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Effects of Envelope Enhancement and Phonics Training on Phoneme Categorisation in Bilingual Preschoolers at Risk for Dyslexia in Singapore

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Abstract

Developmental dyslexia is linked to atypical auditory temporal processing and impaired speech perception. While traditional phonics-based programs are standard for supporting literacy, such instruction often fails to address the underlying perceptual vulnerabilities that contribute to phonological deficits. Envelope Enhancement (EE) is an acoustic modification that amplifies speech onset cues.By reinforcing the rhythmic structure of speech, EE functions as an auditory scaffold for at-risk learners. This 12-week study examined how combined auditory and phonics training affects auditory processing skills in Singaporean bilingual preschoolers at risk for dyslexia. 53 bilingual children aged 5–6 years were assigned to three groups: (1) a phonics-based training group with envelope-enhanced stories (GGEE; n = 18), (2) a phonics-based training group with non-enhanced stories (GGNE; n = 18), and (3) a control group that engaged in a non-phonics control game paired with non-enhanced stories (CGNE; n = 17). The "CROWN" phonemic categorisation task revealed that while perceptual crossover points (phoneme boundaries) remained consistent across groups, the GGEE group exhibited significantly steeper identification slopes at both the post-test and the delayed post-test compared to the GGNE and CGNE groups. These results indicate that the intervention led to a sustained increase in perceptual precision and a reduction in phonetic ambiguity. Such evidence suggests that integrating EE with phonics-based early intervention strengthens auditory mechanisms underlying phonological development. Theoretically, these perceptual gains could lead to improvements in phonological processing skills, but this will require longitudinal follow-up.

Keywords: envelope enhancement, phonics, dyslexia, auditory processing, reading intervention

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INTRODUCTION

Developmental Dyslexia (DD) is a neurodevelopmental disorder characterised by persistent impairments in reading and spelling, emerging despite typical intelligence and adequate instruction (Vellutino et al., 2004). Although widely recognised as having a multifactorial aetiology, this disorder is often rooted in atypical speech perception and auditory temporal processing, particularly when detecting dynamic speech features (Goswami, 2011). These vulnerabilities compromise phonemic categorisation, which involves the identification and classification of discrete speech sounds (Serniclaes et al., 2001). Such impairments can also trigger a developmental cascade, in which inaccurate representations constrain phonological awareness and subsequent grapheme–phoneme mapping (Hazan & Barrett, 2000). Even though such deficits emerge well before formal literacy instruction, existing interventions often overlook these foundational mechanisms during the critical pre-literacy window. Targeting auditory skills alongside phonological processing early may help prevent the accumulation of developmental deficits characteristic of the dyslexic trajectory (Ozernov-Palchik & Gaab, 2016).

Phonemic categorisation is further complicated in bilingual learners who must simultaneously navigate multiple phonological systems (Bialystok et al., 2003). Processing phonemic boundaries, syllabic structures, and prosodic patterns across languages can exacerbate subtle auditory deficits (Dalle, 2023). In Singapore, for instance, English–Mandarin bilingual children encounter variability in voicing contrasts such as /b/ and /p/. The English /b/ is voiced with a short Voice Onset Time (VOT), whereas /p/ is voiceless with a longer VOT, distinguishing words such as 'beach' and 'peach' (Ladefoged, 1973). Mandarin, however, does not employ the same VOT distinctions in an equivalent functional manner. While English stops produced by bilingual caregivers may vary depending on accent, language context, or influence from Mandarin (Sim, 2024). Such inconsistencies create less distinct acoustic cues, making it more difficult for children to form stable phonemic categories and map sounds onto letters across both languages (Ke et al., 2024). When auditory temporal resolution is already weak, this variability can further increase the likelihood of inaccurate phonological representations (Richardson et al., 2004). While bilingual experience can enhance attentional and cognitive flexibility (Bialystok et al., 2003), these advantages do not fully compensate for auditory processing deficits, which may remain hidden amidst the complexities of dual-language development.

Variability in phonemic input and the child's perception of these sounds can obscure early signs of DD, creating diagnostic ambiguity and making the timing of targeted support critical for long-term literacy outcomes. Given that these perceptual challenges arise from deficits in auditory processing, literacy programs delivered before formal instruction may have the greatest impact on foundational skills such as phonemic awareness and orthographic knowledge (Wanzek et al., 2016; Weisleder & Fernald, 2013). This formative period represents a unique developmental window in which neural plasticity and auditory sensitivity are particularly responsive to training (Goswami, 2011; Zangl & Mills, 2007). The developmental trajectory also depends on efficient neural entrainment, whereby cortical oscillatory activity synchronises with the rhythmic modulations of incoming speech (Schneider & Pichora-Fuller, 2000). Such synchronisation is critical for successful speech segmentation and phonemic categorisation (Goswami, 2011; Mandke et al., 2023), yet deficits in auditory temporal processing disrupt this alignment, negatively affecting the emergence of phonological awareness and subsequent literacy skills (Goswami, 2011; Goswami et al., 2013; Richardson et al., 2004). During this stage, the auditory system remains highly plastic, allowing targeted exercises to refine temporal processing and support more efficient speech segmentation (Richardson & Lyytinen, 2014).

Despite this plasticity, formal identification often occurs only after persistent reading difficulties have emerged, a phenomenon known as the dyslexia paradox, which reflects the gap between the optimal early intervention window and the standard wait-to-fail diagnostic model (Ozernov-Palchik & Gaab, 2016). By this point, the ideal period for neural reorganisation may have passed, and entrenched compensatory strategies can make remediation considerably more challenging (Saine et al., 2011). Targeted, linguistically sensitive interventions during the pre-literacy phase, therefore, may capitalise on auditory plasticity and neural entrainment to establish a more stable phonological framework. This foundation could facilitate the transfer of phonological skills across languages and support the brain's rhythmic sensitivity to onset sounds, promoting literacy development in bilingual learners.

