

On the selection of solutions for mutation in differential evolution

Yong WANG (✉)^{1,2}, Zhi-Zhong LIU¹, Jianbin LI³, Han-Xiong LI^{4,5}, and Jiahai WANG⁶

1 School of Information Science and Engineering, Central South University, Changsha 410083, China

2 School of Computer Science and Informatics, De Montfort University, Leicester LE1 9BH, UK

3 Institute of Information Security and Big Data, Central South University, Changsha 410083, China

4 Department of Systems Engineering and Engineering Management, City University of Hong Kong, Hong Kong

5 State Key Laboratory of High Performance Complex Manufacturing, Central South University, Changsha 410083, China

6 School of Data and Computer Science, Sun Yat-sen University, Guangzhou 510006, China

© Higher Education Press and Springer-Verlag Berlin Heidelberg 2016

Table S1

Experimental results of DE/rand/1/bin, U-DE/rand/1/bin, DE/rand/2/bin, and U-DE/rand/2/bin over 25 independent runs on the 14 test functions with 30D from IEEE CEC2005 using 300,000 FEs. "Mean Error" and "Std Dev" indicate the average and standard deviation of the function error values obtained in 25 runs, respectively. Wilcoxon's rank sum test at a 0.05 significance level is performed between DE/rand/1/bin and U-DE/rand/1/bin, and between DE/rand/2/bin and U-DE/rand/2/bin.

Test Functions (30D)		DE/rand/1/bin Mean Error±Std Dev	U-DE/rand/1/bin Mean Error±Std Dev	DE/rand/2/bin Mean Error±Std Dev	U-DE/rand/2/bin Mean Error±Std Dev
<i>Unimodal Functions</i>	F_1	6.54E-18±1.19E-17	1.84E-27±1.37E-27+	5.99E+03±9.25E+02	5.46E-10±7.06E-10+
	F_2	4.97E-02±4.99E-02	7.33E-12±9.99E-12+	2.91E+04±3.69E+03	1.17E+01±8.80E+00+
	F_3	6.41E+05±3.78E+05	1.30E+05±5.78E+04+	1.85E+08±4.87E+07	1.55E+06±7.54E+00+
	F_4	1.37E+01±1.56E+01	7.10E-02±1.50E-01+	3.75E+04±5.48E+03	2.68E+02±1.51E+02+
	F_5	1.30E+02±1.55E+02	5.07E+02±3.22E+02-	1.20E+04±9.40E+02	6.84E+02±4.77E+02+
<i>Basic Multimodal Functions</i>	F_6	2.51E+01±2.62E+01	2.12E+00±2.20E+00+	3.04E+08±6.29E+07	6.25E+01±5.66E+01+
	F_7	5.51E-03±8.35E-03	1.57E-02±1.25E-02-	4.43E+03±7.45E+02	9.34E-03±9.24E-03+
	F_8	2.09E+01±6.91E-02	2.09E+01±6.25E-02=	2.09E+01±3.93E-02	2.06E+01±3.15E-01+
	F_9	2.18E+01±7.73E+00	4.28E+01±1.19E+01-	2.40E+02±1.41E+01	2.62E+01±8.11E+00+
	F_{10}	1.32E+02±8.66E+01	4.94E+01±1.35E+01+	2.88E+02±1.60E+01	3.83E+01±1.44E+01+
	F_{11}	3.76E+01±5.37E+00	1.79E+01±6.80E+00+	3.97E+01±1.23E+00	1.54E+01±7.18E+00+
	F_{12}	4.59E+03±5.07E+03	5.11E+03±4.38E+03=	7.39E+05±8.16E+04	4.51E+03±5.48E+03+
<i>Expanded Multimodal Functions</i>	F_{13}	3.04E+00±8.86E-01	4.35E+00±2.10E+00-	5.20E+01±7.19E+00	3.08E+00±8.67E-01+
	F_{14}	1.34E+01±1.43E-01	1.32E+01±3.58E-01+	1.34E+01±1.88E-01	1.30E+01±3.80E-01+
		+	8	+	14
		-	4	-	0
		=	2	=	0

"+", "-", and "=" denote that the performance of DE without the restrained condition is better than, worse than, and similar to that of DE with the restrained condition, respectively.

Table S2

Experimental results of DE/best/1/bin, U-DE/best/1/bin, DE/best/2/bin, and U-DE/best/2/bin over 25 independent runs on the 14 test functions with 30D from IEEE CEC2005 using 300,000 FEs. "Mean Error" and "Std Dev" indicate the average and standard deviation of the function error values obtained in 25 runs, respectively. Wilcoxon's rank sum test at a 0.05 significance level is performed between DE/best/1/bin and U-DE/best/1/bin, and between DE/best/2/bin and U-DE/best/2/bin.

