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RECORDING THE SSSEP WITH THE CEEGRID

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ABSTRACT: The feasibility of EEG systems in real-world scenarios, particularly as assistive devices for people with impairments, remains limited by practical issues of conventional cap EEG. However, the emergence of the *cEEGrid*, an unobtrusive around-the-ear EEG system, might offer a solution. While the cEEGrid has demonstrated success in measuring event-related potentials, essential for brain-computer interfaces (BCIs) in a variety of settings, its ability to measure steady-state somatosensory evoked potentials (SSSEPs) remains unexplored. Here, we recorded SSSEPs from seven stimulation frequencies in six participants. To allow for a direct comparison, the signal was recorded from a conventional scalp EEG (Brain Products Acticap) and two cEEGrids under the same conditions. Results indicate significant SSSEP elicitation with the Acticap, whereas this was only found for one participant with the cEEGrid. Amplitudes measured with cEEGrids are generally smaller, however, their relative discreet design make them an interesting alternative. Further exploration is necessary to characterise the capabilities of the cEEGrid in a potential SSSEP-based BCI application.

INTRODUCTION

Conventional scalp EEG is often considered impractical in ecological conditions, *i.e.*, daily use in patients' homecare settings. The cEEGrid (Fig. 1), developed since 2015, concealed and unobtrusive around-the-ear EEG system, and may thus be a promising alternative to cap EEG systems [1]. The cEEGrids have successfully measured event-related potentials, such as the N100, P100 and P300 [1–3]. The P300 in particular is an important input signal for many Brain-Computer Interfaces (BCIs), and has already been recorded by the cEEGrid in the visual [4], auditory [2], and even tactile modality [5]. However, its capacity to measure steady-state somatosensory-evoked potentials (SSSEP) has not yet been explored.

The amplitude and the individual frequency of an SSSEP is highly variable between participants [6]. A recent literature review of SSSEP-based BCI observed that a screening procedure is often performed to identify the optimal frequency of stimulation (FOS) for each participant [7].

Here, we report preliminary data from the first six participants of our study. The SSSEP was measured from seven different FOS using two different EEG systems: a conventional cap EEG and two cEEGrids. We hypothesised that the cEEgrid systems can measure SSSEP, but with a lower signal-to-noise ratio (SNR) than the cap EEG.

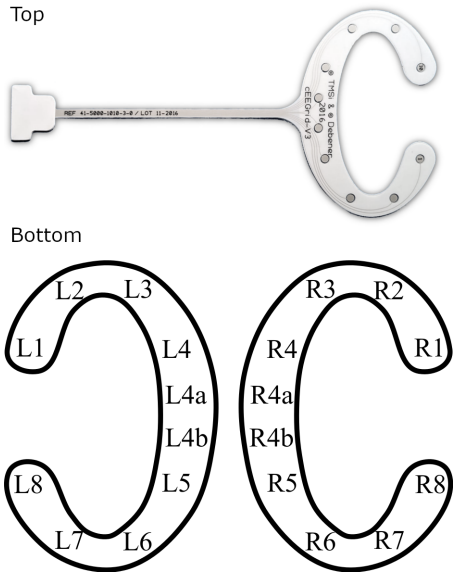

Figure 1: **Top:** A single cEEGrid. **Bottom:** Electrode positions of the left and right ear cEEGrids.

METHODS AND MATERIALS

Methods: Six healthy participants (5 female, 1 male, 26.5 ± 2.3 years) performed one SSSEP screening procedure per EEG system, starting with either cap or cEEGrid in a balanced design. Participants had a 15-minute break in-between. Participants were seated in front a computer screen and equipped with one tactile actuator taped to each wrist (see Fig. 2). Finally, to prevent auditory-evoked potentials from appearing in the EEG data due to the sound of the vibration, the participant wore disposable earplugs during the recordings.

In each trial of the screening procedure, the participant received a train of seven simulations with a duration of 2 seconds, spaced by 0.5 seconds allowing the sensory system to return to an idle state. This train of simulations was preceded by a reference period of 4 seconds. Per stimulation, one of the following FOS were applied: 14, 17, 20, 23, 26, 29, and 32 Hz, on one of the wrists. The stimulation sequence, *i.e.* the combination of FOS and

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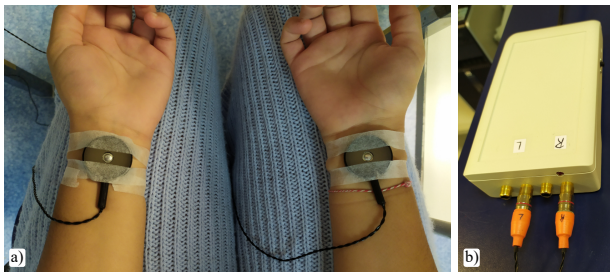

Figure 2: (a) C-2 tactors were taped on the left and right wrists. (b) Stimulation box: a micro-controller establishes the connection to the computer and powers the tactors.

wrist, followed a pseudo-random order, without allowing the same combination of FOS x wrist in direct succession. The protocol is summarised in Figure 3.

