

At the Rhythm of Language:
Neural Bases of Language-Related Frequency Perception in Children

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Abstract

Converging evidence across language and reading acquisition studies suggests that children's sensitivity to rhythmic modulations within the linguistic stream is critical for both language and reading acquisition (Goswami, 2011; Petitto, 2001). This study offers a first-time investigation into the neural bases of "language" related frequency perception in children. We hypothesized that participants would show greater activation in the brain's language regions, especially in the left superior temporal gyrus (STG; Wernicke's area), during exposure to the hypothesized "language" related frequency of 1.5 Hz relative to control frequencies (0.5 Hz and 3 Hz), suggesting that the frequency at which humans process language has a privileged neural status. Children's brain activity was measured with functional Near Infrared Spectroscopy (fNIRS) while they listened to alternating blocks of "beeps" played at a frequency of 0.5 Hz, 1.5 Hz and 3 Hz (age 6-9, N=15). As predicted, participants showed greater activation for "language" 1.5 Hz frequency in left STG, relative to control frequencies ($p < 0.05$). That only the 1.5 Hz frequency recruited robust activation in left STG supports the hypothesis that the brain's sensitivity to slow rhythmic modulation helps the child extract and process critical linguistic information (e.g., syllables and words). These findings carry implications for identifying children at risk for language/reading impairments.

At the Rhythm of Language:

Neural Bases of Language-Related Frequency Perception in Children

One of the greatest puzzles in understanding the neural bases of language is discovering which properties of language the brain tissue finds particularly attractive, such that the brain can extract language from the plethora of various visual and auditory information to which it is exposed. Converging evidence from language and reading acquisition suggests that infants, children and adults may have a preferred sensitivity towards slow-rhythmic modulations inherent in all languages (c.f., Goswami, 2011; Petitto, Baker, Idsardi, & Golinkoff, 2005). Research suggests that sensitivity to these rhythmic modulations may help the person find syllabic boundaries in the linguistic stream, a critical step towards perceiving words and the grammar of any language (c.f., Jusczyk, Houston, & Newsome, 1999; Petitto, 2005; Pinker & Jackendoff, 2005). The present study offers a first-time investigation into the brain basis of “language” frequency perception in typically-developing children.

One of the cornerstones of all language acquisition is learning to extract words and other meaningful units from the otherwise continuous speech stream, where adult speakers rarely pause between words or even phrases. The smallest units of language are phonemes, such as sounds /b/, /d/, and /a/. These phonemes build into syllabic units, such as /ba/ and /da/. In sign languages, phonemes are hand shapes and hand movements, which also combine into syllabic units. These syllabic units alternate rhythmically in the continuous linguistic stream, and our language comprehension system uses this rhythmic alternation, among other cues, to discern syllable and word boundaries (Jusczyk et al.,

1999; Fowler, Smith, & Tassinary, 1986). Infants are known to be sensitive to the rhythmic patterns of language (Fowler et al., 1986), and they use this sensitivity to master syllable and word identification within a continuous linguistic stream by the end of their first year (Jusczyk et al., 1999).

At the beginning of language acquisition, the very first universal milestone in language production is babbling, when at about 5 months of age infants begin to produce rhythmically alternating repetitive meaningless syllables. Hearing infants will produce consonant-vowel syllabic units, such as *bababa*. Sign-exposed infants (hearing or deaf) will also produce rhythmically alternating syllabic units with their hands, a phenomenon known as *manual babbling* (Petitto & Marentette, 1991). Measurements of the infants' hand activity during manual babbling revealed that these rhythmic hand movements occur at a slow rhythmic frequency of about 1-2 Hz (Petitto, Holowka, Sergio, & Ostry, 2001). These findings give rise to a hypothesis that at the route of all language acquisition stands an inherent sensitivity to maximally contrasting rhythmical patterns of about 1-2 Hz, allowing the human brain to extract syllables and words from the linguistic stream, which is critical for language acquisition as well as adult language comprehension and production (c.f. Petitto, 2005). More specifically, it has been hypothesized that brain regions that process phonology, especially the left STG (classic Wernicke's area), are the ones selectively sensitive to this language-related rhythmic modulation, given that infants start babbling out of the right side of their mouth (as controlled by left hemisphere, Holowka & Petitto, 2002), and that this part of the brain is universally sensitive to meaningless phonetic units in both sign and speech (Petitto et al., 2000).

At the beginning of reading acquisition, children must learn to relate spoken language to print through explicit “phonological awareness,” realizing that spoken words are composed of discrete sounds that can be mapped onto letters. Phonological awareness ability in pre-readers predicts later success in learning to read in both alphabetic and non-alphabetic orthographies (Goswami & East 2000; Ziegler & Goswami 2005). A deficit in phonological awareness is thought to be the most common etiology of dyslexia (Bradley and Bryant 1978; Goswami & East 2000), a difficulty in learning to read despite adequate intelligence and reading instruction that affects 5-17% of children (Shaywitz et al., 1998; Wolf, 2007).

