Electronic Supplementary Information (ESI†)

Wearable gold-graphene dry electrode-based headband for effective brain-computer interface applications

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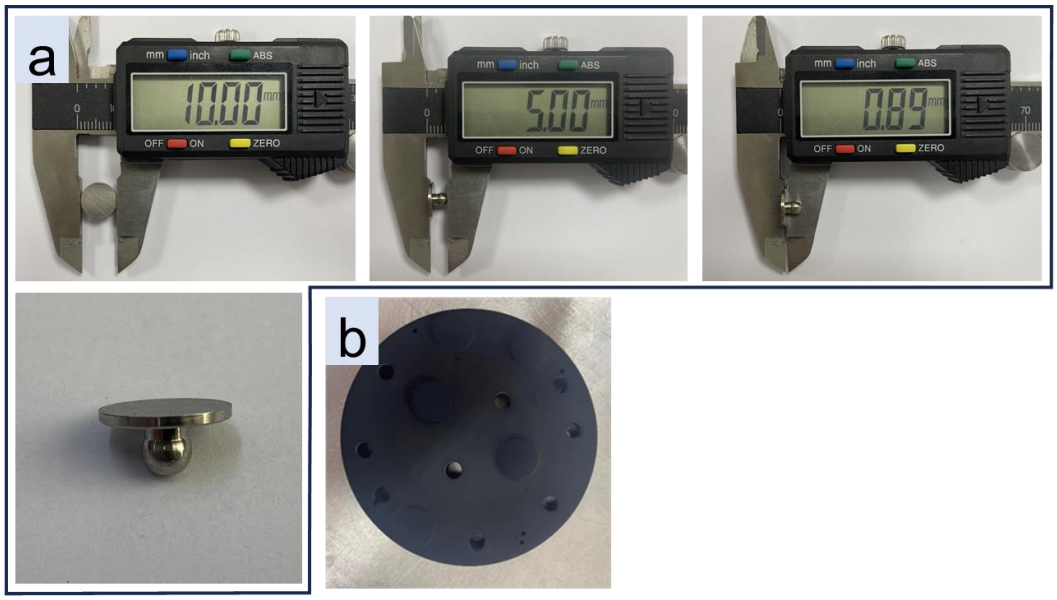

Fig. S1. Photographs of (a) the Ti shank button substrate and (b) two Au-FLG electrodes on the sample stage. Au-FLG, gold-doped few-layer graphene

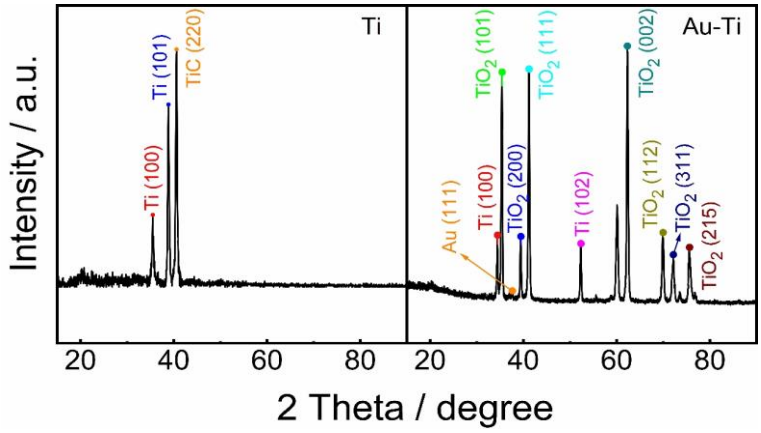

Fig. S2. XRD patterns of the Ti and Au-Ti ($CA/Au^{III} = 20$) button electrodes. XRD, X-ray diffraction

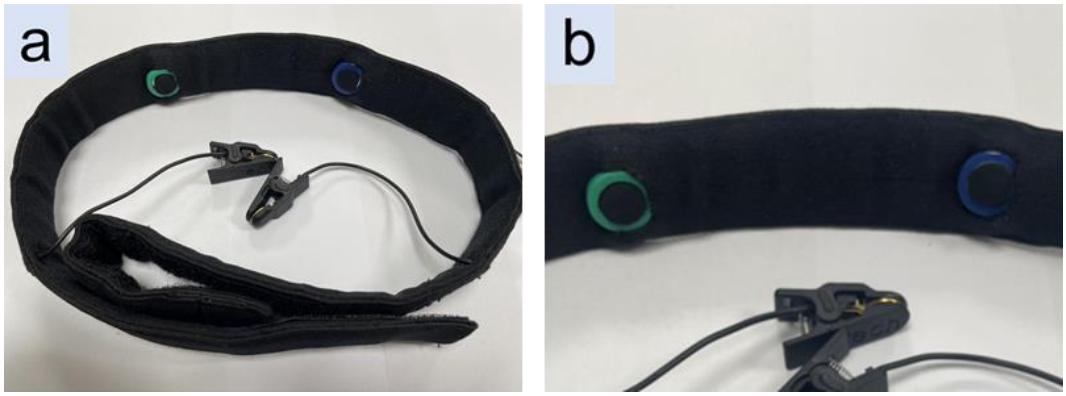

Fig. S3. Optical images of an EEG headband with two Au-FLG day electrodes. (a) Whole. (b) Electrode position. Au-FLG, gold-doped few-layer graphene; EEG, electroencephalogram

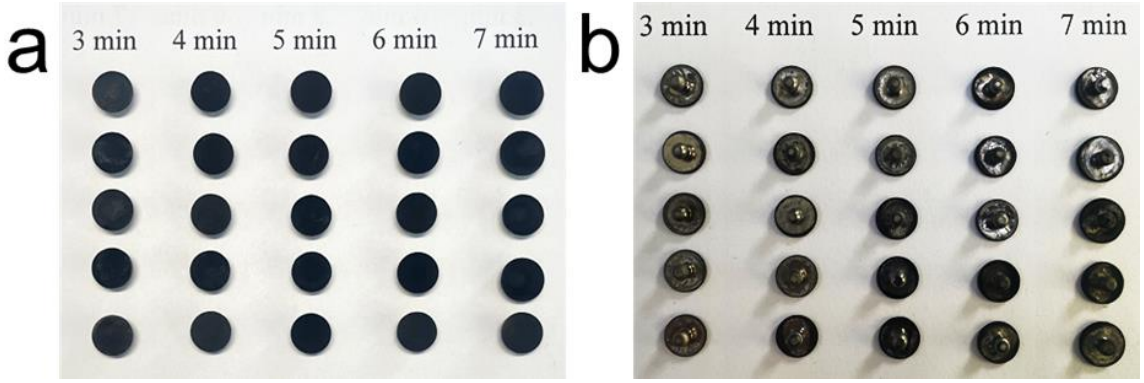

Fig. S4. Optical images of FLG button electrodes. (a) Top. (b) Bottom.

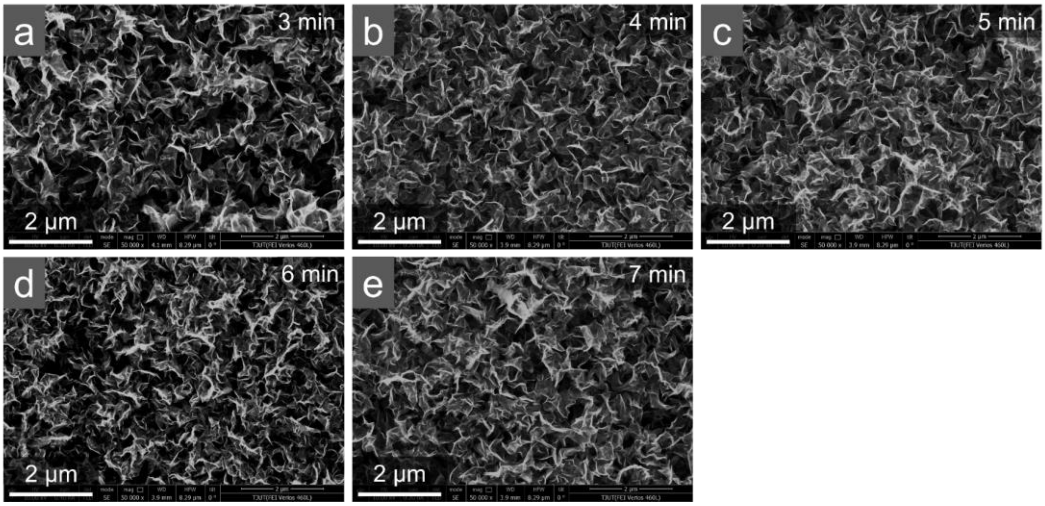

Fig. S5. Surface SEM images of FLG samples with growth times of 3, 4, 5, 6, and 7 min. FLG, few-layer graphene; SEM, scanning electron microscopy

