-Lyer	Orientation $\times$ Target Angle	$\chi^2(3) = 49.97$	$F(2.43, 70.50) = 21.34$	.424	< .001
Ponzo	Orientation $\times$ Target Angle	$\chi^2(3) = 60.27$	$F(1.64, 47.49) = 24.32$	.456	< .001
Rotating Snakes	Orientation $\times$ Target Angle	$\chi^2(3) = 1.85$	$F(1.99, 57.79) = 1.34$	.044	.270

The RM-ANOVA results therefore converged with the primary LME analyses: orientation-dependent planning varied systematically with target angle for Müller-Lyer and Ponzo, whereas no corresponding cohort-level interaction was detected for Rotating Snakes. The participant-level effect sizes were large for Müller-Lyer and Ponzo and small for Rotating Snakes.

S1.3 Implicit Visuomotor Adaptation: Omnibus Analysis

The subject-averaged omnibus RM-ANOVA likewise reproduced the critical Illusion Group $\times$ Orientation $\times$ Clamp Angle interaction observed in the primary LME analysis. The RM-ANOVA yielded a significant three-way interaction, $F(2, 87) = 89.69$, $p < .001$, with a large partial eta squared ($\eta_p^2 = .673$).

Because Clamp Angle had only two levels, sphericity was automatically satisfied for the critical interaction and no Greenhouse–Geisser correction was required. The omnibus result is presented together with the within-illusion analyses in Table 3.

The large participant-level effect size provides complementary evidence that the omnibus interaction remained robust following aggregation to participant-level means. It was not, however, interpreted as an observed-power or post hoc sensitivity estimate. Prospective sensitivity to the primary Illusion Group $\times$ Orientation $\times$ Clamp Angle interaction was evaluated separately using Monte Carlo simulations reported in Supplementary Section S9.

S1.4 Implicit Visuomotor Adaptation: Within-Illusion Analyses

The subject-averaged within-illusion analyses reproduced the inferential pattern of the primary LME analyses. Significant Orientation $\times$ Clamp Angle interactions were observed for Müller-Lyer and Ponzo, whereas no evidence of an Orientation $\times$ Clamp Angle interaction was observed for Rotating Snakes.

For Müller-Lyer, the Orientation $\times$ Clamp Angle interaction was significant, $F(1, 29) = 63.13$, $p < .001$, with a large effect size ($\eta_p^2 = .685$). For Ponzo, the corresponding interaction was also significant, $F(1, 29) = 91.49$, $p < .001$, with a large effect size ($\eta_p^2 = .759$). In contrast, Rotating Snakes showed no evidence of an Orientation $\times$ Clamp Angle interaction, $F(1, 29) = 0.0008$, $p = .978$, with a negligible effect size ($\eta_p^2 < .001$).

Table 3 Subject-averaged RM-ANOVA for Implicit Visuomotor Adaptation, with comparison to the primary LME analyses.

Illusion	Primary effect	LME	RM-ANOVA	η_p^2	p
Omnibus	Illusion $\times$ Orientation $\times$ Clamp Angle	$\chi^2(2) = 53.29$	$F(2, 87) = 89.69$	.673	$< .001$
Müller-Lyer	Orientation $\times$ Clamp Angle	$\chi^2(1) = 23.75$	$F(1, 29) = 63.13$	.685	$< .001$
Ponzo	Orientation $\times$ Clamp Angle	$\chi^2(1) = 25.23$	$F(1, 29) = 91.49$	.759	$< .001$
Rotating Snakes	Orientation $\times$ Clamp Angle	$\chi^2(1) = 0.09$	$F(1, 29) = 0.0008$	.00003	.978

The subject-averaged RM-ANOVAs therefore converged closely with the primary trial-level LME analyses. The omnibus Illusion Group $\times$ Orientation $\times$ Clamp Angle interaction was significant and large ($\eta_p^2 = .673$), as were the corresponding within-illusion interactions for Müller-Lyer ($\eta_p^2 = .685$) and Ponzo ($\eta_p^2 = .759$). In contrast, the Rotating Snakes interaction was effectively absent ($F(1, 29) = 0.0008$, $p = .978$, $\eta_p^2 < .001$).

Therefore, aggregation to participant-level means preserved the central distinction observed in the primary analysis: the two static illusions showed robust orientation-dependent modulation of implicit adaptation that reversed with clamp direction, whereas Rotating Snakes showed no detectable cohort-level orientation-dependent modulation.