In parallel to early language acquisition, when the first unit of language production is a syllable, the earliest manifestation of phonological awareness is the ability to segment words into relatively large phonological units, such as syllables and rimes (e.g., foot-ball, sw-eet; c.f. Goswami & Ziegler, 2005). Temporal Sampling Framework theory (TSF, Goswami, 2011) suggests that phonological awareness and emerging reading abilities in children are highly dependent upon their sensitivity to slow rhythmic modulations which roughly correspond to syllabic and word boundaries. TSF predicts that children with dyslexia may have a select deficit in perceiving these slow rhythmic modulations, a deficit with cascades from speech segmentation difficulties into poor phonological awareness and eventually into poor reading skills (Goswami, 2011; Goswami et al., 2002). A series of studies have shown that children’s sensitivity to slow rhythmic modulations, as tested with auditory tests such as tapping with a metronome or discrimination of onset-rise time differences (see Goswami, 2011 for more details), is highly correlated with children’s phonological awareness and emerging reading abilities

in English as well as other languages, including Chinese (Goswami, et al., 2011). Individuals with dyslexia have been shown to have deficits in perceiving slow rhythmic modulations, and this deficit correlates with their poor phonological awareness and reading abilities (c.f. Goswami, 2011; Goswami et al., 2002, 2011; Thomson, Goswami, Baldeweg, 2009).

Knowing neural mechanisms that are selectively sensitive to slow rhythmic modulations of language may therefore provide a window into understanding what aspects of auditory or visual stream the human brain may find particularly “language-like,” as well as what neural mechanisms help the brain transition from language in speech to language in print. Rhyme judgment tasks are frequently used to investigate the neural bases of language segmentation abilities such as phonological awareness in the developing brain, since rhyming judgments require phonological awareness of the constituent sound parts of words or letter names. Activation is typically observed in left inferior and middle frontal gyri (IFG/MFG) as well as posterior superior temporal gyrus (STG) and parietal regions (c.f. Kovelman, Christodoulou, Gabrieli, 2011). In children, activation in posterior left STG and parietal regions during the rhyme tasks typically increases with age and reading proficiency and is frequently reduced in individuals with dyslexia (Gabrieli, 2009; Shaywitz et al., 2004), suggesting that these regions might be particularly important for phonological segmentation analyses.

Nevertheless, only a few studies have directly explored the brain bases of human sensitivity to slow rhythmic modulations in young children. Evoked response potential and functional Near Infrared Spectroscopy (fNIRS) research with infants listening to temporally structured non-speech signals has shown that responses to slow acoustic

modulations that correspond to syllabic units are lateralized to the posterior temporal regions in the right hemisphere (Telkemeyer et al., 2009). TSF hypothesis thus predicts that phonological deficits in dyslexia may stem from the right-hemisphere auditory region's inability to perceive slow rhythmic modulations critical for language acquisition. These findings and this prediction are inconsistent with research showing that during syllable production in babbling infants mouth aperture is greater on the right side of their mouth, as controlled by the left hemisphere (in contrast to greater left-side aperture for smiles and non-babbling sounds; Holowka & Petitto, 2003), as well as functional Magnetic Resonance Imaging (fMRI) studies showing that adults exhibit greater activation in left posterior STG and parietal regions when asked to process speech implicitly for its slow rhythmic contour. Therefore the question we ask here is what are the brain mechanisms for "language" rhythm perception (1-2 Hz) in young beginning readers (ages 6-9), as they are learning to apply their intuitive language segmentation capabilities towards active phonological awareness and reading abilities.

Converging evidence from language and reading acquisition literature suggests that children's sensitivity to "language" rhythmic modulations is critical for language and reading acquisition, as it may underlie children's ability to segment speech into constituent parts such as syllables. Here we test the hypothesis that children's sensitivity to slow rhythmic modulations of language is a language-governed faculty of the human brain. To test this hypothesis, we examine which brain regions are active when the child is presented with the "language" rhythm (1.5 Hz), and whether left STG, the region known to support phonological processing, is selectively sensitive to this "language" frequency.

In this study, young beginning readers (ages 6-9) without any history of language or reading delays completed a rhythm perception task. Children listened to a brief sound presented at different frequencies: 0.5 Hz, 1.5 Hz, and 3Hz, as their brain activity was measured with functional Near Infrared Spectroscopy (fNIRS). We hypothesized that 1.5 Hz should be particularly salient to the language regions of the brain, as the “language” frequency, because this is the frequency at which young sign-exposed children babble with their hands (Petitto et al., 2001) and individuals with language and reading difficulties appear to have deficits in tapping to a metronome at this frequency (Corriveau & Goswami, 2009). The study also employed a phonological awareness and phonological memory task, as these are the tasks that tap well into language proficiency and language deficits in children with dyslexia and specific language deficit (SLI). We employed these language tasks to help us define the regions of interest critical for language and phonology: IFG, posterior STG and parietal regions. The study also used fNIRS imaging, as it is quiet and child-friendly, and if successful, this method could be further extended to the study of newborns and infants with typical language development as well as those at risk for language and reading impairments.

