Project ID: BESN-390
Title: Resting-state electroencephalography and event-related potentials to lexical tone processing in bilingual Mandarin-English children
Name: Elliot Blin
School: The Bronx High School of Science
Research Site: St. John's University (data collection under approved IRB protocol)
Mentor: Dr. Yan Yu (Qualified Scientist)

Abstract

Background

Resting-state brain activity reflected the intrinsic organization of the brain when it was not engaged in a task, while event-related potentials (ERPs) revealed how the brain responded to specific stimuli such as speech. Mandarin lexical tones required precise pitch discrimination, placing unique demands on the auditory system. Although resting-state EEG had been widely used to study brain development, it remained unclear how resting-state connectivity compared to speech-processing networks in bilingual Mandarin-English children. Additionally, little was known about how these neural networks changed across childhood and into adulthood. This paper examines developmental differences in neural connectivity and organization during both resting-state activity and lexical tone processing.

Objectives

1. to analyze developmental differences in neural connectivity during Mandarin lexical tone processing across three age groups;
2. to compare resting-state and speech-processing networks to determine how intrinsic and task-driven brain activity differed;
3. to characterize the developmental trajectory of coherence and phase-locking responses in bilingual Mandarin-English speakers.

Methodology

All experimental procedures were conducted under the supervision of a qualified mentor at St. John's University and approved by the Institutional Review Board (IRB).

Fifty-three bilingual Mandarin-English participants (younger children ages 5–7, older children ages 8–10, and adults ages 22–34) completed resting-state EEG and a lexical tone listening task. EEG data were recorded using 65 electrodes at 1000 Hz. Connectivity was assessed using coherence and phase-locking

value (PLV) across 1–10 Hz. AEP montages were analyzed for speech conditions, while a DMN montage was used for resting-state data. Connectivity maps and matrices were compared across age groups.

Impact and Significance

1. **Scientific impact:** This study advanced understanding of how bilingual children developed neural networks for processing tonal language, revealing distinct developmental peaks and maturation patterns.

2. **Methodological impact:** The combination of resting-state and speech-evoked EEG provides a multi-dimensional approach to studying bilingual brain development and may inform future assessments of auditory processing in children.

Research Paper

1.1 Background: Lexical Tone Processing in Bilingual Mandarin–English Speakers

Mandarin Chinese is a tonal language in which pitch patterns determine lexical meaning. A single syllable can represent multiple words depending entirely on the contour of the speaker's voice. For instance, the syllable "ma" can mean "mother," "hemp," "horse," or "to scold," depending on whether the pitch stays high and level (Tone 1), rises (Tone 2), dips and rises (Tone 3), or falls sharply (Tone 4). This makes pitch perception not just an acoustic skill in Mandarin, but a core linguistic requirement. In contrast, English does not assign word meaning to tone. Pitch changes in English mainly signal emotional emphasis, sentence type, or stress patterns.

Because bilingual Mandarin–English speakers learn two languages with different sound-to-meaning systems, their auditory brains face unique developmental demands. They must build neural representations that support tonal meaning in Mandarin while also adapting to English speech systems that rely more on consonants, vowels, and stress. Bilingual children are therefore required to switch between two different speech "rulesets," which may reshape how their brains organize auditory networks.

Another important factor is that bilingual children often experience variable input across both languages. Some children receive stronger Mandarin exposure at home and more English at school, while others may hear Mandarin more consistently. This uneven exposure can influence tone perception and neural development. Therefore, studying bilingual tone processing provides insight not only into how tonal perception works, but also into how brain networks adapt to multilingual environments.

1.2 Developmental Changes in Auditory Brain Networks

Neural connectivity is known to change dramatically through childhood. Early in development, children's brains are still building stable communication pathways. Younger children typically show diffuse connectivity patterns, meaning that activity is spread more broadly across the brain and connections between regions are weaker and less coordinated. This is normal because many synaptic pathways are still being formed, and the brain has not yet refined which connections are most essential for language processing.

As children grow, the brain gradually shifts from diffuse organization to specialized organization. Networks strengthen between regions involved in auditory discrimination, phonological analysis, and memory. This increased synchronization supports improved speech perception skills, including the ability to detect subtle acoustic differences such as rising versus falling pitch. In bilingual children, stronger networks are especially important because they must discriminate between tonal contrasts that English speakers normally do not need to notice.

