Web Appendix for "Design and analysis considerations for cohort stepped wedge cluster randomized trials with a decay correlation structure"

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WEB APPENDIX A: CLOSED-FORM SOLUTIONS FOR α_0, α_1 FROM FIRST-STAGE QLS ESTIMATING EQUATIONS

We provide the closed-form solutions to α_0, α_1 based on the first-stage QLS estimating equations. These expressions were first introduced by Shults and Morrow[1], and we review them in our notations for cohort stepped wedge designs. Specifically, the first-stage estimator for α_0 is the solution to the scalar estimating equation

$$\sum_{i=1}^{I} \frac{\partial}{\partial \alpha_0} \left[r_i'(\theta) \left\{ G_i^{-1}(\alpha_0) \otimes F^{-1}(\alpha_1) \right\} r_i(\theta) \right] = 0 \tag{1}$$

This is equivalent to solving for $f(\alpha_0) = 0$, where

$$\begin{aligned} f(\alpha_0) = \sum_{i=1}^{I} \Bigg\{ & [\alpha_0^2 (N_i - 2)(N_i - 1) + 2\alpha_0 (N_i - 1)] \sum_{j=1}^{N_i} r_{ij}'(\theta) F^{-1}(\alpha_1) r_{ij}(\theta) \\ & -2[1 + \alpha_0^2 (N_i - 1)] \sum_{j=1}^{N_i - 1} \sum_{j'=j+1}^{N_i} r_{ij}'(\theta) F^{-1}(\alpha_1) r_{ij'}(\theta) \Bigg\} \Big/ \Big\{ (1-\alpha_0)^2 [1 + (N_i - 1)\alpha_0]^2 \Big\} \end{aligned}$$

For balanced cohort size such that $N_i = N$, a closed-form expression for α_0 is

$$\alpha_0 = \frac{-(N-1)a_1 + \sqrt{(N-1)[(N-1)a_1 - 2a_2](a_1 + 2a_2)}}{(N-1)[a_1(N-2) - 2a_2]}$$

where $a_1 = \sum_{i=1}^{I} \sum_{j=1}^{N_i} r_{ij}'(\theta) F^{-1}(\alpha_1) r_{ij}(\theta)$, and $a_2 = \sum_{i=1}^{I} \sum_{j=1}^{N_i - 1} \sum_{j'=j+1}^{N_i} r_{ij}'(\theta) F^{-1}(\alpha_1) r_{ij}(\theta)$. Similarly, the first-stage estimating equation for α_1

$$\sum_{i=1}^{I} \frac{\partial}{\partial \alpha_1} \left[r_i'(\theta) \left\{ G_i^{-1}(\alpha_0) \otimes F^{-1}(\alpha_1) \right\} r_i(\theta) \right] = 0. \tag{2}$$

is equivalent to the following expression

$$\alpha_1 = \frac{b_m - \sqrt{b_m^2 - 4a_m^2}}{2a_m}$$

where

$$\begin{aligned} a_m &= \sum_{i=1}^{I} \left[q_{i1} \sum_{j=1}^{N_i} \sum_{t=1}^{T-1} r_{ijt} r_{ij,t+1} + q_{i2} \sum_{j=1}^{N_i - 1} \sum_{j'=j+1}^{N_i} \sum_{t=1}^{T-1} (r_{ijt} r_{ij',t+1} + r_{ij't} r_{ij,t+1}) \right] \\ b_m &= \sum_{i=1}^{I} \left[q_{i1} \sum_{j=1}^{N_i} \sum_{t=1}^{T-1} (r_{ijt}^2 + r_{ij,t+1}^2) + 2q_{i2} \sum_{j=1}^{N_i - 1} \sum_{j'=j+1}^{N_i} \sum_{t=1}^{T-1} (r_{ijt} r_{ij't} + r_{ij,t+1} r_{ij',t+1}) \right] \\ q_{i1} &= \frac{1 + (N_i - 2)\alpha_0}{(1-\alpha_0)[1 + (N_i - 1)\alpha_0]} \\ q_{i2} &= \frac{-\alpha_0}{(1-\alpha_0)[1 + (N_i - 1)\alpha_0]} \end{aligned}$$

WEB APPENDIX B: MATRIX-ADJUSTED QLS ESTIMATING EQUATIONS

We justify the proposed matrix-adjusted correlation estimates as follows. Recall that the first-stage estimating equation (1) is equivalent to

$$0=\sum_{i=1}^{I}\frac{\partial}{\partial\alpha_0}\mathrm{tr}\left[\left\{G_i^{-1}(\alpha_0)\otimes F^{-1}(\alpha_1)\right\}r_i(\theta)r_i'(\theta)\right]\propto\sum_{i=1}^{I}\frac{\partial}{\partial\alpha_0}\mathrm{tr}\left[\left\{G_i^{-1}(\alpha_0)\otimes F^{-1}(\alpha_1)\right\}\phi^{-1}r_i(\theta)r_i'(\theta)\right] \tag{3}$$

and $\phi^{-1}r_i(\theta)r_i'(\theta)$ is the nonparametric moment estimator for the correlation matrix. Specifically when I is small, the estimated residual $y_i-\hat{\mu}_i$ tends to be biased towards zero, and following Preisser et al.[2], we have $E[(y_i-\hat{\mu}_i)(y_i-\hat{\mu}_i)']\approx(I-H_i)\mathrm{cov}(y_i)=\phi(I-H_i)A_i^{1/2}\mathrm{corr}(y_i)A_i^{1/2}$ and therefore $E[r_i(\hat{\theta})r_i'(\hat{\theta})]\approx\phi A_i^{-1/2}(I-H_i)A_i^{1/2}\mathrm{corr}(y_i)$. This last equation suggests that $\phi^{-1}A_i^{-1/2}(I-H_i)^{-1}A_i^{1/2}r_i(\hat{\theta})r_i'(\hat{\theta})$ is a better estimator for $\mathrm{corr}(y_i)$ compared to the simple cross-product $\phi^{-1}r_i(\hat{\theta})r_i'(\hat{\theta})$, since the former accounts for finite-sample bias in a multiplicative fashion. Then we define the "matrix-adjusted" estimator $\tilde{R}_i(\theta)=A_i^{-1/2}(I-H_i)^{-1}A_i^{1/2}r_i(\theta)r_i'(\theta)$ for the correlation matrix to replace the simple cross-product $r_i(\theta)r_i'(\theta)$ in (3). See also the Web Appendix B of Li et al.[3] for a full exposition on related technical details. In other words, estimating equation (3) could be replaced by

$$\sum_{i=1}^{I}\frac{\partial}{\partial\alpha_0}\mathrm{tr}\left[\left\{G_i^{-1}(\alpha_0)\otimes F^{-1}(\alpha_1)\right\}\tilde{R}_i(\theta)\right]=0.. \tag{4}$$

When the true correlation is the proportional decay structure, we provide the closed-form updates for the matrix-adjusted estimating equations. Write $\tilde{R}_i(\theta)$ as a block matrix with each block $\tilde{R}_{ijj}$ corresponding to the repeated measurements for the same individual

$$\tilde{R}_i(\theta)=\begin{pmatrix}\tilde{R}_{i11} & \tilde{R}_{i12} & \dots & \tilde{R}_{i1N_i}\\ \tilde{R}_{i21} & \tilde{R}_{i22} & \dots & \tilde{R}_{i2N_i}\\ \vdots & \vdots & \ddots & \vdots\\ \tilde{R}_{iN_i1} & \tilde{R}_{iN_i2} & \dots & \tilde{R}_{iN_iN_i}\end{pmatrix}.$$

After some simplification algebra, we could express α_0 as the solution to $g(\alpha_0)=0$, where

$$\begin{aligned}g(\alpha_0)\;=\;&\sum_{i=1}^{I}\Big\{[\alpha_0^2(N_i-2)(N_i-1)+2\alpha_0(N_i-1)]\sum_{j=1}^{N_i}\mathrm{tr}\left(F^{-1}(\alpha_1)\tilde{R}_{ijj}\right)\\ &-[1+\alpha_0^2(N_i-1)]\sum_{j\neq j'}\mathrm{tr}\left(F^{-1}(\alpha_1)\tilde{R}_{ijj'}\right)\Big\}\Big/\Big\{(1-\alpha_0)^2[1+(N_i-1)\alpha_0]^2\Big\}\end{aligned}$$

Similarly, we solve the following bias-corrected estimating equation for α_1

$$\sum_{i=1}^{I}\frac{\partial}{\partial\alpha_1}\mathrm{tr}\left[\left\{G_i^{-1}(\alpha_0)\otimes F^{-1}(\alpha_1)\right\}\tilde{R}_i(\theta)\right]=0. \tag{5}$$