Method

Participants

Fifteen children participated in the study (4 girls and 11 boys; age mean of 7 yrs., 4 mo. +/- .93 yrs. & range 6 yrs. 1 mo. -9 yrs. 10 mo.). All children were right-handed native speakers of English without any history of language, literacy, or hearing difficulties. Fourteen participants (4 girls and 10 boys, mean age 7 yrs. 3 mo. +/- .96 yrs.) successfully completed the rhyme task and ten (4 girls and 6 boys, mean age 7 yrs. 6 mo.

+/- 1 yr.) participants successfully completed the rhythm task, nine participants completed both rhyme and rhythm tasks. The treatment of all participants and all experimental procedures were in full compliance with the ethical guidelines of the Institutional Review Boards of the University of Michigan Medical School.

Behavioral Measures

Participants completed standardized measures of cognitive, language, and reading abilities, including the Kaufman Brief Intelligence Test (KBIT: Picture Vocabulary and Matrixes subtests; (Kaufman & Kaufman, 1990)), the Comprehensive Test of Phonological Processing (CTOPP: Elision and Blending Words subtests; (Wagner, 1999)), and the Woodcock Reading Mastery Tests - Revised/Normative Update (WRMT-R: Letter and Word ID; (Woodcock, 1998)). Parents also completed a questionnaire detailing their child's language, reading, cognitive and motor development, as well as any family history of learning difficulties. All children had age and grade-appropriate reading, language and IQ abilities (see Table 1).

Imaging Tasks

Phonological awareness and phonological memory task. During fNIRS scanning, participants completed three blocked conditions, including a phonological awareness task (Rhyme task), a phonological memory task (Match task), and fixation (rest). The Rhyme task required participants to listen to a pair of words, segment the words' phonological form into constituent parts, identify the ending or the rhyme, and decide if the endings were identical or not (e.g., "cat" and "bat" rhyme; "cup" and "pan" do not). The Match task required participants to listen to a pair of words and decide if the two word-forms were identical or not (e.g., "dog" and "dog" are identical; "rat" and

“pan” are not). During both tasks, children heard pairs of words and made a yes/no decision about the pairs. There were equal numbers of “yes” and “no” responses for both the rhyme and match tasks. “Yes” and “no” responses were randomized across blocks to preclude participants from making assumptions about the distribution of “yes” and “no” trials during each block. Auditory words were similar across the two tasks and while the Rhyme task demanded phonological awareness and analysis, the Match task simply required the participant to remember the words long enough to make the comparison (1.5 sec).

The experiment began with a 33s lead-in-time during which the baseline physiological measure of the participants’ hemodynamic response was collected. There were six 24s blocks of rhyme and six 24s blocks of match (four trials per block, 6s per trial), the order of the blocks was randomized. Each block was preceded with a 2s instruction and each condition was also color-coded (a black fixation cross with orange background for the Rhyme task, and purple background for the Match task). There was a 15s rest period (white cross on black background) between the experimental blocks.

Word stimuli. All stimuli were real monosyllabic words matched within and across conditions (Rhyme and Match) for concreteness, written and verbal frequency, and number of letters and phonemes (data from MRC Psycholinguistic database; one-way ANOVA, $p > 0.05$, ns, within each condition; ad-hoc t-tests comparing the conditions were also non-significant, $p = .53$ or greater). All words were recorded by a female native speaker of English from the Michigan area using Praat Computer Software (Version 4.4.07).

Rhythm perception imaging task. During fNIRS scanning participants passively listened to a brief sound (13 ms) played at one of the three frequencies: 0.5 Hz, 1.5 Hz and 3 Hz. The 1.5 Hz frequency was of particular interest, given that sign exposed babies babble at 1.5 Hz and adults with SLI fail to tap accurately in tune with 1.5 Hz metronome. An alien “space game” was associated with the task. Children were asked to imagine that they were flying in space and encounter another space ship with aliens that want to communicate. However, the aliens do not speak English and instead speak with beeps. Children were instructed to sit as quiet and as still as possible while listening to the aliens “speaking” in beeps. At the end of each block a 3-second “translation” of the alien message was provided, accompanied by a picture (e.g., My name is Gaga, I like to play tennis on mushrooms, plus a picture of the alien jumping on giant mushrooms with a tennis racket).

The experiment began with a 33.5s lead-in-time during which the baseline physiological measure of the participants’ hemodynamic response was collected. Participants heard four 20s long blocks of each frequency condition. There was a 15s rest period between each block and a black screen with an image of the starry sky was presented during the task and the rest blocks.

fNIRS Imaging Apparatus and Experimental Procedure.