During a block in the screening, the participant received 20 trials spaced by a random-length break of 6 to 8 seconds. After that, four blocks with one EEG system (32-channel cap EEG or two cEEGrids, one per ear), plus four additional blocks using the other EEG system were performed. The completion of the full protocol resulted in a total of 40 stimulation epochs of 2 seconds for each FOS, wrist, EEG system, and participant. Data were recorded using a sampling of 500 Hz. AFz was the ground electrode in the cap EEG while R4b was the ground electrode on a cEEGrid pair.

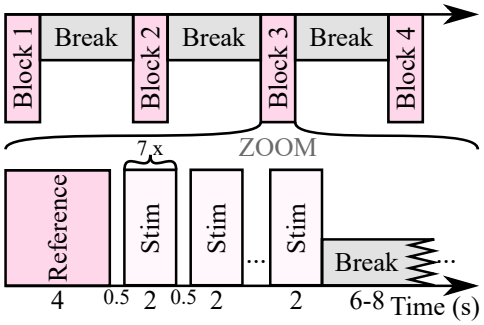

Figure 3: Timeline of the screening session with one EEG system. Each block comprised 20 trials and blocks were separated by 3-minute breaks. This protocol was repeated with the second EEG system 15 minutes after the end of the first screening.

Data Analysis:

Before further processing, we applied an artefact rejection algorithm to the raw EEG. If one or more instances of an electrode peak-to-peak amplitude higher than 100 μV for at least 5 ms was detected in an epoch, that epoch was excluded from further analysis. We then applied two causal filters: a notch filter at 50 Hz to remove power line noise and a bandpass filter from 5 to 35 Hz.

To analyse the data from the cap EEG, the bipolar channels FC3-CP3 and FC4-CP4 were derived, which cover the primary somatosensory cortex. These channels are known to record SSSEPs originating from the right and left wrist stimulation, respectively [8]. For cEEGrid data, we used linear combinations of cEEGrid channels to approximate cap EEG positions over the same cortical areas [9], namely $\widehat{C3}$ and $\widehat{C4}$. This is also in line with previous studies, which showed that the cEEGrid measured the highest event-related potential on vertical bipolar channels [1, 5]. $\widehat{C3}$ and $\widehat{C4}$ are obtained using the following formula:

$$\begin{cases} \widehat{C3} = (L2+L3)/2-(L6+L7)/2 \\ \widehat{C4} = (R2+R3)/2-(R6+R7)/2 \end{cases},$$

using the electrode positions displayed in Figure 1.

We evaluated the SSSEP by two components of the frequency spectrum: the amplitude at the frequency of interest, i.e. the FOS, in relation to the mean amplitude of its neighbouring frequencies in the spectrum. The ratio of these components is a commonly used definition of the SNR in steady-state visually-evoked potentials [10]. The spectrum estimation is performed using the discrete-time Fourier transform algorithm.

To assess the statistical difference between the two components, *i.e.* to test whether SSSEP amplitude is larger than at neighbouring frequencies, we used the non-parametric[1] one-tailed Wilcoxon signed-rank test. The significance level was corrected using the Benjamini-Hochberg procedure to control the false discovery rate (FDR).

Materials:

C-2 Tactors (Engineering Acoustic Inc., Casselberry, USA) were used to administer mechanical vibrations to the participant's wrists, as depicted in Figure 2. The two tactors were powered by a single micro-controller, connected to a host computer. The micro-controller box design was inspired by the work of Pokorny *et al.* [8]. Further information on the initial implementation of our stimulation system can be found in [11]. The stimulation signal comprised a high-frequency sine-wave, around 275Hz, closely aligned with the resonance frequency of the C-2 Tactor. This signal was amplitude-modulated by a square signal at a lower frequency, our FOS. EEG data was recorded using a Brain Products EEG cap (ActiCap) with 32 active electrodes positioned according to the 10-20 international system [9]. Positions AFz and CPz were used as Ground and reference, respectively. The signal was sampled at 500 Hz using a *Brain Products BrainAmp*. Data acquisition and real-time processing were conducted through OpenViBE [12]. Offline signal processing and statistical analysis were carried out using the MNE and SciPy libraries in Python.