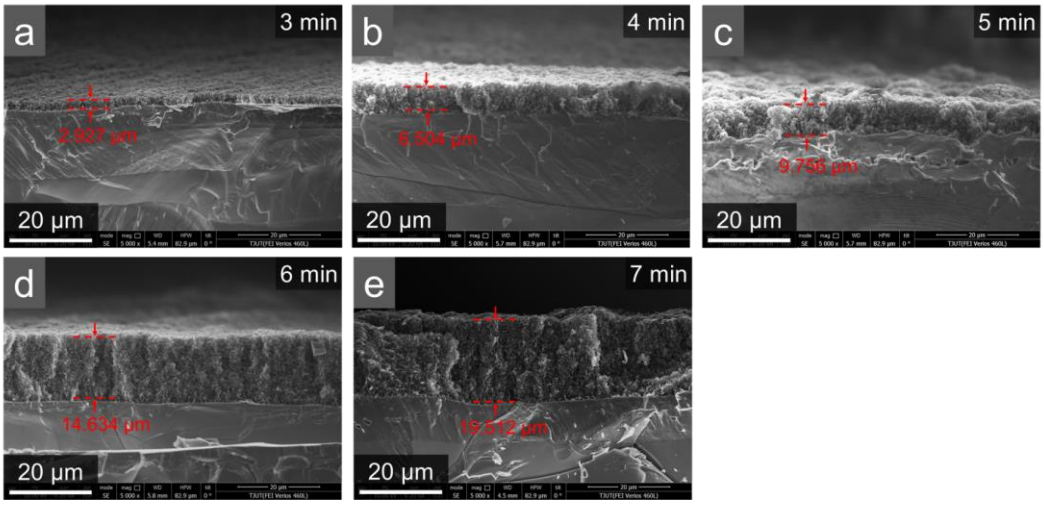

Fig. S6. Cross-sectional SEM images of FLG samples with growth times of (a) 3, (b) 4, (c) 5, (d) 6, and (e) 7 min. The height of graphene films was marked. FLG, few-layer graphene; SEM, scanning electron microscopy

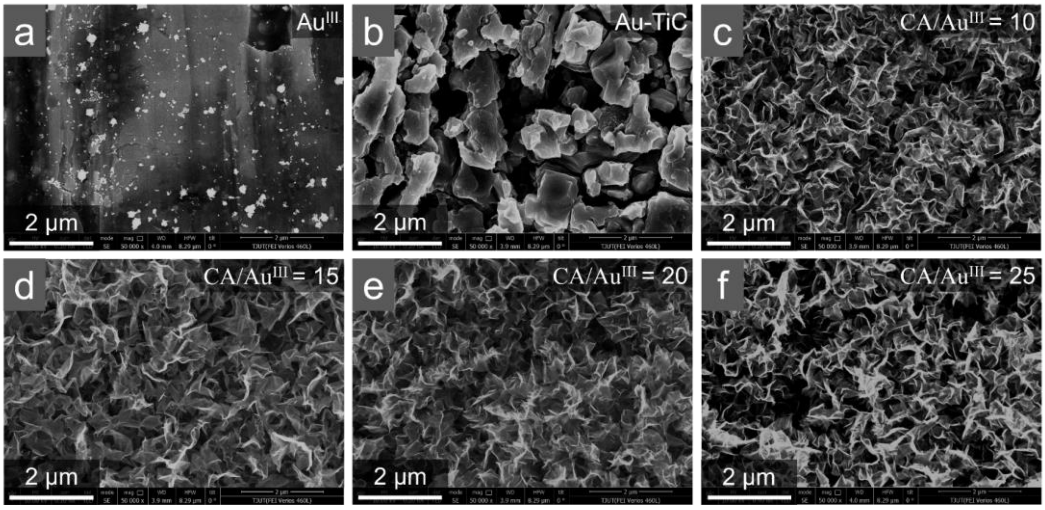

Fig. S7. Surface SEM images of (a) Au^{III} at Ti substrate, (b) Au-TiC layer, and (c–f) Au-FLG samples with different citric acid/$HAuCl_4$(CA/Au^{III}) concentration ratios of 10, 15, 20, and 25. Au-FLG, gold-doped few-layer graphene

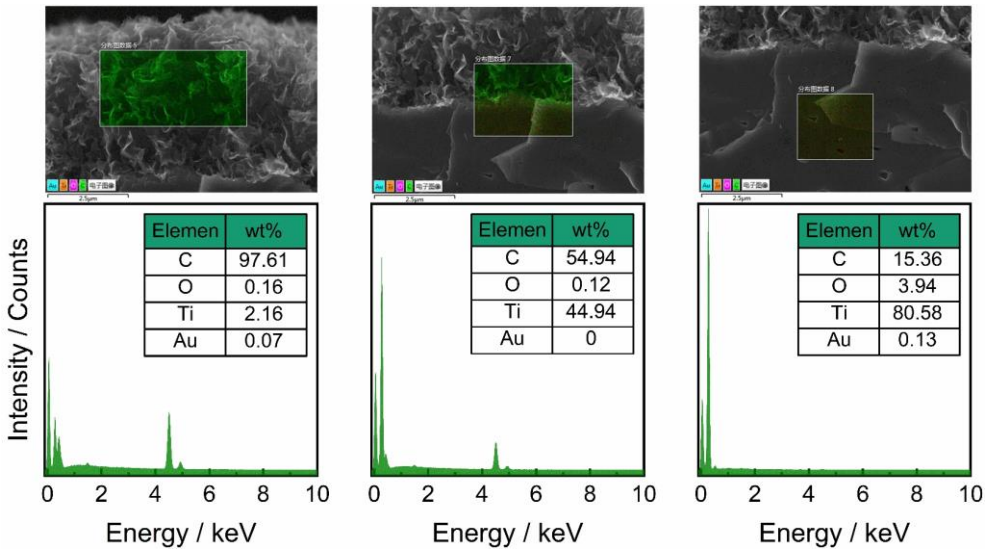

Fig. S8. Cross-sectional SEM images and corresponding EDS spectra of an Au-FLG/Ti electrode with a CA/Au^{III} concentration ratio of 20. Au-FLG, gold-doped few-layer graphene; EDS, energy-dispersive X-ray spectroscopy; SEM, scanning electron microscopy

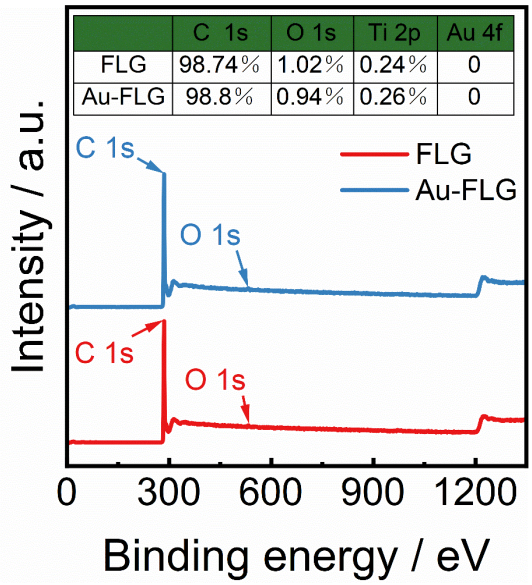

Fig. S9. Survey XPS profiles of FLG and Au-FLG samples. Au-FLG, gold-doped few-layer graphene; XPS, X-ray photoelectron spectrometry

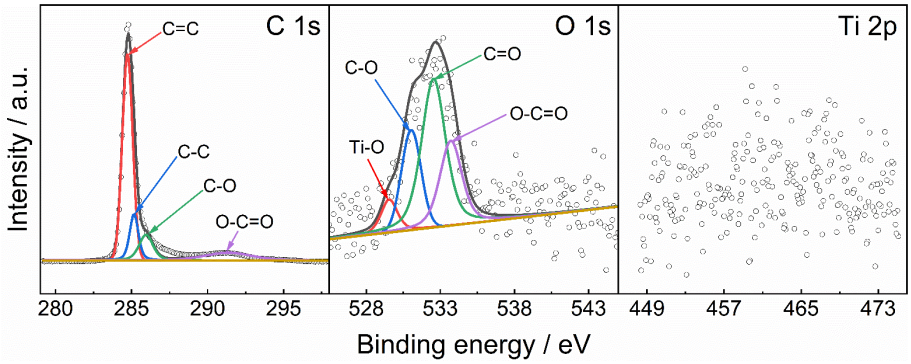

Fig. S10. C 1s and O 1s core-level XPS profiles of the FLG sample with a growth time of 4 min. FLG, few-layer graphene; XPS, X-ray photoelectron spectrometry

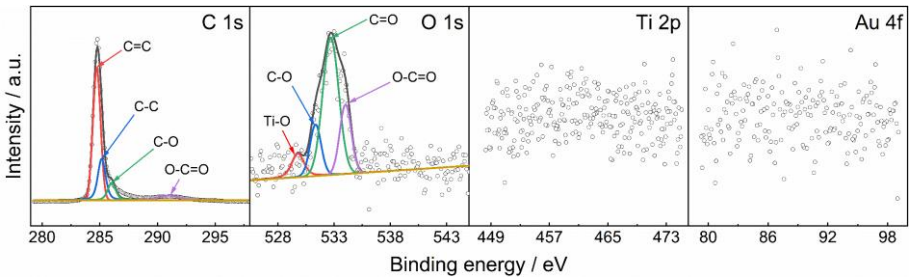

Fig. S11. C 1s, O 1s, Ti 2p, and Au 4f core-level XPS profiles of an Au-FLG sample with a CA/Au^{III} volume ratio of 20 and a growth time of 4 min. Au-FLG, gold-doped few-layer graphene; XPS, X-ray photoelectron spectrometry