Recall that $F^{-1}(\rho)=(1-\rho^2)^{-1}\{I+\rho^2C_2-\rho C_1\}$, $C_2=\mathrm{diag}(0,1,\dots,1,0)$ and C_1 is a tridiagonal matrix with zeros on the main diagonal and ones on the two sub-diagonals. After some simplification algebra, we could express α_1 as

$$\alpha_1=\frac{e_m-\sqrt{e_m^2-d_m^2}}{d_m}$$

where

$$\begin{aligned}d_m\;&=\;\sum_{i=1}^{I}\left[q_{i1}\sum_{j=1}^{N_i}\mathrm{tr}\left(C_1\tilde{R}_{ijj}\right)+q_{i2}\sum_{j\neq j'}\mathrm{tr}\left(C_1\tilde{R}_{ijj'}\right)\right]\\ e_m\;&=\;\sum_{i=1}^{I}\left[q_{i1}\sum_{j=1}^{N_i}\mathrm{tr}\left(\tilde{R}_{ijj}\right)+q_{i1}\sum_{j=1}^{N_i}\mathrm{tr}\left(C_2\tilde{R}_{ijj}\right)+q_{i2}\sum_{j\neq j'}\mathrm{tr}\left(\tilde{R}_{ijj'}\right)+q_{i2}\sum_{j\neq j'}\mathrm{tr}\left(C_2\tilde{R}_{ijj'}\right)\right]\end{aligned}$$

WEB APPENDIX C: CLOSED-FORM VARIANCE OF THE INTERVENTION EFFECT UNDER THE PROPORTIONAL DECAY MODEL

Recall that the $TN \times (T+1)$ design matrix corresponding to cluster i as $Z_i = 1_N \otimes (I_T, X_i)$, where 1_N is a N-vector of ones. The variance of the intervention effect var($\hat{\delta}$) equals to the lower-right element of $\phi \left\{ \sum_{i=1}^{I} Z_i' R_i^{-1}(\tau,\rho) Z_i \right\}^{-1}$, where ϕ is the marginal variance or dispersion. Notice that

$$\sum_{i=1}^{I} Z_i' R_i^{-1} Z_i = \sum_{i=1}^{I} \left[1_N' \otimes \begin{pmatrix} I_T \\ X_i' \end{pmatrix} \right] \left(G_i^{-1}(\tau) \otimes F^{-1}(\rho) \right) \left[1_N \otimes \begin{pmatrix} I_T & X_i \end{pmatrix} \right] = \begin{bmatrix} \Lambda_{11} & \Lambda_{12} \\ \Lambda_{21} & \Lambda_{22} \end{bmatrix},$$

where Λ_{11} is of dimension $T \times T$, $\Lambda_{12} = \Lambda_{21}'$ is of dimension $T \times 1$, and Λ_{22} is a scalar. Define $c = (1-\tau)^{-1}$ and $d = \tau / [(1-\tau)\{(1+(N-1)\tau)\}]$, and after some algebra, we obtain

$$\begin{aligned} \Lambda_{11} &= I(1_N' 1_N) \otimes (cF^{-1}) + I(1_N' J 1_N) \otimes (-dF^{-1}) = IN(c - Nd)F^{-1}, \\ \Lambda_{12} &= I(1_N' 1_N) \otimes \sum_{i=1}^{I} (cF^{-1}) X_i + (1_N' J 1_N) \otimes \sum_{i=1}^{I} (-dF^{-1}) X_i = N(c - Nd) \sum_{i=1}^{I} F^{-1} X_i, \end{aligned}$$

and $\Lambda_{22} = N(c - Nd) \sum_{i=1}^{I} X_i' F^{-1} X_i$. The variance of the intervention effect then becomes

$$\begin{aligned} \text{var}(\hat{\delta}) &= \phi (\Lambda_{22} - \Lambda_{21} \Lambda_{11}^{-1} \Lambda_{12})^{-1} \\ &= \phi \left\{ N(c-Nd) \sum_{i=1}^{I} X_i' F^{-1} X_i - I^{-1} N(c-Nd) \left(\sum_{i=1}^{I} X_i' F^{-1} \right) F \left(\sum_{i=1}^{I} F^{-1} X_i \right) \right\}^{-1} \\ &= \phi I N^{-1} (c-Nd)^{-1} \left\{ I \sum_{i=1}^{I} X_i' F^{-1} X_i - \left(\sum_{i=1}^{I} X_i' \right) F^{-1} \left(\sum_{i=1}^{I} X_i \right) \right\}^{-1}. \end{aligned}$$

The key terms are further expanded as

$$\begin{aligned} I \sum_{i=1}^{I} X_i' F^{-1} X_i &= (1-\rho^2)^{-1} \Big\{ I \sum_{i=1}^{I} (X_{i1} + X_{iT}) + I(1+\rho^2) \sum_{t=2}^{T-2} X_{it} - 2\rho IV \Big\} \\ &= (1-\rho^2)^{-1} \Big\{ -I\rho^2 \sum_{i=1}^{I} (X_{i1} + X_{iT}) + (1+\rho^2) IU - 2\rho IV \Big\} \\ &= (1-\rho^2)^{-1} \Big\{ -I^2 \rho^2 + (1+\rho^2) IU - 2\rho IV \Big\}, \end{aligned}$$

where $U = \sum_{i=1}^{I} \sum_{t=1}^{T} X_{it}$ and $V = \sum_{i=1}^{I} \sum_{t=1}^{T-1} X_{it} X_{i,t+1}$ are design constants that only depend on the stepped wedge assignment layout. The last equality holds because $X_{i1} = 0$, $X_{iT} = 1$ for all i in stepped wedge designs. In particular, the inner summation in V reflects the between-period autoregressive structure to the first order. Next,

$$\begin{aligned} \left(\sum_{i=1}^{I} X_i' \right) F^{-1} \left(\sum_{i=1}^{I} X_i \right) &= (1-\rho^2)^{-1} \Big\{ \left(\sum_{i=1}^{I} X_{i1} \right)^2 + \left(\sum_{i=1}^{I} X_{iT} \right)^2 + (1+\rho^2) \sum_{t=2}^{T-1} \left(\sum_{i=1}^{I} X_{it} \right)^2 - 2\rho Q \Big\} \\ &= (1-\rho^2)^{-1} \Big\{ -\rho^2 \left(\sum_{i=1}^{I} X_{i1} \right)^2 - \rho^2 \left(\sum_{i=1}^{I} X_{iT} \right)^2 + (1+\rho^2) W - 2\rho Q \Big\} \\ &= (1-\rho^2)^{-1} \Big\{ -I^2 \rho^2 + (1+\rho^2) W - 2\rho Q \Big\}, \end{aligned}$$

where the design constants $W = \sum_{t=1}^{T} \left(\sum_{i=1}^{I} X_{it} \right)^2$ and $Q = \sum_{t=1}^{T-1} \left(\sum_{i=1}^{I} X_{it} \right) \left(\sum_{i=1}^{I} X_{i,t+1} \right)$. Again, the outer summation in Q reflects the between-period autoregressive structure to the first order. Further note

$$c - Nd = \frac{1}{1-\tau} - \frac{N\tau}{(1-\tau)\{1+(N-1)\tau\}} = \frac{1}{1+(N-1)\tau}$$

Some further algebra leads to the following closed-form variance expression in Section 4.1 of the main text,

$$\text{var}(\hat{\delta}) = \frac{(\phi I/N)(1-\rho^2)\{1+(N-1)\tau\}}{(IU - W)(1+\rho^2) - 2(IV - Q)\rho}.$$

WEB APPENDIX D: WEB TABLES

Web Table 1 Convergence rates (out of 10000) for quasi-least squares (QLS) and matrix-adjusted quasi-least squares (MAQLS) analyses of simulated outcome data when the treatment effect is zero.

Correlations		Effect size	Design resource			Convergence (%)	
τ	ρ	δ	I	N	T	QLS	MAQLS
0.03	0.2	0.3	18	10	7	100.0	98.3
0.03	0.2	0.3	18	24	4	100.0	99.4
0.03	0.2	0.3	20	14	5	100.0	98.9
0.03	0.2	0.4	21	8	4	100.0	100.0
0.03	0.2	0.5	15	8	4	100.0	100.0
0.03	0.8	0.2	16	12	5	99.9	99.2
0.03	0.8	0.2	24	7	5	100.0	99.8
0.03	0.8	0.3	12	8	5	99.8	98.2
0.03	0.8	0.4	12	5	4	99.8	98.0
0.03	0.8	0.5	10	5	3	99.8	98.4
0.10	0.2	0.3	21	11	8	100.0	99.8
0.10	0.2	0.3	24	11	7	100.0	99.9
0.10	0.2	0.4	15	16	6	100.0	98.4
0.10	0.2	0.4	18	8	7	100.0	100.0
0.10	0.2	0.5	16	7	5	100.0	100.0
0.10	0.8	0.2	20	18	5	100.0	99.7
0.10	0.8	0.3	15	9	4	100.0	100.0
0.10	0.8	0.4	10	20	3	100.0	97.0
0.10	0.8	0.4	12	5	5	100.0	99.5
0.10	0.8	0.5	9	7	4	100.0	99.5

Web Table 2 Convergence rates (out of 10000) for quasi-least squares (QLS) and matrix-adjusted quasi-least squares (MAQLS) analyses of simulated outcome data when the treatment effect is nonzero.

