Neurocognitive Basis of Prosody Perception in Children

Rennie Pasquinelli

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Advisors: Dr. Ioulia Kovelman and Dr. Anne-Michelle Tessier

Abstract

Sentence prosody is an important source of information in both language acquisition and processing. The prosodic contour includes patterns of pitch, loudness, and temporal word grouping. There is a long-standing disagreement in the field on whether or not successful prosodic processing requires engagement of cognitive mechanisms that extend beyond the left-lateralized language network. Here we take an innovative approach to testing this long-standing theoretical dilemma by investigating the neurocognitive basis of prosody perception in typically developing children. Should successful prosodic processing rely on the classic language network, children would show engagement of left inferior frontal and superior temporal regions. Alternatively, should prosodic processing rely on additional perceptual and cognitive processes, children would also show engagement of bilateral middle/superior frontal, parietal, and auditory cortex regions classically associated with auditory perception, memory, and attention processes. To test these predictions, we used functional Near Infrared Spectroscopy (fNIRS) to measure neural response to prosody and control auditory language conditions in 29 normally-hearing children (ages 6-10). This study found significant bilateral activation in the temporal lobe when children were tested on differing intonation contours. These results suggest both the left and right temporal lobe are responsible for processing prosody in language.

Neurocognitive Basis of Prosody Perception in Children

Speech perception is a process that involves segmental and suprasegmental perception (Plante, Holland, and Schmithorst, 2006). Suprasegmental information, known as prosody, provides listeners with crucial information in gauging meaning from spoken sentences, including the rhythm of speech, speech rate, volume, and pitch (Ito, 2014). These components of language convey expressive and pragmatic intent, conveying both information about the emotional components of an utterance as well as the linguistic structure. The information listeners gauge from prosody provide us with fundamental aspects of spoken language. It can assist listeners in segmenting words, identify points of emphasis, as well as reveal sentence type (question vs. statement). A sentence with the same words can carry completely different meaning solely based on prosodic information. For example, the sentences “Melissa loved her alligator.” and “Melissa loved her alligator?” when spoken aloud, are only differentiated by the speaker’s intonation, yet the first is a declarative statement and the second is a question. We can see the phonetic differences of these utterances in their corresponding waveforms in Figure 1.

Prosody is uniquely important when children are acquiring language as it provides cues for early communication skills. Beginning at infancy, children use prosodic cues for several aspects of linguistic decoding, including (1) learning the rhythm and stress patterns of their language, (2) segmenting words from utterances, (3) understanding intentions of utterances, (4) learning turn-taking with interlocutors, and (5) indicating focus of a sentence and paying selective attention (Ito, 2014; Plante, Holland, and Schmithorst, 2006). While children begin incorporating prosodic cues into their speech at a very early age, the literature surrounding prosodic development shows both production and perception of prosody continuously improves into adolescence (Myers & Myers, 1983). The literature indicates that children are utilizing prosodic cues to assist in linguistic decoding by the age of five, but some aspects of prosodic knowledge continues to develop well past age five, suggesting prosodic development continues throughout school years (Wells, Peppé, & Goulandris, 2004; Ito et al., 2012). For example, young listeners are still learning to identify the focus of their interlocutor's utterance up to the age of 11 (Wells, Peppé, & Goulandris, 2004).

Previous studies have investigated the development of prosodic production and perception, which is an important step towards discovering the timeline for prosody and language acquisition. Few studies, however, investigate the neurological basis for prosody, and even fewer in children. This study looks at the development of prosody in children. We explored the neurological basis for the processing of prosody with functional Near Infrared Spectroscopy (fNIRS).