Auditory-based strategies such as EE offer a promising solution to early phonological challenges. Originally developed for cochlear implant technology, EE amplifies speech rise times to increase the perceptual salience of phonemic boundaries (Koning & Wouters, 2012). By emphasising the onset of speech sounds, this method clarifies the acoustic cues essential for speech segmentation, allowing children to more accurately parse continuous speech into discrete sound units. Evidence indicates that EE improves speech perception across varied listening environments, enhancing both the speed and accuracy of phonemic discrimination (Chandrasekaran et al., 2009; Van Hirtum et al., 2021). These benefits occur without the need for explicit training or prior reading experience, making EE particularly well-suited for preschoolers. In a bilingual environment, such as Singapore's, this mechanism is particularly relevant because, by highlighting phonetic contrasts that differ across languages, EE reduces the cognitive load associated with navigating multiple linguistic inputs and mitigates the risk of phonological confusion (Mandke et al., 2023).

As EE sharpens the quality of the auditory signal, literacy acquisition further requires that these refined sounds be mapped onto their corresponding written symbols. Phonics-based instruction delivers this necessary structural training in letter–sound mapping. Adaptive programs like GraphoGame have demonstrated efficacy in supporting foundational skills in children at risk for DD (Kyle et al., 2013; Richardson & Lyytinen, 2014). However, the success of such instruction is fundamentally contingent upon the integrity of the underlying auditory signal. For children with temporal auditory deficits, the inability to perceive subtle phonemic contrasts may severely limit the efficiency of phonics training, as the brain struggles to map letters onto distorted or "fuzzy" phonological representations (Boets et al., 2011; Vandermosten et al., 2012).

Integrating EE with phonics-based training thus addresses this bottleneck by remediating the sensory deficit in the moment of responding to the literacy task (Mandke et al., 2023). This combined approach offers a clear synergistic advantage: EE sharpens the perceptual clarity of speech onsets (Koning & Wouters, 2012), facilitating the precise phonemic categorisation necessary for children to fully capitalise on phonics instruction (Kamykowska et al., 2014; Saine et al., 2011). For bilingual learners, this integration is critical. These children must reconcile divergent phonological systems while simultaneously establishing robust categories in multiple languages, a process that places significant demands on both auditory discrimination (Maassen et al., 2001) and working memory (Gathercole et al., 2006; Swanson, 1999). By reinforcing the auditory-phonological interface through EE, this integrated framework ensures that the sensory foundations are sufficiently robust (McArthur & Bishop, 2001; Moore, 2008) when supporting the complex cognitive transition to dual-language literacy (Ke et al., 2024).

Singapore's English-plus-one framework under the bilingual education policy (Ministry of Education, Singapore, 2022) provides a unique context for evaluating this integrated auditory and phonics intervention, as most children receive early and sustained dual-language input. While English is the primary household language for 48.3% of the population, a significant proportion maintain mother tongue exposure (Mandarin: 29.9%, Malay: 9.2%, Tamil: 2.5%; Ng & Chiew, 2024; Sim, 2024). Managing diverse orthographic and phonological systems requires constant linguistic reconciliation (Polka & Bohn, 2003; Sebastián-Gallés et al., 2005). As noted earlier, in complex bilingual environments, variability in speech input, including phonetic, prosodic, and contextual differences, can create cross-language interference, leading to temporary shifts in phonological perception and production (Nittrouer, 1999; Tallal, 1984). This interference arises as bilingual children map sounds across languages with different phonological structures, which can make phoneme categorisation less stable (Bialystok et al., 2003; Iverson & Kuhl, 1996). Interventions such as EE may help by amplifying critical temporal and amplitude cues, supporting the formation of more distinct and robust phonological representations that are less susceptible to temporary shifts caused by cross-language variability (Ahissar et al., 2006; Ziegler et al., 2009; Van Hirtum et al., 2021).

Responding to these unique linguistic demands, the present study represents a novel attempt to evaluate this integrated approach. We implemented a 12-week tablet-based intervention combining GraphoGame English with an auditory story-game featuring EE, based on methodologies established by Koning and Wouters (2012). The intervention targeted phonemic categorisation, critical for early reading development, which is particularly relevant for bilingual learners navigating multiple phonological systems. We hypothesised that bilingual children at cognitive risk for DD would demonstrate immediate improvements in phonemic categorisation following the intervention, with significant benefits maintained over time. By strengthening auditory processing skills before formal literacy instruction, EE may provide a developmental head start and mitigate some of the cascading deficits that are typically associated with DD.

METHOD

The present research forms part of a broader longitudinal investigation examining the auditory and phonological processing abilities of bilingual children in Singapore identified as being at risk for DD. The study protocol was formally preregistered on the Open Science Framework (https://osf.io/t6hsd) (Chin, 2024). The intervention architecture was developed to align with the stringent evidence standards required for group experimental designs in the field of educational psychology.

Participants

The participants for this study were recruited through a home-based screening process involving preschoolers in their first and second years (K1 and K2). Recruitment took place between 1 June 2024 and 30 September 2024. Parents of preschoolers were approached via the Early Childhood Development Agency and the Dyslexia Association Singapore with an informational letter and research flyer containing a sign-up questionnaire. The research flyer was also shared on social media platforms, such as Facebook groups created for parents of children with special educational needs. Prior to participation, parents or legal guardians were provided with a detailed Participant Information Sheet and given the opportunity to ask questions. Written informed consent was obtained from all parents/guardians before their child could take part in the study. Children aged six years and above also provided age-appropriate written assent before beginning any tasks. Ethical approval for the study was obtained from the Nanyang Technological University Institutional Review Board (IRB-2024-009). All procedures were conducted in accordance with the ethical principles of the Belmont Report and the Declaration of Helsinki.