Correlations		Effect size	Design resource			Convergence (%)	
τ	ρ	δ	I	N	T	QLS	MAQLS
0.03	0.2	0.3	18	10	7	100.0	98.3
0.03	0.2	0.3	18	24	4	100.0	99.4
0.03	0.2	0.3	20	14	5	100.0	98.9
0.03	0.2	0.4	21	8	4	100.0	100.0
0.03	0.2	0.5	15	8	4	100.0	100.0
0.03	0.8	0.2	16	12	5	99.9	99.2
0.03	0.8	0.2	24	7	5	100.0	99.8
0.03	0.8	0.3	12	8	5	99.8	98.2
0.03	0.8	0.4	12	5	4	99.8	98.0
0.03	0.8	0.5	10	5	3	99.8	98.4
0.10	0.2	0.3	21	11	8	100.0	99.8
0.10	0.2	0.3	24	11	7	100.0	99.9
0.10	0.2	0.4	15	16	6	100.0	98.4
0.10	0.2	0.4	18	8	7	100.0	100.0
0.10	0.2	0.5	16	7	5	100.0	100.0
0.10	0.8	0.2	20	18	5	100.0	99.7
0.10	0.8	0.3	15	9	4	100.0	100.0
0.10	0.8	0.4	10	20	3	100.0	97.0
0.10	0.8	0.4	12	5	5	100.0	99.5
0.10	0.8	0.5	9	7	4	100.0	99.5

Web Table 3 Percent relative bias of the correlation parameters based on quasi-least squares (QLS) and matrix-adjusted quasi-least squares (MAQLS) for each simulation scenario when the treatment effect is nonzero.

Correlations		Effect size	Design resource			Percent bias for τ		Percent bias for ρ	
τ	ρ	δ	I	N	T	QLS	MAQLS	QLS	MAQLS
0.03	0.2	0.3	18	10	7	-26.6	3.6	-0.6	0.2
0.03	0.2	0.3	18	24	4	-16.0	5.5	-0.3	0.0
0.03	0.2	0.3	20	14	5	-20.2	3.4	-0.5	0.1
0.03	0.2	0.4	21	8	4	-29.4	3.2	-0.4	0.2
0.03	0.2	0.5	15	8	4	-41.3	4.7	-0.7	0.3
0.03	0.8	0.2	16	12	5	-26.2	4.4	-0.6	0.0
0.03	0.8	0.2	24	7	5	-27.6	0.7	-0.6	-0.1
0.03	0.8	0.3	12	8	5	-49.4	8.4	-2.1	-0.3
0.03	0.8	0.4	12	5	4	-74.4	6.4	-2.3	-0.5
0.03	0.8	0.5	10	5	3	-92.2	-0.6	-1.6	-0.5
0.10	0.2	0.3	21	11	8	-9.2	3.9	-0.6	0.6
0.10	0.2	0.3	24	11	7	-8.1	3.4	-0.4	0.6
0.10	0.2	0.4	15	16	6	-11.8	7.1	-0.6	1.1
0.10	0.2	0.4	18	8	7	-12.7	3.9	-0.8	0.7
0.10	0.2	0.5	16	7	5	-16.7	3.7	-0.7	1.0
0.10	0.8	0.2	20	18	5	-8.0	4.9	-0.1	0.2
0.10	0.8	0.3	15	9	4	-15.2	3.1	-0.2	0.2
0.10	0.8	0.4	10	20	3	-16.9	6.4	-0.1	0.3
0.10	0.8	0.4	12	5	5	-27.0	2.6	-1.5	0.0
0.10	0.8	0.5	9	7	4	-29.7	3.9	-1.0	0.1

Web Table 4 Simulation scenarios, nominal size, along with the empirical type I error rates corresponding to the QLS z-tests and MAQLS z-test with different variance estimators. Empirical type I error rates between 0.045 and 0.055 are considered acceptable based on the margin of error from a binomial model with 10000 Monte Carlo replications.

							MB[b]		BC0[c]		BC1[d]		BC2[e]		BC3[f]	
τ	ρ	δ	I	N	T	Pred[a]	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS
0.03	0.2	0	18	10	7	0.050	0.056	0.048	0.084	0.084	0.068	0.068	0.051	0.051	0.070	0.071
0.03	0.2	0	18	24	4	0.050	0.061	0.049	0.081	0.081	0.066	0.065	0.051	0.050	0.066	0.065
0.03	0.2	0	20	14	5	0.050	0.061	0.051	0.083	0.083	0.069	0.069	0.058	0.058	0.070	0.070
0.03	0.2	0	21	8	4	0.050	0.061	0.052	0.079	0.079	0.066	0.066	0.053	0.053	0.066	0.066
0.03	0.2	0	15	8	4	0.050	0.070	0.057	0.096	0.097	0.077	0.077	0.058	0.058	0.077	0.077
0.03	0.8	0	16	12	5	0.050	0.066	0.056	0.091	0.090	0.074	0.073	0.056	0.056	0.074	0.073
0.03	0.8	0	24	7	5	0.050	0.059	0.053	0.078	0.077	0.066	0.066	0.056	0.055	0.067	0.066
0.03	0.8	0	12	8	5	0.050	0.071	0.060	0.109	0.106	0.081	0.079	0.059	0.058	0.082	0.079
0.03	0.8	0	12	5	4	0.050	0.067	0.057	0.104	0.103	0.079	0.078	0.058	0.057	0.076	0.075
0.03	0.8	0	10	5	3	0.050	0.074	0.063	0.113	0.112	0.083	0.082	0.057	0.056	0.072	0.071
0.10	0.2	0	21	11	8	0.050	0.060	0.050	0.081	0.081	0.069	0.069	0.057	0.057	0.070	0.070
0.10	0.2	0	24	11	7	0.050	0.060	0.051	0.076	0.077	0.064	0.064	0.053	0.053	0.065	0.065
0.10	0.2	0	15	16	6	0.050	0.062	0.048	0.098	0.097	0.075	0.075	0.058	0.057	0.078	0.078
0.10	0.2	0	18	8	7	0.050	0.059	0.048	0.087	0.088	0.071	0.071	0.056	0.056	0.073	0.073
0.10	0.2	0	16	7	5	0.050	0.065	0.052	0.091	0.091	0.072	0.072	0.055	0.055	0.073	0.073
0.10	0.8	0	20	18	5	0.050	0.062	0.053	0.079	0.079	0.064	0.064	0.052	0.052	0.065	0.065
0.10	0.8	0	15	9	4	0.050	0.065	0.055	0.091	0.091	0.072	0.072	0.053	0.053	0.070	0.070
0.10	0.8	0	10	20	3	0.050	0.076	0.056	0.116	0.117	0.084	0.085	0.060	0.060	0.073	0.074
0.10	0.8	0	12	5	5	0.050	0.069	0.058	0.105	0.105	0.079	0.079	0.058	0.057	0.080	0.079
0.10	0.8	0	9	7	4	0.050	0.076	0.060	0.122	0.120	0.088	0.086	0.058	0.057	0.084	0.083

[a] Pred: Nominal type I error rate.

[b] MB: Model-based variance.

[c] BC0: Uncorrected sandwich variance of Liang and Zeger (1986).

[d] BC1: Bias-corrected sandwich variance of Kauermann and Carroll (2001).

[e] BC2: Bias-corrected sandwich variance of Mancl and DeRouen (2001).

[f] BC3: Bias-corrected sandwich variance of Fay and Graubard (2001).

Web Table 5 Simulation scenarios, nominal size, along with the empirical type I error rates corresponding to the QLS t-tests and MAQLS t-test with different variance estimators. The degrees of freedom is set to be $\text{DoF} = I - 2$. Empirical type I error rates between 0.045 and 0.055 are considered acceptable based on the margin of error from a binomial model with 10000 Monte Carlo replications.