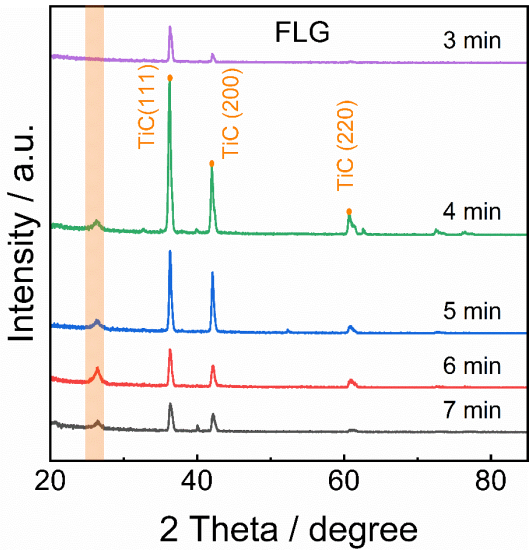

Fig. S12. XRD patterns of the five FLG samples with growth times of 3–7 min. FLG, few-layer graphene; XRD, X-ray diffraction

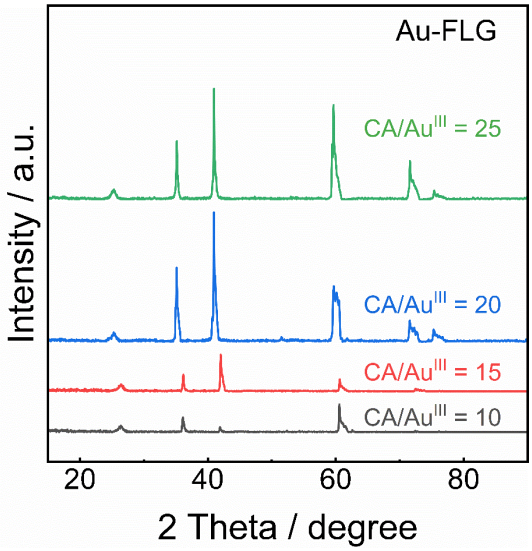

Fig. S13. XRD patterns of the Au-FLG samples prepared with CA/Au^{III} concentration ratios of 10–25 and a growth time of 4 min. Au-FLG, gold-doped few-layer graphene; XRD, X-ray diffraction

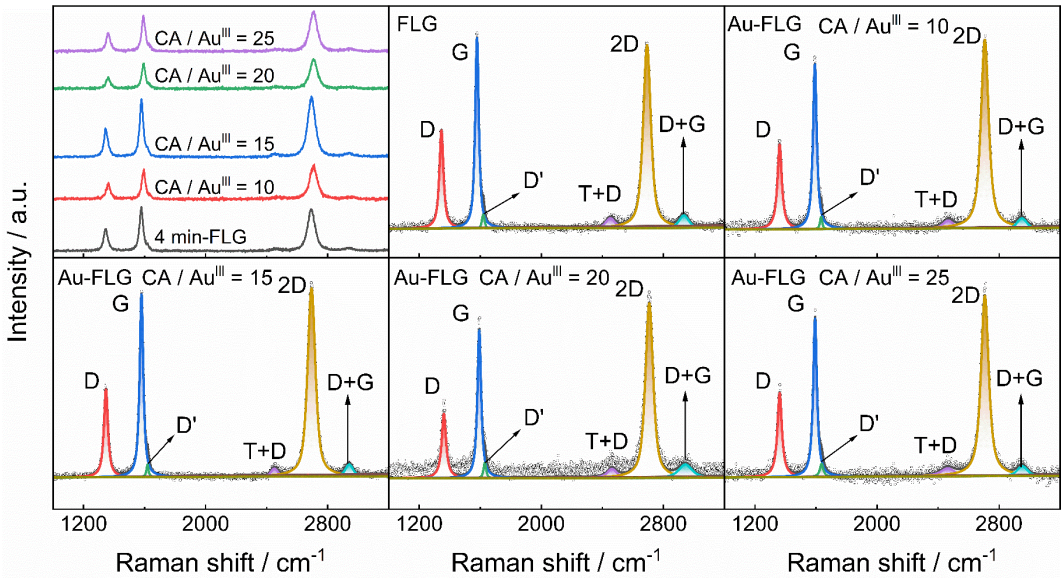

Fig. S14. Raman spectra of the 4 min-FLG and four Au-FLG samples with different CA/Au^{III} volume ratios and a growth time of 4 min. Au-FLG, gold-doped few-layer graphene

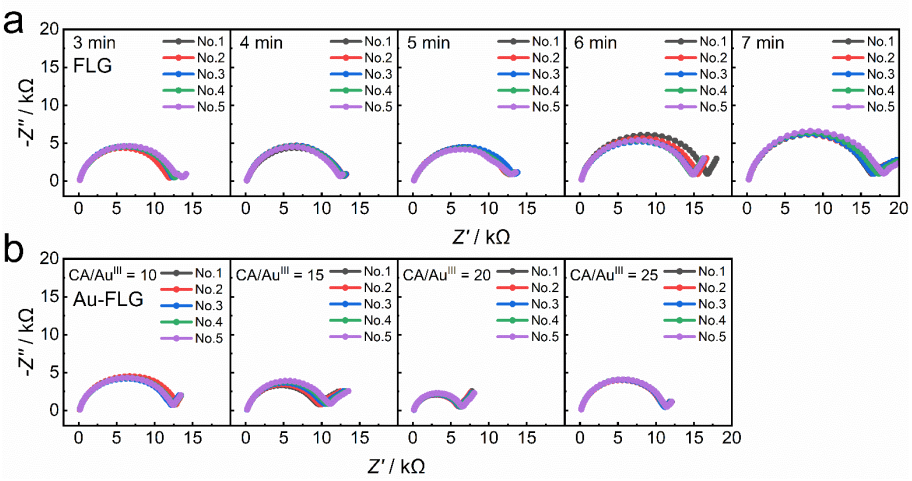

Fig. S15. Nyquist plots obtained through EIS using different FLG and Au-FLG electrodes on the forearm skin: (a) with FLG growth times of 3–7 min, and (b) Au-FLG/Ti prepared with CA/Au^{III} ratios of 10–25 and a growth time of 4 min. Au-FLG, gold-doped few-layer graphene; EIS, electrochemical impedance spectroscopy

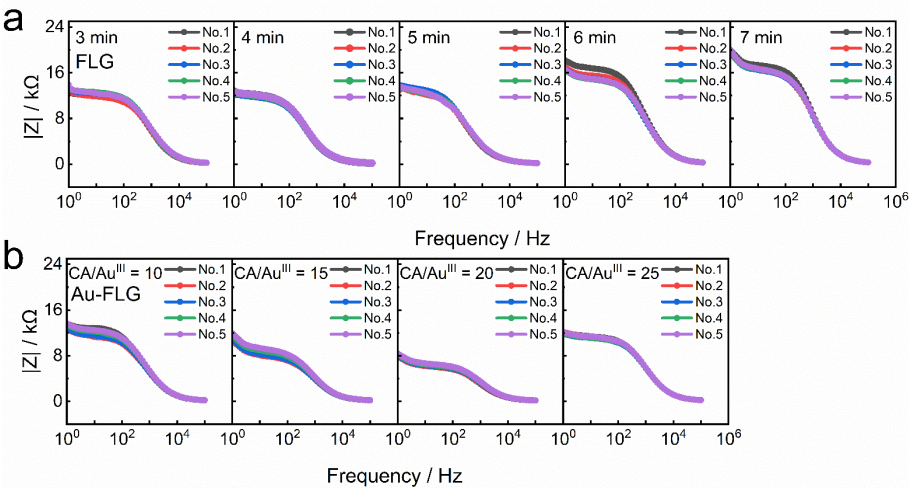

Fig. S16. Frequency-impedance plots obtained through EIS using different FLG and Au-FLG electrodes on the forearm skin: (a) with FLG growth times of 3–7 min, and (b) Au-FLG/Ti prepared with CA/Au^{III} concentration ratios of 10–25 and growth times of 4 min. Au-FLG, gold-doped few-layer graphene; EIS, electrochemical impedance spectroscopy

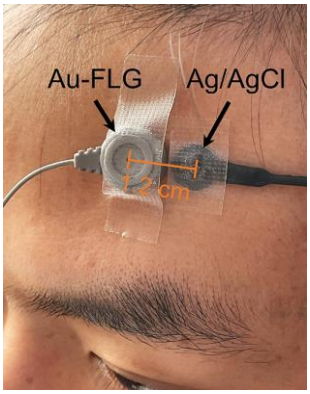

Fig. S17. Position of Au-FLG and Ag/AgCl electrodes on the scalp (Fp1).