To record the hemodynamic response we used a Hitachi ETG-4000 with 44 channels, acquiring data at 10 Hz (Figure 1a). The lasers were factory set to 690 and 830 nm. The 16 lasers and 14 detectors were segregated into two 5 X 3 arrays corresponding to 30 probes (15 probes per array; Figure 1b). Once the participant was comfortably seated, one array was placed on each side of the participant’s head. Positioning of the

array was accomplished using the 10–20 system (Jasper, 1958) to maximally overlay regions classically involved in language. We anchored the most frontal bottom probe on F7/F8 and middle bottom probe on T3/T4 coordinates (see a detailed video demonstration of this procedure in Shalinsky, Kovelman, Berens, & Petitto, 2009). During recording, channels were tested for noise prior to the beginning of the recording session. Digital photographs were taken of the positioning of the probe arrays on the participant's head prior to and after the recording session to identify if the arrays had moved during testing. An MPEG video recording was synchronized with the testing session, so any apparent movement artifacts could be confirmed during offline analysis and used to score participants' responses.

Parents of the participants and the participants signed the consent and assent forms. Participants were then introduced to the system, 10-20 measurements were taken, probes were placed and photos of each probe position were taken. Participants received brief training for each task immediately prior to the corresponding task.

All stimuli in this experiment were presented using MATLAB (MathWorks) Psychtoolbox Version 3 (developed by Mario Kleiner, David Brainard, Denis Pelli, Chris Broussard, and Roy Han), presented with a MacBookPro “Core 2 Duo” 3.06 (2009 model) with a 27-inch screen and auditory stimuli were played via the built-in Mac stereo speakers.

fNIRS data analyses. After the recording session, data were exported and analyzed using Matlab-based software developed by Mark Shalinsky (see details in Kovelman, Shalinsky, White, Schmitt, Berens, Paymer, & Petitto, 2009; Shalinsky et al., 2009). Conversion of the raw data to hemoglobin values was accomplished in two steps.

Under the assumption that scattering is constant over the path length, we first calculated the attenuation for each wavelength by comparing the optical density of light intensity during the task to the calculated baseline of the signal. We then used the attenuation values for each wavelength and sampled time points to solve the modified Beer–Lambert equation to convert the wavelength data to a meaningful oxygenated and deoxygenated hemoglobin response (HbO and Hb, respectively).

The data was then filtered to remove physiological noise, including heart rate and respiration. Following this, the data was carefully examined for motion artifacts: raw time course data for each participant was plotted and time periods where signal change occurring over a period of time that was too fast to be physiological (3 seconds or less) were removed from further analyses. A total of 19 children were tested and 4 were excluded due to data quality (equipment failure, overall signal quality, or excessive motion).

Mean values of oxy-hemoglobin were calculated from the time-course omitting the first half of the time-course for each block (Rhyme/Match analyses window: 15-30s from the beginning of the block; Rhythm analyses window: 10-20s from the beginning of the block). Analyses window for the Rhyme/Match task spanned from the beginning of the block (immediately following the instructions) to 5s after the end of the block. For the Rhyme/Match task we extracted mean values of oxy-hemoglobin within 15-35s of the blocks for each condition separately.

fNIRS group analyses. The first step in analyses was to identify the regions of interest (ROIs) involved in linguistic processing, phonological memory and analyses. In order to explore which channels showed significant positive activation during the

language tasks we ran a one-tailed t-test ($p < 0.05$) for mean values of oxy-hemoglobin for mean values of Rhyme/Match conditions (mean H₂O values averaged across the two tasks). In order to explore the brain bases of slow rhythm perception we conducted a 3 X 2 repeated measures ANOVA (3 frequencies X 2 hemispheres) for each ROI ($p < 0.05$).

Results

Imaging results

Brain bases of phonological awareness and phonological memory. In order to identify channels that showed significant activation during phonological awareness, word memory and general linguistic processing, we combined average activation values across the Rhyme and Match conditions and ran a one-sample t-test for the left hemisphere. The analyses revealed significant positive activations in left posterior STG (channel 13), parietal (channel 9), and IFG (channel 20).

Brain bases of slow rhythm perception.

Posterior STG. Significant interaction between frequency and hemisphere ($F(2,18) = 4.2$) showed that in the left hemisphere participants had significantly greater activation during the 1.5 Hz condition, as compared to 0.5 Hz and 3 Hz conditions, while in the right hemisphere participants showed a parametric increase in activation from 0.5 Hz to 1.5 Hz (significant linear trend at $F(1,9) = 11.4$, $p = 0.008$; Figure 3a). Overall, participants showed greatest activation for 1.5 Hz frequency (main effect of frequency: $F(2,18) = 7.5$). Finally, overall activation on the right was greater than activation on the left across all three frequencies (main effect of hemisphere: $F(1,9) = 10$).