Test Functions (30D)		DE/best/1/bin Mean Error±Std Dev	U-DE/best/1/bin Mean Error±Std Dev	DE/best/2/bin Mean Error±Std Dev	U-DE/best/2/bin Mean Error±Std Dev
<i>Unimodal Functions</i>	F_1	2.11E-27±9.05E-28	2.89E+01±6.59E+01-	1.62E+03±7.05E+02	6.48E-02±3.24E-01+
	F_2	4.94E-14±1.15E-13	9.24E+02±2.51E+03-	2.02E+04±5.54E+03	2.16E-03±2.85E-03+
	F_3	1.30E+05±7.26E+04	6.10E+06±1.09E+07-	1.29E+08±3.53E+07	5.54E+05±3.80E+05+
	F_4	3.25E+00±1.27E+01	3.08E+03±6.19E+03-	3.00E+04±5.56E+03	3.93E+01±5.23E+01+
	F_5	2.38E+02±2.00E+02	4.27E+03±1.36E+03-	9.19E+03±9.80E+02	4.97E+02±3.60E+02+
<i>Basic Multimodal Functions</i>	F_6	2.03E+00±2.24E+00	4.02E+07±1.32E+08-	5.64E+07±3.62E+07	1.22E+01±1.21E+01+
	F_7	2.02E-02±2.20E-02	9.14E+01±1.61E+02-	1.58E+03±5.84E+02	2.45E-02±2.85E-02+
	F_8	2.09E+01±5.99E-02	2.10E+01±9.62E-02-	2.09E+01±4.12E-02	2.01E+01±2.12E-01+
	F_9	6.35E+01±2.60E+01	1.54E+02±4.04E+01-	2.37E+02±1.53E+01	6.69E+01±2.06E+01+
	F_{10}	8.99E+01±3.23E+01	1.86E+02±4.76E+01-	2.80E+02±1.98E+01	7.39E+01±1.85E+01+
	F_{11}	2.05E+01±5.01E+00	3.37E+01±3.40E+00-	3.96E+01±9.58E-01	2.36E+01±7.88E+01+
	F_{12}	1.15E+04±1.17E+04	6.46E+04±6.34E+04-	6.82E+05±7.45E+04	4.80E+03±8.92E+03+
<i>Expanded Multimodal Functions</i>	F_{13}	5.99E+00±2.60E+00	2.21E+01±7.20E+00-	3.32E+01±7.79E+00	7.33E+00±2.50E+00+
	F_{14}	1.29E+01±4.69E-01	1.36E+01±1.85E-01-	1.34E+01±1.62E-01	1.30E+01±2.98E-01+
		+	0	+	14
		-	14	-	0
		=	0	=	0

"+", "-", and "=" denote that the performance of DE without the restrained condition is better than, worse than, and similar to that of DE with the restrained condition, respectively.

Table S3

Experimental results of DE/current-to-best/1/bin, U-DE/current-to-best/1/bin, DE/current-to-rand/1/bin, and U-DE/current-to-rand/1/bin over 25 independent runs on the 14 test functions with 30D from IEEE CEC2005 using 300,000 FEs. "Mean Error" and "Std Dev" indicate the average and standard deviation of the function error values obtained in 25 runs, respectively. Wilcoxon's rank sum test at a 0.05 significance level is performed between DE/current-to-best/1/bin and U-DE/current-to-best/1/bin, and between DE/current-to-rand/1/bin and U-DE/current-to-rand/1/bin.

Test Functions (30D)		DE/current-to-best/1/bin Mean Error±Std Dev	U-DE/current-to-best/1/bin Mean Error±Std Dev	DE/current-to-rand/1/bin Mean Error±Std Dev	U-DE/current-to-rand/1/bin Mean Error±Std Dev
<i>Unimodal Functions</i>	F_1	1.53E-27±1.09E-27	2.53E-26±4.51E-26-	1.79E-17±3.22E-17	2.10E-29±6.35E-29+
	F_2	2.63E-16±7.21E-16	5.48E-25±2.26E-24+	2.56E-02±2.16E-02	9.61E-17±4.00E-16+
	F_3	1.24E+05±5.81E+04	3.10E+04±1.62E+04+	7.04E+05±3.76E+05	1.00E+05±6.46E+04+
	F_4	1.11E-01±2.53E-01	2.55E+00±1.22E+01-	1.95E+01±1.79E+01	2.58E-03±3.72E-03+
	F_5	2.30E+02±2.07E+02	1.43E+03±4.89E+02-	1.82E+02±9.87E+01	9.03E+01±1.52E+02+
<i>Basic Multimodal Functions</i>	F_6	1.27E+00±1.89E+00	1.59E+00±1.99E+00-	4.74E+00±3.11E+00	9.56E-01±1.73E+00+
	F_7	1.69E-02±1.24E-02	2.28E-02±2.63E-02=	1.65E-03±3.74E-03	1.35E-02±7.21E-03-
	F_8	2.09E+01±5.22E-02	2.09E+01±4.83E-02=	2.09E+01±3.28E-02	2.09E+01±5.36E-02=
	F_9	3.77E+01±9.71E+00	9.60E+01±2.74E+01-	1.90E+02±1.10E+01	2.88E+01±8.17E+00+
	F_{10}	5.49E+01±1.86E+01	1.32E+02±5.77E+01-	2.14E+02±1.12E+01	3.92E+01±1.27E+01+
	F_{11}	1.60E+01±5.77E+00	2.89E+01±3.29E+00-	3.95E+01±7.05E-01	2.01E+01±5.79E+00+
	F_{12}	1.29E+04±1.93E+04	1.49E+04±1.76E+04=	3.13E+03±3.54E+03	3.75E+03±4.87E+03=
<i>Expanded Multimodal Functions</i>	F_{13}	3.63E+00±1.02E+00	9.82E+00±2.99E+00-	1.80E+01±1.11E+00	3.48E+00±7.88E-01+
	F_{14}	1.31E+01±2.33E-01	1.21E+01±3.90E-01+	1.34E+01±1.63E-01	1.30E+01±2.44E-01+
		+	3	+	11
		-	8	-	1
		=	3	=	2

"+", "-", and "=" denote that the performance of DE without the restrained condition is better than, worse than, and similar to that of DE with the restrained condition, respectively.

Table S4

Experimental results of JADE, U-JADE, jDE, and U-jDE over 51 independent runs on the 28 test functions with 30D from IEEE CEC2013 using 300,000 FEs. "Mean Error" and "Std Dev" indicate the average and standard deviation of the function error values obtained in 51 runs, respectively. Wilcoxon's rank sum test at a 0.05 significance level is performed between JADE and U-JADE, and between jDE and U-jDE.