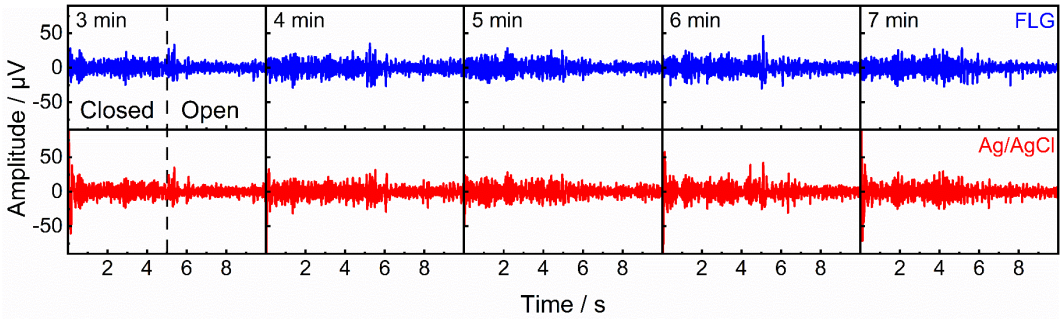

Fig. S18. EEG signals collected from the forehead Fp1 using FLG electrodes with different growth times of 3–7 min and gel-Ag/AgCl electrodes for the closed/open eye paradigm. Each cycle is 10 s, with eyes closed and opened each for 5 s. FLG, few-layer graphene; EEG, electroencephalogram

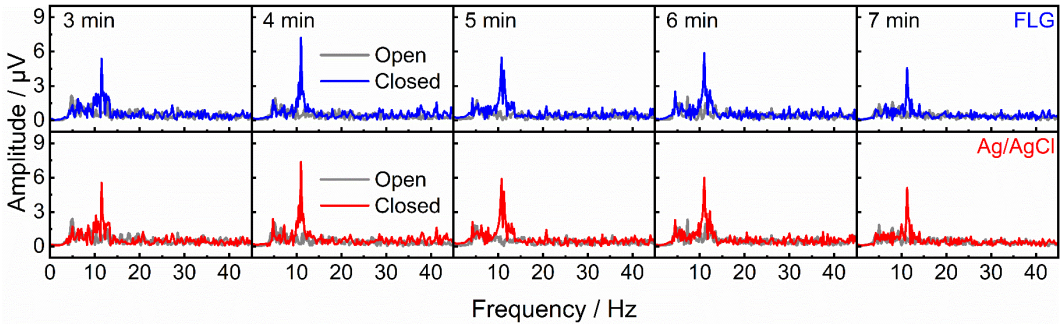

Fig. S19. Amplitude spectra of the EEG signals for the closed/open eyes paradigm collected from the forehead Fp1 using five FLG electrodes with different growth times of 3–7 min and gel-Ag/AgCl electrodes. FLG, few-layer graphene; EEG, electroencephalogram

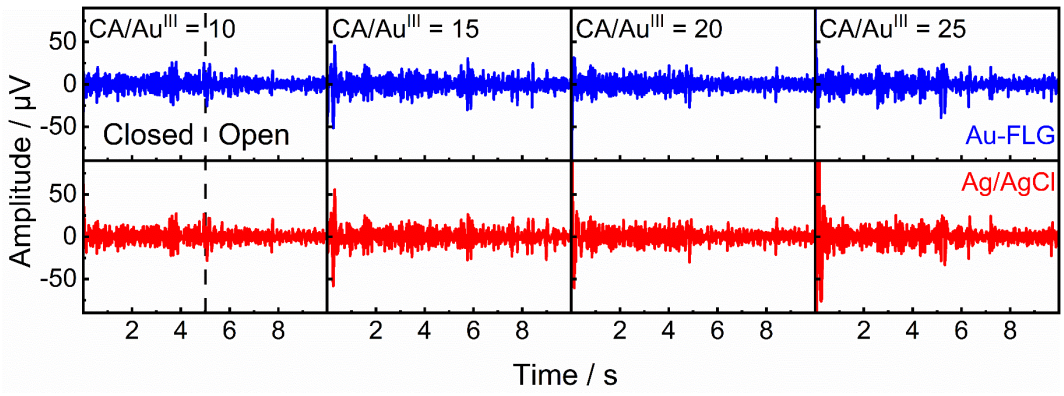

Fig. S20. EEG signals collected from the forehead Fp1 using four Au-FLG electrodes with CA/Au^{III} ratios of 10–25 and gel-Ag/AgCl wet electrodes for the closed/open eye paradigm. Each cycle is 10 s, with eyes closed and opened each for 5 s. Au-FLG, gold-doped few-layer graphene; EEG, electroencephalogram

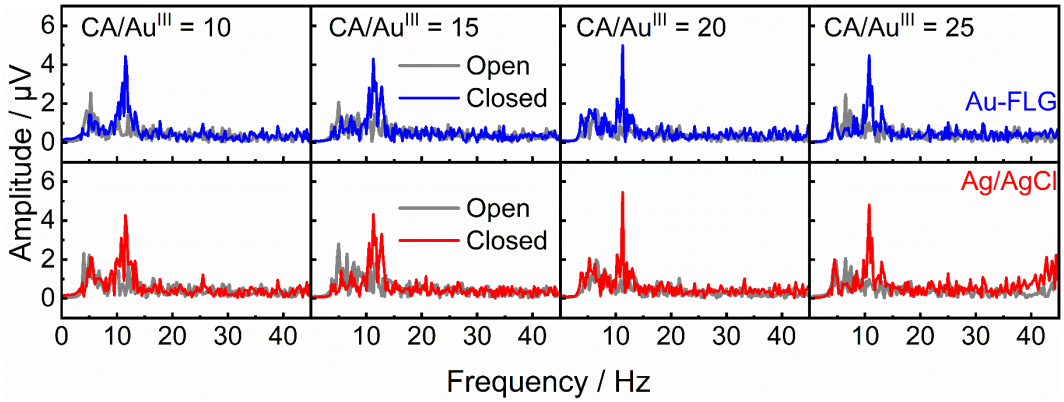

Fig. S21. Amplitude spectra of the EEG signals for the closed/open eyes paradigm collected from the forehead Fp1 using four Au-FLG electrodes with CA/Au^{III} ratios of 10–25 and a gel-Ag/AgCl wet electrode. EEG, electroencephalogram; Au-FLG, gold-doped few-layer graphene

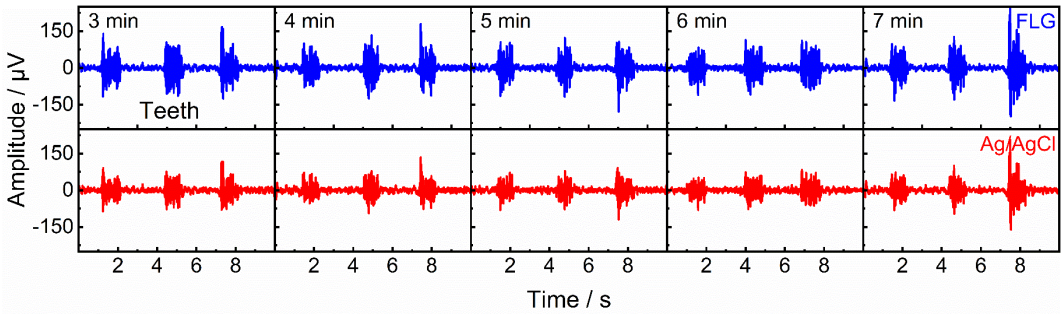

Fig. S22. EMG signals collected from the forehead Fp1 using FLG electrodes with different growth times of 3–7 min and gel-Ag/AgCl electrodes for the teeth-grinding paradigm. Teeth are rubbed every 3 s. EMG, electromyogram; FLG, few-layer graphene

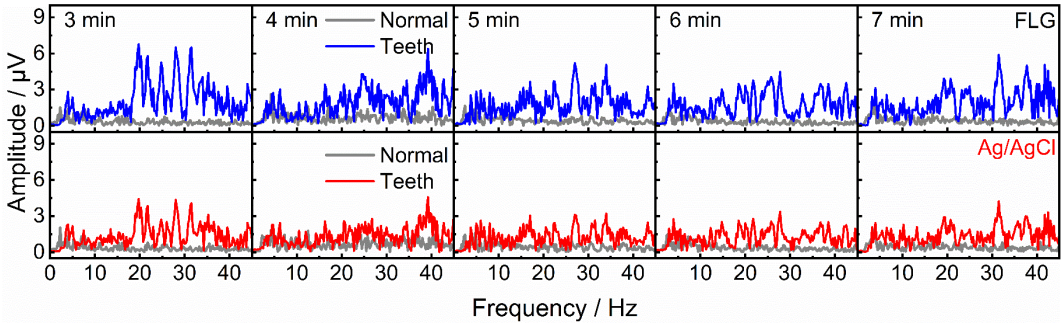

Fig. S23. Amplitude spectra of the EMG signals for the teeth-grinding paradigm collected from the forehead Fp1 using five FLG electrodes with different growth times of 3–7 min and gel-Ag/AgCl electrodes. EMG, electromyogram; FLG, few-layer graphene

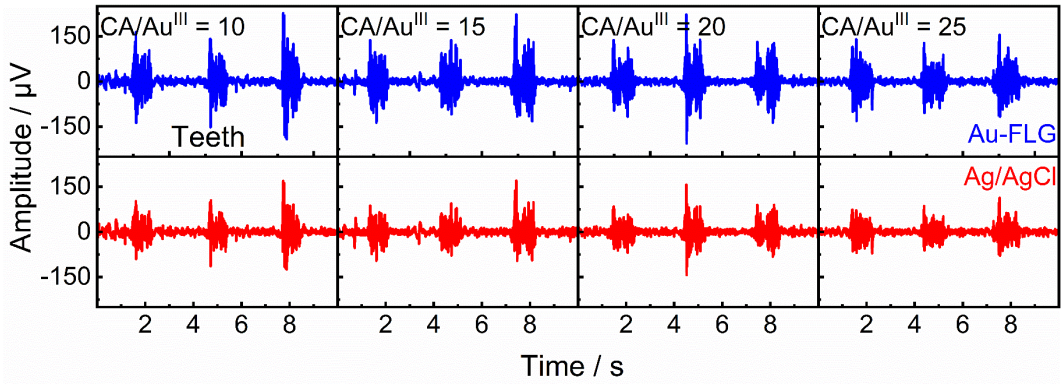

Fig. S24. EMG signals collected from the forehead Fp1 using four Au-FLG electrodes with different CA/Au^{III} ratios of 10–25 (grown for 4 min) and gel-Ag/AgCl electrodes, with the teeth-grinding paradigm. Teeth are rubbed every 3 s. Au-FLG, gold-doped few-layer graphene; EMG, electromyogram