							MB[b]		BC0[c]		BC1[d]		BC2[e]		BC3[f]	
τ	ρ	δ	I	N	T	Pred[a]	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS
0.03	0.2	0	18	10	7	0.050	0.041	0.034	0.063	0.063	0.047	0.047	0.038	0.038	0.049	0.049
0.03	0.2	0	18	24	4	0.050	0.043	0.034	0.061	0.060	0.048	0.047	0.036	0.036	0.047	0.047
0.03	0.2	0	20	14	5	0.050	0.044	0.038	0.065	0.065	0.054	0.054	0.044	0.044	0.055	0.055
0.03	0.2	0	21	8	4	0.050	0.045	0.038	0.061	0.061	0.050	0.050	0.040	0.040	0.049	0.049
0.03	0.2	0	15	8	4	0.050	0.045	0.037	0.070	0.070	0.053	0.053	0.041	0.041	0.053	0.053
0.03	0.8	0	16	12	5	0.050	0.044	0.038	0.068	0.067	0.051	0.051	0.038	0.038	0.051	0.051
0.03	0.8	0	24	7	5	0.050	0.047	0.043	0.063	0.062	0.053	0.052	0.043	0.043	0.053	0.053
0.03	0.8	0	12	8	5	0.050	0.043	0.035	0.072	0.070	0.051	0.049	0.034	0.032	0.052	0.050
0.03	0.8	0	12	5	4	0.050	0.040	0.034	0.070	0.069	0.051	0.050	0.036	0.035	0.050	0.049
0.03	0.8	0	10	5	3	0.050	0.038	0.030	0.070	0.070	0.047	0.046	0.032	0.031	0.039	0.038
0.10	0.2	0	21	11	8	0.050	0.044	0.038	0.066	0.066	0.053	0.053	0.043	0.044	0.055	0.056
0.10	0.2	0	24	11	7	0.050	0.044	0.038	0.061	0.061	0.051	0.051	0.043	0.043	0.052	0.052
0.10	0.2	0	15	16	6	0.050	0.041	0.031	0.069	0.068	0.052	0.052	0.040	0.040	0.054	0.053
0.10	0.2	0	18	8	7	0.050	0.040	0.034	0.067	0.067	0.053	0.052	0.040	0.040	0.054	0.054
0.10	0.2	0	16	7	5	0.050	0.044	0.034	0.065	0.066	0.051	0.051	0.038	0.038	0.052	0.052
0.10	0.8	0	20	18	5	0.050	0.046	0.038	0.061	0.061	0.048	0.048	0.039	0.039	0.048	0.048
0.10	0.8	0	15	9	4	0.050	0.044	0.037	0.066	0.066	0.048	0.048	0.037	0.037	0.046	0.046
0.10	0.8	0	10	20	3	0.050	0.038	0.028	0.072	0.073	0.049	0.049	0.030	0.030	0.040	0.040
0.10	0.8	0	12	5	5	0.050	0.041	0.033	0.070	0.069	0.050	0.049	0.034	0.033	0.049	0.049
0.10	0.8	0	9	7	4	0.050	0.038	0.028	0.074	0.072	0.048	0.047	0.030	0.029	0.046	0.045

[a] Pred: Nominal type I error rate.

[b] MB: Model-based variance.

[c] BC0: Uncorrected sandwich variance of Liang and Zeger (1986).

[d] BC1: Bias-corrected sandwich variance of Kauermann and Carroll (2001).

[e] BC2: Bias-corrected sandwich variance of Mancl and DeRouen (2001).

[f] BC3: Bias-corrected sandwich variance of Fay and Graubard (2001).

Web Table 6 Simulation scenarios, nominal size, along with the empirical type I error rates corresponding to the QLS t-tests and MAQLS t-test with different variance estimators. The degrees of freedom is set to be DoF $= I - (T + 1)$. Empirical type I error rates between 0.045 and 0.055 are considered acceptable based on the margin of error from a binomial model with 10000 Monte Carlo replications.

							MB[b]		BC0[c]		BC1[d]		BC2[e]		BC3[f]	
τ	ρ	δ	I	N	T	Pred[a]	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS
0.03	0.2	0	18	10	7	0.050	0.032	0.026	0.049	0.050	0.040	0.040	0.032	0.032	0.041	0.041
0.03	0.2	0	18	24	4	0.050	0.040	0.031	0.056	0.055	0.043	0.043	0.034	0.034	0.043	0.043
0.03	0.2	0	20	14	5	0.050	0.040	0.033	0.062	0.062	0.050	0.051	0.040	0.040	0.051	0.051
0.03	0.2	0	21	8	4	0.050	0.042	0.035	0.058	0.058	0.047	0.047	0.037	0.037	0.046	0.047
0.03	0.2	0	15	8	4	0.050	0.039	0.030	0.063	0.063	0.048	0.048	0.036	0.037	0.047	0.047
0.03	0.8	0	16	12	5	0.050	0.038	0.031	0.058	0.058	0.044	0.044	0.034	0.033	0.045	0.045
0.03	0.8	0	24	7	5	0.050	0.044	0.041	0.060	0.059	0.050	0.049	0.041	0.041	0.050	0.049
0.03	0.8	0	12	8	5	0.050	0.028	0.021	0.051	0.049	0.034	0.032	0.023	0.022	0.034	0.032
0.03	0.8	0	12	5	4	0.050	0.031	0.026	0.056	0.055	0.042	0.041	0.028	0.027	0.040	0.039
0.03	0.8	0	10	5	3	0.050	0.028	0.022	0.057	0.057	0.038	0.037	0.025	0.025	0.033	0.032
0.10	0.2	0	21	11	8	0.050	0.037	0.032	0.056	0.056	0.046	0.046	0.035	0.035	0.047	0.047
0.10	0.2	0	24	11	7	0.050	0.041	0.034	0.056	0.057	0.048	0.048	0.039	0.039	0.048	0.048
0.10	0.2	0	15	16	6	0.050	0.031	0.021	0.055	0.054	0.042	0.041	0.030	0.030	0.043	0.042
0.10	0.2	0	18	8	7	0.050	0.033	0.025	0.055	0.055	0.042	0.042	0.032	0.031	0.044	0.044
0.10	0.2	0	16	7	5	0.050	0.036	0.027	0.057	0.058	0.043	0.043	0.031	0.032	0.043	0.044
0.10	0.8	0	20	18	5	0.050	0.042	0.034	0.056	0.056	0.044	0.045	0.035	0.035	0.044	0.044
0.10	0.8	0	15	9	4	0.050	0.038	0.032	0.057	0.057	0.042	0.042	0.032	0.032	0.041	0.041
0.10	0.8	0	10	20	3	0.050	0.029	0.022	0.060	0.061	0.037	0.038	0.024	0.024	0.031	0.031
0.10	0.8	0	12	5	5	0.050	0.026	0.021	0.049	0.049	0.034	0.033	0.023	0.022	0.033	0.033
0.10	0.8	0	9	7	4	0.050	0.017	0.011	0.042	0.041	0.026	0.025	0.015	0.015	0.025	0.024

[a] Pred: Nominal type I error rate.

[b] MB: Model-based variance.

[c] BC0: Uncorrected sandwich variance of Liang and Zeger (1986).

[d] BC1: Bias-corrected sandwich variance of Kauermann and Carroll (2001).

[e] BC2: Bias-corrected sandwich variance of Mancl and DeRouen (2001).

[f] BC3: Bias-corrected sandwich variance of Fay and Graubard (2001).

Web Table 7 Simulation scenarios, predicted power, along with the empirical power corresponding to the QLS z-tests and MAQLS z-test with different variance estimators. Differences from the prediction within 0.008 are considered acceptable based on the margin of error from a binomial model with 10000 Monte Carlo replications.