RESULTS

Spectrum analysis revealed a significant SSSEP elicitation for at least one FOS for all participants with the conventional cap system. Participant #1 showed significant SSSEPs at 20, 26, and 32 Hz on the right wrist, while 20 and 32 Hz yielded significant SSSEP amplitudes on the left wrist. Participant #2 displayed a significant SSSEP

[1] Using Shapiro–Wilk tests for normality and an alpha risk level at 0.05, the normality hypothesis could not be maintained on 39.6% of our conventional EEG samples and 55.3% for the cEEGrid samples.

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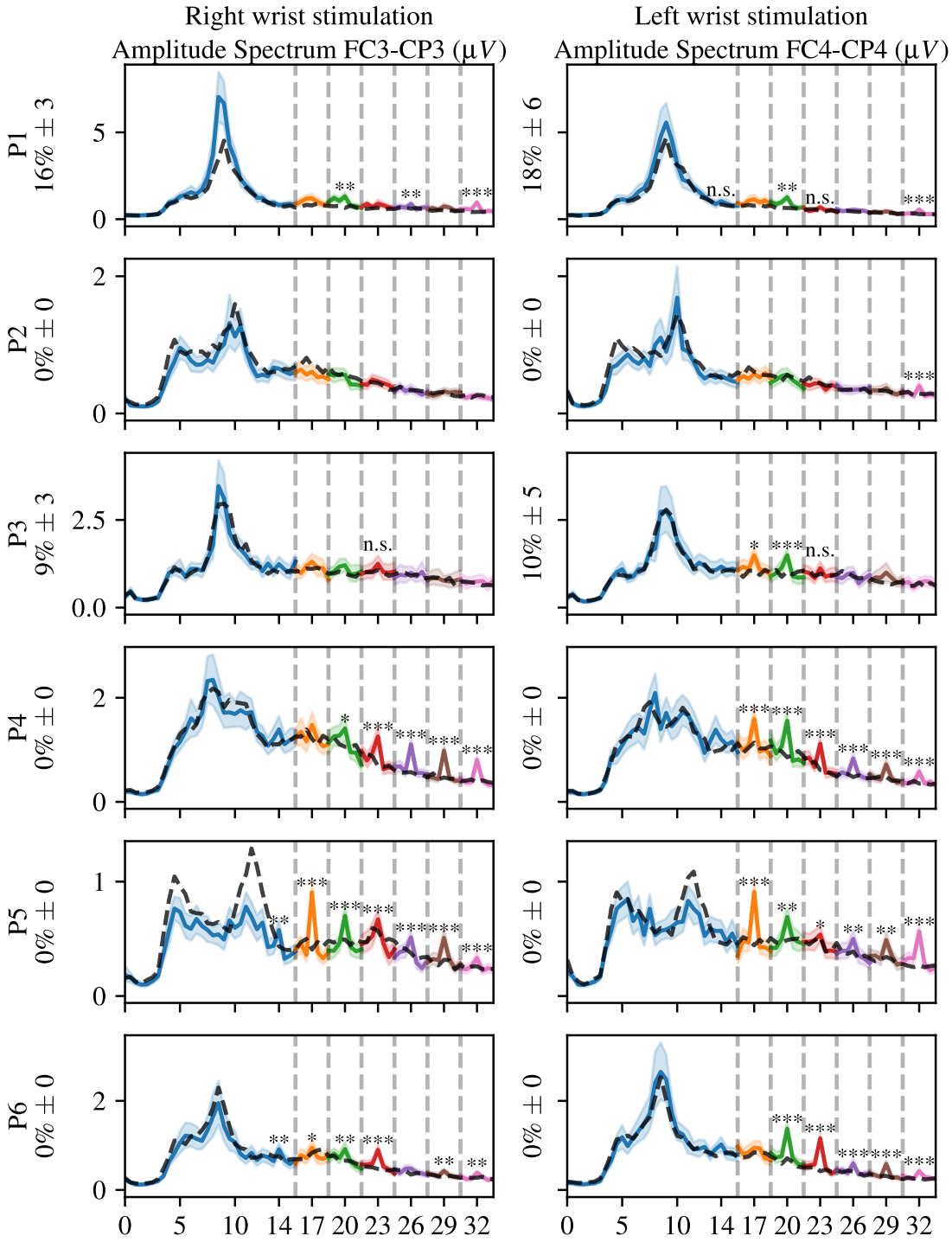