Older children, especially between ages eight and ten, often show a developmental peak in connectivity. Their brains have built many robust pathways, but pruning and efficiency optimization have not yet fully reduced network spread. This can produce especially strong coherence and phase-alignment patterns. Adults, on the other hand, show more compact and efficient networks. Through pruning, the brain eliminates redundant connections and retains the strongest, most useful pathways. This means adult connectivity may look weaker overall than older children's, but it reflects efficiency rather than immaturity.

1.3 Resting-State EEG vs. Speech-Evoked EEG

Resting-state EEG captures intrinsic neural activity while the participant is not actively processing a task. These baseline signals reveal how the brain communicates at rest and are often associated with large-scale systems such as the default mode network. Resting-state connectivity is valuable because it reflects the brain's foundational organization—how regions "default" into communication patterns when no stimulus is present. In developmental neuroscience, resting-state EEG is commonly used to estimate overall neural maturity, because more organized resting networks usually indicate more developed neural systems.

However, resting-state connectivity does not necessarily match speech-processing connectivity observed during auditory tasks. When the brain listens to lexical tones, it must engage specialized auditory systems: detecting pitch direction, tracking contour shape over time, comparing input to stored tone categories, and mapping the result to Mandarin meaning. This requires auditory cortex, temporal–parietal regions, and language networks that become temporarily synchronized during a tone task.

In bilingual Mandarin–English children, the gap between resting-state and task-based networks may be even larger. Resting-state networks reflect general maturity, but tone tasks test a specific linguistic skill that bilingual children develop on their own timeline. Comparing rest and task EEG in the same participants allows researchers to see whether intrinsic organization predicts speech processing, or whether speech-processing networks mature through a different developmental pathway.

1.4 Why Lexical Tone Perception Is a Strong Test of Bilingual Auditory Development

Lexical tones are an especially strong system for testing auditory development because they require rapid tracking of pitch movement over time. Unlike consonants, which can be separated by clear categorical differences, tones depend on continuous signals. Children must hear not only that a pitch

changes, but how it changes (rising, falling, dipping). This makes tone perception highly sensitive to neural timing and coordination.

For bilingual Mandarin–English children, tone perception also tests how robustly Mandarin networks are maintained while English networks grow. If a bilingual child primarily uses English in school, English processing pathways may strengthen earlier, while Mandarin tone pathways depend more on home exposure. This could delay or alter tone-specific network organization. Therefore, tones are a powerful window into how bilingual brains balance two systems under different exposure conditions.

1.5 Rationale for Using Connectivity Measures (Coherence and PLV)

To study tone perception development, this analysis focuses on neural connectivity rather than just ERP amplitude or latency alone. ERP amplitudes show how strongly a brain responds to a stimulus, but they do not reveal how well different brain regions work together. Connectivity measures provide that missing piece.

Coherence measures the strength of synchronization between brain signals from different regions. High coherence suggests that regions are communicating effectively and consistently. Phase-Locking Value (PLV) measures how stable that synchronization timing is across repeated trials. High PLV indicates that neural timing is reliable, meaning the brain is consistently aligning its processing response to the stimulus.

These measures are particularly useful for developmental studies because they show network maturation. In younger children, low coherence and PLV reflect weaker coordination. In older children, coherence and PLV often increase as networks start to emerge efficiently. In adults, coherence may decrease slightly because neural pruning reduces redundant connections and retains the strongest, most useful pathways. Using coherence and PLV therefore allows researchers to track not only whether the brain responds to tones, but also how different networks become more coordinated over time.

Part 2. RESEARCH QUESTION(S), HYPOTHESIS(ES), ENGINEERING GOAL(S), EXPECTED OUTCOMES: How is this based on the rationale described above?

The main research questions address how neural connectivity during resting-state and Mandarin lexical tone processing differs across developmental stages in bilingual Mandarin–English speakers.

The main hypotheses of this study are that younger bilingual children show weaker and less organized connectivity than older children and adults; older children exhibit the strongest connectivity patterns, and adults show more efficient but less widespread neural networks due to neural pruning.