							MB[b]		BC0[c]		BC1[d]		BC2[e]		BC3[f]	
τ	ρ	δ	I	N	T	Pred[a]	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS
0.03	0.2	0.3	18	10	7	0.899	0.907	0.894	0.910	0.910	0.889	0.889	0.865	0.866	0.890	0.890
0.03	0.2	0.3	18	24	4	0.886	0.898	0.882	0.901	0.901	0.882	0.882	0.856	0.857	0.881	0.881
0.03	0.2	0.3	20	14	5	0.897	0.908	0.896	0.911	0.912	0.891	0.892	0.870	0.870	0.893	0.893
0.03	0.2	0.4	21	8	4	0.875	0.882	0.870	0.887	0.887	0.866	0.866	0.840	0.840	0.866	0.866
0.03	0.2	0.5	15	8	4	0.907	0.910	0.896	0.917	0.917	0.895	0.896	0.868	0.868	0.896	0.896
0.03	0.8	0.2	16	12	5	0.886	0.893	0.881	0.899	0.899	0.873	0.873	0.842	0.842	0.873	0.873
0.03	0.8	0.2	24	7	5	0.882	0.885	0.877	0.891	0.892	0.875	0.875	0.857	0.858	0.874	0.875
0.03	0.8	0.3	12	8	5	0.941	0.938	0.930	0.943	0.945	0.920	0.923	0.892	0.895	0.919	0.922
0.03	0.8	0.4	12	5	4	0.952	0.949	0.943	0.957	0.958	0.938	0.940	0.912	0.914	0.936	0.937
0.03	0.8	0.5	10	5	3	0.946	0.950	0.938	0.957	0.957	0.935	0.935	0.898	0.898	0.922	0.922
0.10	0.2	0.3	21	11	8	0.878	0.885	0.872	0.893	0.893	0.874	0.874	0.850	0.850	0.877	0.877
0.10	0.2	0.3	24	11	7	0.878	0.887	0.872	0.890	0.890	0.874	0.874	0.852	0.852	0.876	0.877
0.10	0.2	0.4	15	16	6	0.906	0.917	0.894	0.919	0.919	0.897	0.896	0.864	0.864	0.899	0.898
0.10	0.2	0.4	18	8	7	0.916	0.927	0.914	0.930	0.930	0.911	0.911	0.889	0.889	0.914	0.914
0.10	0.2	0.5	16	7	5	0.886	0.898	0.878	0.905	0.905	0.880	0.880	0.850	0.851	0.882	0.882
0.10	0.8	0.2	20	18	5	0.861	0.873	0.856	0.879	0.879	0.855	0.855	0.831	0.831	0.855	0.855
0.10	0.8	0.3	15	9	4	0.895	0.901	0.885	0.905	0.905	0.880	0.880	0.849	0.849	0.877	0.877
0.10	0.8	0.4	10	20	3	0.944	0.954	0.937	0.959	0.959	0.935	0.936	0.899	0.900	0.922	0.922
0.10	0.8	0.4	12	5	5	0.932	0.934	0.926	0.940	0.941	0.917	0.919	0.886	0.888	0.916	0.918
0.10	0.8	0.5	9	7	4	0.973	0.974	0.967	0.976	0.976	0.961	0.961	0.930	0.931	0.959	0.959

[a] Pred: Predicted power.

[b] MB: Model-based variance.

[c] BC0: Uncorrected sandwich variance of Liang and Zeger (1986).

[d] BC1: Bias-corrected sandwich variance of Kauermann and Carroll (2001).

[e] BC2: Bias-corrected sandwich variance of Mancl and DeRouen (2001).

[f] BC3: Bias-corrected sandwich variance of Fay and Graubard (2001).

Web Table 8 Simulation scenarios, predicted power, along with the empirical power corresponding to the QLS t-tests and MAQLS t-test with different variance estimators. The degrees of freedom is set to be $\text{DoF} = I - 2$. Differences from the prediction within 0.008 are considered acceptable based on the margin of error from a binomial model with 10000 Monte Carlo replications.

							MB[b]		BC0[c]		BC1[d]		BC2[e]		BC3[f]	
τ	ρ	δ	I	N	T	Pred[a]	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS
0.03	0.2	0.3	18	10	7	0.860	0.879	0.862	0.883	0.884	0.859	0.859	0.825	0.826	0.861	0.862
0.03	0.2	0.3	18	24	4	0.844	0.869	0.849	0.876	0.876	0.849	0.849	0.819	0.819	0.848	0.848
0.03	0.2	0.3	20	14	5	0.862	0.883	0.865	0.887	0.887	0.863	0.864	0.836	0.837	0.865	0.865
0.03	0.2	0.4	21	8	4	0.839	0.855	0.838	0.860	0.860	0.834	0.834	0.807	0.807	0.833	0.833
0.03	0.2	0.5	15	8	4	0.859	0.875	0.857	0.890	0.890	0.857	0.857	0.816	0.817	0.856	0.856
0.03	0.8	0.2	16	12	5	0.838	0.860	0.839	0.863	0.863	0.831	0.832	0.794	0.794	0.832	0.832
0.03	0.8	0.2	24	7	5	0.852	0.862	0.854	0.869	0.870	0.851	0.852	0.827	0.829	0.851	0.852
0.03	0.8	0.3	12	8	5	0.887	0.901	0.891	0.912	0.914	0.880	0.884	0.838	0.840	0.882	0.884
0.03	0.8	0.4	12	5	4	0.903	0.918	0.908	0.930	0.931	0.898	0.900	0.862	0.863	0.895	0.897
0.03	0.8	0.5	10	5	3	0.878	0.905	0.887	0.921	0.921	0.875	0.875	0.818	0.819	0.855	0.854
0.10	0.2	0.3	21	11	8	0.843	0.859	0.841	0.869	0.869	0.844	0.844	0.815	0.815	0.847	0.847
0.10	0.2	0.3	24	11	7	0.848	0.863	0.848	0.868	0.868	0.849	0.849	0.826	0.826	0.851	0.851
0.10	0.2	0.4	15	16	6	0.858	0.881	0.851	0.888	0.888	0.855	0.855	0.817	0.817	0.859	0.859
0.10	0.2	0.4	18	8	7	0.879	0.902	0.883	0.906	0.906	0.882	0.883	0.854	0.854	0.885	0.886
0.10	0.2	0.5	16	7	5	0.838	0.861	0.837	0.873	0.872	0.840	0.841	0.802	0.803	0.843	0.844
0.10	0.8	0.2	20	18	5	0.821	0.841	0.818	0.848	0.847	0.821	0.821	0.788	0.788	0.820	0.820
0.10	0.8	0.3	15	9	4	0.845	0.864	0.843	0.870	0.870	0.836	0.837	0.796	0.796	0.833	0.833
0.10	0.8	0.4	10	20	3	0.875	0.912	0.879	0.920	0.921	0.881	0.881	0.820	0.821	0.856	0.857
0.10	0.8	0.4	12	5	5	0.875	0.897	0.882	0.905	0.907	0.871	0.872	0.825	0.828	0.871	0.872
0.10	0.8	0.5	9	7	4	0.914	0.942	0.924	0.948	0.949	0.910	0.911	0.855	0.856	0.906	0.907

[a] Pred: Predicted power.

[b] MB: Model-based variance.

[c] BC0: Uncorrected sandwich variance of Liang and Zeger (1986).

[d] BC1: Bias-corrected sandwich variance of Kauermann and Carroll (2001).

[e] BC2: Bias-corrected sandwich variance of Mancl and DeRouen (2001).

[f] BC3: Bias-corrected sandwich variance of Fay and Graubard (2001).

Web Table 9 Simulation scenarios, predicted power, along with the empirical power corresponding to the QLS t-tests and MAQLS t-test with different variance estimators. The degrees of freedom is set to be DoF $= I - (T + 1)$. Differences from the prediction within 0.008 are considered acceptable based on the margin of error from a binomial model with 10000 Monte Carlo replications.

							MB[b]		BC0[c]		BC1[d]		BC2[e]		BC3[f]	
τ	ρ	δ	I	N	T	Pred[a]	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS	QLS	MAQLS
0.03	0.2	0.3	18	10	7	0.832	0.857	0.836	0.864	0.864	0.833	0.833	0.798	0.799	0.837	0.837
0.03	0.2	0.3	18	24	4	0.833	0.863	0.840	0.868	0.869	0.840	0.841	0.806	0.807	0.839	0.839
0.03	0.2	0.3	20	14	5	0.850	0.873	0.854	0.879	0.880	0.854	0.855	0.825	0.825	0.856	0.856
0.03	0.2	0.4	21	8	4	0.831	0.848	0.832	0.855	0.855	0.827	0.827	0.799	0.799	0.827	0.827
0.03	0.2	0.5	15	8	4	0.842	0.864	0.842	0.877	0.877	0.841	0.841	0.800	0.800	0.840	0.840
0.03	0.8	0.2	16	12	5	0.815	0.838	0.817	0.845	0.845	0.812	0.811	0.768	0.768	0.811	0.811
0.03	0.8	0.2	24	7	5	0.845	0.857	0.849	0.864	0.865	0.844	0.845	0.820	0.820	0.844	0.845
0.03	0.8	0.3	12	8	5	0.838	0.864	0.847	0.880	0.883	0.836	0.838	0.784	0.786	0.837	0.840
0.03	0.8	0.4	12	5	4	0.876	0.899	0.883	0.911	0.913	0.876	0.878	0.827	0.828	0.873	0.875
0.03	0.8	0.5	10	5	3	0.847	0.881	0.857	0.899	0.898	0.847	0.847	0.778	0.778	0.822	0.822
0.10	0.2	0.3	21	11	8	0.819	0.841	0.820	0.850	0.849	0.821	0.822	0.792	0.792	0.826	0.826
0.10	0.2	0.3	24	11	7	0.835	0.854	0.837	0.859	0.858	0.838	0.838	0.814	0.814	0.841	0.841
0.10	0.2	0.4	15	16	6	0.820	0.850	0.811	0.860	0.859	0.823	0.822	0.774	0.774	0.828	0.827
0.10	0.2	0.4	18	8	7	0.853	0.879	0.856	0.887	0.887	0.861	0.861	0.827	0.827	0.864	0.864
0.10	0.2	0.5	16	7	5	0.815	0.841	0.817	0.856	0.857	0.821	0.821	0.777	0.777	0.823	0.824
0.10	0.8	0.2	20	18	5	0.808	0.830	0.806	0.840	0.839	0.808	0.808	0.776	0.776	0.808	0.808
0.10	0.8	0.3	15	9	4	0.826	0.849	0.826	0.856	0.856	0.820	0.820	0.777	0.778	0.817	0.817
0.10	0.8	0.4	10	20	3	0.843	0.889	0.849	0.900	0.901	0.849	0.850	0.779	0.781	0.823	0.824
0.10	0.8	0.4	12	5	5	0.823	0.854	0.833	0.870	0.871	0.824	0.826	0.764	0.767	0.824	0.826
0.10	0.8	0.5	9	7	4	0.835	0.884	0.852	0.897	0.898	0.833	0.834	0.743	0.744	0.825	0.825

[a] Pred: Predicted power.