Figure 4: Cap EEG data from channels FC3-CP3 and FC4-CP4. Frequency spectra were concatenated for FOS 14 to 32 Hz (color coded), with lighter shades representing 95% CI. Dashed black lines show the mean spectrum from reference period. Significant results (*, **, ***) marked for $p \leq 0.05, 0.01, 0.001$, FDR controlled by Benjamini-Hochberg procedure. Null hypotheses rejected at 0.05 alpha level, but not surviving FDR procedure are denoted "*n.s.*". Numbers next to the participant code show the mean percentage of rejected trials after artefact detection using peak-to-peak analysis.

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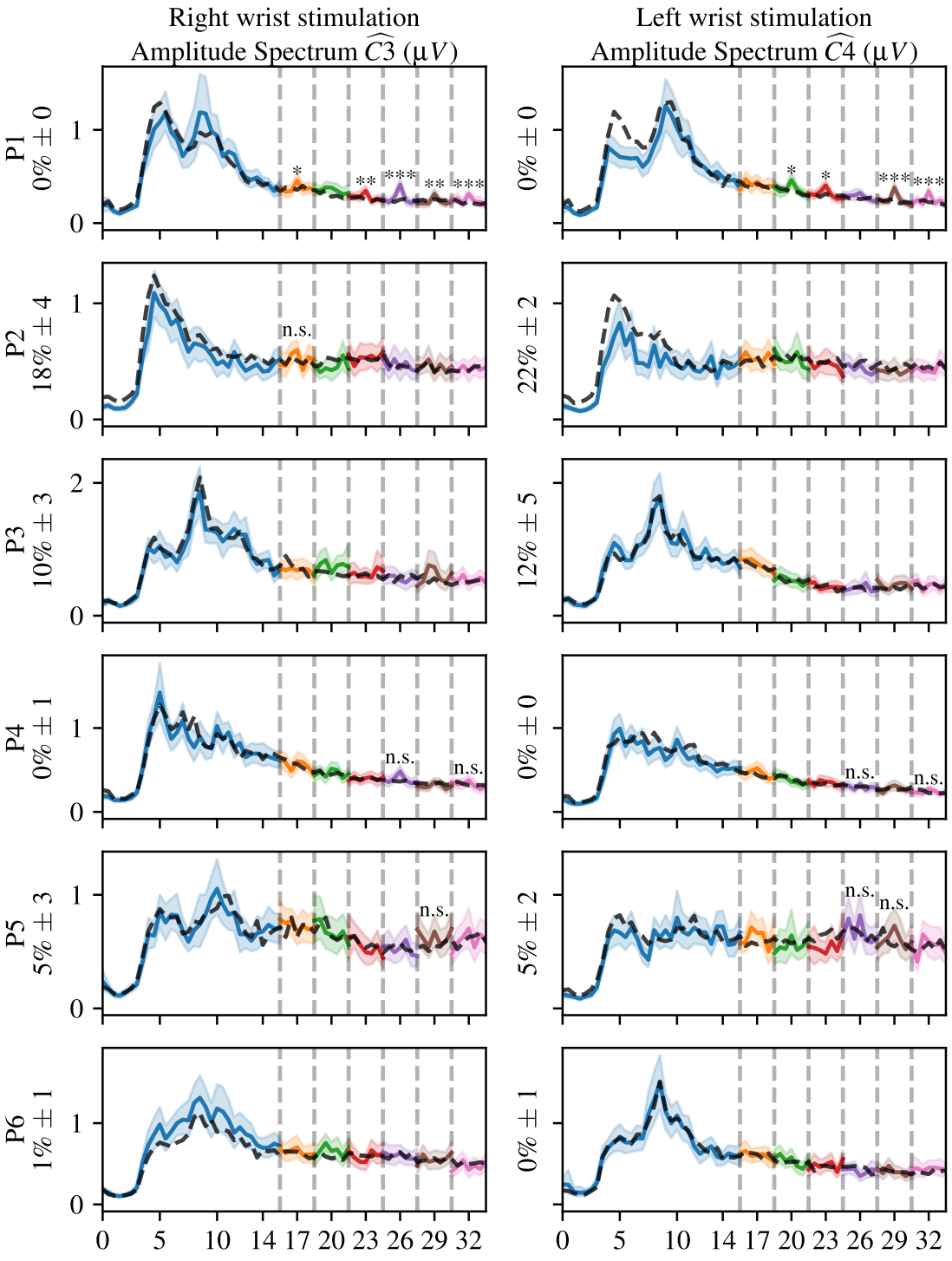

