

Supplementary Material

**Grade-Control Outdoor Turning Flight of Robo-pigeon with
Quantitative Stimulus Parameters**

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1 Supplementary Data

TABLE S1. Number of successful turning flight control trials and success rate for all subjects under parameters of SF.

Subjects	60Hz				80Hz				100Hz				120Hz			
	Trials	Successful	Failed	SR	Trials	Successful	Failed	SR	Trials	Successful	Failed	SR	Trials	Successful	Failed	SR
P_01	8	6	2	75.00%	6	4	2	66.67%	6	3	3	50.00%	5	2	3	40.00%
P_02	10	5	5	50.00%	7	4	3	57.14%	8	4	4	50.00%	13	6	7	46.15%
P_03	5	4	1	80.00%	5	3	2	60.00%	8	5	3	62.50%	11	6	5	54.55%
P_04	7	4	3	57.14%	8	5	3	62.50%	6	2	4	33.33%	10	3	7	30.00%
P_05	8	5	3	62.50%	7	4	3	57.14%	8	3	5	37.50%	11	5	6	45.45%
P_06	5	3	2	60.00%	8	4	4	50.00%	7	3	4	42.86%	11	6	5	54.55%
P_07	13	10	3	76.92%	10	8	2	80.00%	2	0	2	0.00%	3	0	3	0.00%
P_08	8	5	3	62.50%	9	5	4	55.56%	11	4	7	36.36%	12	6	6	50.00%
P_09	12	8	4	66.67%	8	5	3	62.50%	8	3	5	37.50%	9	3	6	33.33%
P_10	10	6	4	60.00%	8	5	3	62.50%	5	2	3	40.00%	N/A	N/A	N/A	N/A
P_11	8	5	3	62.50%	8	4	4	50.00%	5	2	3	40.00%	7	3	4	42.86%
P_12	5	4	1	80.00%	7	5	2	71.43%	4	2	2	50.00%	N/A	N/A	N/A	N/A
Total	99	65	34	N/A	91	56	35	N/A	78	33	45	40.00%	92	40	52	39.69%
Mean±SD	66.10%±2.58%				61.29%±2.28%				41.39%±4.44%				39.69%±4.21%			

Note: Abbreviations: SF, the stimulus frequency; SR, the success rate of robo-pigeons turning flight control; N/A not applicable.

TABLE S2. Number of successful turning flight control trials and success rate for all subjects under parameters of SD.

Subjects	2s				3s				4s				5s			
	Trials	Successful	Failed	SR	Trials	Successful	Failed	SR	Trials	Successful	Failed	SR	Trials	Successful	Failed	SR
P_01	3	3	0	100.00%	2	2	0	100.00%	5	2	3	40.00%	N/A	N/A	N/A	N/A
P_02	6	4	2	66.67%	13	7	6	53.85%	7	3	4	42.86%	2	2	0	100.00%
P_03	10	6	4	60.00%	8	5	3	62.50%	5	3	2	60.00%	7	2	5	28.57%
P_04	8	5	3	62.50%	6	3	3	50.00%	6	3	3	50.00%	6	2	4	33.33%
P_05	7	4	3	57.14%	9	6	3	66.67%	6	3	3	50.00%	7	4	3	57.14%
P_06	11	6	5	54.55%	5	4	1	80.00%	3	2	1	66.67%	9	4	5	44.44%
P_07	10	5	5	50.00%	12	7	5	58.33%	7	3	4	42.86%	8	2	6	25.00%
P_08	8	5	3	62.50%	11	8	3	72.73%	7	4	3	57.14%	7	5	2	71.43%
P_09	11	5	6	45.45%	9	4	5	44.44%	8	4	4	50.00%	5	1	4	20.00%
P_10	7	5	2	71.43%	9	6	3	66.67%	5	3	2	60.00%	7	3	4	42.86%
P_11	14	8	6	57.14%	7	4	3	57.14%	5	2	3	40.00%	8	3	5	37.50%
P_12	15	9	6	60.00%	13	9	4	69.23%	5	3	2	60.00%	6	2	4	33.33%
Total	110	65	45	N/A	104	65	39	N/A	69	35	34	N/A	72	30	42	44.87%
Mean±SD	62.28%±4.21%				65.13%±3.94%				51.63%±2.40%				44.87%±6.18%			

Note: Abbreviations: SF, the stimulus duration; SR, the success rate of robo-pigeons turning flight control; N/A not applicable.

TABLE S3. Number of successful turning flight control trials and success rate for all subjects under parameters of ISI.