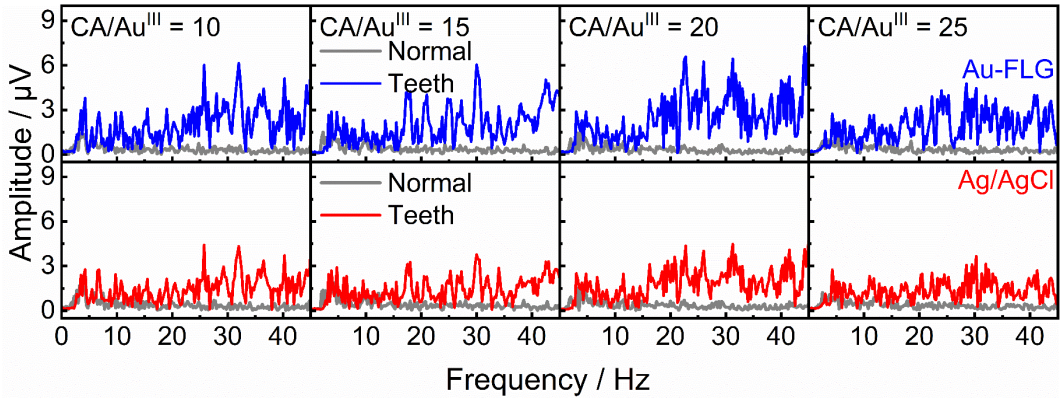

Fig. S25. Amplitude spectra of the EMG signals for the teeth-grinding paradigm collected from the forehead Fp1 using four Au-FLG electrodes with different CA/Au^{III} ratios of 10–25 (growth time: 4 min) and gel-Ag/AgCl electrodes. Au-FLG, gold-doped few-layer graphene; EMG, electromyogram

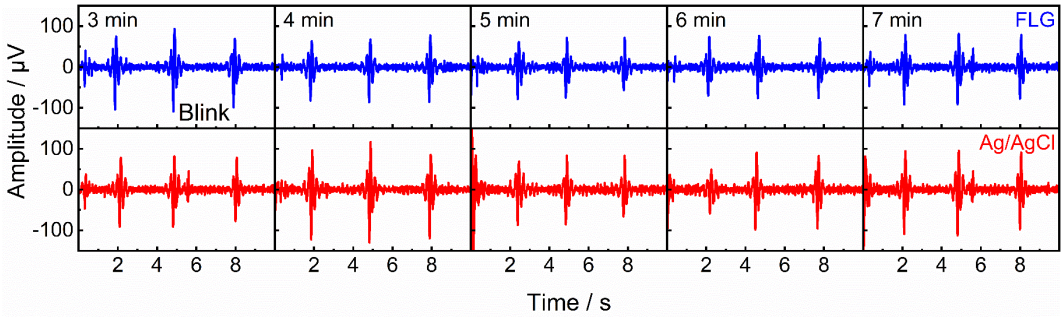

Fig. S26. EOG signals collected from the forehead Fp1 using FLG electrodes with different growth times of 3–7 min and gel-Ag/AgCl dry electrodes for the eye-blinking paradigm. The eyes are blinking once every 3 s. EOG, electrooculogram; FLG, few-layer graphene

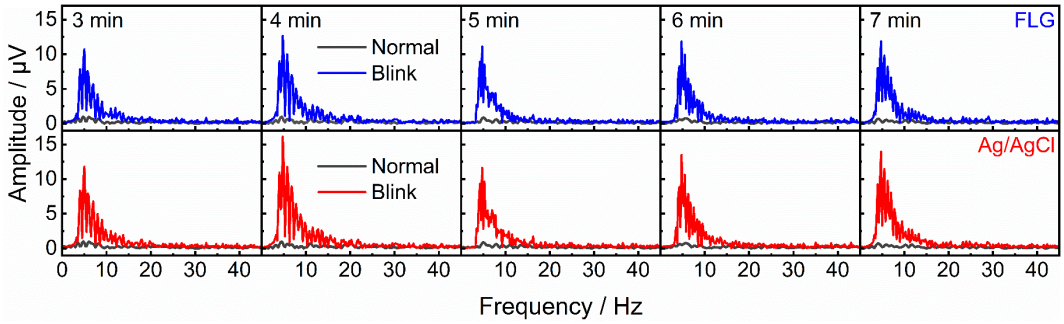

Fig. S27. Amplitude spectra of the EOG signals for the eye-blinking paradigm collected from the forehead Fp1 using five FLG dry electrodes with different growth times of 3–7 min and gel-Ag/AgCl electrodes. EOG, electrooculogram; FLG, few-layer graphene

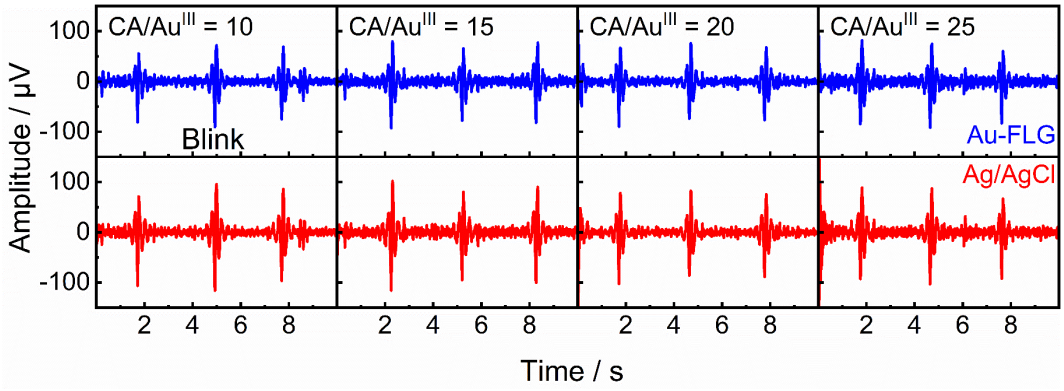

Fig. S28. EOG signals for the eye-blinking paradigm collected from the forehead Fp1 using four Au-FLG dry electrodes with different CA/Au^{III} ratios of 10–25 (growth time: 4 min) and gel-Ag/AgCl wet electrodes. Au-FLG, gold-doped few-layer graphene; EOG, electrooculogram

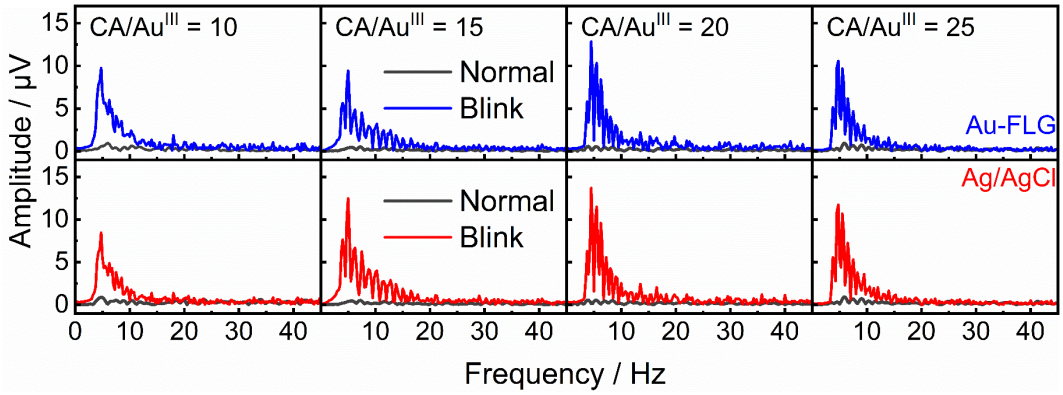

Fig. S29. Amplitude spectra of the EOG signals for the eye-blinking paradigm collected from the forehead Fp1 using four Au-FLG dry electrodes with different CA/Au^{III} ratios of 10–25 (growth time: 4 min) and gel-Ag/AgCl wet electrodes. Au-FLG, gold-doped few-layer graphene; EOG, electrooculogram

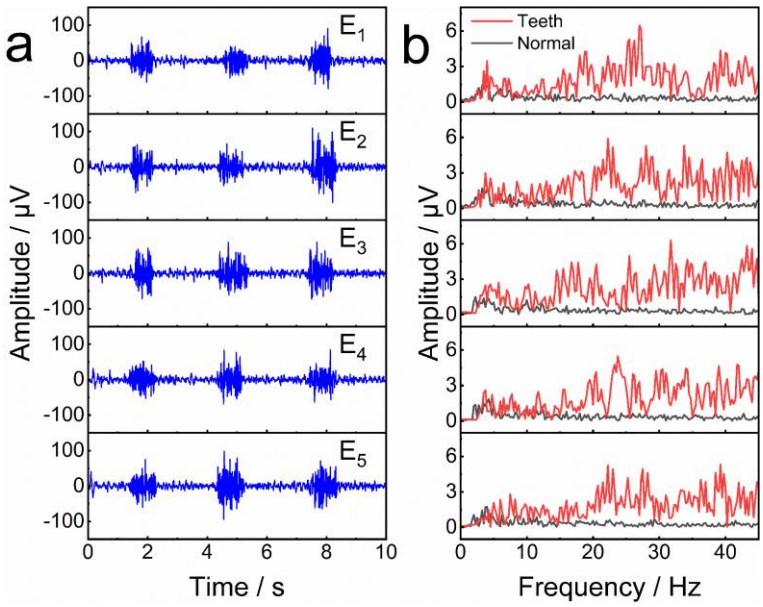

Fig. S30. Reproducibility. (a) Time- and (b) frequency-domain EMG spectra collected from the forehead Fp1 position using five Au-FLG electrodes with a CA/Au^{III} volume ratio of 20 in the teeth-grinding paradigm. Teeth are rubbed every 3 s. Au-FLG, gold-doped few-layer graphene; EMG, electromyogram

