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Tukey–Kramer Post Hoc Analysis

Workflow:
1. Run one–way ANOVA using pooled within–group error variance.
2. Use Tukey–Kramer unequal–n standard errors for all pairwise comparisons.
3. Use one family–wide Studentized Range critical value and adjusted p–values.

Interpretation summary:
                      method
1 Tukey–Kramer post hoc test
                                                                                                  use_case
1 Equal–variance pairwise mean comparison after one–way ANOVA, especially when group sample sizes are unequal.
  anova_p_value pooled_mse q_critical significant_pairs total_pairs
1  5.705728e–10   9.764634   3.642648                 4           6
  smallest_group_n largest_group_n largest_to_smallest_n_ratio
1               35             305                   8.714286
  levene_brown_forsythe_p_value
1                     0.3803575
                                                                                        main_warning
1 If variance heterogeneity is serious, consider Games–Howell or Tamhane's T2 instead of Tukey–Kramer.

ANOVA result:
  target_variable group_variable number_of_groups total_n
1              G3      studytime                4     649
  grand_mean ss_between df_between ms_between ss_within_error
1   11.90601   465.0778          3   155.0259        6298.189
  df_within_error ms_within_error_pooled_mse f_statistic
1             645                   9.764634    15.87627
       p_value eta_squared omega_squared alpha
1 5.705728e–10  0.06876527    0.06434105  0.05
  anova_decision_alpha_0_05
1        Reject equal means

Levene / Brown–Forsythe context:
                                              context_test
1 Median–centered Levene / Brown–Forsythe equal–variance context
  statistic   p_value
1  1.026312 0.3803575
                                                                                      interpretation
1 Tukey–Kramer uses pooled ANOVA error variance; check this context before relying on equal–variance post hoc results.
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Group summary

	group	n	mean	standard_deviation	standard_error	variance	minimum	maximum	ci95_low	ci95_high
1	1	212	10.84434	3.218624	0.2210560	10.359541	0	18	10.41107	11.27761
2	2	305	12.09180	3.243125	0.1857008	10.517860	0	19	11.72783	12.45578
3	3	97	13.22680	2.502104	0.2540502	6.260524	8	18	12.72887	13.72474
4	4	35	13.05714	3.038410	0.5135850	9.231933	6	19	12.05052	14.06377

Tukey–Kramer pairwise comparisons

	comparison_order	group_1_lower_mean	group_2_higher_mean
1	1	1	2
2	2	1	4
3	3	1	3
4	4	2	4
5	5	2	3
6	6	4	3

	group_1_mean	group_2_mean	n_group_1	n_group_2
1	10.84434	12.09180	212	305
2	10.84434	13.05714	212	35
3	10.84434	13.22680	212	97
4	12.09180	13.05714	305	35
5	12.09180	13.22680	305	97
6	13.05714	13.22680	35	97

	mean_difference_high_minus_low	pooled_mse
1	1.2474637	9.764634
2	2.2128032	9.764634
3	2.3824645	9.764634
4	0.9653396	9.764634
5	1.1350008	9.764634
6	0.1696613	9.764634

	tukey_kramer_standard_error	q_statistic	df_error
1	0.1975788	6.313752	645
2	0.4031434	5.488874	645
3	0.2708560	8.796057	645
4	0.3943379	2.448001	645
5	0.2575670	4.406624	645
6	0.4356925	0.389406	645

	k_groups_family_size	q_critical_familywise
1	4	3.642648
2	4	3.642648
3	4	3.642648
4	4	3.642648
5	4	3.642648
6	4	3.642648

	tukey_kramer_adjusted_p_value	simultaneous_ci_low
1	5.590331e−05	0.5277536
2	6.612040e−04	0.7442940
3	5.071332e−09	1.3958316
4	3.083885e−01	−0.4710944
5	1.031067e−02	0.1967750
6	9.927036e−01	−1.4174129

	simultaneous_ci_high	decision_alpha_0_05
1	1.967174	Significant
2	3.681312	Significant
3	3.369097	Significant
4	2.401774	Not significant
5	2.073227	Significant
6	1.756735	Not significant

	method_note
1	True Tukey–Kramer: pooled ANOVA MSE, unequal–n SE, one family–wide Studentized Range critical value.
2	True Tukey–Kramer: pooled ANOVA MSE, unequal–n SE, one family–wide Studentized Range critical value.
3	True Tukey–Kramer: pooled ANOVA MSE, unequal–n SE, one family–wide Studentized Range critical value.
4	True Tukey–Kramer: pooled ANOVA MSE, unequal–n SE, one family–wide Studentized Range critical value.
5	True Tukey–Kramer: pooled ANOVA MSE, unequal–n SE, one family–wide Studentized Range critical value.
6	True Tukey–Kramer: pooled ANOVA MSE, unequal–n SE, one family–wide Studentized Range critical value.

Homogeneous subset letters

group	mean	n	tukey_kramer_homogeneous_subset_letters	letter_rule
3	13.22680	97	A	Groups sharing a letter are not significantly different by Tukey–Kramer at alpha=.05.
4	13.05714	35	A	Groups sharing a letter are not significantly different by Tukey–Kramer at alpha=.05.
2	12.09180	305	B	Groups sharing a letter are not significantly different by Tukey–Kramer at alpha=.05.
1	10.84434	212	C	Groups sharing a letter are not significantly different by Tukey–Kramer at alpha=.05.