Examining these hypotheses is important because it provides insight into brain connectivity measurements of bilingual neural processing across childhood and adulthood. It helps us understand whether there is a developmental peak in speech-related network organization and whether resting-state connectivity reflects the same maturation pattern as speech-evoked processing. The specific aims of the study are: 1) to determine how coherence and phase-locking value (PLV) change with age during lexical tone perception; 2) to compare resting-state and task-based connectivity; and 3) to identify developmental patterns that describe how bilingual auditory networks mature.

Part 3. Procedures: Detail all procedures and experimental design including methods for data collection.

3.1. ERP Stimulus

The ERP stimuli consisted of Mandarin lexical tones, which are speech sounds distinguished by pitch contours. Four standard Mandarin tones were used: Tone 1 (high-level), Tone 2 (rising), Tone 3 (dipping–rising), and Tone 4 (falling). These tones were recorded by a native Mandarin speaker in a sound-controlled environment as part of the mentor-led study protocol. The clearest productions were selected and normalized for intensity, duration, and sound quality. Each tone was trimmed to remove unwanted noise and was presented multiple times to each participant.

All tone recordings were produced by a native Mandarin speaker in a quiet controlled room. To ensure sound quality, stimuli were normalized and adjusted until each token had consistent intensity and pitch characteristics. During the experiment, tones were delivered in randomized order so that participants could not predict which tone would occur next. Each tone type occurred the same number of times per block. Stimuli were presented binaurally through calibrated headphones.

During the experiment, tones were delivered in short blocks with rest periods to minimize fatigue. Each block contained an equal number of tone presentations. EEG was recorded continuously as participants listened quietly without responding. Trials were time-locked to the onset of each tone. Horizontal and vertical eye blinks were removed using standard artifact correction procedures.

Lexical tone stimuli are highly appropriate for this analysis because pitch contour carries meaning in Mandarin. For bilingual Mandarin-English children, perceiving tones requires the auditory system to coordinate spectral and temporal information precisely. This makes tone perception an ideal test of neural timing and network organization, and provides a strong test of bilingual auditory developmental and neural connectivity.

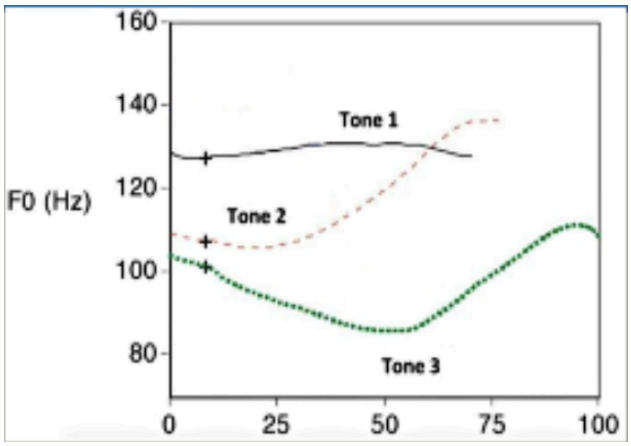


Figure 1. Fundamental frequency (F0) contours of the four Mandarin lexical tones used as ERP stimuli (Tone 1–4).

3.2. Experimental Design

Three groups of participants were tested: younger children (5–7 years old), older children (8–10 years old), and adults (22–34 years old). All participants were bilingual Mandarin–English speakers with early exposure to both languages. Each participant completed two EEG conditions:

1. Lexical tone listening (speech-processing condition)

2. Resting-state EEG (baseline condition)

The dependent variables included EEG waveforms and connectivity measures (coherence and phase-locking value) extracted from speech and resting-state conditions. The independent variable was developmental stage (younger children, older children, adults). Connectivity features from the three groups were compared to identify developmental trends in neural organization.

3.3. Procedure

Step 1. Each participant (and parent/guardian for child participants) completed informed consent/assent and a brief language background questionnaire. This questionnaire confirmed bilingual exposure history, age of acquisition for each language, and general developmental information. Participants were seated in a quiet EEG testing room with minimal external noise.

Step 2. A trained research assistant, under mentor supervision, fitted the participant with a 65-channel EEG cap. Conductive gel was applied at each electrode site until impedances reached an acceptable level for recording. Participants were reminded to remain relaxed, minimize head movement, and reduce blinking during stimulus presentation. Younger children received simple task instructions and a short practice block to ensure comfort and understanding.