Parietal. Participants showed overall greater activation in the right hemisphere as compared to the left hemisphere (main effect of hemisphere: $F(1,9) = 7.9$; Figure 3b).

There was no significant interaction between frequency and hemisphere, and no significant frequency differences. Nevertheless, as can be seen in Figure 3b, participants' activation to 1.5 Hz frequency was greater on the left than on the right, and in the left hemisphere, participants' activation to 1.5 Hz was greater than activation for 0.5 Hz and 3 Hz.

Inferior frontal gyrus. Participants showed an overall greater activation for 3 Hz, relative to 0.5 Hz and 1.5 Hz ($F(2,18) = 3.7$; Figure 3c). This increase was linear from 0.5 Hz to 3 Hz, though the linearity significance was marginal ($F(1,8) = 4.1, p = 0.08$).

Discussion

Slow rhythmic modulations in language help mark syllabic and word boundaries in a continuous speech stream, a critical feature that helps infants extract syllables and words during language acquisition (Fowler et al., 1986; Jusczyk et al., 1999). The first milestone in language acquisition is babbling, when infants start producing meaningless syllabic units (in sign and speech) at a slow frequency of about 1-2 Hz. The first precursor to successful reading acquisition is phonological awareness for syllables, and individuals with deficits in phonological awareness appear to have a select deficit at tapping with a metronome at about 1.5-2.5 Hz (Corriveau & Goswami, 2009). We hypothesized that the brain regions critical for phonological processing of language might be selectively sensitive to this slow rhythmic modulation of language at a frequency of 1.5 Hz. Our findings support this hypothesis and show that the left posterior STG region (part of the classic Wernicke's area) is selectively sensitive to 1.5 Hz "language" frequency, as compared to slower and faster (0.5 Hz and 3 Hz) frequencies.

Rhythmic modulations are inherent to two aspects of human cognition and perception: language and music. Decades of research have shown that much of auditory analyses for language takes place in the left hemisphere, while much of the auditory analyses for music, including musical rhythm, takes place in the right hemisphere (Zatorre & Gandour, 2007). The present study demonstrates that the left hemisphere has a relatively specialized preference for the 1.5 Hz frequency, the frequency at which infants babble and individuals with SLI fail to keep pace. Conversely, the right hemisphere posterior temporal region, as well as all other regions of interest, showed an overall greater activation for all auditory frequencies tested in the study, as well as a parametric increase in activation with frequency increase. Taken together, these findings suggest that left hemisphere phonological regions have a very select sensitivity to what may be a “language-preferred frequency” of about 1.5 Hz, while right hemisphere may have a more generalized ability to process and discriminate multiple auditory frequency ranges.

TSF hypothesis suggests that children with dyslexia and language impairments may have an auditory processing impairment for slow frequency modulations in the right hemisphere auditory regions. Our findings suggest that there may be two potential pathways to deficits in phonological processing. If the deficit is fundamentally within the language-learning capacity, and children with dyslexia indeed have a deficit at perceiving rhythmic modulations of language at about 1.5 Hz, then language deficits might be driven by the left hemisphere’s inability to segment the spoken language into appropriate temporal units such as syllables and words. If the deficit is fundamentally general-auditory, possibly within a broader range of slow frequencies (1-10 Hz), then the dyslexia may be driven by the failure of the right hemisphere to provide the left hemisphere with

the necessary auditory information that helps the child extract statistical regulations in the complex auditory input (Aslin et al., 1999; Saffran, 1996). However, one of the major caveats of this study is that we only examined typically-developing readers and further research is warranted to understand the brain bases of phonological rhythmic deficits in dyslexia.

Neuroimaging research suggests that upon hearing language, the neural networks of the adult brain appear to enter a coordinated dance between the slow and the rapid frequency modulations of the linguistic stream and the endogenous rhythmic oscillations of the neural activity. In particular, neuronal firing rate is known to oscillate at different frequency bands, including Delta (1.5-4 Hz); Theta (4-10 Hz), and Gamma (30-80 Hz). All of these frequencies are present in the human speech, with slower frequencies corresponding closer to the syllabic boundaries (Delta-Theta), and faster frequencies corresponding to individual phonemes. Human speech is thought to elicit these slow Delta-Theta and rapid Gamma neural oscillations, allowing the brain to align neuronal excitability to the most informative parts of speech (Morillon et al., 2010).

Electroencephalogram (EEG)-fMRI investigations show that these endogenous neural oscillations, as elicited by language, can be localized to brain regions broadly involved in language perception and production, including posterior STG, IFG, as well as auditory, motor and parietal regions (Luo & Poeppel, 2007; Morillon et al., 2010). The brain may have therefore evolved neural pace-maker mechanisms that can effectively align with rhythmically-oscillating properties of language phonology in order to support speech segmentation as well as language production.