Test Functions (30D)		JADE Mean Error±Std Dev	U-JADE Mean Error±Std Dev	jDE Mean Error±Std Dev	U-jDE Mean Error±Std Dev
<i>Unimodal Functions</i>	cf_1	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
	cf_2	7.80E+03±6.74E+03	6.88E+03±5.13E+03+	1.39E+05±8.26E+04	1.37E+05±9.15E+04=
	cf_3	1.74E+06±5.71E+06	3.42E+05±1.46E+06+	1.25E+06±1.69E+06	1.35E+06±1.87E+06=
	cf_4	5.35E+03±1.36E+04	4.72E+03±1.12E+04+	5.22E+00±5.57E+00	5.25E+00±5.63E+00=
	cf_5	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
<i>Basic Multimodal Functions</i>	cf_6	3.62E+00±9.17E+00	1.03E+00±5.17E+00+	1.33E+01±4.45E+00	1.27E+01±3.85E+00+
	cf_7	5.26E+00±8.25E+00	4.11E+00±5.01E+00+	3.56E+00±3.07E+00	3.35E+00±2.91E+00+
	cf_8	2.09E+01±4.33E-02	2.09E+01±1.31E-01=	2.09E+01±4.65E-02	2.09E+01±4.78E-02=
	cf_9	2.61E+01±1.83E+00	2.63E+01±1.42E+00=	2.82E+01±1.34E+00	2.51E+01±5.67E+00+
	cf_{10}	3.67E-02±2.45E-02	3.72E-02±2.53E-02=	4.01E-02±2.63E-02	3.66E-02±2.89E-02=
	cf_{11}	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
	cf_{12}	2.38E+01±4.16E+00	2.37E+01±4.32E+00=	5.97E+01±1.01E+01	5.34E+01±8.96E+00+
	cf_{13}	4.43E+01±1.27E+01	4.50E+01±1.38E+01=	9.08E+01±1.67E+01	8.06E+01±1.78E+01+
	cf_{14}	3.31E-02±2.39E-02	3.32E-02±2.88E-02=	2.44E-03±6.78E-03	1.51E-02±1.67E-02-
	cf_{15}	3.31E+03±3.01E+02	3.28E+03±3.43E+02=	5.11E+03±3.59E+02	4.85E+03±3.65E+02+
	cf_{16}	1.70E+00±6.69E-01	1.76E+00±7.43E-01=	2.37E+00±2.77E-01	2.36E+00±3.32E-01=
	cf_{17}	3.04E+01±2.74E-14	3.04E+01±3.45E-14=	3.04E+01±3.82E-14	3.04E+01±4.08E-14=
	cf_{18}	7.69E+01±6.06E+00	7.67E+01±6.01E+00=	1.59E+02±1.56E+01	1.49E+02±1.63E+01+
cf_{19}	1.45E+00±1.20E-01	1.47E+00±1.01E-01=	1.61E+00±1.55E-01	1.64E+00±1.41E-01=	
cf_{20}	1.05E+01±5.07E-01	1.06E+01±5.35E-01=	1.16E+01±3.63E-01	1.16E+01±3.50E-01=	
<i>Composition Functions</i>	cf_{21}	3.09E+02±7.22E+01	2.96E+02±6.02E+01+	2.76E+02±7.29E+01	2.76E+02±7.31E+01=
	cf_{22}	9.14E+01±3.49E+01	9.18E+01±2.80E+01=	1.31E+02±2.36E+01	1.09E+02±2.27E+01+
	cf_{23}	3.47E+03±4.74E+02	3.48E+03±4.57E+02=	5.49E+03±5.05E+02	5.48E+03±5.85E+02=
	cf_{24}	2.13E+02±1.23E+01	2.09E+02±7.13E+00+	2.13E+02±1.11E+01	2.14E+02±1.04E+01=
	cf_{25}	2.74E+02±1.17E+01	2.73E+02±9.89E+00=	2.49E+02±8.68E+00	2.49E+02±6.25E+00=
	cf_{26}	2.19E+02±4.92E+01	2.12E+02±3.78E+01+	2.05E+02±2.65E+01	2.02E+02±1.57E+01=
	cf_{27}	6.76E+02±2.33E+02	6.85E+02±2.33E+02=	6.86E+02±1.90E+02	6.23E+02±1.52E+02+
	cf_{28}	3.19E+02±1.39E+02	3.19E+02±1.39E+02=	3.00E+02±0.00E+00	3.00E+02±0.00E+00=
		+	8	+	9
		-	0	-	1
		=	20	=	18

"+", "-", and "=" denote that the performance of DE without the restrained condition is better than, worse than, and similar to that of DE with the restrained condition, respectively.

Table S5

Experimental results of SaDE, U-SaDE, EPSDE, and U-EPSDE over 51 independent runs on the 28 test functions with 30D from IEEE CEC2013 using 300,000 FEs. "Mean Error" and "Std Dev" indicate the average and standard deviation of the function error values obtained in 51 runs, respectively. Wilcoxon's rank sum test at a 0.05 significance level is performed between SaDE and U-SaDE, and between EPSDE and U-EPSDE.