Of the 102 respondents, 81 children whose parents provided consent participated in the screening and were evaluated according to the study's exclusion criteria. Eligible children were required to be bilingual English speakers with no history of brain injury or neurological conditions, and with no prior or suspected diagnosis of autism spectrum disorder or attention deficit hyperactivity disorder. Children who scored below the 10th percentile (corresponding to a standard score of 75.3) on either the Raven's Coloured Progressive Matrices, 2nd Edition (Raven, 2000) or the Peabody Picture Vocabulary Test, 5th Edition (Dunn, 2019) were excluded from the study. This resulted in a final sample of

76 children. Among these, 58 were identified as having a heightened cognitive risk for DD, defined by scoring below the 30th percentile relative to age-matched peers on two out of three key reading-related measures: the Comprehensive Test of Phonological Processing, 2nd Edition (CTOPP-2) (Wagner et al., 2013), the Test of Word Reading Efficiency, 2nd Edition (TOWRE-2) (Torgesen et al., 2012), and the Wide Range Achievement Test, 5th Edition (WRAT-5) (Wilkinson & Robertson, 2017). These measures are recognised as strong predictors of DD. Out of the 58 children identified as at risk for DD, five did not return for the post-test, resulting in a final sample of 53 children being included in the data analysis.

To protect participant privacy, all data were de-identified and stored in password-protected, encrypted files, with access limited to authorised researchers. No identifying information is reported in this manuscript. Although the study involved an educational and behavioural intervention, it is not considered a clinical trial, as it did not evaluate a health-related intervention or medical outcome.

Procedure

The study followed a pre-test, post-test, and delayed post-test design. 53 children were assigned to one of three groups using block randomisation. The first group, referred to as the GGEE group (n=18), engaged in a 10-minute phonics-based training using GraphoGame, combined with 5–8 minutes of actively listening to envelope-enhanced (EE) stories. The second group, the GGNE group (n=18), also played GraphoGame for 10 minutes but listened to stories without envelope enhancement (NE) for 5–8 minutes. The third group served as the active control group (CGNE group; n=17), playing control games (i.e., Lego City My City) for 10 minutes while listening to NE stories for 5–8 minutes. Block randomisation ensured that the groups were balanced in terms of birth trimester and sex, and there were no significant differences among groups in age (months), non-verbal IQ, receptive vocabulary, or bilingual distribution (see Table 1 for participant characteristics).

All children underwent an initial baseline assessment of the primary outcome measure (i.e., phonemic categorisation task). They were then instructed to complete the smart-device-based intervention at home, which involved playing the assigned games four days per week for a 12-week period. All children adhered to the schedule, resulting in an average intervention duration of 14 weeks. All children completed 100% of the EE intervention and the required GraphoGame training (Chin et al., 2025). Each child used their personal smart device and was provided with a Logitech H111 headset. The research team calibrated the devices to ensure consistent sound levels for the EE intervention. Following the intervention, children completed a post-test approximately two weeks later and a delayed post-test three months later, both administered by the research team to reassess performance on the phonemic categorisation task. A chi-squared test indicated no significant differences in drop-out rates among the three groups (χ^2 (2, n=5) =0.40, p= .82).

Table 1. Participant Characteristics

Characteristics	Levels	GGEE (n = 18)		GGNE (n = 18)		CGNE (n =17)		Group Comparison	
		M	*SD*	*M*	*SD*	*M*	*SD*	*F*	*p*ᵃ
Age pre-test (months)		67.3	5.88	70.2	5.01	71.9	3.14	3.062	p = .061
Non-verbal IQ		104	11.8	95.5	8.72	98.1	9.87	3.182	p = .054
Receptive vocabulary		88.8	4.93	82.7	8.12	84.8	3.17	1.377	p = .268
Language background	English-Mandarin / English-Malay/ English-Tamil/ English-Other	17/1/0/0		13/3/1/1		17/0/0/0		7.38	p = .216
Sex	Male/ Female	10/8		11/7		11/6		$\chi^2(2)=0.14$	p = .931

Note. GG = GraphoGame; EE = envelope enhanced; NE = not envelope enhanced; CG = control group; M = mean; SD = standard deviation. Group comparisons for continuous variables were conducted using one-way ANOVAs (F). For categorical data (i.e., Sex), group comparisons were conducted using Chi-square tests ($\chi 2$).
[a] Due to small cell sizes in Language background, p-value is derived from Fisher's Exact Test.

Intervention

Envelope Enhancement

The 24 spoken stories were processed using MATLAB R2024b (The MathWorks Inc., 2024), employing signal processing procedures adapted from Koning and Wouters (2012). Detailed methodology and implementation procedures are further described in Chin and Aruthanan (2025). Initially, the original signal $s(t)$ was resampled to a sampling frequency of 16 kHz and divided into frames of 128 samples, with a frame advance of 32 samples. The signal was transformed into the time–frequency domain using a Hann-windowed, frame-based fast Fourier transform (FFT).

Frequency bins were then combined through a weighted sum of their powers, mapping them to 23 critical channels defined by the critical bandwidths outlined by Fastl and Zwicker (2013). The envelope $E(t,k)$ for each channel was derived by taking the square root of the power per channel. A slow envelope $E_{slow}(t,k)$ was generated by applying a fourth-order Butterworth low-pass filter with a 20 Hz cutoff frequency to $E(t,k)$. This process introduced a time delay in response to sudden energy increases in $E(t,k)$. The filtered signal was then half-wave rectified and amplified by a factor of A_{slow}=8 to produce $E^{slow}(t,k)$. This ensured that $E_{slow}(t,k)$ was higher than $E(t,k)$ during quasi-stationary segments, while $E(t,k)$ exceeded $E_{slow}(t,k)$ during energy onsets. Subtracting $E_{slow}(t,k)$ from $E(t,k)$ yielded a signal with peaks at envelope onsets and negative values during stationary phases. A peak envelope signal $E_{peak}(t,k)$ was obtained by subtracting $E_{slow}(t,k)$ from $E(t,k)$, followed by half-wave rectification and amplification by A_{peak}=3.5. The final peak signal $p(t)$ in the time domain was created by mapping the 23 bands back to 128 frequency bins, performing an inverse fast Fourier transform, and recombining the frames using a weighted overlap-add method. This peak signal $p(t)$ was then added to the original signal $s(t)$, resulting in the envelope-enhanced signal $sEE(t)$ (see Figure 1).