While research on endogenous neural oscillations suggests that language contains and can elicit a rather broad range of frequencies, our findings suggest that there might be a preferred narrow range of slow frequencies of about 1.5 Hz, to which left posterior temporal regions critical for phonological processing might be particularly sensitive. This select sensitivity to 1.5 Hz within the “phonological” regions of the brain is present in children who are transitioning from implicit sensitivity to language units to an active sensitivity to these units as they are learning to read. Infant acquisition evidence suggests that this left-hemisphere preferential sensitivity to 1.5 Hz might be the cause rather than a consequence of language experience (Petitto et al., 2001). Nevertheless, this hypothesis remains to be tested with young infants, possibly using the present method.

This study utilized fNIRS to investigate the neural bases of "language" related (1.5 Hz) frequency perception in typically-developing children. In the beginning readers (ages 6-9), left hemisphere regions that are involved in phonological awareness and phonological memory showed a select sensitivity to 1.5 Hz frequency, a frequency that may help the child segment continuous speech stream into smaller meaningful units, such as syllables or words. The child brain's sensitivity to this frequency within the classic language regions may support early language acquisition, as well as other children's ability to transition from language in speech to language in print. These findings carry implications for helping understand neural mechanisms that help support early language acquisition across languages and modalities as well as reading acquisition in typical development and dyslexia.

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Table 1

Behavioral Scores

Experimental Group	Mean (SD)	
	Rhyme	Rhythm
<i>N</i>	14	10
Age (years)	7.3 ± .96	7.5 ± 1.1
Behavioral Measures		
KBIT Verbal IQ	113.2 ± 9.3	113.5 ± 8.8
Standard Score		
KBIT Non Verbal IQ	115 ± 8.1	114.9 ± 9.6
Standard Score		
CTOPP Phonological	111.7 ± 19.7	123.8 ± 15
Awareness Composite ^a		
Standard Score		
CTOPP Phonological	25.9 ± 6.6	27.6 ± 5
Awareness Composite ^a		
Raw Score (max = 40)		
Woodcock Letter ID	96.5 ± 6.7	103.7 ± 10.2
Standard Score		
Woodcock Word ID	105.8 ± 7.5	122.2 ± 14.1
Standard Score		

In-scanner Task Performance

Accuracy

(% correct)

96.1 ± 7.5

Note. All participants fell within normal range for language abilities and IQ

^a Composite of Elision and Blending Words

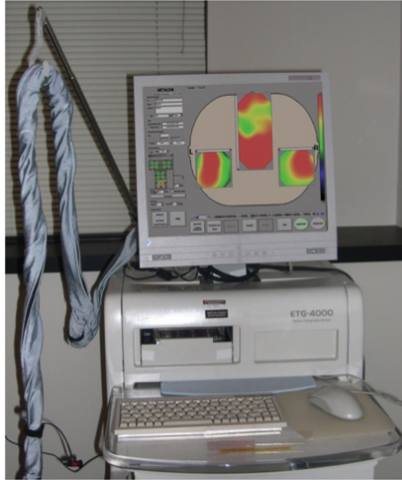
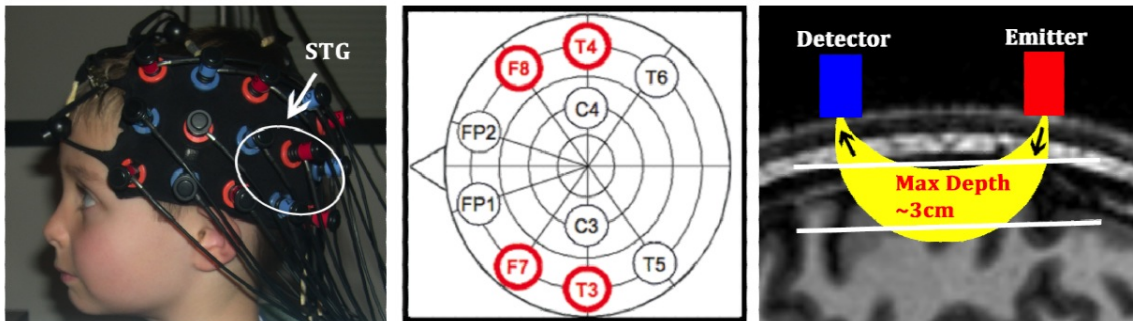
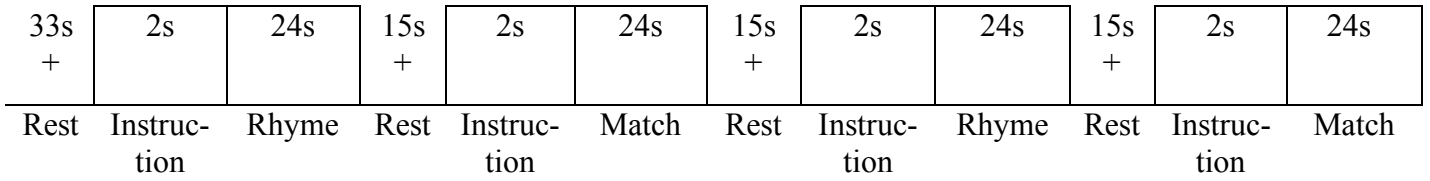
a.*b.*