Neuroimaging research with adults presents us with a mixed picture. Previous neuroimaging studies of prosody perception in normal-hearing (NH) adults reveal varying sites of activation in the brain, but tend to support bilateral activation in prosody tasks. For example, a 2006 study using functional magnetic resonance imaging (fMRI) found activation areas varied greatly from participant to participant based on age (Plante, Holland, and Schmithorst, 2006). Pediatric participants showed activation in frontal, temporal, and parietal regions, while participants across the 5-18 year-old range showed bilateral activation in the superior temporal gyrus and right lateralization in the middle frontal gyrus. Frontal lobe activation is not often found associated with prosodic processing, but locations including the lateral precentral gyrus and the middle and inferior frontal gyrus have been reported as activated in the past (Plante, Holland, and Schmithorst, 2006). A 2012 fMRI study also found bilateral activation with sentence-level prosody perception in adults. They reported bilateral activation in both the superior temporal pole regions and posterior inferior temporal lobe (Fedorenko, Hsieh, and Balewski, 2012).

Mixed results from fMRI studies of NH participants show variation in brain activation for prosody perception, especially when accounting for age, further suggesting listeners are learning how to utilize prosodic cues in speech throughout development. The goal of the present study was to shed light on the nature of prosodic processing and acquisition, and the extent to which language versus other neurocognitive systems are engaged in prosodic processes in young children during the key ages of the fine-tuning of the prosodic system.

The present study uses fNIRS, an emerging neuroimaging technology used to study activity in the cerebral cortex. fNIRS quantifies the changes in oxygenated and deoxygenated hemoglobin levels-- serving as an indication of neural activity-- through changing optical properties (Ferrari and Quaresima, 2012). Changing optical properties of blood provide a more direct metabolic marker in comparison to an fMRI BOLD signal, which solely relies on deoxyhemoglobin (Huppert et al., 2006). fNIRS is particularly useful for young populations due to its noninvasive nature.

Should successful prosodic processing rely on what we know as the classic language network, our fNIRS protocol should reveal activation of the left inferior frontal and superior temporal regions (Hickok and Poeppel, 2007). Alternatively, children would also show engagement of bilateral middle/superior frontal, parietal, and auditory cortex regions classically associated with auditory perception, memory and attention processes. We also expect to find positive correlations in children’s language scores and accuracy in the fNIRS intonation identification task. We may also find that children have an easier time identifying that sentences contain the same words when they are given stimuli containing the same words and intonation, but when a conflict is present (differing intonation with the same words), it may be more difficult for children to identify the similarities of the sentences. Our findings will contribute to literature surrounding language acquisition and processing, as it concentrates on an area of language processing where little is known.

Method

Participants

Twenty-nine typically-developing/normally-hearing, monolingual English children ages 6-10 years old (18 females, age range = 6.33-10.75 years, mean age = 8.37 years) were included in this study. All participants were recruited and lived in a Midwestern city in the United States. See Table 1 for more information on demographics and performance.

Experimental Tasks

Standardized Assessments of Language & Literacy. Each participant completed a series of language and literacy assessments. Every assessment was administered and scored online by a trained native English speaker and audio recorded. A complete list of the administered behavioral tests can be found in Appendix B, but for the purposes of this paper, only the Oral Expression subtest of the Oral and Written Language Skills (OWLS), Second Edition and the Woodcock Johnson Tests of Achievement, Third Edition: Sound Awareness are discussed (see Table 1 for participants' average scores). OWLS was used to test for vocabulary and expression, as it requires children to look at photos and answer questions or form sentences about the images. The Oral Expression subtest tests for lexical/semantic, syntactic, supralinguistic, and pragmatic linguistic abilities. Woodcock Johnson Sound Awareness was used to look at reading and phonological aptitude; this subtest required children to perform sound manipulations in familiar words, including Rhyming, Deletion, Reversal and Substitution.