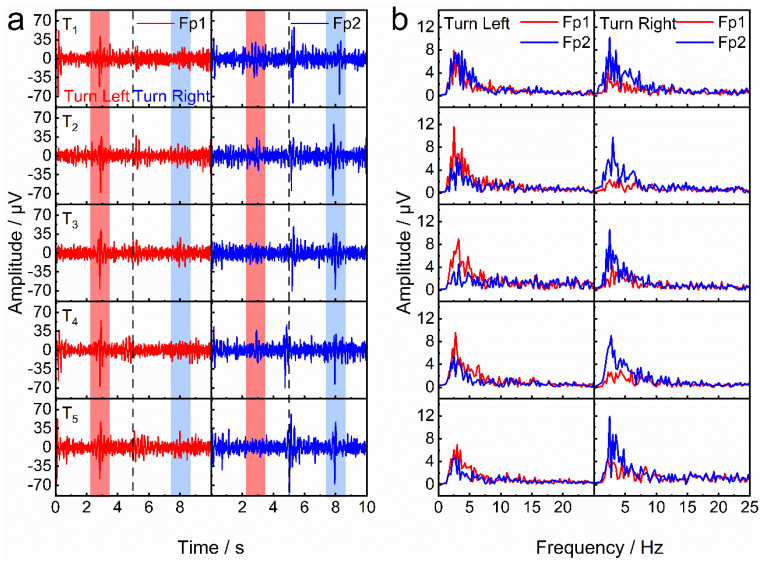

Fig. S31. Five repeatability experiments. (a) Time- and (b) frequency-domain spectra collected from the forehead Fp1 and Fp2 positions using one Au-FLG electrode with the CA/Au^{III} ratio of 20. A cycle lasts for 10 s, with the eyeball turning left at 3 s and right at 8 s. Au-FLG, gold-doped few-layer graphene

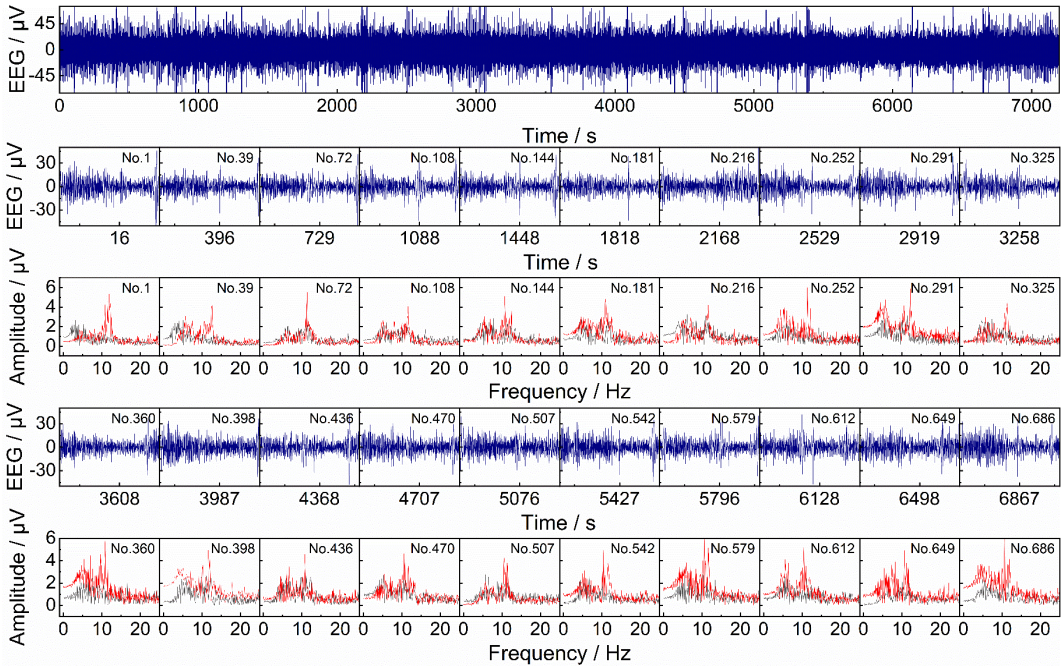

Fig. S32. Short-term stability of an Au-FLG electrode for 2 h. The figure contains both time-domain and frequency-domain spectra. Cycle of 10 s, with the serial number indicating the order of recording for each cycle.

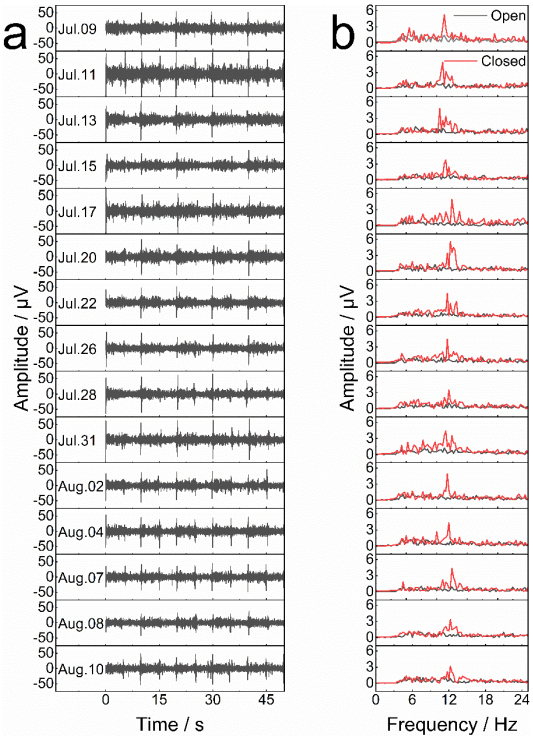

Fig. S33. Long-term stability of the Au-FLG electrode: (a) Time-domain diagram. (b) Frequency-domain diagram. Au-FLG, gold-doped few-layer graphene

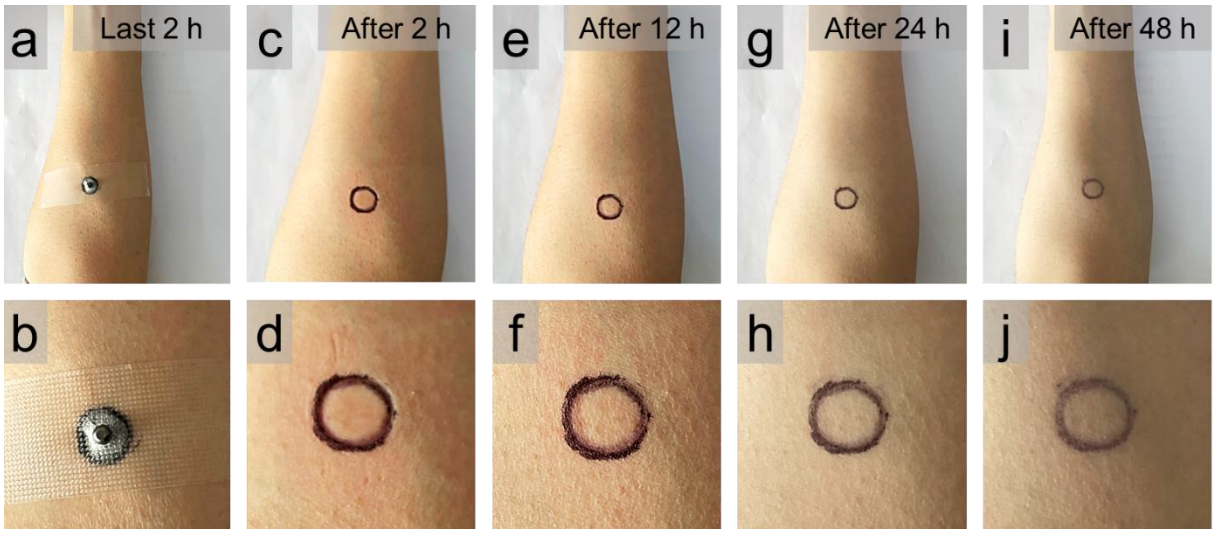

Fig. S34. Skin irritation. (a, b) Au-FLG button electrode attached to the forearm skin. After removing the electrode for (c, d) 2 h, (e, f) 12 h, (g, h) 24 h, and (i,j) 48 h.