Step 3. Lexical tone listening task. Participants listened passively to Mandarin lexical tones presented through calibrated headphones. Tone stimuli were delivered in multiple short, randomized blocks so that no tone pattern was predictable. Each block contained an equal number of Tone 1, Tone 2, Tone 3, and Tone 4 trials. Participants were not asked to respond verbally or by button press, reducing

motion artifacts. EEG signals were recorded continuously, and ERP segments were time-locked to tone onset for later averaging by tone category.

Step 4. Resting-state recording. After completing the tone task, participants transitioned to resting-state EEG collection. Resting-state data included an eyes-open period followed by an eyes-closed period, each lasting several minutes. Participants were instructed to stay still and let their minds rest without focusing on any specific task. This provided baseline default-mode network data for comparison with the tone-processing condition during analysis.

Step 5. The EEG cap was removed, remaining gel was cleaned, and participants were debriefed. Parents received a simple verbal explanation of the study's purpose, and participants were given an opportunity to ask questions. All EEG data were stored securely for offline preprocessing and connectivity analysis.

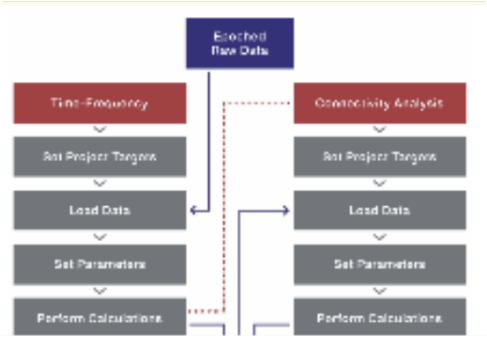


Figure 2. Data analysis workflow for time-frequency decomposition and connectivity calculations (coherence and phase-locking value) applied to resting-state and speech conditions.

Part 4. Risk and Safety: Identify any potential risks and safety precautions needed.

4.1. COVID-19 related safety procedures

Participants and accompanying parents/guardians followed standard health and safety guidance at the testing location. Participants were asked not to attend if they felt sick or had symptoms of a contagious illness. The EEG booth, headphones, chair, and any touch surfaces were cleaned and disinfected before and after each session. Hand sanitizer was available, and participants were encouraged to sanitize hands

upon entry and exit. If needed by the testing location, masks were worn to reduce any risk of transmission.

4.2. Experimental-related risks and safety precautions

- The EEG/ERP experiment was a noninvasive procedure, and no pain or harm occurred during participation.
- The main potential risk was mild discomfort when the 65-channel EEG net/cap was placed on the participant's head, or slight tingling from the saline/gel used to help recordings.
- To minimize discomfort, trained researchers applied the cap gently, monitored impedance to avoid excessive gel application, and checked in with participants frequently. Participants were allowed to request breaks at any time, and breaks were scheduled between blocks to prevent fatigue—especially for younger children.
- Participants were permitted to discontinue the session at any moment without penalty.
- The total expected participation time was about 2–3 hours including breaks, so the session was paced appropriately for children.

4.3. Confidentiality and protection of participants

- All participant records were kept confidential. Identifying information was stored securely, and only researchers directly involved in the project had access.
- Any findings shared in posters, papers, or presentations were reported in group form, and no individual was identified.
- EEG data may be deposited into a research data library to support future scientific work, but only after the data were de-identified and stripped of personal information.

4.4. Voluntary participation and consent/assent

- Participation was completely voluntary, and participants could withdraw at any time without penalty. Parents/guardians provided informed consent for child participants, and children provided assent in age-appropriate language.

- Adult participants provided their own consent. Participants and families were allowed to withdraw at any time or skip any question without penalty or impact on their relationship with the researchers.

Part 5. Data Analysis: Describe the procedures you will use to analyze the data/results.

Step 1. Off-line data analysis

The EEG/ERP brain waves were refiltered using a bandpass filter of 0.1–30 Hz. All waveforms were segmented according to the tone onset event. Horizontal and vertical eye blinks were removed, and other movement noise was removed using Brain Electrical Source Analysis (BESA). Each segment was averaged according to its tone category (Tone 1, Tone 2, Tone 3, Tone 4). Resting-state EEG was processed separately and re-referenced using the average of all 65 channels. Time-frequency decomposition was conducted within the 1–10 Hz range using wavelet-based methods to prepare the data for connectivity analysis.