Figure 5: cEEGrid data from channels $\widehat{C3}$ and $\widehat{C4}$. Frequency spectra were concatenated for FOS 14 to 32 Hz (color coded), with lighter shades representing 95% CI. Dashed black lines show the mean spectrum from reference period. Significant results (*, **, ***) marked for $p \leq 0.05, 0.01, 0.001$, FDR controlled by Benjamini-Hochberg procedure. Null hypotheses rejected at 0.05 alpha level, but not surviving FDR procedure are denoted "*n.s.*". Numbers next to the participant code show the mean percentage of rejected trials after artefact detection using peak-to-peak analysis.

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only at 32 Hz on the right wrist. Participant #3 exhibited only two significant SSSEPs at 17 and 20 Hz on the left wrist. Participant #4 showed significant SSSEPs at every FOS except 14 Hz on both wrists and 17 Hz on the right wrist. Participant #5 displays significant SSSEPs at every FOS, except 14 Hz on both arms. Finally, participant 6 showed significant SSSEPs at almost all FOS, except at 26 Hz on the right wrist, as well as at 14 and 17 Hz on the left wrist. Every spectrum calculated from the cap EEG data are displayed in Figure 4.

Frequency spectra from the cEEGrid recordings are displayed in Figure 5. We found significant SSSEPs for participant #1 at 17, 23, 26, 29, and 32 Hz on the right wrist, while at 20, 23, 29, and 32 Hz on the left wrist exhibited significant SSSEPs. The remaining five participants showed no significant SSSEPs at any FOS, however, some SSSEPs were significant before FDR correction, those SSSEPs are highlighted as "n.s.". For example, a descriptive but finally insignificant SSSEP was found at FOS at 17 Hz (right wrist) for participant #2.

DISCUSSION AND CONCLUSION

The present study investigated whether the cEEGrid system can be used to record SSSEP. In this preliminary study, we performed two sequential EEG recordings using two different EEG systems: a conventional ActiCap cap system and two cEEGrids around the ear. Our results show that for each participant, a significant SSSEP was recorded with the cap EEG, while only one participant exhibited significant SSSEP amplitude using the cEEGrid. Three other participants showed descriptive increases in activity at the FOS, but this observation was not significant after the false discovery rate correction procedure. Collectively these results indicate that the cEEGrid may help to bridge the translational gap in EEG-based BCI studies, assuming that as a smaller and less obtrusive system, it could be accepted more readily by potential end-users.

Overall, the amplitudes of the SSSEPs found on the cEEGrid were smaller as compared to the cap-recorded SSSEPs, which is well in line with previous observations [2, 4]. This could be explained by the fact that, unlike the cEEGrid, the cap EEG recorded directly over the region of interest in somatosensory-evoked potentials, *i.e.* primary somatosensory cortex. Remarkably however, the cEEGrid still recorded significant SSSEPs under some conditions, using vertical linear combination of electrodes to approximate positions C3 and C4. In addition, the amount of artefacts leading to rejection of a trial using peak-to-peak amplitude analysis was similar between EEG systems. This demonstrates that recording this signal is generally possible with the cEEGrid, without the practical disadvantages of a gel based EEG cap (*e.g.*, gel in the hair, visual appeal).

There were certain limitations to this preliminary study. The EEG systems were applied in a pseudo-random sequential order, unlike in [5, 13]. Thus, without simultaneous recordings, we are limited in our ability to examine the correlation between the two systems. This approach was chosen to prevent interference between the active cap electrodes and the unshielded cEEGrid. A limitation arising from the cEEGrid is that the cEEGrids were disinfected and reused (using new sticker) while electrode quality was remained good, as assessed with bucket tests. Genereally, cEEGrid application to individuals with facial hair was difficult and required additional tape to ensure a satisfactory impedance. Future versions of the cEEGrid could benefit from solving this problem.

The present study adds to the growing body of literature comparing the cEEGrid with conventional EEG systems, and provides first evidence that the cEEGrid may record SSSEPs. Future studies should address this potentially limiting aspect of the cEEGrid hardware. Finally, for the full study, we will increase the number of included participants to improve statistical power. As for now, our preliminary results are moderately encouraging for SSSEP recording endeavours.

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