[b] MB: Model-based variance.

[c] BC0: Uncorrected sandwich variance of Liang and Zeger (1986).

[d] BC1: Bias-corrected sandwich variance of Kauermann and Carroll (2001).

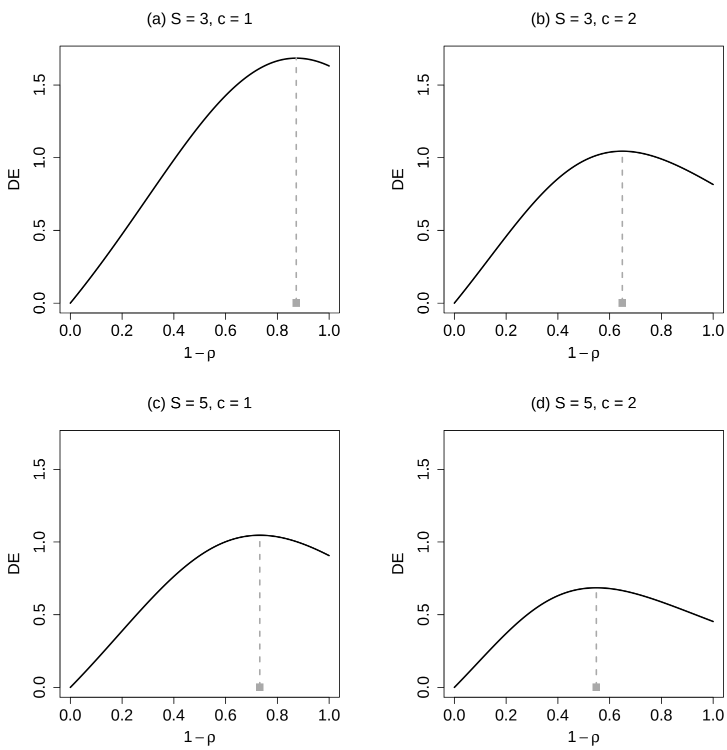
[e] BC2: Bias-corrected sandwich variance of Mancl and DeRouen (2001).

[f] BC3: Bias-corrected sandwich variance of Fay and Graubard (2001).

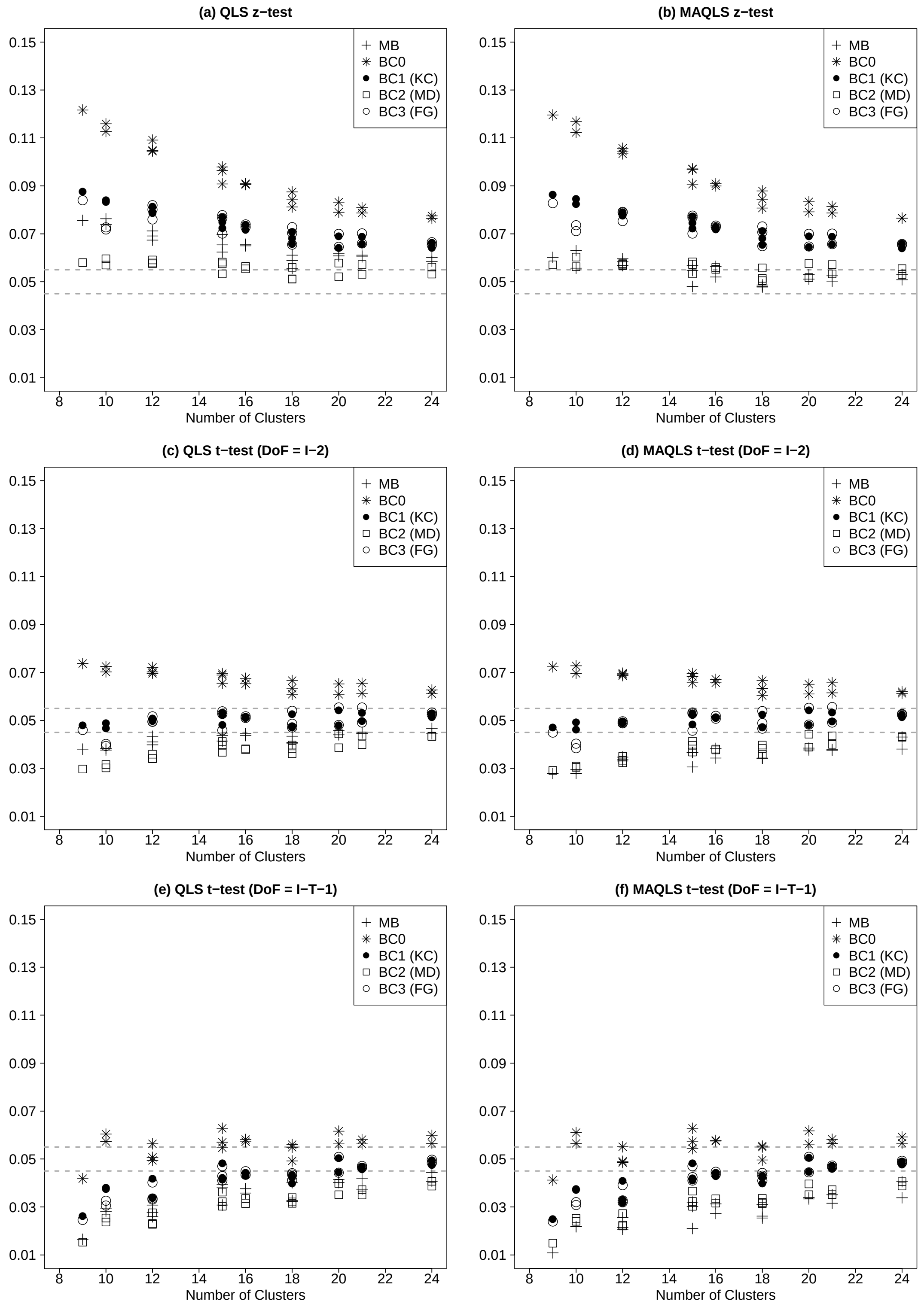
WEB APPENDIX E: WEB FIGURES

	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$	$t = 6$
			$s = 1$	$s = 2$		$s = 3$
cluster 1	0	0	1	1	1	1
cluster 2	0	0	1	1	1	1
cluster 3	0	0	0	1	1	1
cluster 4	0	0	0	1	1	1
cluster 5	0	0	0	0	0	1
cluster 6	0	0	0	0	0	1
	$b = 2$		$c_1 = 1$	$c_2 = 2$		$c_3 = 1$