Test Functions (30D)		SaDE Mean Error±Std Dev	U-SaDE Mean Error±Std Dev	EPSDE Mean Error±Std Dev	U-EPSDE Mean Error±Std Dev
<i>Unimodal Functions</i>	cf_1	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
	cf_2	4.03E+05±1.91E+05	4.26E+05±2.42E+05=	8.16E+05±5.00E+06	8.64E+05±3.50E+06=
	cf_3	1.72E+07±3.10E+07	1.38E+07±1.84E+07+	1.52E+08±4.11E+08	5.73E+07±3.25E+08+
	cf_4	3.28E+03±1.67E+03	3.43E+03±1.84E+03=	8.47E+03±2.78E+04	3.30E+03±9.79E+03+
	cf_5	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
<i>Basic Multimodal Functions</i>	cf_6	3.09E+01±2.92E+01	2.93E+01±2.80E+01+	9.31E+00±1.02E+00	9.07E+00±2.23E+00+
	cf_7	2.90E+01±1.41E+01	2.52E+01±1.12E+01+	6.56E+01±4.88E+01	6.01E+01±3.84E+01+
	cf_8	2.09E+01±5.08E-02	2.09E+01±5.52E-02=	2.09E+01±4.52E-02	2.09E+01±4.28E-02=
	cf_9	1.78E+01±2.09E+00	1.75E+01±2.91E+00=	3.36E+01±3.59E+00	3.38E+01±3.63E+00=
	cf_{10}	2.69E-01±1.51E-01	2.72E-01±1.34E-01=	9.78E-02±6.92E-02	9.95E-02±5.80E-02=
	cf_{11}	1.56E-01±4.61E-01	1.85E-01±5.47E-01=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
	cf_{12}	4.81E+01±1.14E+01	4.57E+01±9.52E+00+	4.86E+01±9.87E+00	4.89E+01±1.65E+01=
	cf_{13}	9.87E+01±2.45E+01	9.92E+01±1.92E+01=	7.94E+01±1.75E+01	7.90E+01±2.06E+01=
	cf_{14}	7.76E-01±1.04E+00	7.82E-01±1.08E+00=	3.47E-01±4.89E-01	2.88E-01±3.52E-01+
	cf_{15}	4.74E+03±1.02E+03	4.75E+03±1.03E+03=	6.65E+03±8.15E+02=	6.57E+03±7.55E+02=
	cf_{16}	2.24E+00±2.62E-01	2.22E+00±2.63E-01=	2.49E+00±2.59E-01	2.44E+00±2.94E-01=
	cf_{17}	3.04E+01±4.62E-02	3.04E+01±4.34E-02=	3.04E+01±4.86E-02	3.04E+01±2.22E-03=
	cf_{18}	1.30E+02±4.36E+01	1.17E+02±4.37E+01+	1.36E+02±1.74E+01	1.34E+02±1.35E+01=
cf_{19}	4.10E+00±8.18E-01	3.83E+00±9.04E-01+	1.86E+00±2.40E-01	1.85E+00±2.15E-01=	
cf_{20}	1.08E+01±6.55E-01	1.06E+01±7.11E-01=	1.32E+01±6.00E-01	1.30E+01±6.75E-01+	
<i>Composition Functions</i>	cf_{21}	3.14E+02±6.22E+01	3.20E+02±6.58E+01=	2.90E+02±7.61E+01	2.95E+02±8.23E+01+
	cf_{22}	1.26E+02±4.47E+01	1.19E+02±3.44E+01+	3.33E+02±1.58E+02	3.00E+02±1.22E+02+
	cf_{23}	4.68E+03±1.10E+03	4.36E+03±1.11E+03+	7.07E+03±7.79E+02	6.86E+03±8.09E+02+
	cf_{24}	2.26E+02±6.69E+00	2.25E+02±5.70E+00=	2.90E+02±6.65E+00	2.88E+02±7.83E+00=
	cf_{25}	2.64E+02±1.22E+01	2.65E+02±1.14E+01=	2.98E+02±2.94E+00	2.98E+02±2.85E+00=
	cf_{26}	2.10E+02±3.53E+01	2.05E+02±2.51E+01+	3.59E+02±6.55E+01	3.61E+02±4.89E+01=
	cf_{27}	5.94E+02±6.53E+01	5.86E+02±7.75E+01+	1.21E+03±7.03E+01	1.20E+03±7.91E+01=
	cf_{28}	3.00E+02±0.00E+00	2.96E+02±2.85E+01+	3.20E+02±1.43E+02	3.00E+02±0.00E+00+
	+	11	+	9	
	-	0	-	0	
	=	17	=	19	

"+", "-", and "=" denote that the performance of DE without the restrained condition is better than, worse than, and similar to that of DE with the restrained condition, respectively.

Table S6

Experimental results of CoDE, U-CoDE, LSHADE, U-LSHADE, JADE/eig, and U-JADE/eig over 51 independent runs on the 28 test functions with 30D from IEEE CEC2013 using 300,000 FEs. "Mean Error" and "Std Dev" indicate the average and standard deviation of the function error values obtained in 51 runs, respectively. Wilcoxon's rank sum test at a 0.05 significance level is performed between CoDE and U-CoDE, between LSHADE and U-LSHADE, and between JADE/eig and U-JADE/eig.