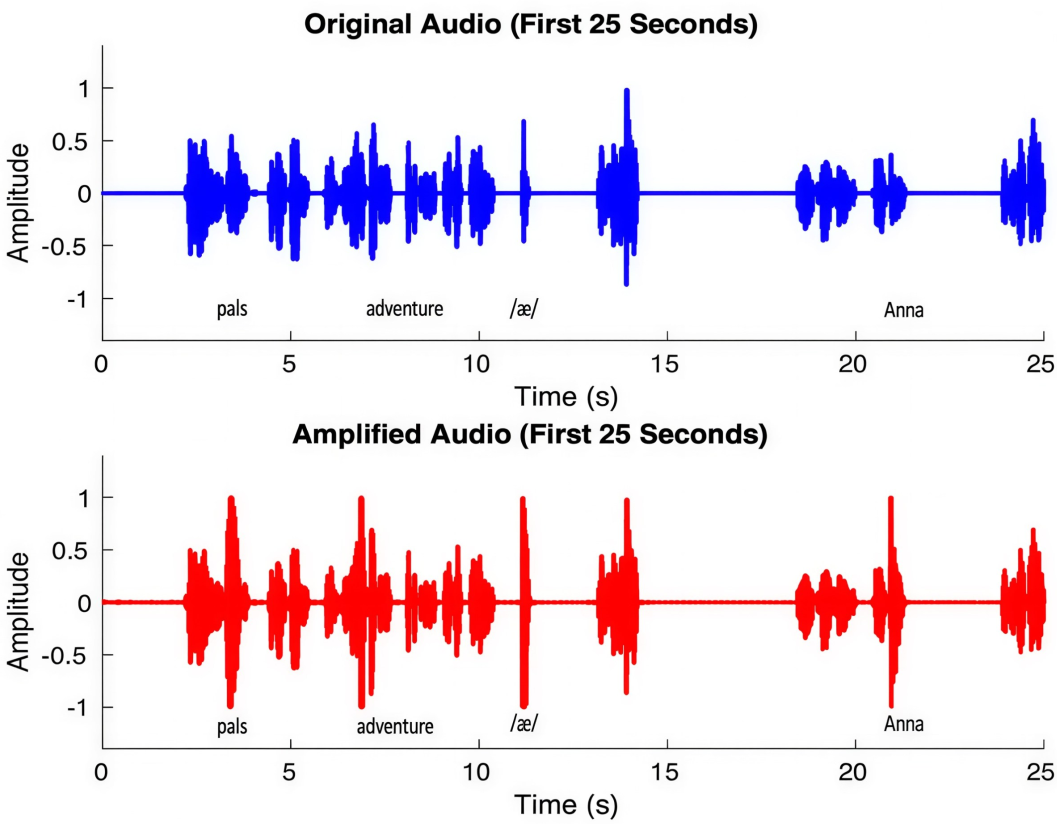


Figure 1. EE/NE Stimulus: A Sample Waveform of the First 25 Second ("pals adventure /ae/...Anna") from One of the Stories without EE (upper) and with EE (lower)

Each story, lasting between 5 and 8 minutes, was created to suit the target age group. A female speaker proficient in standard Singaporean English recorded the stories using child-directed speech, employing elevated pitch, exaggerated prosodic contours, a slower speech rate, an expanded intonation range, and precise phoneme articulation to enhance acoustic clarity. These recordings were paired with corresponding visual stimuli for integration into a smart-device-based intervention. Two versions of the game were designed: one featuring envelope-enhanced stories and another with non-enhanced stories. Each session involved a short story, and children were expected to complete one session daily. After completing all 24 stories, the children restarted the story set from the beginning. Over the 12-week intervention period, this schedule resulted in 48 playing days, with three days off each week. To promote active listening, children answered two simple questions related to the story content at the end of each session. Correct answers rewarded them with virtual coins, which could be used to buy items for their avatars, helping to sustain engagement. Researchers tracked their progress monthly using an online logging system.

Box 1 presents information about envelope enhancement, along with approaches for enhancing speech envelope.

Box 1. Envelope Enhancement at a Glance

What is the speech envelope? Speech is a stream of sound that gets louder and softer many times each second. If you trace the peaks of these sound fluctuations over time, and apply mathematical or filtering techniques, a broader curve or outline of the sound patterns is obtained; referred to as the speech envelope. Unlike for other forms of sound, like music, the speech envelope provides crucial information for speech perception. It rises sharply at the start of each new syllable, with an even steeper rise at the start of consonants like /p/ and /b/, then falls during the quieter stretches in between. These sharp rises, called onset cues, are how the brain knows where one speech sound stops and the next begins. Children at risk for dyslexia are often less sensitive to these cues, which is one reason why similar words can sound "fuzzy" to them.

What happens when we enhance the envelope? We can use software to enhance the envelope without changing how the speaker actually talks. We start with a normal recording of a story and pass it through three steps. First, the software splits the recording into sound bands so each pitch range can be handled separately. Second, within each band, it tracks the rise and fall of energy and picks out the brief moments where energy climbs fastest. Those are the onset cues at the start of syllables and consonants. Third, it amplifies just those onsets and mixes them back into the recording. The result is a new audio file where the starts of sounds stand out a little more, while everything else is left alone: the vowels, the spacing, the rhythm, and the overall loudness all stay the same. We do not raise the volume, slow the speech down, or change the words. Think of sharpening a photo. The picture is the same, but the edges are easier to spot. To the child, the story still sounds natural, and the onset cues are just a bit easier for the brain to lock onto.