Neuroimaging Intonation Tasks. During the neuroimaging, participants were given a forced-choice AX task created in E-Prime to target sentence-level intonation. This task is loosely inspire by Plante et al.'s (2003) fMRI study which aimed to locate activated brain regions when children were focused specifically on sentence intonation. In the version completed for this study, participants indicated whether two sentences were the same, where two sentences are the same if they contain the same words. Stimuli were controlled for syntactic and lexical properties, and each follows one of four intonation contours: (1) Declarative statement, where pitch consistently falls across the entire sentence, (2) Yes/no echo question, where pitch consistently falls until a small rise on the last stressed syllable, (3) Declarative statement with subject focus, where there is a quick pitch rise/fall on the subject, and pitch consistently falls afterwards, or (4) Yes/no echo question with subject focus, where there is a quick pitch rise on the subject, then pitch remains high (see Figure 2 for examples). The full set of 24 sentences can be seen in Appendix A. Stimuli were paired in order to fit a *Same Words, Same Intonation* condition (Same), a *Same Words, Different Intonation* condition (Different Intonation), and a *Different Words, Same Intonation* condition (Different Words). For example, in the Same condition, children heard "Melissa loved her alligator?" twice; in the Different Intonation condition, children heard "Melissa loved her alligator?" (question) and "Melissa loved her alligator." (declarative); in the Different Words condition, children heard "Melissa loved her alligator?" and "A lion licked your radio." (see Figure 3). The stimuli were counterbalanced; every sentence was heard six times by each participant, one each in two of the intonation contours, and twice in the other two contours. There were 24 trials of each condition. Due to the length of the task, the stimuli were presented over two separate tasks, with a short break for participants in between. Thirty-two of the sentences were in the first task, while the other 32 were in the second task.

Provided with a two-input button box, participants would hear a pair of two sentences, and press one button if the sentences contained the same words (same and different intonation conditions), and another button if the sentences contained different words (different word condition). In attempts to maintain children's focus on the task, a cartoon image of a dog was presented while the sentences were played (Figure 4). After the stimuli were played, a question mark would flash on the screen, requiring the participant to press one of the two buttons to indicate if the words in sentences were the same. Sentences 1 and 2 were played over a time course of 4.5 seconds,, and participants had 10 seconds to respond before the next pairing was presented. If a participant responded before the 10 seconds, the next pairing would begin. Each part totaled 10 minutes. Before the task began, a research assistant trained on the behavioral measures would instruct the participant to listen for the same words in the set of two sentences, and press the yellow button if the words were the same, and the blue button if the words were different. Before beginning a practice trial on the computer, the research assistant read a series of sample stimuli and asked the participant which button they would press. Then, the participant partook in three practice trials on the computer— one trial for each condition. If the participant completed the practice trials correctly, they would begin the experiment. If they had issues with any of the practice trials, the research assistant would review the condition they had the issue with by providing more explanation and more examples of such condition. This task was a part of a broader study which investigated other aspects of the neurology of language perception. All but one participant completed the intonation tasks before a rhyme judgment task, while participant 30 completed the rhyme judgment task before the intonation tasks.

fNIRS Neuroimaging Protocol. Device. This study used a TechEN-CW6 system with 690 and 830 nm wavelengths. The layout included 6 sources of near-infrared light and 12 detectors. They were spaced ~3 cm apart, and there were 46 channels in total. A custom-made cap was constructed from a silicone rubber material. The neuroimaging set-up included 46 channels, with 23 channels per hemisphere covering frontal, temporal, parietal and portions of the occipital lobe (see Figure 5).

Data Processing & Analyses. The data were firstly passed through a quality control process. Then the wavelengths data were converted into hemoglobin concentration change further analysis using modified Beer-Lambert Law (MBLL). The converted hemoglobin concentration data was analyzed using a two-level general linear model framework to detect measurement channels that were statistically related to the timing of the stimulus events using NIRS-toolbox.

Group-level analyses were conducted using a mixed effects model. The beta coefficients weighed by their associated covariance estimated from the first level were used as dependent variable, the subject-condition order was used as fixed-effect terms, and the subject ID was included as random-effect terms. In particular, we estimated participants brain activity during each of the experimental conditions and used mixed effects model to estimate the main effects of task and condition. Moreover, to explore the relationship between participants' age, cognition, and language status, we include raw scores of language performance and reaction time as additional covariates in the mixed effects model.