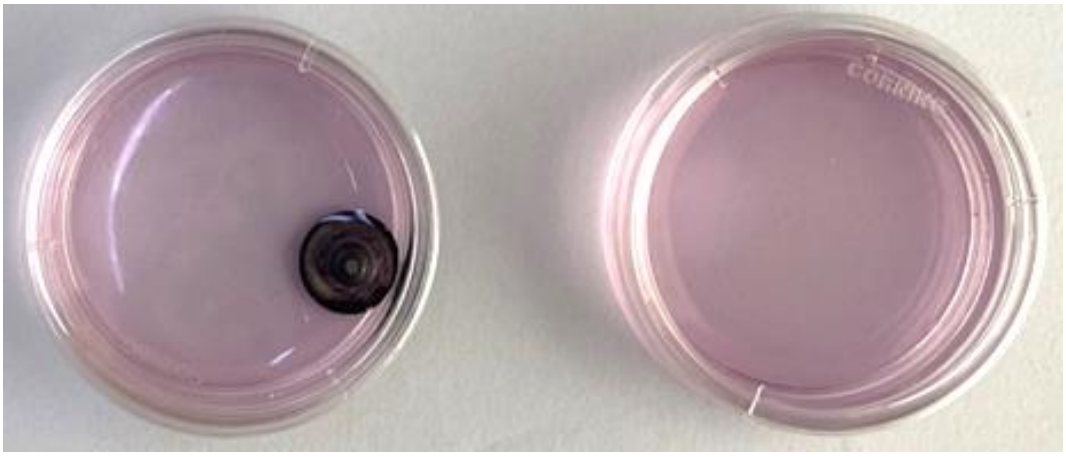

Fig. S35. Photograph of L929 cells cultured in environments with and without Au-FLG electrode.

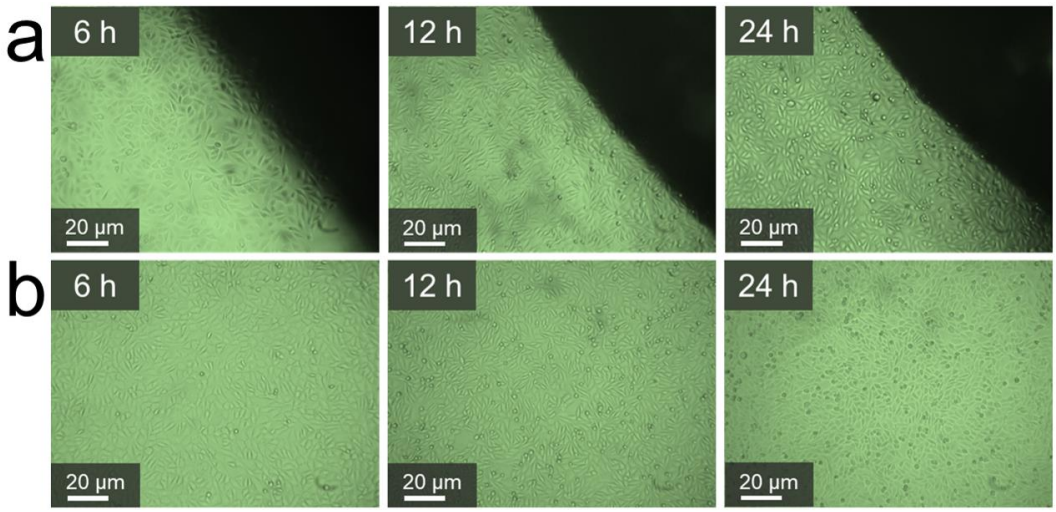

Fig. S36. Optical microscope images of L929 cells during cultivation in the (a) presence and (b) absence of Au-FLG electrode.

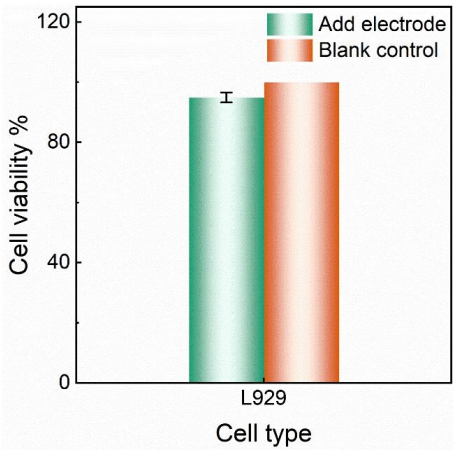

Fig. S37. Cell viability of L929 in culture medium with and without Au-FLG electrode.

Comfort Evaluation Form

Subjects	Wearing time			Pain				Comfort			Sign
	Long	Middle	Short	High	Middle	Low	No	High	Middle	Low	
1			✓				✓	✓			Mo hun Li
2	✓						✓	✓			Hao Bai
3			✓				✓		✓		ZhihaoZhuang
4		✓			✓				✓		Jinzhe Zao
5			✓				✓	✓			Yuhang Zheng
6			✓				✓	✓			Xinyu Zhang
7			✓				✓	✓			Zhiyu Tao
8			✓				✓	✓			NingyuMo
9			✓				✓	✓			Haisheng Tang
10			✓				✓	✓			Wensen Luo
11			✓				✓	✓			chaoyan Li
12			✓				✓	✓			Yihang Wu
13			✓				✓	✓			Junhao Jia
14			✓				✓	✓			JiaWei Liu
15			✓			✓		✓			RuiyV Rong
16		✓					✓	✓			BingZhang
17			✓				✓	✓			Jiahui Tang
18			✓				✓	✓			Xiaolong Wu
19			✓				✓	✓			Jie Chen
20			✓				✓		✓		ZiTeng Li
21			✓				✓	✓			shiming chen
22			✓				✓	✓			Jiao Zu
23			✓				✓	✓			Zhiming Chen
24			✓				✓	✓			Yunfei Yang
25			✓				✓	✓			Yongtian Ma
26			✓			✓				✓	Lianzheng Ren
27			✓				✓	✓			Chunxia Gao
28			✓				✓	✓			ZhanXin Shen
29			✓				✓	✓			Jinwei Hu
30			✓				✓	✓			Binfei Wang

Yuhang Zheng Apr.12.2024

Fig. S38. Comfort evaluation form

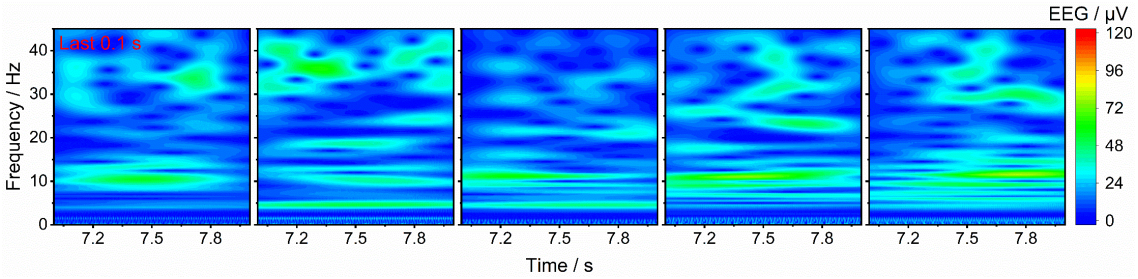

Fig. S39. Time-frequency spectra of EEG signals recorded using an Au-FLG button electrode in the Fp1 channel of the forehead, with eyes closed for 0.1 s. The figure provides five experimental results. Au-FLG, gold-doped few-layer graphene; EEG, electroencephalogram

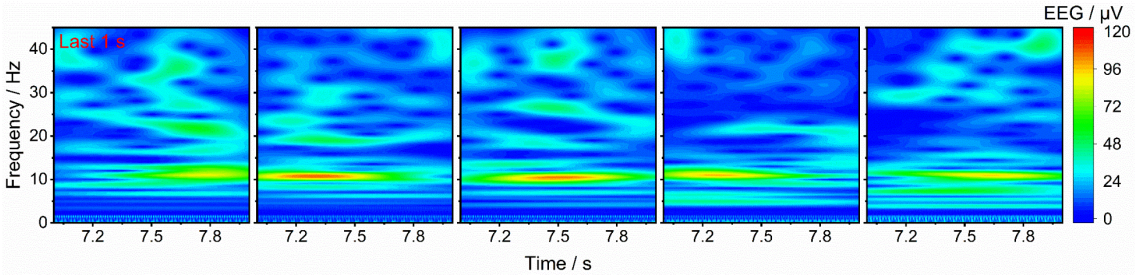

Fig. S40. Time-frequency spectra of EEG signals recorded using an Au-FLG button electrode in the Fp1 channel of the forehead, with eyes closed for 1 s. Au-FLG, gold-doped few-layer graphene; EEG, electroencephalogram

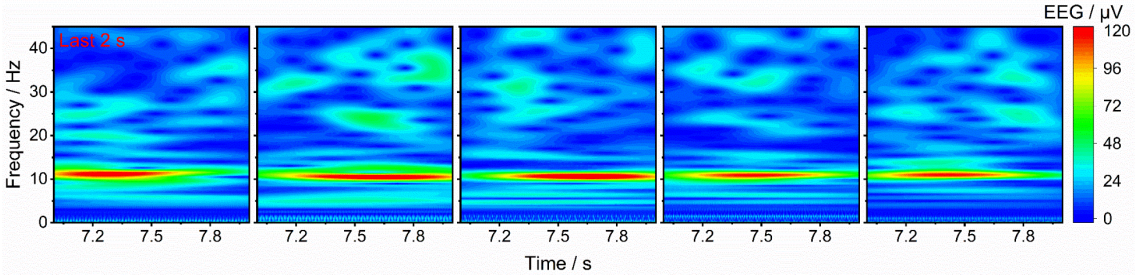

Fig. S41. Time-frequency spectra of EEG signals recorded using an Au-FLG button electrode in the Fp1 channel of the forehead, with eyes closed for 2 s. Au-FLG, gold-doped few-layer graphene; EEG, electroencephalogram