GraphoGame

Participants in the GGEE and GGNE groups were provided with access to GraphoGame English (Richardson & Lyytinen, 2014), a digital phonics intervention comprising multiple mini-games structured into three core modules: grapheme, phonology, and reading. These mini-games targeted a range of literacy-related skills, including a grapheme introduction and visual discrimination, phoneme identification within words, phoneme blending, spelling, phoneme segmentation, and syllable and word reading, as well as reinforcement of grapheme-phoneme correspondences and single-word decoding. The modular design facilitates systematic training and assessment of foundational reading skills critical for literacy development. Additionally, certain levels were designed to assess general cognitive skills and intrinsic motivation for gameplay. The game content was systematically scaffolded, with increasing difficulty calibrated to sustain engagement throughout the 12-week intervention period. Participants were required to progress sequentially through the games, while retaining the ability to revisit previous levels when required. To enhance motivation, children earned virtual coins upon advancement, which could be exchanged for accessories to customise their in-game avatars in a virtual store.

Measures: Pre-test and post-test

Phonemic Categorisation Task

The phoneme categorisation task was conducted at each participant's home using the CROWN (Categorical Recognition for Onsets of Word Names) Game, a gamified, computer-based tool. This task, validated with strong inter-task reliability (r = 0.67), effectively measures phoneme categorisation in preschoolers (Ke et al., 2024).

Participants began with practice trials to ensure task comprehension. The game assessed phoneme perception in Singaporean bilingual children at cognitive risk for DD by requiring identification of auditory stimuli along a VOT continuum from pre-voiced "beach" (−60 ms) to aspirated "peach" (+90 ms). During each trial, children were presented with a single audio token along with two images displayed on the screen. They were instructed to select the picture that matched the sound, responding within a five-second window. The task comprised 10 blocks of 16 trials each, randomly presenting all VOT steps once per block, for a total of 160 trials. To control for handedness and side biases, the positions of the images were alternated across trials within each block. The entire task lasted approximately 10–12 minutes.

Gamification elements maintained engagement, for example, children helped a cartoon monkey choose between images by pressing keys ("c" or "m"), receiving immediate audiovisual feedback. Initial practice trials provided explicit feedback, while subsequent training blocks required independent responses without corrective input. Progress was visually tracked via tokens earned after each completed block. Participants who did not complete training were excluded from analysis. Completion of all blocks yielded 10 responses per VOT step, enabling the construction of individual psychometric functions. Logistic regression was used to estimate both the slope and the categorical boundary (threshold) of /b/ versus /p/ categorisation across the continuum, enabling quantification of phoneme discrimination accuracy and category boundary placement.

Data Analysis

For each point on the VOT continuum, the proportion of /p/ decisions was calculated. An individual identification curve was then fitted to the data using a logistic function, following the statistical approach outlined by Boets et al. (2011). The curve-fitting procedure was implemented using the R package "quickpsy". The threshold was defined as the point on the fitted psychometric function where an individual transitioned from predominantly making "beach" decisions to predominantly making "peach" decisions. Specifically, this corresponds to the VOT value at which the fitted curve reaches 50% /p/ decisions. During the curve-fitting process, the slope value was derived as the second parameter used to fit each individual curve. This slope represents the standard deviation of the psychometric function (Linares & López-Moliner, 2016), providing a measure of the steepness of the transition between /b/ and /p/ decisions across the VOT continuum.

To examine differences in perception, separate Linear Mixed Model (LMM) analyses were conducted for both categorisation slope and phoneme boundary threshold. These analyses were carried out using the generalised LMM module in R, with the identity link function specified. Time and intervention groups (GGEE, GGNE, and CGNE) were included as fixed factors in the models. To account for individual differences, participants were included as a random factor in all analyses. Significant interactions were further investigated using Bonferroni post hoc tests. Due to the skewed distribution, slope values were log-transformed prior to statistical testing.

RESULTS

Categorisation Slope

Figure 2 presents the combined data for all three groups (GGEE, GGNE, and CGNE) regarding the /p/-/b/ contrast, while Figure 3 highlights individual variability. All groups demonstrated within-group variability at pretest, post-test, and delayed-post-test, with children's categorisation slopes generally progressing toward more adult-like patterns by the delayed post-test.

Linear mixed model analyses revealed a significant Time × Group interaction, $F(4, 99.33) = 11.22$, $p < .001$, and a significant main effect of Time, $F(2, 99.33) = 35.84$, $p < .001$. The main effect of Group was not significant, $F(2, 50.12) = 1.97$, $p = .15$. These results indicate that slope trajectories over time differed significantly across groups. Bonferroni-adjusted