Test Functions (30D)		CoDE Mean Error±Std Dev	U-CoDE Mean Error±Std Dev	LSHADE Mean Error±Std Dev	U-LSHADE Mean Error±Std Dev	JADE/eig Mean Error±Std Dev	U-JADE/eig Mean Error±Std Dev
<i>Unimodal Functions</i>	cf_1	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
	cf_2	1.86E+05±9.59E+04	8.28E+04±4.98E+04+	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	8.53E+03±7.30E+03	7.31E+03±5.50E+03+
	cf_3	1.13E+09±6.65E+08	9.43E+05±2.39E+06+	1.78E+00±1.05E+01	5.81E-02±4.01E-01+	4.97E+05±2.46E+06	1.16E+04±5.30E+04+
	cf_4	6.21E-01±7.05E-01	1.07E-01±2.29E-01+	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	4.13E-07±7.45E-07	5.79E-07±6.28E-07=
	cf_5	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
<i>Basic Multimodal Functions</i>	cf_6	7.21E+00±7.14E+00	4.11E+00±8.99E+00+	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	3.10E+00±8.59E+00	1.11E+00±5.19E+00+
	cf_7	6.84E+02±2.09E+02	7.33E+01±4.00E+01+	6.45E-01±4.46E-01	5.60E-01±4.99E-01+	2.35E+00±2.46E+00	5.02E+00±7.65E+00-
	cf_8	2.09E+01±6.18E-02	2.08E+01±9.72E-02+	2.08E+01±1.12E-01	2.07E+01±1.87E-01=	2.09E+01±5.69E-02	2.09E+01±5.69E-02=
	cf_9	3.22E+01±1.42E+00	1.38E+01±3.26E+00+	2.63E+01±1.28E+00	2.58E+01±1.78E+00+	2.57E+01±1.78E+00	2.60E+01±1.77E+00=
	cf_{10}	9.05E-03±2.32E-02	3.74E-02±2.52E-02-	2.90E-04±1.44E-03	2.90E-04±1.44E-03=	3.11E-02±1.90E-02	2.56E-02±1.72E-02+
	cf_{11}	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
	cf_{12}	1.89E+02±1.61E+01	3.68E+01±9.00E+00+	5.44E+01±1.32E+01	5.46E+01±1.35E+01=	2.51E+01±4.64E+00	2.49E+01±4.25E+00+
	cf_{13}	2.04E+02±1.50E+01	7.58E+01±2.40E+01+	5.95E+00±2.78E+00	5.42E+00±2.09E+00+	5.42E+01±1.32E+01	5.25E+01±1.33E+01+
	cf_{14}	1.19E+02±2.52E+01	3.28E+00±3.53E+00+	3.11E-02±2.54E-02	2.44E-02±2.19E-02+	2.45E+01±5.92E+00	2.50E+01±7.13E+00=
	cf_{15}	6.65E+03±3.57E+02	3.53E+03±5.76E+02+	2.69E+03±3.45E+02	2.70E+03±3.49E+02=	3.27E+03±3.56E+02	3.16E+03±3.54E+02+
	cf_{16}	2.46E+00±2.51E-01	3.40E-01±2.36E-01+	7.85E-01±1.75E-01	5.25E-01±3.09E-01+	1.81E+00±6.80E-01	1.53E+00±8.91E-01+
	cf_{17}	2.09E+01±1.86E-01	3.04E+01±3.29E-02+	3.04E+01±7.24E-12	3.04E+01±1.60E-11=	3.06E+01±9.09E-02	3.06E+01±7.13E-02=
	cf_{18}	3.49E+02±1.21E+01	6.42E+01±1.27E+01+	5.16E+01±3.21E+00	5.18E+01±2.64E+00=	7.75E+01±6.74E+00	7.53E+01±5.65E+00+
cf_{19}	6.14E+00±5.49E-01	1.56E+00±2.82E-01+	1.17E+00±9.37E-01	1.18E+00±9.90E-01=	1.72E+00±1.36E-01	1.69E+00±1.54E-01=	
cf_{20}	1.25E+01±2.46E-01	1.06E+01±6.65E-01+	1.02E+01±1.45E+00	1.03E+01±1.49E+00=	1.04E+01±4.75E-01	1.03E+01±4.28E-01=	
<i>Composition Functions</i>	cf_{21}	3.17E+02±1.09E+02	3.03E+02±9.35E+01+	2.93E+02±3.69E+01	2.93E+02±3.44E+01=	3.14E+02±7.28E+01	2.91E+02±7.04E+01+
	cf_{22}	1.01E+03±2.18E+02	1.09E+02±2.72E+01+	1.08E+02±2.37E+00	1.08E+02±2.51E+00=	1.44E+02±2.10E+01	1.46E+02±3.25E+01=
	cf_{23}	6.93E+03±3.24E+02	3.54E+03±6.49E+02+	2.49E+03±2.90E+02	2.50E+03±3.37E+02=	3.24E+03±3.90E+02	3.29E+03±3.78E+02=
	cf_{24}	2.77E+02±5.19E+00	2.21E+02±8.24E+00+	2.00E+02±8.01E-01	2.00E+02±7.13E-01=	2.09E+02±1.18E+01	2.09E+02±1.23E+01=
	cf_{25}	3.01E+02±3.77E+00	2.84E+02±1.35E+01+	2.41E+02±4.45E+00	2.42E+02±6.80E+00=	2.63E+02±1.54E+01	2.61E+02±1.62E+01=
	cf_{26}	2.00E+02±6.39E-03	2.15E+02±4.19E+01-	2.00E+02±2.72E-14	2.00E+02±2.63E-14=	2.09E+02±3.22E+01	2.10E+02±3.45E+01=
	cf_{27}	1.10E+03±3.74E+01	6.05E+02±9.58E+01+	3.02E+02±5.64E+00	3.02E+02±6.35E+00=	5.52E+02±1.97E+02	5.09E+02±2.15E+02+
	cf_{28}	3.00E+02±4.66E-10	3.00E+02±0.00E-10=	3.00E+02±0.00E+00	3.00E+02±0.00E+00=	3.21E+02±1.51E+02	3.00E+02±0.00E+00+
	+	22	+	6	+	12	
	-	2	-	0	-	1	
	=	4	=	22	=	15	

"+", "-", and "=" denote that the performance of DE without the restrained condition is better than, worse than, and similar to that of DE with the restrained condition, respectively.

Table S7

Experimental results of JADE, U-JADE, jDE, and U-jDE over 51 independent runs on the 28 test functions with 50D from IEEE CEC2013 using 500,000 FEs. "Mean Error" and "Std Dev" indicate the average and standard deviation of the function error values obtained in 51 runs, respectively. Wilcoxon's rank sum test at a 0.05 significance level is performed between JADE and U-JADE, and between jDE and U-jDE.