Results

Language & Literacy Assessments. Mean standard scores and standard deviations for the OWLS test of oral expression and Woodcock Johnson test of sound awareness are reported in Table 1. No significant correlations were found on performance between the two assessments ($p > .05$).

fNIRS Experimental Task. Mean percent behavioral response accuracy and response time on the intonation task are reported in Table 1. Differences in accuracy on the three experimental conditions are reported visually in Figure 6. Percent accuracies across Same (M = 93.1, SD = 10.46), Different Intonation (M = 78.45, SD = 21.6), and Different Words (M = 85.49, SD = 19.08) conditions were significantly different from chance ($p < .001$). A one-way ANOVA of accuracy between conditions was significant, $F(2, 83) = 4.289$, $p = .01$, where accuracy for the Same condition ($t(28) = 21.44$, $p < .001$) significantly differed from the Different Intonation condition ($t(28) = 6.84$, $p < .001$). Accuracy on the Same and Different Intonation conditions did not differ from the Different Word condition ($t(28) = 10.32$, $p < .001$). As expected, it was more difficult for children to accurately identify when two sentences have the same words when they had differing prosodic contours. A one-way ANOVA of reaction time was not significant, ($F(2, 86) = .047$, $p = .95$), where reaction times did not significantly differ across conditions. Accuracy and reaction time positively correlated for each condition; for the Same condition ($r(28) = .7$, $p < .001$); the Different Intonation condition ($r(28) = .69$, $p < .001$); and the Different Words condition ($r(28) = .59$, $p = .001$). Combined intonation accuracy correlated positively with the supralinguistic subtest of the OWLS oral expression assessment ($r(28) = .54$, $p = .003$). Supralinguistic questions in the OWLS measure complex language where meaning is not directly available, such as figurative language, verbal reasoning, double-meaning, and indirect response.

Neural Activation. Mixed effects analysis of oxy-hemoglobin (HbO) concentrations, where average beta values (β) reflect average activation patterns across conditions, revealed children had significant bilateral activation in several channels across conditions (see Table 2). The Same condition elicited significant bilateral activation across all areas of interest including the frontal lobe (Channel 2), the temporal lobe (Channels 9, 11, 12), and the temporoparietal regions (Channel 18). The Different Intonation condition shows significant activation in left superior and medial temporal gyrus activation (Channels 10, 11, 12, 13), as well as bilateral activation in the temporal and temporoparietal regions (Channels 11, 13, 14, 16, 18, 20). Lastly, the Different Words condition evoked significant bilateral activation across all areas of interest (Channels 1-4; 9-13; 14, 16; and 17, 18). Average brain activity across conditions in the left hemisphere is shown in Figure 7. As is clear in both Figure 7 and Table 2, all 3 conditions elicited robust activation in left temporoparietal regions.

Discussion

This study investigated the extent to which prosody is processed by the classic language network, which is composed of the left inferior frontal superior temporal regions. This is, as far as we know, one of the first studies to investigate the neural networks of prosodic processing in children. Past neuroimaging studies show conflicting results for prosodic processing in adults; some find varied areas of activation including bilateral activation in the superior temporal gyrus and right lateralization in the middle frontal gyrus (Plante, Holland, and Schmithorst, 2006). Alternatively, some fMRI results find bilateral activation in the superior temporal pole and posterior inferior temporal lobe (Fedorenko, Hsieh, and Balewski, 2012). fNIRS findings revealed that during the prosodic Different Intonation condition participants showed robust bilateral temporal activation, in regions responsible for processing auditory input and converting it to phonological representations. In contrast, the condition that engaged lexical sentence comparison (Different Words) resulted in greater frontal as well as temporal activation, even though this condition was easier for the participants than the prosodic condition (Different Intonation), as they had greater accuracy and faster reaction time for the Different Words condition. Contrary to prior suggestions that prosody requires extra neural resources, our findings find that even though the prosodic condition was relatively more challenging, it elicited activations that were more focal to the temporal phonology regions.