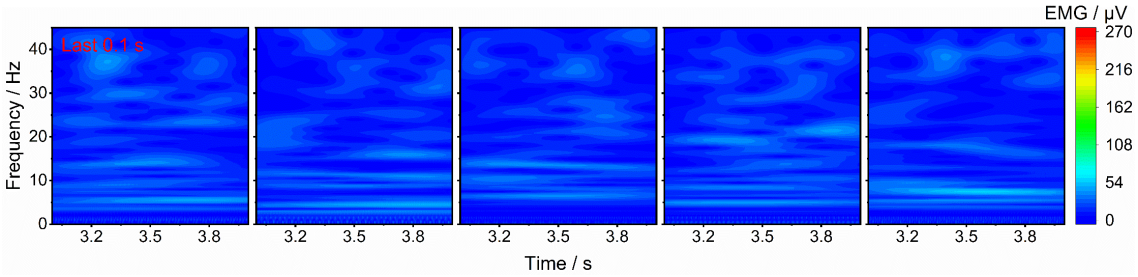

Fig. S42. Time-frequency spectra of EMG signals recorded on the Fp1 channel of the forehead using an Au-FLG button electrode with the grinding teeth for 0.1 s. Au-FLG, gold-doped few-layer graphene; EMG, electromyogram

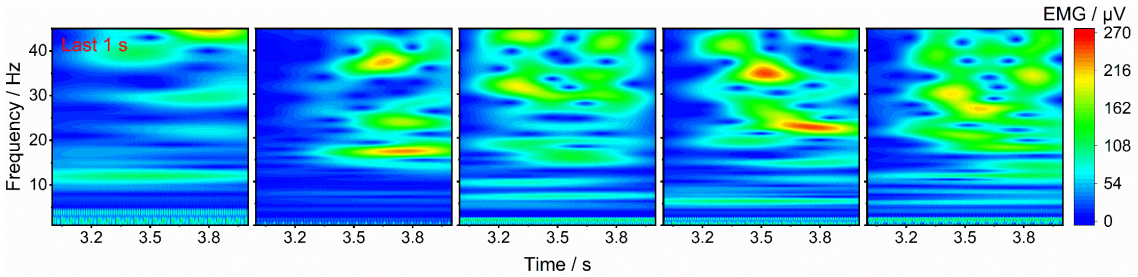

Fig. S43. Time-frequency spectra of EMG signals recorded on the Fp1 channel of the forehead using an Au-FLG button electrode with the grinding teeth for 1 s. Au-FLG, gold-doped few-layer graphene; EMG, electromyogram

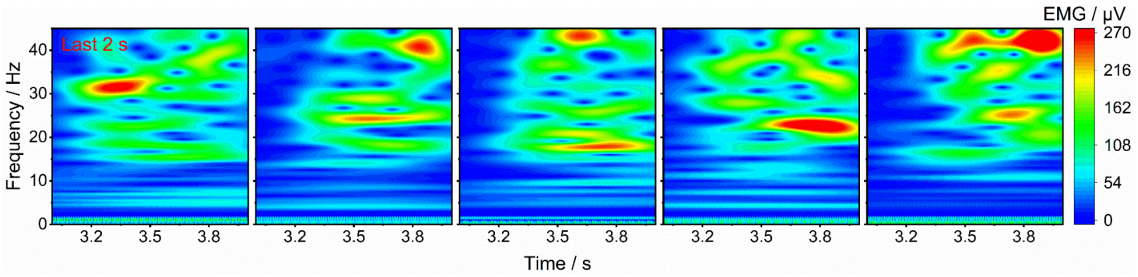

Fig. S44. Time-frequency spectra of EMG signals recorded on the Fp1 channel of the forehead using an Au-FLG button electrode with the grinding teeth for 2 s. Au-FLG, gold-doped few-layer graphene; EMG, electromyogram

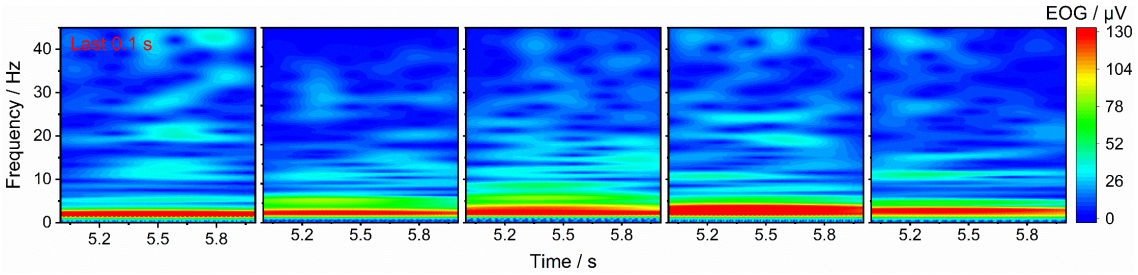

Fig. S45. Time-frequency spectra of EOG signals recorded on the Fp1 channel of the forehead using an Au-FLG button electrode with the eyeball turned to the left for 0.1 s. Au-FLG, gold-doped few-layer graphene; EOG, electrooculogram

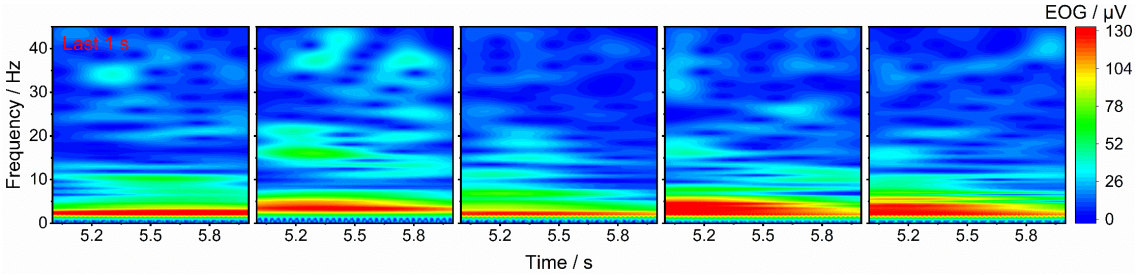

Fig. S46. Time-frequency spectra of EOG signals recorded on the Fp1 channel of the forehead using an Au-FLG button electrode with the eyeball turned to the left for 1 s. Au-FLG, gold-doped few-layer graphene; EOG, electrooculogram

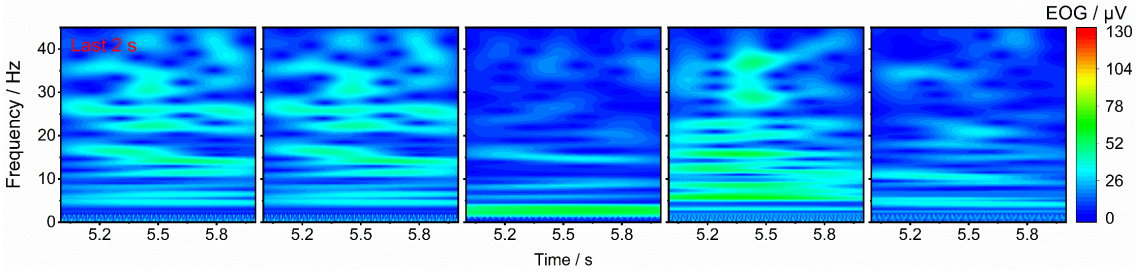

Fig. S47. Time-frequency spectra of EOG signals recorded on the Fp1 channel of the forehead using an Au-FLG button electrode with the eyeball turned to the left for 2 s. Au-FLG, gold-doped few-layer graphene; EOG, electrooculogram

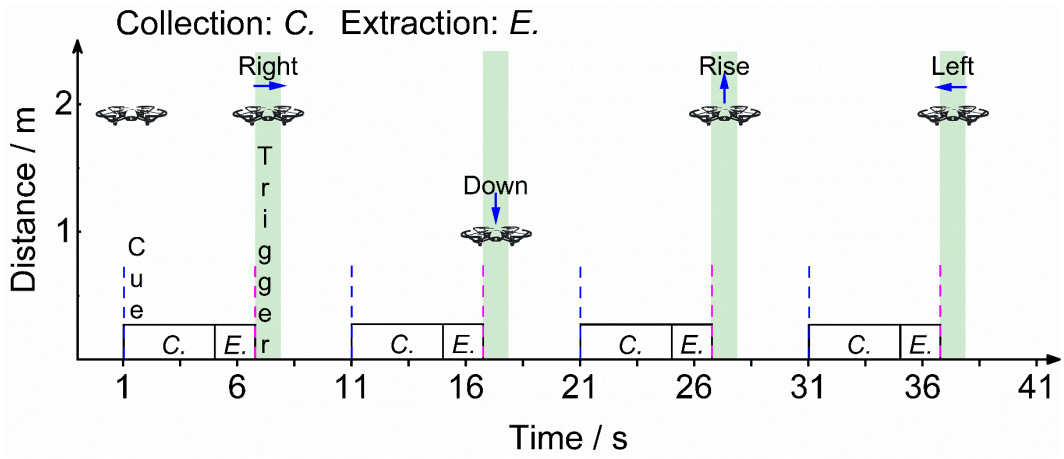

Fig. S48. A brainwave game plan for controlling UAVs for image monitoring.