Test Functions (50D)		JADE	U-JADE	jDE	U-jDE
		Mean Error±Std Dev	Mean Error±Std Dev	Mean Error±Std Dev	Mean Error±Std Dev
<i>Unimodal Functions</i>	cf_1	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
	cf_2	2.35E+04±1.11E+04	2.42E+04±1.47E+04=	5.24E+05±2.44E+05	5.45E+05±2.11E+05=
	cf_3	4.87E+06±9.77E+06	3.83E+06±9.61E+06+	7.05E+06±1.58E+07	5.13E+06±9.38E+06+
	cf_4	9.78E+03±2.02E+04	5.36E+03±1.66E+04+	1.20E+01±9.97E+00	1.22E+01±1.60E+01=
	cf_5	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
<i>Basic Multimodal Functions</i>	cf_6	4.37E+01±1.11E+00	4.28E+01±5.66E+00+	4.38E+01±4.43E-01	4.39E+01±7.65E-01=
	cf_7	2.29E+01±1.04E+01	2.32E+01±1.34E+01=	1.81E+01±6.92E+00	1.92E+01±7.07E+00=
	cf_8	2.11E+01±1.03E-01	2.11E+01±8.98E-02=	2.11E+01±4.65E-02	2.12E+01±3.60E-02=
	cf_9	5.46E+01±2.01E+00	5.41E+01±2.36E+00=	5.50E+01±2.61E+00	5.38E+01±4.86E+00+
	cf_{10}	3.09E-02±2.09E-02	3.11E-02±2.24E-02=	5.30E-02±3.55E-02	5.35E-02±4.06E-02=
	cf_{11}	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
	cf_{12}	5.68E+01±9.48E+00	5.61E+01±9.39E+00=	1.06E+02±1.64E+01	9.25E+01±2.17E+01+
	cf_{13}	1.28E+02±2.52E+01	1.27E+02±2.33E+01=	1.81E+02±2.80E+01	1.70E+02±2.49E+01+
	cf_{14}	4.28E-02±2.61E-02	4.25E-02±2.70E-02=	6.33E-03±1.69E-02	4.64E-03±1.03E-02=
	cf_{15}	6.97E+03±4.67E+02	6.97E+03±4.72E+02=	9.87E+03±4.40E+02	9.59E+03±6.84E+02+
	cf_{16}	2.00E+00±7.86E-01	2.01E+00±7.91E-01=	3.01E+00±3.58E-01	2.97E+00±4.40E-01+
	cf_{17}	5.08E+01±3.52E-14	5.08E+01±3.61E-14=	5.08E+01±6.97E-14	5.08E+01±7.89E-14=
	cf_{18}	1.40E+02±1.11E+01	1.41E+02±1.06E+01=	2.79E+02±2.54E+01	2.59E+02±1.91E+01+
	cf_{19}	2.75E+00±1.82E-01	2.69E+00±2.01E-01+	2.91E+00±2.06E-01	2.88E+00±2.10E-01+
cf_{20}	1.96E+01±6.07E-01	1.97E+01±5.72E-01=	2.14E+01±4.47E-01	2.11E+01±5.10E-01+	
<i>Composition Functions</i>	cf_{21}	8.06E+02±4.07E+02	7.69E+02±4.19E+02+	5.79E+02±4.58E+02=	5.83E+02±4.65E+02=
	cf_{22}	2.43E+01±4.63E+01	1.28E+01±5.55E+00+	1.03E+02±5.13E+01	2.05E+01±1.23E+01+
	cf_{23}	7.32E+03±8.42E+02	7.28E+03±5.69E+02+	1.08E+04±7.47E+02	1.06E+04±6.76E+02=
	cf_{24}	2.49E+02±2.10E+01	2.47E+02±2.04E+01=	2.55E+02±1.49E+01	2.53E+02±1.20E+01=
	cf_{25}	3.52E+02±2.62E+01	3.52E+02±1.86E+01=	3.08E+02±2.11E+01	3.01E+02±1.04E+01+
	cf_{26}	3.40E+02±1.05E+02	3.42E+02±1.01E+02=	2.32E+02±6.69E+01	2.34E+02±7.05E+01=
	cf_{27}	1.40E+03±3.22E+02	1.32E+03±3.01E+02+	1.09E+03±2.23E+02=	1.03E+03±1.55E+02=
	cf_{28}	5.73E+02±7.00E+02	5.73E+02±6.98E+02=	4.57E+02±4.12E+02	4.00E+02±2.41E-14+
		+	8	+	12
		-	0	-	0
		=	20	=	16

"+", "-", and "=" denote that the performance of DE without the restrained condition is better than, worse than, and similar to that of DE with the restrained condition, respectively.

Table S8

Experimental results of SaDE, U-SaDE, EPSDE, and U-EPSDE over 51 independent runs on the 28 test functions with 50D from IEEE CEC2013 using 500,000 FEs. "Mean Error" and "Std Dev" indicate the average and standard deviation of the function error values obtained in 51 runs, respectively. Wilcoxon's rank sum test at a 0.05 significance level is performed between SaDE and U-SaDE, and between EPSDE and U-EPSDE.