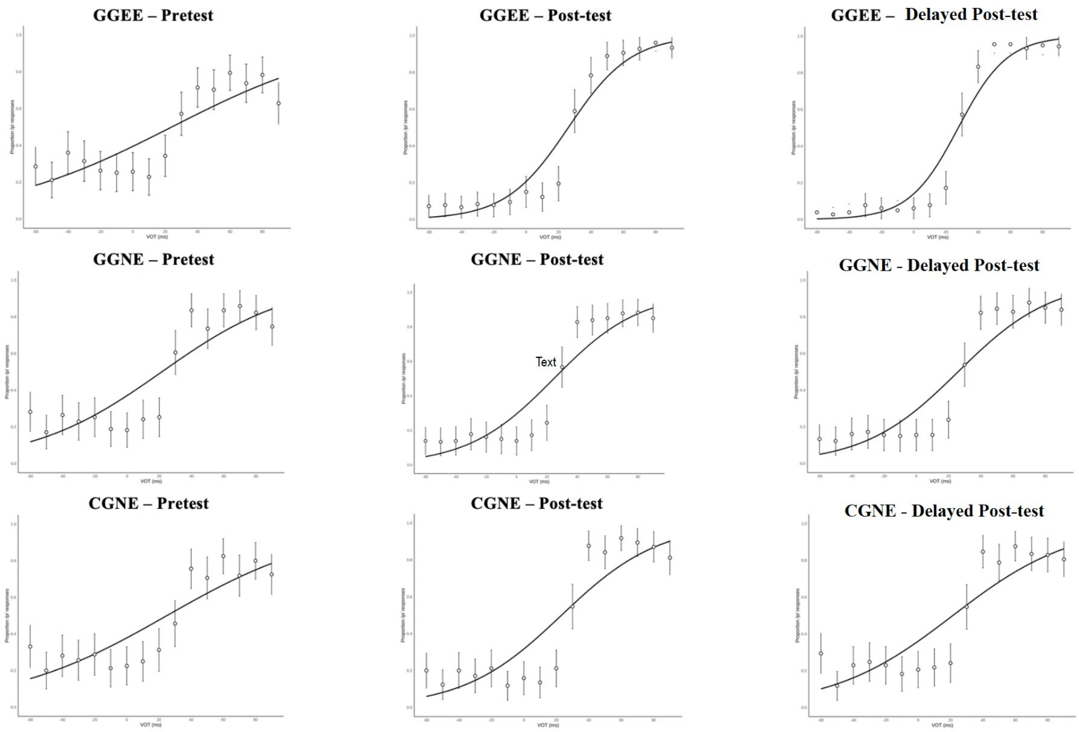


Figure 2. Identification Functions for the /p/-/b/ Contrast Aggregated over Participants for GGEE, GGNE, and CGNE Groups at Pretest, Post-Test, and Consolidation Test

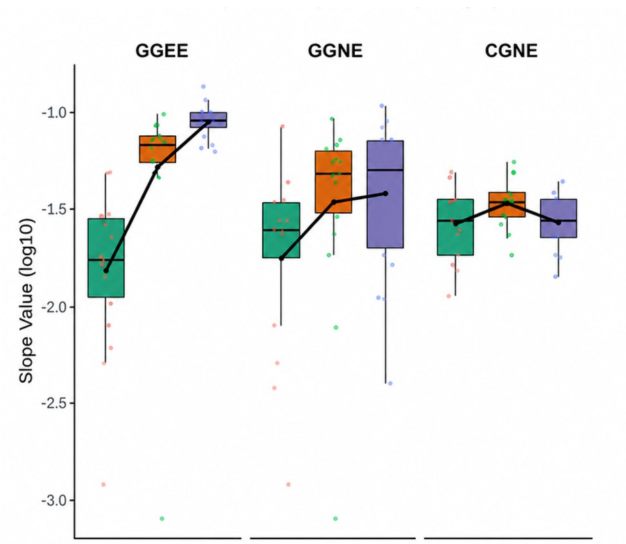


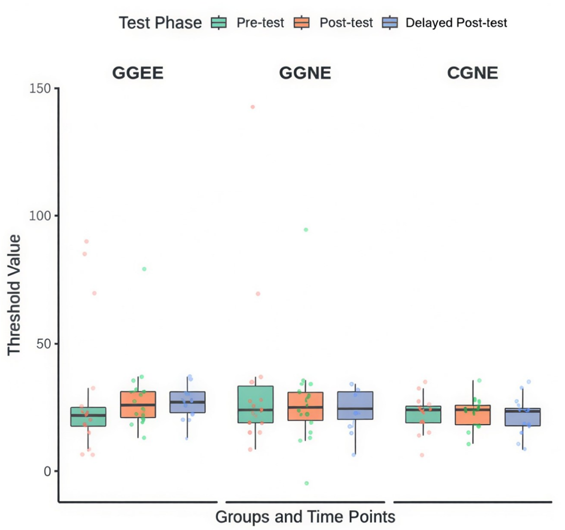
Figure 3. Box Plot of Slope Values for /p/-/b/ Identification Function

Note. A higher log value indicates a steeper slope. The green boxes represent the pretest, the orange boxes represent the post-test, and the purple boxes represent the delayed post-test. The dots represent individual data points. Slopes were log-transformed to correct for skewness in the original distribution. The range of values shown can be appreciated better by noting first that logistic functions, as seen in Figure 1, have their maximal slope at the phoneme boundary.

pairwise comparisons showed that the GGEE group exhibited the most substantial gains, with significantly steeper slopes from Time 1 to Time 2 ($p < .0001$) and from Time 1 to Time 3 ($p < .0001$). The GGNE group also showed significant improvement, particularly from Time 1 to Time 3 ($p = .0028$), though the magnitude of change was smaller. The CGNE group did not demonstrate significant change across time points (*ps* > .05). At post-test (Time 3), the GGEE group had significantly steeper slopes than both CGNE ($p = .0006$) and GGNE ($p = .0498$). Model-estimated marginal means at Time 3 further support this: GGEE = −1.05, GGNE = −1.42, and CGNE = −1.57, indicating that participants in the GGEE group produced more sharply defined phoneme boundaries.

Phoneme Boundary (Threshold)

Figure 4 displays the phoneme boundary thresholds for the /p/-/b/ contrast across the GGEE, GGNE, and CGNE groups at pretest, post-test, and delayed post-test. The results of the linear mixed model analysis examined threshold values across three groups (GGEE, GGNE, CGNE) and three time points (Pre-test, Post-test, Delayed Post-test), testing for main effects of Time, Group, and their interaction. The main effect of Time was not statistically significant, $F(2, 142.82) = 0.45$, $p = .637$, indicating that threshold values did not change meaningfully across the three testing phases when averaging across all groups. Similarly, the main effect of Group was also non-significant, $F(2, 69.91) = 1.07$, $p = .348$, suggesting no overall differences in threshold values between the groups regardless of time point. The Time × Group interaction was likewise non-significant, $F(4, 142.82) = 0.45$, $p = .773$, indicating that the pattern of change over time in threshold values did not differ across the three groups.



Note. The green boxes represent the pretest, the orange boxes represent the post-test, and the purple boxes represent the delayed post-test. The dots represent individual data points.

Figure 4. Box Plot of Phoneme Boundary for /p/-/b/

Post hoc pairwise comparisons further confirmed these findings. Within each group, threshold values remained statistically unchanged across the pre-test, post-test, and delayed Post-test phases (all ps > .05). Likewise, comparisons between groups at each individual time point revealed no significant differences (all *ps* > .05). All pairwise comparisons were adjusted using the Bonferroni correction, and none reached statistical significance. Overall, these findings suggest that none of the intervention groups showed measurable changes in phoneme boundary thresholds over time, indicating that the interventions did not influence basic temporal resolution for the /p/-/b/ contrast.