Step 2. Connectivity and group comparison analysis

Neural connectivity was calculated using coherence and phase-locking value (PLV) for both the speech condition and the resting-state condition. Connectivity matrices and brain network maps were generated for each participant and averaged within each age group (younger children, older children, adults). Group differences were evaluated through descriptive comparison of network strength, organization, and distribution across conditions. The main developmental patterns were identified by comparing coherence/PLV heatmaps and connectivity visualizations between the three age groups, focusing on how tone-processing networks differ from resting-state networks.

RESULTS

ERP Waveform Results

Event-related potentials (ERPs) elicited by Mandarin lexical tones showed clear developmental differences across age groups. Grand-average waveforms recorded at the Cz electrode and left mastoid

revealed systematic changes in both amplitude and temporal structure from younger children to adults. Younger children exhibited broader, less sharply defined ERP components, with increased variability across trials, indicating immature neural encoding of pitch contours.

Older children demonstrated larger and more consistent ERP responses relative to younger children, with clearer negative and positive deflections following tone onset. These waveforms showed more precise timing and greater peak separation compared to younger children, suggesting improved neural synchronization and auditory discrimination. Adult participants displayed reduced overall ERP amplitudes but more compact and stable waveforms, reflecting increased neural efficiency and pruning.

Across all groups, Tone 3 (the dipping tone) elicited the strongest ERP responses. This effect was most pronounced in older children, who showed enhanced negativity consistent with mismatch negativity (MMN)-like responses. The heightened response to Tone 3 reflects its greater acoustic complexity and increased demands on pitch tracking mechanisms. Adult responses to Tone 3 were smaller in amplitude but showed faster recovery to baseline, indicating efficient processing of complex tonal information.

Connectivity Results During Lexical Tone Processing

Connectivity analyses revealed robust developmental differences in network organization during tone perception. Coherence and phase-locking value (PLV) measures showed that older children exhibited the strongest and most widespread connectivity during lexical tone processing. These networks involved frontal, temporal, and parietal regions, indicating coordinated activity across distributed auditory and cognitive areas.

Younger children showed weaker connectivity overall, with fewer long-range connections and lower synchronization between brain regions. Their networks appeared more fragmented, consistent with early-stage neural organization. In contrast, adults demonstrated more focal and streamlined connectivity patterns, with fewer but stronger connections, suggesting efficient neural communication.

Connectivity matrices and brain network visualizations further illustrated these developmental trends. Older children displayed dense connectivity patterns across multiple regions, while younger children showed sparse networks and adults showed selectively strengthened pathways. These patterns were consistent across both coherence and PLV measures.

Resting-State Connectivity Results

Resting-state EEG connectivity exhibited less pronounced differences across age groups than tone-evoked connectivity. All groups showed baseline synchronization within large-scale networks, including frontal and posterior regions. However, developmental differences in resting-state coherence were subtler and less spatially organized than those observed during tone processing.

Older children still exhibited slightly stronger resting-state connectivity than younger children, suggesting ongoing maturation of intrinsic networks. Adult resting-state networks appeared more refined but less widespread, consistent with stable, efficient intrinsic organization. Overall, resting-state measures reflected general maturation but did not capture the task-specific reorganization observed during tone perception.

Comparison Between Resting-State and Speech-Evoked Connectivity

Direct comparisons between resting-state and lexical tone conditions indicated that task demands significantly modulated neural network organization. During tone processing, connectivity was stronger, more synchronized, and more spatially structured than during rest. This effect was especially prominent in older children, whose networks showed clear task-driven reconfiguration.

Younger children showed minimal differentiation between resting-state and task-based connectivity, suggesting that their networks were not yet specialized for tone processing. Adults exhibited clear but localized differences between conditions, indicating specialized but efficient recruitment of auditory networks.

Together, these findings demonstrate that speech-evoked EEG provides a more sensitive measure of developmental differences than resting-state EEG alone.