Children in this study had lower average accuracy on the Different Intonation condition than the other two conditions, which did not require conflicting prosodic cues. These results correspond with theoretical findings that prosodic development continues into adolescence (Myers & Myers, 1983). Specifically, Wells and colleagues found that young listeners are still struggling to identify the subject of a spoken sentence up until age 11 (2004). Identifying subjects in a spoken sentence was an important part of the Different Intonation condition in this study, suggesting these results further align with theoretical underpinnings of prosodic development.

As for performance on the intonation task itself, we found a significant difference in accuracy between the Same and Different Intonation conditions. This suggests performance on this task may be determined by ability to track words (the Same and Different Words condition, where no significant difference in performance was found), and intonation processing (the Different Intonation condition). As predicted, significantly higher average accuracy was shown in the Same condition ($M = 93.10$, $SD = 10.46$) as compared to the Different Intonation condition ($M = 78.45$, $SD = 21.60$). For children in this age range, then, it may be the case that it is easier to track words without the presence of prosodic changes. We also found a significant correlation between accuracy and reaction time on each condition of the intonation task, suggesting the longer a child took to determine if the words in the two sentences were the same or different, the more likely they were to answer correctly.

Another finding of note is the positive correlation between overall intonation task accuracy and performance on the supralinguistic subtest of the OWLS test for oral expression. As mentioned previously, supralinguistic questions tested children for their linguistic knowledge of figurative and indirect language, e.g. *The girl went to the library for a special book on insects but got another book instead. Why do you think this happened?* Supralinguistic questions are among the fewest in the assessment due to their level of difficulty for children, suggesting they may require linguistic knowledge that is fine-tuned later in development, similar to intonation. This positive correlation between the tasks follows, then, given the difficulty of each. Both intonation and supralinguistic information appear to require executive functioning that is still developing for 6- to 10-year-old children.

In the presence of conflicting views surrounding the processing of prosody, these findings suggest prosody is a linguistic and phonological phenomenon, as opposed to one associated with memory or attention processes. Performance on the intonation task not only significantly activated areas of the brain traditionally associated with language processing, but also related strongly to children's overall linguistic growth, as reflected by behavioral correlations between performance on the intonation task and standard language assessments. While other views of prosodic processing suggest prosodic processing may be reliant on areas of the brain not associated with language or phonological processing, our findings show strong activation of temporal phonological regions.

Limitations. The length of the intonation task was ultimately too much for some children, making it hard to know if some participants' lower results were due to an actual issue with comprehension of the task, or rather lack of interest and effort.

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The author can be reached at renpasq@umich.edu.

Table 1

Participants' mean demographics and performance scores for language expression, reading, sound awareness, and intonation tasks

Measure	Participants' mean (standard deviation)
Age	8.37 (1.16)
Demographics	
Mother's education	6.86 (1.08)
Father's education	6.59 (1.58)
OWLS Oral Expression	108.69 (9.82)
Woodcock Johnson Sound Awareness (*N* = 26)	114.35 (13.29)
Intonation Accuracy (%)	
Same	93.10 (10.46)
Different Intonation	78.45 (21.60)
Different Words	85.49 (19.08)
Total	80.84 (20.31)
Intonation Response Time (s) (*N* = 29)	
Same	4.63 (0.62)
Different Intonation	4.58 (0.75)
Different Words	4.59 (0.83)

Note. *N* = 29 unless otherwise indicated (18 females). Language expression, reading, and sound awareness scores are standard scores. Parents' education background was placed on a scale of 1-6; (1) primary education; (2) secondary education; (3) high school diploma or GED; (4) some college; (5) Associate's degree; (6) Bachelor's degree; (7) Master's degree; (8) Doctorate (PhD) or equivalent (MD, DD, etc.).