Subjects	2s				3s				4s				5s			
	Trials	Successful	Failed	SR	Trials	Successful	Failed	SR	Trials	Successful	Failed	SR	Trials	Successful	Failed	SR
P_01	5	3	2	60.00%	5	2	3	40.00%	8	3	5	37.50%	7	5	2	71.43%
P_02	5	4	1	80.00%	8	6	2	75.00%	7	5	2	71.43%	8	5	3	62.50%
P_03	5	2	3	40.00%	5	2	3	40.00%	5	1	4	20.00%	7	4	3	57.14%
P_04	4	2	2	50.00%	6	2	4	33.33%	8	3	5	37.50%	5	2	3	40.00%
P_05	7	5	2	71.43%	6	5	1	83.33%	5	4	1	80.00%	N/A	N/A	N/A	N/A
P_06	9	6	3	66.67%	7	5	2	71.43%	6	3	3	50.00%	5	2	3	40.00%
P_07	7	4	3	57.14%	6	3	3	50.00%	6	3	3	50.00%	6	2	4	33.33%
P_08	6	3	3	50.00%	9	4	5	44.44%	9	4	5	44.44%	5	2	3	40.00%
P_09	8	5	3	62.50%	7	5	2	71.43%	6	4	2	66.67%	6	3	3	50.00%
P_10	5	4	1	80.00%	6	5	1	83.33%	5	4	1	80.00%	5	3	2	60.00%
P_11	5	3	2	60.00%	8	6	2	75.00%	6	5	1	83.33%	7	4	3	57.14%
P_12	5	4	2	80.00%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total	71	45	27	N/A	73	45	28	N/A	71	39	32	N/A	61	32	29	N/A
Mean±SD	63.14%±3.46%				60.66%±5.03%				56.44%±5.55%				51.15%±5.15%			

Note: Abbreviations: SF, the inter-stimulus interval; SR, the success rate of robo-pigeons turning flight control; N/A not applicable.

TABLE S4. Results of Wilcoxon signed-rank test for stimulus parameters of SF, SD and ISI.

Parameters	$\bar{V}$				$\bar{C}$				T_r				θ				$\bar{R}$			
SF	60Hz	80Hz	100Hz	120Hz	60Hz	80Hz	100Hz	120Hz	60Hz	80Hz	100Hz	120Hz	60Hz	80Hz	100Hz	120Hz	60Hz	80Hz	100Hz	120Hz
60Hz		-0.343	-2.278	-2.769		-3.067	-3.261	-4.301		1.055	-1.341	-1.511		-2.989	-4.319	-4.537		-1.996	-2.757	-3.855
80Hz	0.732		-1.689	-2.930	0.002**		-2.135	-3.441	0.291		-0.684	-0.382	0.003**			-3.603	0.046*		-2.260	-3.266
100Hz	0.023*	0.091		-0.009	0.001**	0.033*		-2.457	0.180	0.494		-0.178	0.000**	0.001**		-1.496	0.006*	0.024*		-1.275
120Hz	0.006**	0.003**	0.993		0.000**	0.001**	0.014*		0.131	0.702	0.859		0.000**	0.000**	0.135		0.000**	0.001*	0.202	
N	65	56	33	40	65	56	33	40	65	56	33	40	65	56	33	40	65	56	33	40
SD	2s	3s	4s	5s	2s	3s	4s	5s	2s	3s	4s	5s	2s	3s	4s	5s	2s	3s	4s	5s
2s		-2.140	-3.309	-2.303		-2.179	-2.522	-2.396		-0.432	-0.429	-0.487		-1.895	-3.518	-3.195		-2.476	-2.135	-2.411
3s	0.032*		-0.983	-1.070	0.029*		-0.803	-0.072	0.666		-0.377	-0.037	0.058		-1.867	-2.475	0.013*		-0.031	-1.359
4s	0.001**	0.326		-0.205	0.012*	0.422		-0.381	0.668	0.706		-0.322	0.000**	0.062		-0.521	0.033*	0.975		-0.501
5s	0.021*	0.284	0.837		0.017*	0.943	0.704		0.626	0.970	0.747		0.001**	0.013*	0.603		0.016*	0.174	0.616	
N	65	65	35	30	65	65	35	30	65	65	35	30	65	65	35	30	65	65	35	30
ISI	2s	3s	4s	5s	2s	3s	4s	5s	2s	3s	4s	5s	2s	3s	4s	5s	2s	3s	4s	5s
2s		-0.672	-0.851	-0.206		-2.534	-2.540	-2.263		-0.438	-2.137	-2.185		-2.676	-4.684	-4.463		-2.906	-2.027	-2.900
3s	0.502		-0.809	-0.337	0.011*		-0.461	-1.047	0.662		-1.440	-1.651	0.007**		-2.146	-3.347	0.004**		-0.220	-1.842
4s	0.395	0.418		-1.402	0.011*	0.645		-1.440	0.033*	0.150		-0.318	0.000**	0.032*		-1.822	0.043*	0.826		-2.670
5s	0.837	0.736	0.161		0.024*	0.295	0.150		0.029*	0.099	0.751		0.000**	0.001**	0.068		0.004**	0.065	0.008**	
N	45	45	39	32	45	45	39	32	45	45	39	32	45	45	39	32	45	45	39	32

Note: The bottom left indicates the significant difference between the variables, * $p < 0.05$, ** $p < 0.01$; The top right indicates the Rank between the variables. Abbreviations: SF, the stimulus frequency; SD, the stimulus duration; ISI, the inter-stimulus interval; N was the number of trials; $\bar{V}$, the mean flight speed of robo-pigeons; $\bar{C}$, the mean turning curvature of the robo-pigeons turning flight; T_r , the response time of turning flight behavior of robo-pigeons; θ , the mean turning angle of the robo-pigeons turning flight; $\bar{R}$, the mean turning radius of the robo-pigeons turning flight.