DISCUSSION

The "dyslexia paradox" presents a substantial challenge to delivering timely and effective interventions for children at cognitive risk for DD (Ozernov-Palchik & Gaab, 2016). Although early interventions prior to formal reading instruction are widely advocated, current phonics-based approaches may not fully address the dual challenges faced by bilingual children who concurrently experience auditory processing difficulties. This underscores the need for context-sensitive interventions that explicitly target auditory perceptual deficits alongside phonics instruction before reading acquisition begins. The present study examined the combined impact of EE and phonics-based training in bilingual preschoolers at cognitive risk for DD in Singapore.

The findings demonstrate that combining EE with phonics sharpens phonemic categorisation. At post-test, both the GGEE and GGNE groups showed steeper identification slopes relative to baseline, reflecting improved categorical precision, with the most pronounced gains observed in the GGEE group. While the phonics-only group exhibited measurable improvement, these gains were consistently smaller than those in the combined EE condition, suggesting that phonological mapping alone may not fully optimise categorical precision in children at risk for DD. By the delayed post-test, improvements in the GGEE group were maintained and further consolidated, whereas the control group showed minimal change. The significant Time × Group interaction indicates that these developmental trajectories were shaped by intervention type rather than maturation, highlighting the added benefit of EE in reinforcing phonemic discrimination.

These behavioural gains are consistent with mechanistic changes in auditory processing that have been linked to underlying neural entrainment in prior work (Goswami, 2011; Mandke et al., 2023). Steeper categorisation slopes indicate reduced ambiguity across adjacent stimuli and more abrupt transitions between phoneme categories, reflecting strengthened auditory processing skills. The enhancement observed in the GGEE group at delayed post-test therefore suggests sustained refinement of phonemic representations rather than transient perceptual adaptation.

These results imply that EE provided perceptual scaffolding that augmented phonics instruction, allowing children to establish more sharply defined phoneme categories during a developmentally sensitive pre-literacy window. This interpretation aligns with prior evidence showing that EE enhances speech perception by emphasising amplitude onset cues critical for voicing contrasts (Van Hirtum et al., 2021). Aligning with theoretical accounts proposing that strengthened low-level auditory encoding stabilises higher-order phonological representations (Goswami, 2011), these findings support a dual-mechanism framework in which bottom-up perceptual refinement and top-down grapheme–phoneme mapping interact to stabilise early phonological representations.

Beyond improvements in categorical precision, phoneme boundary locations remained generally stable across groups and time points. This suggests that EE primarily sharpened the precision of category transitions without substantially altering the perceptual anchor of the /p/-/b/ contrast. Such stability suggests that category anchors may already be relatively well-formed in this cohort, and that intervention effects operate by sharpening perceptual sensitivity rather than shifting category boundaries.

Importantly, variability observed in a subset of participants suggests that phoneme categorisation outcomes are not solely determined by auditory discrimination but also reflect cognitive processes associated with DD risk. In the present study, while most participants demonstrated stable boundary perception, a subset showed less consistent categorisation patterns, potentially indicating difficulty in reliably mapping auditory tokens to phoneme categories. Alternatively, this variability may reflect task-related cognitive demands, where sustained attention, working memory, and response consistency are required to produce stable categorisation. Variability in these cognitive processes may result in more gradient response patterns and less stable threshold estimates. This interpretation is consistent with evidence that children at cognitive risk for reading difficulties exhibit greater intra-individual variability under cognitive load (Ahissar et al., 2006; Vandermosten et al., 2012), which can lead to more gradient responses (McMurray et al., 2010; Ziegler et al., 2009).

Taken together, these findings suggest that variability in threshold estimates, where observed, may reflect the interaction between perceptual encoding and executive functioning demands in DD, rather than purely auditory-phonemic differences. This highlights that phoneme categorisation tasks capture both perceptual and cognitive components of performance, with implications for interpreting threshold measures and designing interventions that reduce cognitive load while strengthening auditory processing.

While within-group variability in categorisation may reflect cognitive constraints associated with DD risk, the between-group stability of phoneme boundaries may instead reflect the influence of bilingual language experience. In Singapore's multilingual environment, children are exposed to English alongside other languages, resulting in acoustically variable yet functionally consistent input. Such exposure may contribute to the early establishment of relatively stable phonemic anchors, even when surface-level phonetic input varies.

This interpretation aligns with findings from McDonald and Kaushanskaya (2023), who reported that bilingual children maintain broadly accurate phoneme boundaries while demonstrating flexibility in perceptual responses. English–Mandarin bilingual speech introduces systematic phonetic variability (Sim, 2024), and exposure to multi-accent contexts can result in broader but adaptive phonemic boundaries (Ng & Chiew, 2024). In this context, variability in phoneme categorisation may reflect adaptation to diverse linguistic input rather than impairment. Thus, the limited change in boundary location observed in this study may reflect the robustness of bilingual phonological systems rather than a limitation of the intervention.

The dissociation between slope enhancement and boundary stability highlights the specificity of EE combined with phonics training. While EE appears to strengthen the precision of phonemic representations, bilingual language experience appears to support stable and adaptive boundary representations despite phonetic variability. These findings indicate that phonemic representations in the pre-literacy period are modifiable in terms of precision and stability, even when category placement is already broadly established. This underscores the potential of early, targeted interventions to refine auditory processing in bilingual children at cognitive risk for DD, while accounting for the unique influence of bilingual language environments.