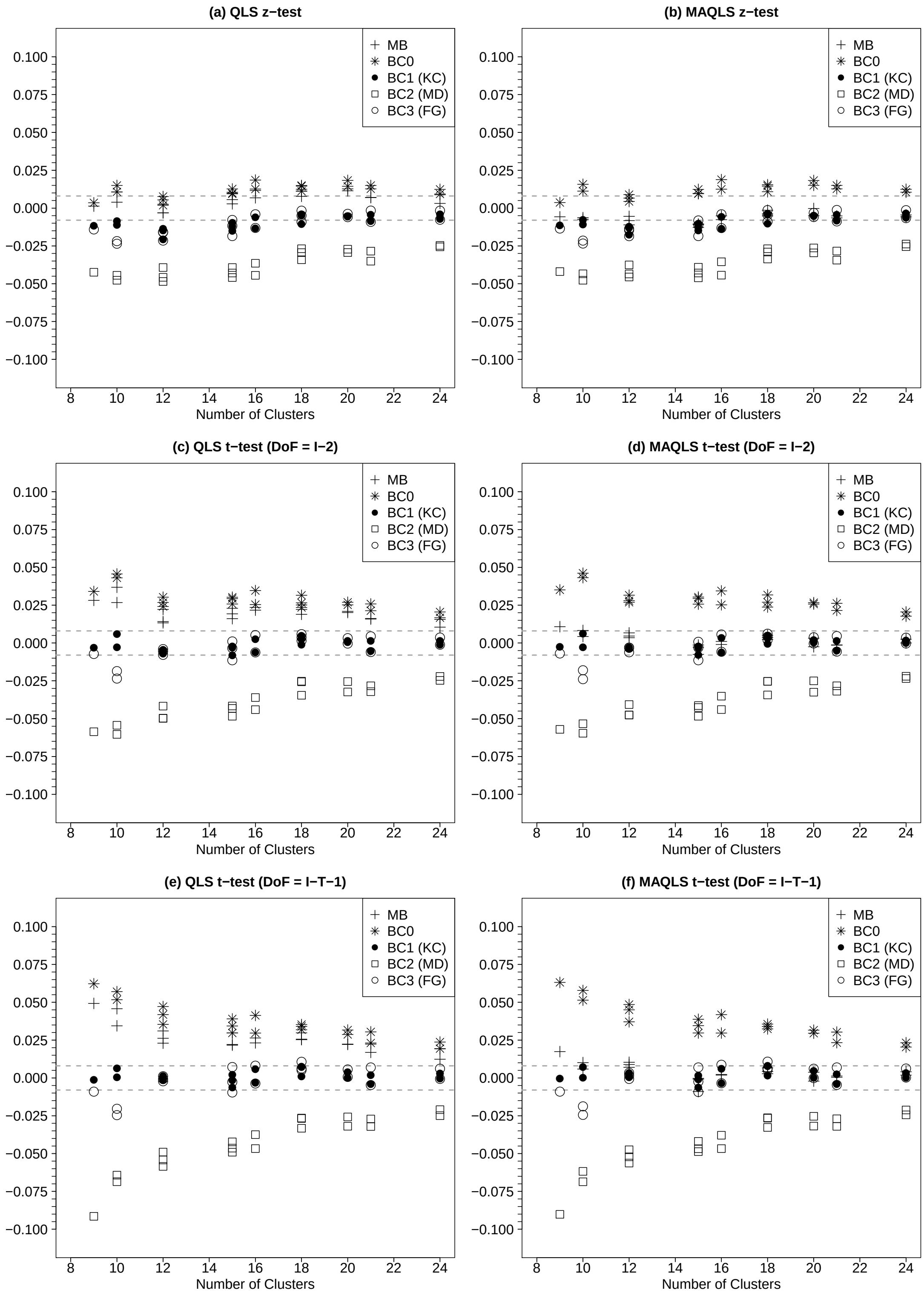
Web Figure 1 A schematic illustration of a stepped wedge design with $I = 6$ clusters and $T = 6$ periods, with $b = 2$ baseline periods, $c_1 = c_3 = 1$ and $c_2 = 2$. Each cell with a zero entry indicates a control cluster-period and each cell with a one entry indicates an intervention cluster-period.



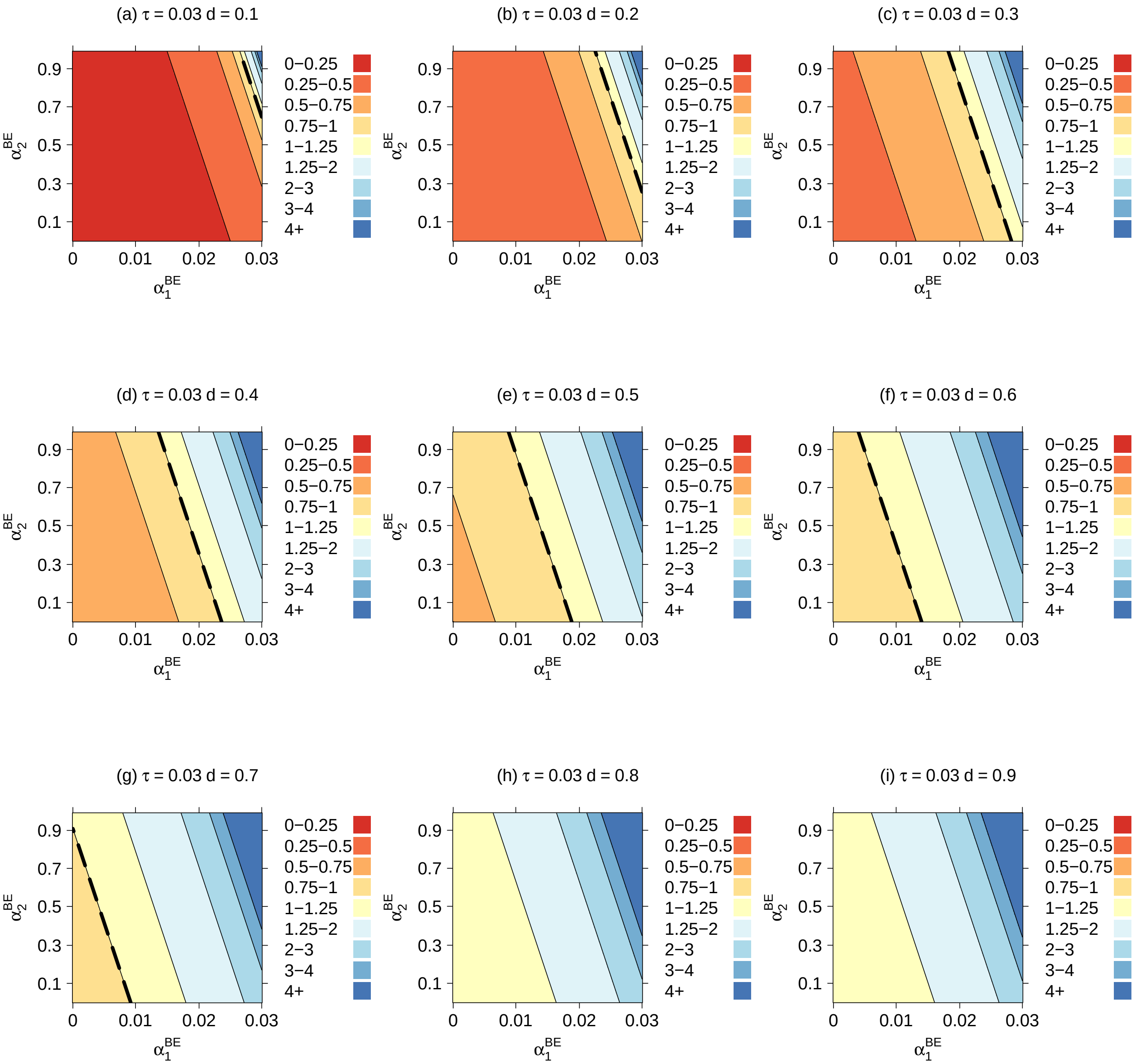
Web Figure 2 The design effect as a function of the degree of correlation decay, defined as $1 - \rho$. The x-axis is $1 - \rho$ so that the degree of decay increases from left to right. For illustration, the cohort size and the within-period correlation are fixed at $N = 20$ and $\tau = 0.1$. Corresponding to the analytical result in Section 4.2, the maximum design effect is attained when $\rho = r$ (gray square dot), a value between 0 and 1 and determined by the number of steps S and the number of measurements between steps c.