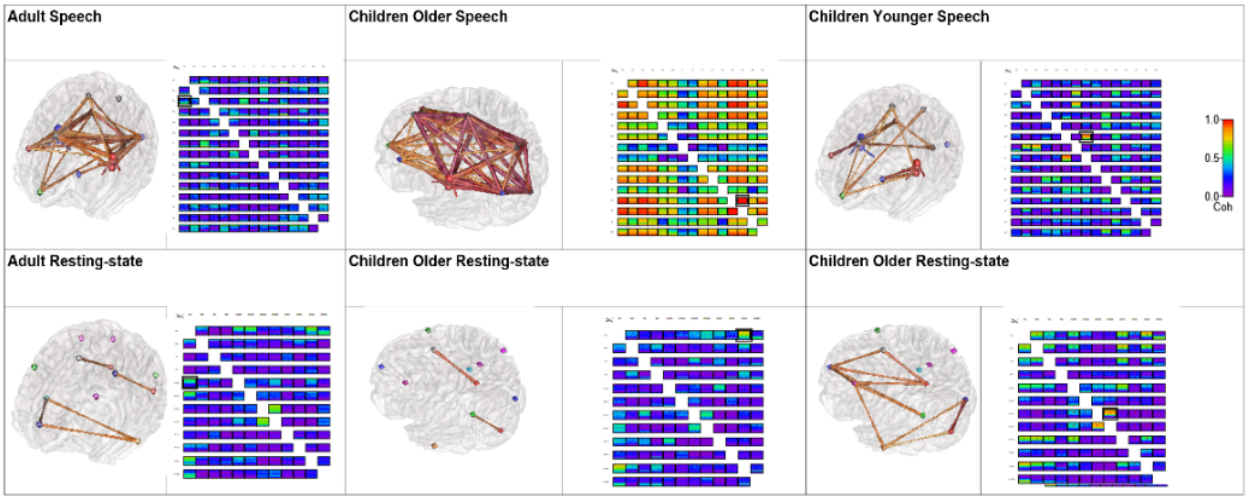


Figure 3. Neural connectivity networks and coherence matrices during Mandarin lexical tone processing (speech condition) and resting-state EEG across age groups. The top row shows speech-evoked connectivity for adults, older children, and younger children, respectively. The bottom row shows resting-state connectivity for the same groups. Brain network graphs depict significant coherence connections between EEG channels, while accompanying heatmaps represent coherence strength across channel pairs. Older children exhibit the most widespread and synchronized connectivity during speech processing, whereas younger children show weaker, more diffuse networks and adults display more focal connectivity patterns. Resting-state connectivity is less differentiated across age groups compared to speech-evoked networks. All EEG data were collected under an IRB-approved protocol.

DISCUSSION

Developmental Changes in Lexical Tone Processing

The results demonstrated clear developmental changes in neural responses to Mandarin lexical tones in bilingual Mandarin–English speakers. Younger children showed immature ERP responses and weak connectivity, consistent with ongoing development of auditory pathways. Older children exhibited a peak in neural synchronization and connectivity strength, indicating a critical developmental stage for tone perception. Adults showed more efficient but less extensive connectivity, reflecting neural pruning and specialization.

These findings support the hypothesis that auditory networks involved in tone processing undergo a non-linear developmental trajectory, with older childhood representing a period of heightened neural integration.

Resting-State vs. Task-Based Connectivity

While resting-state EEG provided baseline measures of intrinsic brain organization, it did not fully predict task-based connectivity patterns. Tone-evoked connectivity revealed stronger age-related differences, suggesting that active auditory tasks are more effective for identifying functional neural development. This highlights the importance of combining resting-state and task-based measures when studying bilingual auditory processing.

Implications for Bilingual Auditory Development

Lexical tone perception serves as a powerful probe of auditory and linguistic development in bilingual children. Because Mandarin tone processing requires precise pitch tracking, it places high demands on neural timing and coordination. The observed developmental patterns suggest that bilingual experience shapes auditory network maturation in distinct ways, particularly during middle childhood.

Limitations and Future Directions

This study was limited by sample size and its cross-sectional design. Longitudinal studies would provide deeper insight into individual developmental trajectories. Future research could also examine how language dominance, proficiency, or socio-linguistic environment further influence neural connectivity patterns in bilingual children.

Conclusion

This study demonstrated that bilingual Mandarin–English speakers show age-dependent differences in ERP responses and neural connectivity during lexical tone processing. Older children

exhibited the strongest and most synchronized networks, while adults showed more efficient connectivity patterns. Task-based EEG measures revealed developmental changes more clearly than resting-state measures alone. Together, these findings contribute to a deeper understanding of bilingual auditory development and highlight the value of combining ERP and connectivity analyses.

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