Table 2

Mean oxy-hemoglobin (HbO) concentration patterns across conditions

		SAME		**DIFFERENT INTONATION**		**DIFFERENT WORDS**	
		Left	**Right**	**Left**	**Right**	**Left**	**Right**
		β, *t*	**β, *t***	**β, *t***	**β, *t***	**β, *t***	**β, *t***
	Channel						
Frontal	1	0.63, 0.43	1.26, 0.96	-1.94, -1.31	1.13, 0.85	4.35, 2.92**	2.66, 1.98*
	2	3.79, 2.63*	2.69, 2.07*	0.68, 0.46	1.03, 0.79	6.45, 4.37*	4.42, 3.34**
	3	-0.11, -0.06	-1.57, -1.04	0.08, 0.05	-1.27, -0.83	-0.87, -0.53	3.78, 2.45*
	4	-0.5, -0.30	0.78, 0.61	2.18, 1.27	2.17, 1.66	2.93, 1.70	0.8, 0.61
Temporal (STG, MTG)	7	0.97, 0.50	0.56, 0.35	1.14, 0.58	0.07, 0.05	3.20, 1.61	-0.4, -0.24
	9	-2.36, 1.07	5.44, 2.62*	0.11, 0.05	1.25, 0.59	1.80, 0.80	5.27, 2.49*
	10	1.23, 0.57	2.50, 1.28	5.56, 2.54*	0.69, 0.35	6.53, 2.97*	5.86, 2.96*
	11	4.52, 1.98*	0.36, 0.21	7.03, 3.04*	3.51, 2.00*	7.40, 3.18*	10.33, 5.85**
	12	0.88, 0.41	4.15, 1.85	6.92, 3.19*	3.33, 1.46	6.85, 3.15*	7.39, 3.23*
	13	5.54, 2.66*	-1.28, -0.47	8.99, 4.28**	7.84, 2.87*	7.26, 3.44*	5.98, 2.17*
Tempropariental	14	7.78, 2.97*	1.16, 0.41	9.87, 3.74**	2.68, 0.93	8.11, 3.06*	6.35, 2.18*
	16	4.09, 1.98	3.06, 1.57	8.30, 4.00*	5.86, 2.97*	7.82, 3.74**	8.50, 4.26**
Temporal (ITG)	17	-0.3, -0.15	-0.88, -0.50	-1.2, -0.58	-0.29, -0.16	-4.52, -2.18*	2.41, 1.35
	18	-1.07, -0.62	4.22, 2.27*	2.69, 1.55	4.73, 2.52*	5.06, 2.89*	5.65, 2.99*
	19	-5.47, -0.78	-1.43, -0.36	-8.14, -1.14	-6.95, -1.72	-11.42, -1.58	-6.28, -1.55
	20	2.34, 1.97	3.88, 1.75	5.11, 2.35*	6.23, 2.79*	1.89, 0.86	4.28, 1.91

*$p < 0.05$ **$p < 0.001$

Note. Beta values (β) and t-statistics of fNIRS channels are reported across conditions for the intonation task.

Figure 1

Figure 1. Left: The waveform for the declarative statement "Melissa loved her alligator." Right: The waveform for the question "Melissa loved her alligator?" Stimuli recorded by a female native English speaker. Photos captured in Praat.

Figure 2

Intonation contour	Example
Declarative statement with constant pitch fall	Melissa loved her alligator.
Yes/no echo question with constant pitch fall until last syllable	Melissa loved her alligator?
Declarative statement with subject focus	*Melissa* loved her alligator.
Yes/no echo question with subject focus	*Melissa* loved her alligator?

Figure 2. Examples of the varying intonation contours present in the intonation task.

Figure 3

Condition	Example	Correct response
Same	“Melissa loved her alligator?” “Melissa loved her alligator?	Same
Different intonation	“Melissa loved her alligator.” “Melissa loved her alligator?”	Same
Different words	“Melissa loved her alligator.” “A lion licked your radio.”	Different

Figure 3. Examples across conditions for the intonation task.

Figure 4

Figure 4. Participants were presented with this photo of a dog (Stanley) while making intonation judgments so as to draw their attention to the task.