S1.5 Summary

Across both motor tasks, the subject-averaged RM-ANOVAs reproduced the principal inferential pattern of the trial-level LME analyses. For Reach Planning Bias, the omnibus Illusion Group $\times$ Target Angle $\times$ Orientation interaction remained significant after aggregation, and significant Orientation $\times$ Target Angle interactions were retained for Müller-Lyer and Ponzo but not Rotating Snakes. For Implicit Visuomotor Adaptation, the omnibus Illusion Group $\times$ Orientation $\times$ Clamp Angle interaction and the corresponding within-illusion interactions for Müller-Lyer and Ponzo remained significant, whereas the Rotating Snakes interaction was effectively zero.

These sensitivity analyses therefore provide convergent participant-level evidence that the principal findings were not dependent on retaining trial-level observations in the primary LME framework. The accompanying η_p^2 values characterise the magnitude of the participant-level effects but should not be interpreted as substitutes for the prospective sensitivity analyses used to evaluate the detectable effect sizes of the primary trial-level models.

S2 Perceptual Task

An independent psychophysical task was used to verify conscious perception of the relevant illusion features outside the motor paradigms. All participants achieved 100% accuracy. The stimulus orientations and response requirements are shown in Fig. 1.

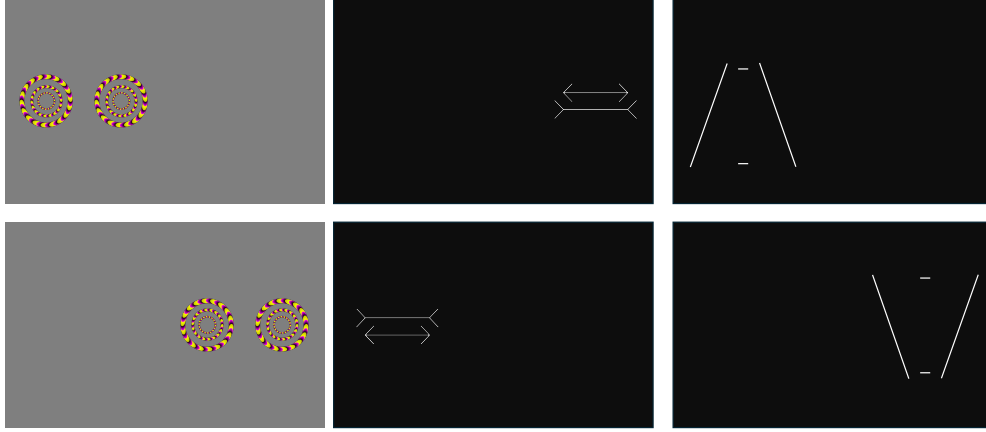


Fig. 1 Independent psychophysical assessment of illusion perception. The figure shows representative stimulus configurations presented without reach targets, endpoint error-clamp markers, or physical movement. **Column 1 (Rotating Snakes):** concentric chevron wheels producing clockwise or counter-clockwise illusory rotation; participants reported whether rotational motion was perceived and its direction. **Column 2 (Müller-Lyer):** opposing arrow orientations; participants reported which arrow appeared longer. **Column 3 (Ponzo):** converging or diverging perspective contexts containing identical horizontal probe lines; participants reported which line appeared longer. The eight-trial perceptual block was counterbalanced relative to the motor experiments.

S3 Perceptual Task Order: Demand-Effect Control Analysis

Perceptual-task order (*Pre-* vs. *Post-task*; $n = 45$ per order) was included as a between-subjects factor in supplementary LME models. Task order did not moderate the principal orientation-dependent effects in Reach Planning Bias, $\chi^2(2) = 0.70$, $p = .704$, or Implicit Adaptation, $\chi^2(2) = 0.27$, $p = .876$.

Condition-specific analyses likewise showed no task-order moderation of the Orientation $\times$ Clamp Angle interaction for Müller-Lyer ($p = .983$), Ponzo ($p = .747$), or Rotating Snakes ($p = .682$).

S4 Kinematic and Task-Effort Controls

Reaction time and movement duration did not differ systematically across illusion groups during Reach Planning Bias (both FDR-adjusted $p = .216$) or Implicit Adaptation (RT: $p = .506$; MD: $p = .594$).