Test Functions (50D)		SaDE	U-SaDE	EPSDE	U-EPSDE
		Mean Error±Std Dev	Mean Error±Std Dev	Mean Error±Std Dev	Mean Error±Std Dev
<i>Unimodal Functions</i>	cf_1	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
	cf_2	8.65E+05±3.14E+05	8.78E+05±3.25E+05=	1.41E+07±2.86E+07	3.62E+06±1.41E+07+
	cf_3	8.62E+07±1.13E+08	7.95E+07±7.20E+07+	2.75E+09±8.50E+09	4.23E+08±1.31E+09+
	cf_4	5.11E+03±1.92E+03	5.23E+03±1.85E+03=	1.12E+04±3.54E+04	5.25E+03±2.13E+04+
	cf_5	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
<i>Basic Multimodal Functions</i>	cf_6	5.31E+01±1.95E+01	5.33E+01±1.99E+01=	3.62E+01±1.87E+00	3.57E+01±4.71E+00+
	cf_7	4.97E+01±8.99E+00	4.99E+01±9.13E+00=	8.44E+01±3.31E+01	7.62E+01±3.19E+01+
	cf_8	2.11E+01±4.06E-02	2.11E+01±3.39E-02=	2.11E+01±3.67E-02	2.11E+01±4.47E-02=
	cf_9	3.96E+01±4.61E+00	3.83E+01±3.44E+00+	7.05E+01±3.47E+00	6.96E+01±4.02E+00+
	cf_{10}	2.69E-01±1.68E-01	2.78E-01±1.55E-01=	1.32E-01±7.41E-02	1.24E-01±6.97E-02+
	cf_{11}	2.04E+00±1.78E+00	2.04E+00±1.71E+00=	9.75E-02±3.59E-01	9.53E-02±2.78E-01+
	cf_{12}	1.25E+02±2.45E+01	1.18E+02±2.14E+01+	1.62E+02±2.87E+01	1.66E+02±3.57E+01=
	cf_{13}	2.56E+02±3.96E+01	2.47E+02±3.97E+01+	2.46E+02±4.99E+01	2.47E+02±4.17E+01=
	cf_{14}	7.22E+00±5.81E+00	6.95E+00±3.62E+00+	9.96E+02±8.15E+02	8.73E+02±8.16E+02+
	cf_{15}	8.54E+03±2.11E+03	8.61E+03±2.23E+03=	1.40E+04±5.84E+02	1.38E+04±5.97E+02+
	cf_{16}	3.12E+00±3.09E-01	3.03E+00±2.56E-01=	3.35E+00±3.20E-01	3.27E+00±2.98E-01+
	cf_{17}	5.12E+01±4.33E-01	5.13E+01±3.93E-01=	5.08E+01±3.02E-01	5.10E+01±1.15E+00=
	cf_{18}	1.58E+02±7.35E+01	1.59E+02±7.41E+01=	3.37E+02±2.63E+01	3.41E+02±2.67E+01=
	cf_{19}	1.09E+01±2.67E+00	1.09E+01±2.33E+00=	6.17E+00±8.21E-01	6.18E+00±9.64E-01=
cf_{20}	1.99E+01±9.52E-01	2.00E+01±1.03E+00=	2.25E+01±9.77E-01	2.24E+01±9.60E-01=	
<i>Composition Functions</i>	cf_{21}	8.32E+02±3.73E+02	8.34E+02±3.60E+02=	7.71E+02±4.05E+02	7.78E+02±4.02E+02=
	cf_{22}	9.30E+01±2.18E+02	3.36E+01±5.52E+01+	2.04E+03±5.57E+02	2.07E+03±5.50E+02=
	cf_{23}	8.40E+03±2.11E+03	8.42E+03±2.26E+03=	1.41E+04±6.16E+02	1.40E+04±8.00E+02=
	cf_{24}	2.78E+02±1.01E+01	2.78E+02±1.03E+01=	3.81E+02±5.38E+00	3.79E+02±5.19E+00=
	cf_{25}	3.45E+02±9.28E+00	3.43E+02±1.01E+01=	3.83E+02±4.15E+00	3.82E+02±3.83E+00=
	cf_{26}	2.95E+02±9.08E+01	2.69E+02±9.05E+01+	4.73E+02±8.59E+00	4.67E+02±3.30E+01=
	cf_{27}	1.18E+03±1.20E+02	1.18E+03±1.05E+02=	2.11E+03±4.34E+01	2.10E+03±5.01E+01+
	cf_{28}	5.34E+02±6.71E+02	4.00E+02±1.79E-14+	7.65E+02±1.01E+03	7.68E+02±1.05E+03=
		+	8	+	12
		-	0	-	0
		=	20	=	16

"+", "-", and "=" denote that the performance of DE without the restrained condition is better than, worse than, and similar to that of DE with the restrained condition, respectively.

Table S9

Experimental results of CoDE, U-CoDE, LSHADE, U-LSHADE, JADE/eig, and U-JADE/eig over 51 independent runs on the 28 test functions with 50D from IEEE CEC2013 using 500,000 FEs. "Mean Error" and "Std Dev" indicate the average and standard deviation of the function error values obtained in 51 runs, respectively. Wilcoxon's Rank sum test at a 0.05 significance level is performed between CoDE and U-CoDE, between LSHADE and U-LSHADE, and between JADE/eig and U-JADE/eig.