Figure 5

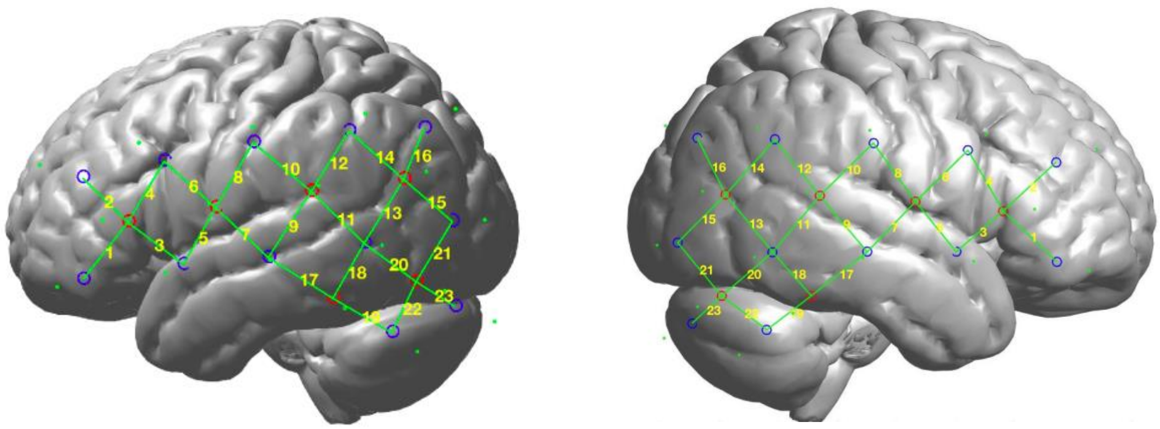

Figure 5. Left: fNIRS optode map for left hemisphere. Right: fNIRS optode map for right hemisphere.