Figure 1. fNIRS imaging apparatus and experimental procedure. (a) Hitachi ETG-4000 with 44 channels, acquiring data at 10 Hz, used to record the hemodynamic response. (b) Probe placement over bilateral STG, 10x20 coordinates, and measurement between optodes.

a.



b.

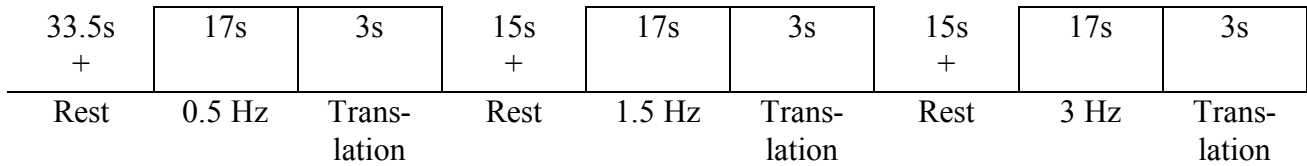
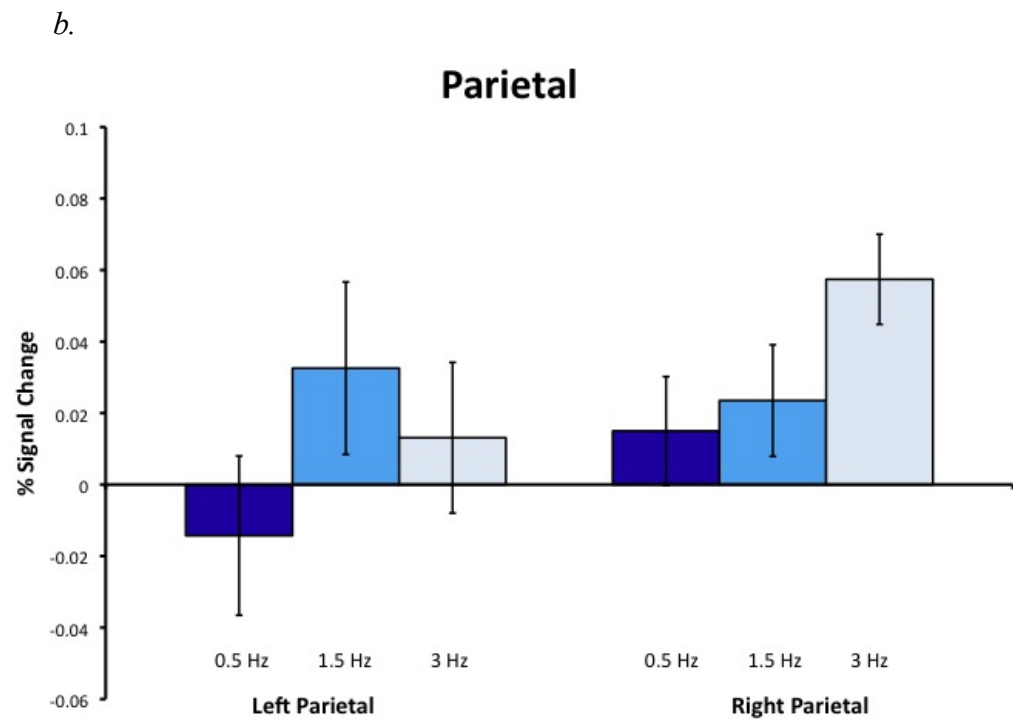
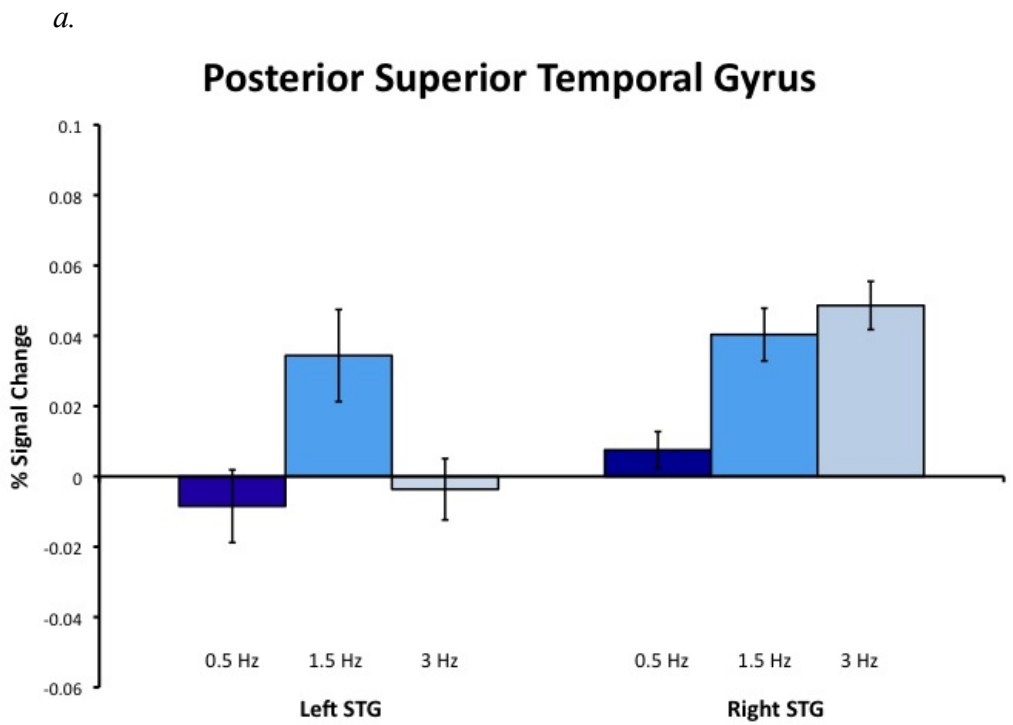