Test Functions (50D)		CoDE	U-CoDE	LSHADE	U-LSHADE	JADE/eig	U-JADE/eig
		Mean Error±Std Dev	Mean Error±Std Dev	Mean Error±Std Dev	Mean Error±Std Dev	Mean Error±Std Dev	Mean Error±Std Dev
<i>Unimodal Functions</i>	cf_1	6.03E-07±1.91E-07	0.00E+00±0.00E+00+	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
	cf_2	2.32E+06±9.91E+05	5.40E+05±2.11E+05+	7.47E+02±1.12E+03	7.58E+02±1.34E+03=	4.05E+04±2.42E+04	3.88E+04±1.98E+04+
	cf_3	3.31E+10±4.98E+09	1.43E+06±2.33E+06+	4.67E+03±1.30E+04	3.09E+03±1.23E+04+	3.21E+06±7.47E+06	2.50E+06±5.09E+06+
	cf_4	2.35E+03±4.57E+03	3.96E-01±3.50E-01+	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	8.72E-03±4.76E-02	6.23E-03±4.17E-02=
	cf_5	4.01E-04±7.37E-05	0.00E+00±0.00E+00+	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
<i>Basic Multimodal Functions</i>	cf_6	4.40E+01±3.38E-01	4.34E+01±4.50E-14+	4.34E+01±2.17E-14	4.34E+01±2.17E-14=	4.21E+01±8.69E+00	4.23E+01±8.65E+00=
	cf_7	1.17E+03±3.13E+02	5.06E+01±1.92E+01+	2.51E+00±1.25E+00	2.11E+00±1.34E+00+	2.19E+01±1.01E+01	2.65E+01±1.08E+01-
	cf_8	2.11E+01±4.24E-02	2.11E+01±4.17E-02=	2.11E+01±1.00E-01	2.09E+01±1.70E-01=	2.11E+01±8.87E-02	2.11E+01±8.42E-02=
	cf_9	6.50E+01±1.71E+00	2.44E+01±5.17E+00+	5.28E+01±2.45E+00	5.26E+01±1.92E+00=	5.32E+01±2.01E+00	5.27E+01±2.42E+00+
	cf_{10}	1.97E+00±4.55E-01	3.02E-02±2.11E-02+	9.08E-03±9.93E-03	9.75E-03±9.51E-03=	2.82E-02±1.84E-02	2.63E-02±2.08E-02+
	cf_{11}	4.93E+01±3.51E+00	1.26E+01±6.08E+00+	0.00E+00±0.00E+00	0.00E+00±0.00E+00=	0.00E+00±0.00E+00	0.00E+00±0.00E+00=
	cf_{12}	4.80E+02±1.74E+01	6.78E+01±1.53E+01+	1.44E+01±2.59E+00	1.45E+01±2.48E+00=	6.88E+01±1.12E+01	6.57E+01±1.11E+01+
	cf_{13}	4.83E+02±1.91E+01	1.39E+02±3.77E+01+	2.09E+01±8.05E+00	2.09E+01±7.89E+00=	1.51E+02±2.53E+01	1.49E+02±2.68E+01=
	cf_{14}	3.03E+03±2.26E+02	1.30E+03±2.75E+02+	2.13E-01±4.60E-02	2.14E-01±5.12E-02=	6.85E+01±1.10E+01	6.41E+01±1.02E+01+
	cf_{15}	1.39E+04±4.14E+02	6.60E+03±8.33E+02+	6.31E+03±3.35E+02	6.29E+03±3.82E+02=	6.91E+03±4.44E+02	6.73E+03±4.63E+02+
	cf_{16}	3.22E+00±3.55E-01	2.88E+00±5.83E-01+	1.25E+00±2.16E-01	1.05E+00±3.92E-01+	1.92E+00±8.91E-01	1.74E+00±8.62E-01+
	cf_{17}	1.16E+02±4.48E+00	8.89E+01±3.65E+00+	5.08E+01±1.60E-03	5.08E+01±2.45E-03=	5.15E+01±1.82E-01	5.14E+01±1.76E-01=
	cf_{18}	5.46E+02±2.09E+01	1.10E+02±2.85E+01+	1.04E+02±5.80E+00	1.02E+02±6.04E+00=	1.47E+02±9.21E+00	1.48E+02±1.02E+01=
	cf_{19}	2.17E+01±1.33E+00	1.26E+01±2.08E+00+	2.50E+00±1.30E-01	2.52E+00±1.46E-01=	3.48E+00±3.15E-01	3.49E+00±3.29E-01=
cf_{20}	2.26E+01±2.11E-01	2.08E+01±1.09E-01+	1.82E+01±4.22E-01	1.82E+01±6.46E-01=	1.97E+01±5.28E-01	1.96E+01±5.65E-01=	
<i>Composition Functions</i>	cf_{21}	2.18E+02±1.29E+02	4.78E+02±4.18E+02-	8.51E+02±4.24E+02	8.03E+02±4.34E+02+	7.86E+02±3.67E+02	7.88E+02±3.75E+02=
	cf_{22}	4.74E+03±3.76E+02	1.86E+03±5.16E+02+	1.37E+01±1.38E+00	1.38E+01±1.54E+00=	1.36E+02±9.72E+01	1.17E+02±6.54E+01+
	cf_{23}	1.40E+04±3.82E+02	6.89E+03±9.71E+02+	5.78E+03±4.14E+02	5.79E+03±4.65E+02=	7.14E+03±6.44E+02	7.11E+03±5.64E+02=
	cf_{24}	3.60E+02±5.81E+00	2.37E+02±1.12E+01+	2.11E+02±5.89E+00	2.11E+02±5.02E+00=	2.43E+02±1.74E+01	2.44E+02±1.72E+01=
	cf_{25}	3.85E+02±3.56E+00	3.83E+02±4.25E+00+	2.78E+02±6.55E+01	2.77E+02±6.22E+01=	3.31E+02±2.72E+01	3.29E+02±2.94E+01=
	cf_{26}	2.32E+02±8.54E+01	2.59E+02±7.80E+01-	2.47E+02±5.29E+01	2.48E+02±5.40E+01=	3.47E+02±9.52E+01	3.49E+02±9.27E+01=
	cf_{27}	1.96E+03±4.82E+01	8.83E+02±1.48E+01+	4.04E+02±5.24E+01	3.84E+02±4.45E+01+	1.15E+03±3.56E+02	1.18E+03±3.34E+02=
	cf_{28}	4.00E+02±1.81E-03	4.00E+02±2.27E-14+	4.00E+02±4.95E-14	4.00E+02±3.50E-14=	5.17E+02±5.88E+02	4.00E+02±5.74E-14+
		+	25	+	5	+	10
		-	2	-	0	-	1
		=	1	=	23	=	17

"+", "-", and "=" denote that the performance of DE without the restrained condition is better than, worse than, and similar to that of DE with the restrained condition, respectively.