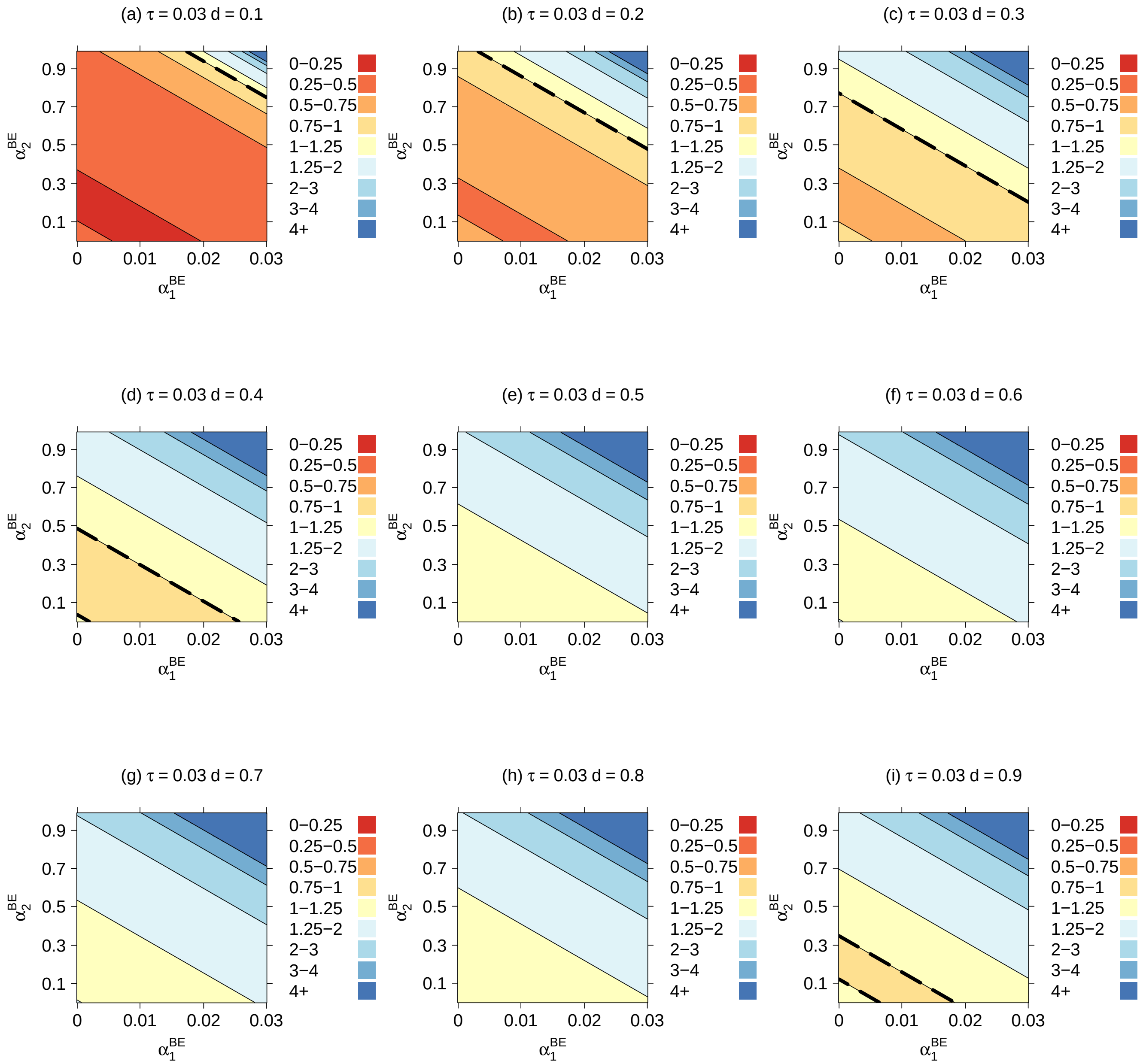
Web Figure 3 Empirical type I error rates for (a) QLS z-tests, (b) MAQLS z-tests, (c) QLS t-tests with DoF $= I - 2$, (d) MAQLS t-tests with DoF $= I - 2$, (e) QLS t-tests with DoF $= I - (T + 1)$ and (f) MAQLS t-tests with DoF $= I - (T + 1)$. MB: model-based variance; BC0: uncorrected sandwich variance; BC1: KC-corrected sandwich variance; BC2: MD-corrected sandwich variance; BC3: FG-corrected sandwich variance. The acceptable bounds are shown with the dashed horizontal lines. For each value of I, there may be multiple points with the same symbol indicating results with different combinations of design resources and correlation parameters.



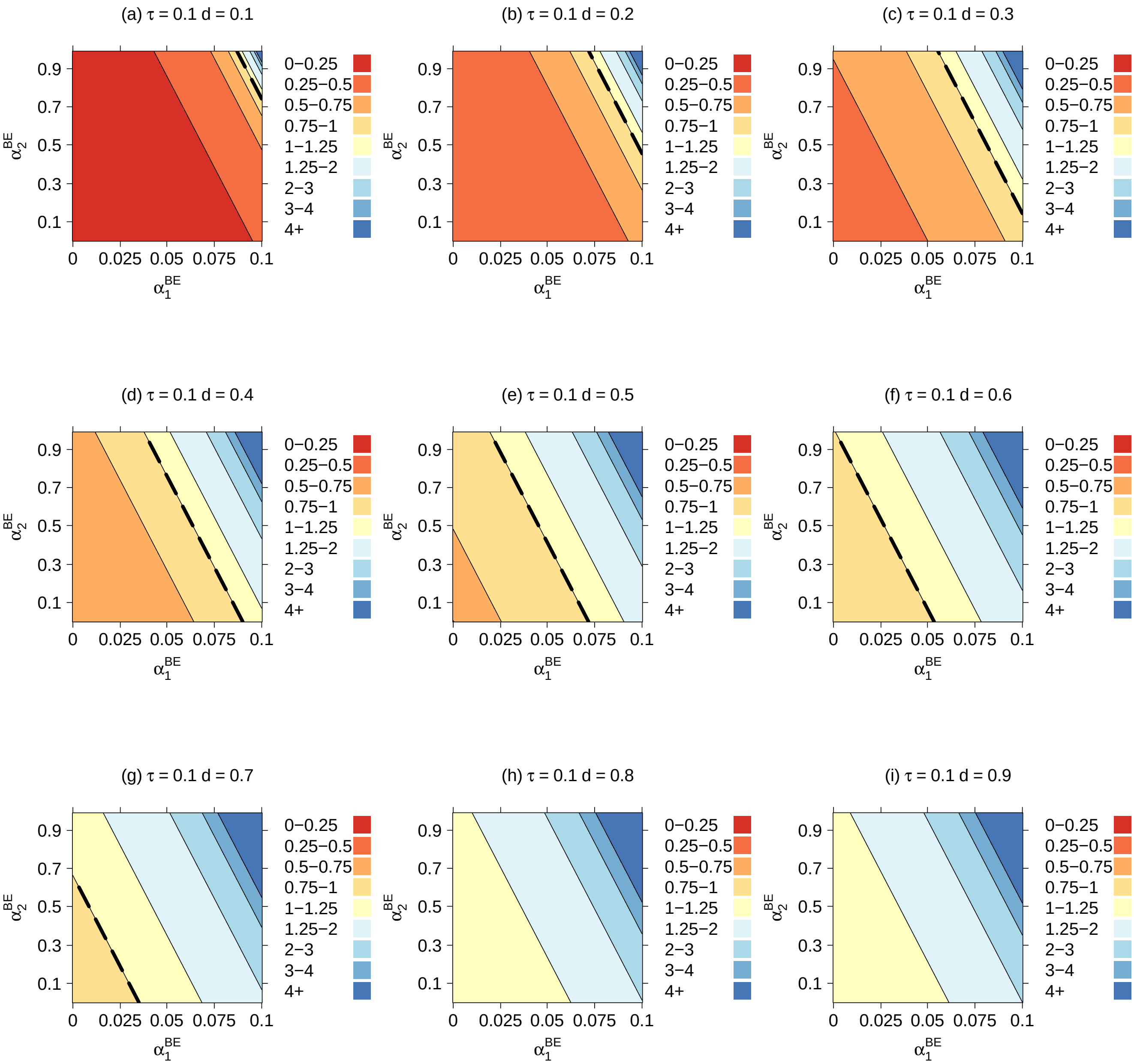
Web Figure 4 Differences between the empirical power and the predicted power of (a) QLS z-tests, (b) MAQLS z-tests, (c) QLS t-tests with DoF $= I - 2$, (d) MAQLS t-tests with DoF $= I - 2$, (e) QLS t-tests with DoF $= I - (T + 1)$ and (f) MAQLS t-tests with DoF $= I - (T + 1)$. MB: model-based variance; BC0: uncorrected sandwich variance; BC1: KC-corrected sandwich variance; BC2: MD-corrected sandwich variance; BC3: FG-corrected sandwich variance. The acceptable bounds are shown with the dashed horizontal lines. For each value of I, there may be multiple points with the same symbol indicating results with different combinations of design resources and correlation parameters.



Web Figure 5 Contour plots for the relative variance obtained under the proportional decay correlation model and the block exchangeable correlation model, for varying values of the proportional decay model decay parameter d and the block exchangeable model correlation parameters α_1^{BE}, α_2^{BE}. In all panels, the within-period correlation $\tau = 0.03$, the number of periods $T = 4$ and the cohort size $N = 100$. The dashed thick line indicates the equality of variances.



Web Figure 6 Contour plots for the relative variance obtained under the proportional decay correlation model and the block exchangeable correlation model, for varying values of the proportional decay model decay parameter d and the block exchangeable model correlation parameters α_1^{BE}, α_2^{BE}. In all panels, the within-period correlation $\tau = 0.03$, the number of periods $T = 8$ and the cohort size $N = 20$. The dashed thick line indicates the equality of variances.



Web Figure 7 Contour plots for the relative variance obtained under the proportional decay correlation model and the block exchangeable correlation model, for varying values of the proportional decay model decay parameter d and the block exchangeable model correlation parameters α_1^{BE}, α_2^{BE}. In all panels, the within-period correlation $\tau = 0.1$, the number of periods $T = 4$ and the cohort size $N = 20$. The dashed thick line indicates the equality of variances.

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