Figure 2. Block design. (a) Phonological awareness and phonological memory task:

Participants listened to pairs of words and were instructed to decide either if the words rhymed or matched. (b) Rhythm task: Participants passively listened to a brief sound at one of three frequencies (.5 Hz, 1.5 (language) Hz, 3 Hz).



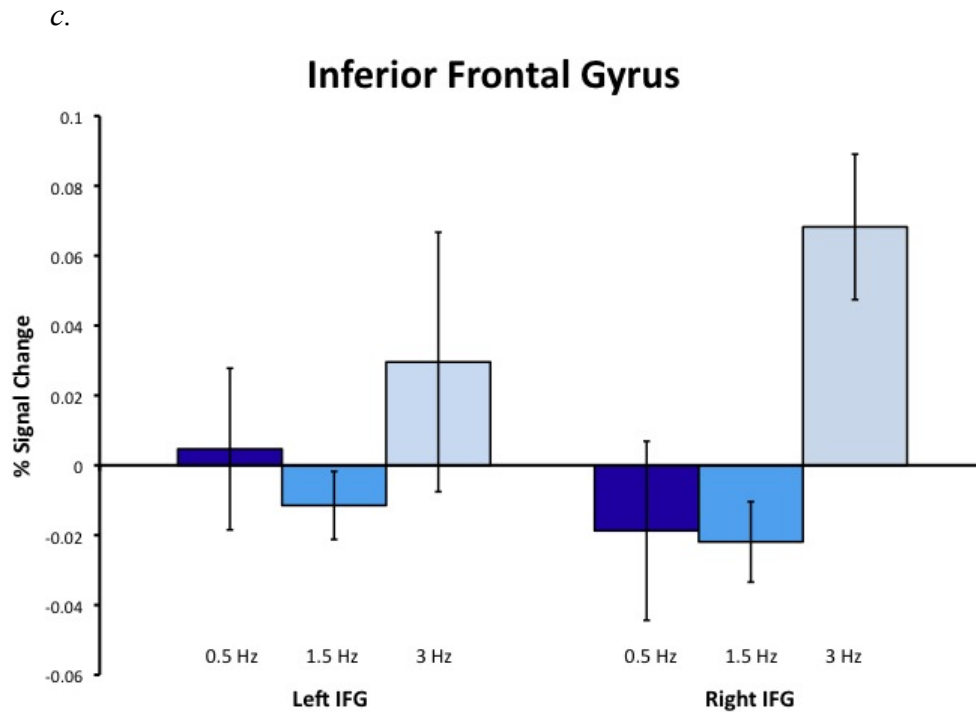


Figure 3. Average brain activation in regions of interest. (a) Posterior STG: A significant interaction between frequency and hemisphere showed that in the left hemisphere participants had significantly greater activation during the 1.5 Hz condition, as compared to 0.5 and 3 Hz conditions. Right hemisphere showed a parametric increase in activation from 0.5 to 1.5 Hz. Overall, participants showed greatest activation for 1.5 Hz frequency. There was also a main effect of hemispheres- overall activation on the right was greater than activation on the left across all three frequencies. (b) Parietal region: Participants' activation to 1.5 Hz was greater on the left than on the right, and in the left hemisphere, participants' activation to 1.5 Hz was greater than activation for 0.5 and 3 Hz. (c) IFG: Participants showed an overall greater activation for 3 Hz, relative to 0.5 and 1.5 Hz.