Trial-abort rates were higher for Rotating Snakes (7.50%) than Müller-Lyer (3.61%) or Ponzo (1.43%) conditions, $F(2, 87) = 10.52$, $p < .001$. However, abort rates did not differ between the resilient Congruent and Incongruent phenotypes during Reach Planning Bias ($p = .535$) or Implicit Adaptation ($p = .456$).

Reaction time and movement duration likewise did not differ between Rotating Snakes phenotypes during Reach Planning Bias (RT: FDR-adjusted $p = .139$; MD: FDR-adjusted $p = .113$) or Implicit Adaptation (RT: $p = .678$; MD: $p = .113$).

Together, these analyses provide no evidence of systematic differences in reaction time, movement duration, or trial engagement that covaried with the principal illusion-related effects or the identified phenotypes.

S5 Temporal Variation in Reach Planning Biases

As a secondary analysis, orientation-dependent planning effects were assessed across the first, second, and final thirds of the 320-trial exposure period using the Exposure $\times$ Orientation $\times$ Target interaction.

The interaction was not significant for Müller-Lyer, $\chi^2(3) = 2.62$, $p_{\text{Holm}} = .454$, but was significant for Ponzo, $\chi^2(3) = 13.15$, $p_{\text{Holm}} = .0087$, and Rotating Snakes, $\chi^2(3) = 20.49$, $p_{\text{Holm}} < .001$. Therefore, the orientation-dependent planning pattern varied across exposure for Ponzo and Rotating Snakes but not Müller-Lyer.

These temporal interactions do not by themselves establish progressive habituation, recalibration, or learning of the illusions. Target angles were pseudorandomised and counterbalanced across the full trial set rather than organised around a systematic directional perturbation.

S6 Temporal Variation in Implicit Adaptation

As a secondary analysis, orientation-dependent adaptation was assessed across the first, second, and final thirds of the 160-triplet exposure period using the Exposure Period $\times$ Orientation $\times$ Clamp Angle interaction.

No significant interaction was observed for Müller-Lyer, $\chi^2(3) = 3.19$, $p_{\text{Holm}} = .717$, Ponzo, $\chi^2(3) = 5.04$, $p_{\text{Holm}} = .507$, or Rotating Snakes, $\chi^2(3) = 3.22$, $p_{\text{Holm}} = .717$. Therefore, there was no evidence that the orientation-dependent component of implicit adaptation changed systematically across exposure for any illusion condition.

S7 Unsupervised Phenotyping: Bidirectional Architecture Verification

To assess whether the identified phenotypic architecture depended on the choice of anchor domain, phenotype assignment was repeated using Implicit Adaptation and then validated using the independent Reach Planning Bias data.

The reciprocal procedure recovered the same resilient Rotating Snakes subset ($N = 21$). Significant Phenotype $\times$ Orientation interactions were reproduced in the adaptation-anchor model, $\chi^2(1) = 15.16$, $p < .001$, and the out-of-sample planning

verification model, $\chi^2(1) = 12.56$, $p < .001$. Neither Phenotype nor Orientation main effect was significant (all $p > .20$). Full model statistics are provided in Table 4.

Table 4 Type III Wald χ^2 statistics for bidirectional phenotyping verification.

Task Domain	Effect Term	Wald χ^2	df	p
Adaptation Anchor	Intercept	0.35	1	.556
Adaptation Anchor	Phenotype	0.47	1	.492
Adaptation Anchor	Orientation	0.46	1	.497
Adaptation Anchor	Phenotype $\times$ Orientation	15.16	1	< .001
Planning Verification	Intercept	19.97	1	< .001
Planning Verification	Phenotype	1.60	1	.206
Planning Verification	Orientation	0.55	1	.457
Planning Verification	Phenotype $\times$ Orientation	12.56	1	< .001

S8 Left-Handed Cohort Analysis

To assess whether the principal pattern was also observed in left-handed participants, a supplementary cohort of left-handed participants was analysed ($N = 12$, $n = 4$ per illusion group).

For Reach Planning Bias, the Illusion Group $\times$ Orientation $\times$ Target Angle interaction was significant, $\chi^2(6) = 25.37$, $p < .001$. For Implicit Adaptation, the corresponding Illusion Group $\times$ Orientation $\times$ Clamp Angle interaction was not significant, $\chi^2(2) = 4.64$, $p = .200$.