Figure 6

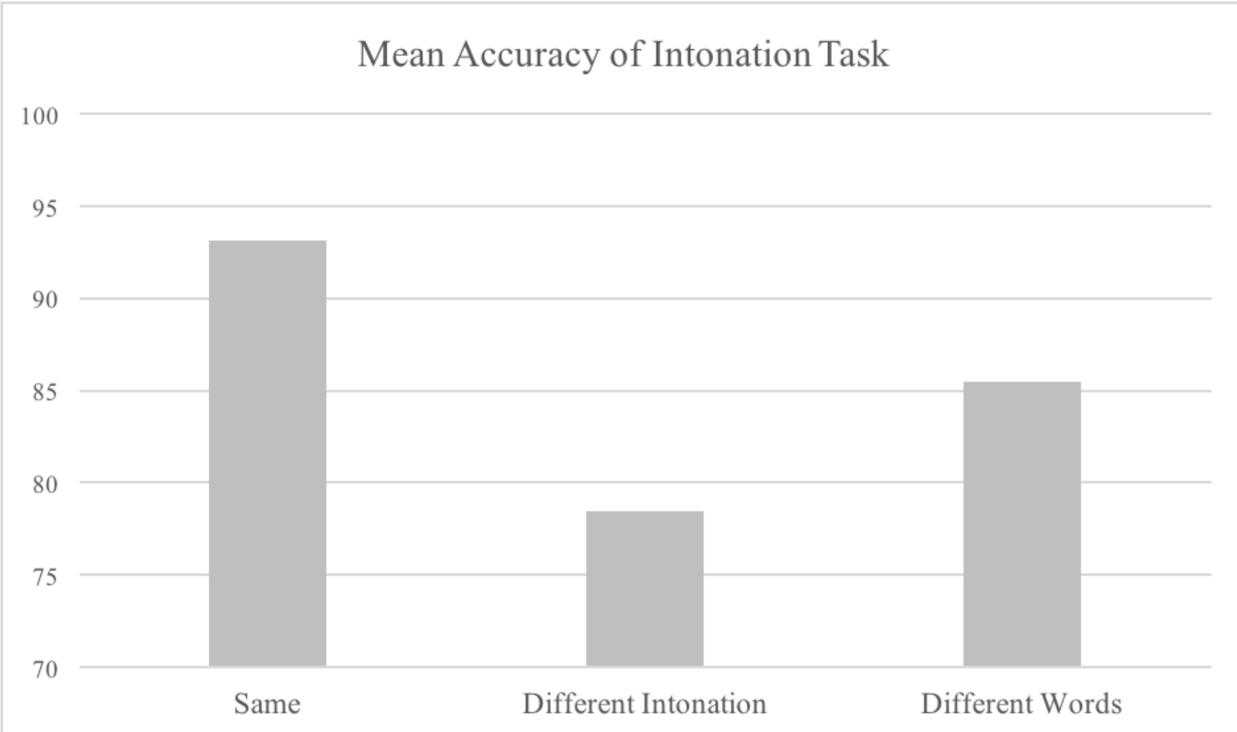

Figure 6. Mean accuracy (percent) across conditions of the intonation task.

Figure 7

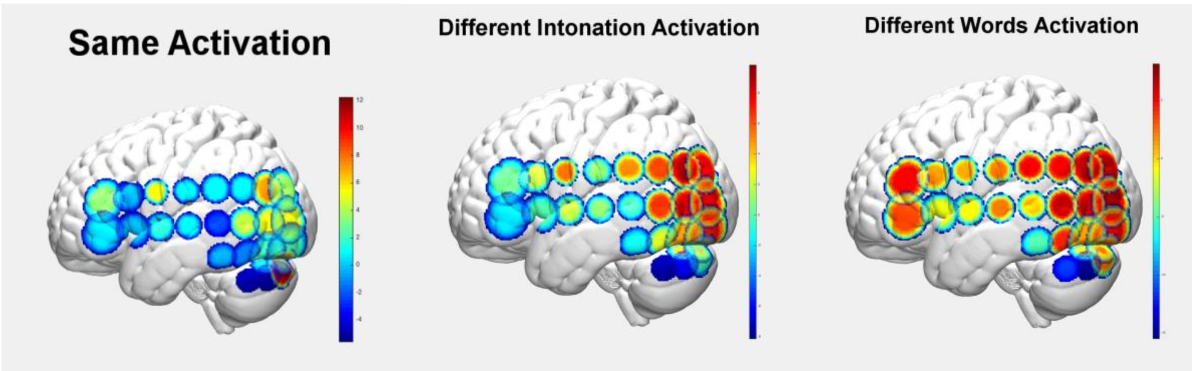

Figure 7. Activation across all conditions, represented in beta-values per channel, in the left hemisphere across participants (*N* = 28). Red indicates positive values, while blue indicates lower values. Note the robust activation in left temporoparietal regions for all three conditions, robust left temporal activation for the Different Intonation condition, robust frontal activation for the Different Words condition, and the overall more widespread activation elicited by the Different Words condition.

Appendix A

Complete list of intonation task stimuli

Lucy sang to her iguana	Amanda washed a monkey
Melissa loved her alligator	Robbie owned a mushroom
Andrew melted a lollipop	Ryan went to a magic show
Oliver ran a newspaper	Melanie found an eggplant
Lisa woke a reindeer	Nora yelled in a museum
Nancy ate a marshmallow	Linda licked an onion
An elephant arrived too early	An owl looked in her mirror
Your neighbor laughed at a whale	Your movie was about robots
A rabbit had a nightmare	A winner lost all his money
My window opened too loudly	A wolf swam all morning
Her mommy rubbed her elbow	Her moose used to be yellow
A lion licked your radio	Your animals made him nervous

Appendix B

Children were administered the Woodcock Johnson Tests of Achievement, Third Edition: Sound Awareness and Letter-Word Identification; the Oral Expression subtest of the Oral and Written Language Skills (OWLS), Second Edition; the Nonword Repetition task from Comprehensive Test of Phonological Processing (CTOPP), First Edition; and the Digit Span task from the Weschler Intelligence Scale for Children, Fifth Edition.