BCI on the head; (C) The top view of the control module. It is in size of 30 mm × 24mm × 12 mm (L ×

W × H) and in mass of 14.9 g including a rechargeable battery.

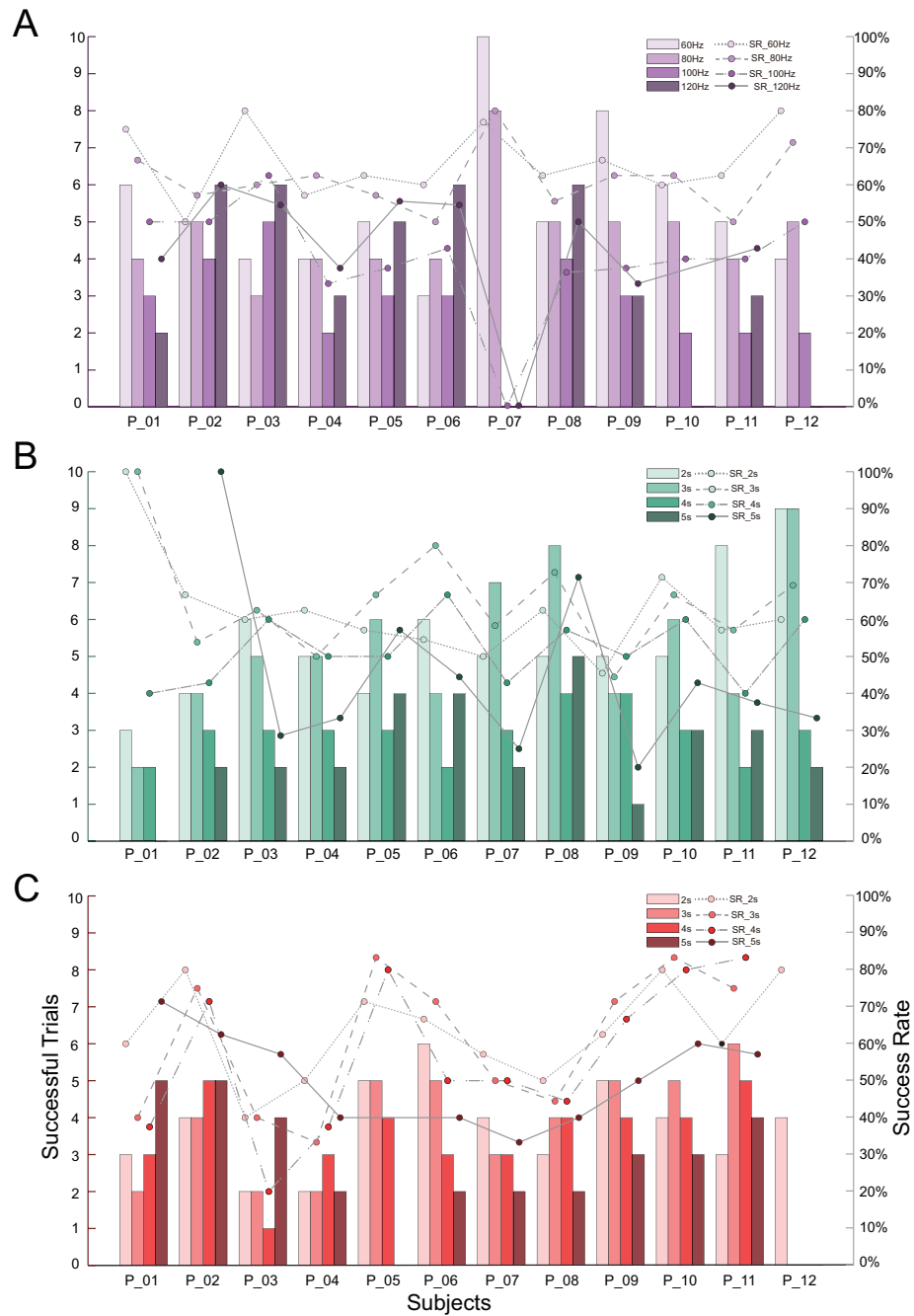


FIGURE. S2 Number of successful turning flight control trials and success rate for all subjects under different stimulation parameters of SF (A), SD (B) and ISI (C).