Given the small number of left-handed participants per illusion group and the absence of a formal handedness-by-effect interaction analysis, these results are treated as descriptive rather than as a formal test of handedness moderation.

S9 Prospective Monte Carlo Sensitivity Analyses

Prospective Monte Carlo sensitivity analyses were conducted separately for the Reach Planning Bias and Implicit Adaptation experiments. In each analysis, the empirical baseline variability from the corresponding experiment was used to calibrate the simulation, and the planned test-phase structure was reproduced. Baseline trials were used to establish the empirical variance parameters and were not counted as additional observations in the simulated test phases. The sensitivity parameter was defined as the maximum pairwise difference between illusion groups in the corresponding higher-order interaction.

S9.1 Reach Planning Bias

The Reach Planning Bias simulation reproduced the planned 320 individual test reaches per participant. The empirical planning data yielded a pooled within-participant baseline SD of 3.18° and a separately estimated participant-level random-intercept SD of 1.02° . The sensitivity parameter was the maximum pairwise difference between illusion groups in the Illusion Group $\times$ Orientation $\times$ Target interaction.

The simulated power curve is shown in Table 5. The 80% and 90% sensitivity points were estimated by interpolation between adjacent simulated effect sizes and subsequently evaluated using 5,000 additional Monte Carlo simulations. No model fits failed and no singular fits were observed.

The largest observed pairwise difference in orientation-dependent target effects between illusion groups was approximately 1.35° , substantially exceeding both sensitivity points.

Table 5 Monte Carlo sensitivity analysis for Reach Planning Bias. Power estimates are based on 1,000 simulated datasets at each effect magnitude.

Maximum pairwise interaction contrast ($^\circ$)	Estimated power	95% MC CI
0.00	.055	.042–.071
0.25	.341	.312–.371
0.50	.907	.887–.924
0.75	1.000	.996–1.000
1.00	1.000	.996–1.000
1.25	1.000	.996–1.000
1.50	1.000	.996–1.000
1.75	1.000	.996–1.000
2.00	1.000	.996–1.000
Interpolated 80% sensitivity point	0.453	0.452–0.454
Interpolated 90% sensitivity point	0.497	0.496–0.498

Table 6 Final Monte Carlo evaluation of Reach Planning Bias sensitivity points.

Target power	Sensitivity point ($^\circ$)	Observed power	95% MC CI	MC SE
80%	0.453	.861	.852–.871	.0049
90%	0.497	.926	.919–.933	.0037

S9.2 Implicit Adaptation

The Implicit Adaptation simulation reproduced the planned 160 test triplets per participant. The empirical adaptation data yielded a pooled within-participant baseline SD of 2.99° and a separately estimated participant-level random-intercept SD of 1.16° . The sensitivity parameter was the maximum pairwise difference between illusion groups in the Illusion Group $\times$ Orientation $\times$ Clamp Angle interaction.

The simulated power curve is shown in Table 7. The 80% sensitivity point occurred at 0.750° , while interpolation between the 0.75° and 1.00° grid points yielded a 90% sensitivity point of 0.903° . Both points were subsequently evaluated using 5,000 additional Monte Carlo simulations. No model fits failed and no singular fits were observed.

The observed illusion-specific Orientation $\times$ Clamp Angle interaction contrasts were -1.428° for Müller-Lyer, $+1.666^\circ$ for Ponzo, and $+0.004^\circ$ for Rotating Snakes. These yielded an observed maximum pairwise difference of 3.094° , substantially exceeding both prospective sensitivity points.

Table 7 Monte Carlo sensitivity analysis for Implicit Adaptation. Power estimates are based on 1,000 simulated datasets at each effect magnitude.

Maximum pairwise interaction contrast ($^\circ$)	Estimated power	95% MC CI
0.00	.045	.033–.060
0.25	.142	.121–.165
0.50	.407	.376–.438
0.75	.800	.774–.824
1.00	.963	.949–.974
1.25	.999	.994–1.000
1.50	1.000	.996–1.000
1.75	1.000	.996–1.000
2.00	1.000	.996–1.000

Table 8 Final Monte Carlo evaluation of Implicit Adaptation sensitivity points.

Target power	Sensitivity point ($^\circ$)	Observed power	95% MC CI	MC SE
80%	0.750	.803	.791–.814	.0056
90%	0.903	.923	.915–.930	.0038