IMPLICATIONS FOR PRACTICE

These findings carry substantive implications for both early childhood education and clinical practice in Singapore, while also bearing relevance for all multilingual societies globally. In Singapore's linguistically stratified social ecology, children are routinely required to negotiate multiple phonological systems prior to the onset of formal literacy instruction (Ministry of Education, Singapore, 2022). The observation that EE-based gains in auditory temporal processing emerge during the pre-literacy phase underscores the necessity of reconceptualising early identification frameworks. Rather than adopting a reactive model contingent upon manifest reading failure (Ozernov-Palchik & Gaab, 2016), preschool screening protocols should incorporate indices of auditory temporal sensitivity, which can be assessed using engaging, game-based paradigms such as the "CROWN" phonemic categorisation task. Within a high-performing and academically accelerated system such as Singapore's, delayed identification may allow subtle perceptual vulnerabilities to consolidate into stable phonological and orthographic deficits. Early detection and intervention during periods of heightened neuroplasticity are therefore not merely advantageous but developmentally strategic (Saine et al., 2011).

Moreover, these findings highlight potential limitations in an over-reliance on phonics as a singular instructional solution for children at cognitive risk for developmental dyslexia

(DD). While systematic phonics remains indispensable (Richardson & Lyytinen, 2014), it presupposes sufficiently specified phonological representations, which are not uniformly present in this population (Vellutino et al., 2004). When phonological encoding is underspecified, grapheme–phoneme instruction alone may be insufficient to drive robust gains in reading fluency and spelling accuracy. Integrating envelope-enhanced (EE) auditory input into early literacy instruction therefore introduces a biologically informed scaffold (Koning & Wouters, 2012), strengthening the fidelity of bottom-up sensory processing alongside top-down orthographic mapping. In this way, EE may help address the foundational perceptual constraints that limit responsiveness to phonics-based interventions, supporting more efficient phoneme categorisation.

A related, but distinct, set of considerations arises in bilingual learners, where the challenge extends beyond phonological under-specification to variability introduced by cross-linguistic interaction. Grapheme–phoneme mappings acquired in one language may not transfer seamlessly when acoustic-phonetic representations are influenced by another, particularly in the presence of differing phonotactic constraints and prosodic patterns (Dalle, 2023). In multilingual contexts such as Singapore, this variability is further amplified by multi-accent English input, which can complicate phoneme discrimination. EE -modified input may therefore play a complementary role by enhancing the salience of temporally relevant acoustic cues, helping learners stabilise phonological categories across languages and accents. From an applied perspective, this underscores the need to recalibrate intervention goals: rather than targeting conformity to monolingual phonetic norms, educational approaches should prioritise the development of stable, adaptable, and functionally robust phonological categories. This entails designing assessment and training tools that explicitly account for input variability while maintaining sensitivity to linguistically meaningful contrasts (Van Hirtum et al., 2021). By aligning intervention with both neurocognitive constraints and sociolinguistic realities, educational systems can move beyond reactive remediation towards anticipatory, precision-based prevention, with potential to support literacy outcomes across diverse at-risk populations as evidence accumulates (Wanzek et al., 2016).

LIMITATIONS AND FUTURE DIRECTIONS

Despite the encouraging results, several limitations warrant consideration. First, while EE training robustly sharpened phonemic categorisation slopes, it remains unclear whether these gains translate into enhanced phonological awareness or long-term reading proficiency. Longitudinal follow-up, which will be reported in an upcoming paper, is essential to determine whether strengthening low-level auditory processing produces the cascading effects necessary to mitigate risk for DD (Vellutino et al., 2004).

Second, while the random assignment supports strong internal validity for comparisons among intervention groups, the the modest sample size (N = 53) and targeted recruitment through bilingual community channels in Singapore limit generalisability to the broader population of at-risk bilingual preschoolers. The absence of a typically developing control group also constrains comparisons to normative trajectories. While EE may benefit all children (Van Hirtum et al., 2021), a universal application could inadvertently widen performance gaps. Future research should therefore scale up the study with larger and more diverse participant samples, including typically developing children, to determine whether targeted or universal implementation strategies are most effective for supporting early literacy in bilingual contexts.

Third, the observed stability in phoneme boundary perception suggests that categorical anchors may be relatively robust in this cohort, whereas variability in a subset of participants highlights the influence of cognitive factors associated with DD risk. In particular, variability in categorisation may reflect interactions between perceptual processing and executive functions, including working memory and sustained attention, which are known to affect performance under cognitive load (Ahissar et al., 2006; Vandermosten et al., 2012). To address this, future designs should prioritise task architectures that minimise cognitive demands, such as adaptive pacing and simplified response formats, in order to better isolate true auditory-phonemic gains from task-related variability. This will improve the precision of outcome measures and strengthen conclusions regarding intervention efficacy for DD-related processing.

Fourth, future research should further disentangle the influence of bilingual language experience from DD-related cognitive constraints. For instance, comparing at-risk bilingual children with monolingual peers could clarify whether stable phonemic boundaries arise from multilingual exposure or reflect universal developmental patterns. Conversely, examining typically developing bilinguals alongside at-risk cohorts would help determine whether observed variability reflects the executive demands associated with dyslexia risk or a normative adaptation to diverse linguistic input. Systematically teasing apart these sociolinguistic and neurocognitive factors will clarify which effects are driven by the clinical profile and which are shaped by the bilingual environment, thereby informing more precise and context-sensitive intervention strategies.

CONCLUSION

EE- based auditory and phonics training directly enhances phonemic categorisation in bilingual preschoolers at cognitive risk for DD, producing gains well before the maturation of this auditory process typically occurs. This demonstrates that EE can support foundational auditory processing before formal reading instruction, capitalising on a period of heightened developmental sensitivity. Importantly, these results offer an initial glimpse into a preventive strategy for addressing auditory processing difficulties in this population. As follow-up data become available, these results will be further evaluated to determine how early gains translate into longer-term outcomes in phonological awareness. Overall, these findings highlight the promise of early, targeted auditory and phonics interventions for refining phonemic categorisation during the pre-literacy window. Whether such gains translate into improvements in phonological processing skills is a hypothesis to be tested in the planned follow-up. By strengthening low-level auditory processing alongside phoneme-grapheme mapping, this approach offers an evidence-based strategy for supporting at-risk multilingual learners.

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