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Article

Exploration of Teacher-Student Neural Coupling Occurring During the Teaching and Learning of Science

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Abstract: Verbal communication to relay information between students and the teacher, i.e., talk, lies at the heart of all science classrooms. This study investigated and began to characterize the neurological basis for the talk between science teachers and students in terms of speaker-listener coupling in a naturalistic setting. Speaker-listener coupling is the time-locked moment in which speaker vocalizations result in activity in the listeners brain. This activity is highly predictive and tightly ties to listener understanding. The design for this study was an observational stimulus-response study using neuroimaging data obtained from talk sessions between a teacher and a student. Results were obtained using a functional near-infrared spectrometer and an artificial neural network model. Examination of the data suggested that speaker-listener coupling occurs between a student and a teacher during successfully understood verbal communications. This study promotes further research into the exploration of how individual interactions between persons (speakers and listeners) via talk are perceived and influence individual cognition. Study outcomes suggest coupled brains create new knowledge, integrate practices and content, and verbal and nonverbal communication systems which are constrained at two levels the environmental level and the speaker listener level. The simplicity of brain-to-brain coupling as a reference system may simplify the understanding of behaviors seen during the learning of science in the classroom.

Keywords: Speaker-listener Coupling, Student-Teacher Talk, Science Education, fNIRS, Neuroimaging

1. Introduction

For over fifty years classroom communication between a speaker and listener and the way it contributes to learning has been a key topic of research in the science of learning as well as other fields, such as neuroscience (Liu *et al.*, 2017; Stephens, Silbert, & Hasson, 2010), cognitive psychology (Piazza *et al.*, 2020; Richardson & Dale, 2005), and science education (Benek & Bezir Akcay, 2019). Each of these fields seem to agree that there are significant links between verbal communications among students and teachers (talking) and cognition (thinking) and learning (Clough & Duff, 2020). The acceptance of the existence of these links is driven by empirical evidence derived from teacher and student behaviors and has led to the development of multiple talk-based pedagogies in science teaching (Khong et al., 2019). An underlying assumption of talk-related pedagogies is that good teaching promotes talk between students and other students and between students and teachers (van der Veen *et al.*, 2017). During talk, students and the teacher may engage in activities which prompt questioning, reasoning, and utterances which reflect, and which involve decisions, understanding, thoughts, and responses via working memory manipulations and encoding in long term memory. Critical to this process is the understanding of the speaker's talk by the listener. The results of talk between speakers and listeners (teachers and students) are often characterized as successful when a student (listener) can articulate understandings about a topic on a written assessment. From this behavior, manifested on an assessment, it is inferred that the student is able or unable to engage clusters of cognitive resources and apply an existing semantic network to address the assessment (Hand *et al.*, 2018). Assessments of understanding are used at all levels of the P-20 continuum to characterize effective teaching and learning occurring through talk.

Verbal communication to relay information between students and between students and the teacher, lies at the heart of all science classrooms. Talk is the use of specific sound patterns within the structures of language to convey ideas and relay information from one person to another (Holler & Levinson, 2019). The intent of talk in the science classroom is to address and promote the engagement of specific semantic networks and application of cognitive resources. Talk in the classroom is used to relay information with the intent of building understanding and integration of content and practices. While there are certainly many more forms of communication in the classroom, none are as prevalent as talk (Lefstein et al., 2020). Research in science education and other related fields has focused on the identification, exploration, and promotion of talk between teachers and children and between children themselves to foster specific engagement for learning purposes e.g., Khong, Saito, & Gilies (2019). Research has illustrated that the talk involving open-ended questions, strongly promotes learning (Salloum & BouJaoude, 2019). However, the cognitive mechanism that underlies the value of talk is not well understood and studied in science education. One proposed explanatory mechanism to understand and more clearly identify productive talk, engagement of cognitive resources, and applications of specific semantic and procedural networks, is through a neural process known as speaker-listener coupling. Speaker-listener coupling is the time-locked synchronization of a speaker's and listener's brains resulting from the activity in the speaker's brain in response to verbalizations which directly precede synchronized activity in the listener's brain. This synchronization occurs because of fundamental biological structures and functions in the human brain (Stankovski *et al.*, 2017). The synchronization of speaker and listener brain activity is indicative of understanding of the speaker by the listener, which can manifest itself behaviorally as applications of knowledge and engagement (Czeszumski *et al.*, 2020).

Despite findings in science education research that talk is beneficial, there is still evidence that classroom activities and learning using talk do not routinely occur (Goodwin *et al.*, 2020). Talk in classrooms is often one-way and consists of closed questions with little initiation and promotion of underlying reasoning. There is still little understanding of the mechanism for why some forms of talk may promote positive learning gains while others do not. Research in science education often focuses on the organization (Lim & Wilkinson, 2019), modes (Larrain et al., 2018), and environments (Sawyer *et al.*, 2018) that seem to promote greater talk in the classroom. As opposed to other studies which have examined speaker-listener coupling in laboratory settings with controlled interactions, this study seeks to examine if speaker-listener coupling is present in a semi-naturalistic setting seeking to approximate the talk which may occur in the science classroom.

1.1. Purpose and Research Questions

The purpose of this study is to investigate and begin to characterize the talk between teachers and students in terms of speaker-listener coupling in a semi-naturalistic setting via speaker-listener coupling patterns of hemodynamic responses. These patterns are thought to illustrate understanding of content versus confusion. The research questions for this study are:

While engaged in talk, which characteristics of speaker-listener coupling are present between a student and teacher?

Which patterns of hemodynamic response related to teacher and student talk correspond to understanding or confusion during speaker-listener coupling?

Based upon the research questions the authors offer the following hypotheses. Hypothesis 1, based upon previous research in which speaker-listener coupling has been identified in laboratory settings (Camerer & Mobbs, 2017), is that a statistically significant relationship will exist in the form of speaker-listener coupling between a student and a teacher when they are engaged in talk. The hypothesis for research question two is speaker-listener coupling will only occur during talk in which understanding between the speaker and the listener is achieved (Liu *et al.*, 2017). Substantiation of the hypotheses will provide evidence that the talk occurring between a teacher and student unfolds through engaged participation by the listener and time-locked synchronization of neural activity will signify understanding of the topic. In contrast, lack of understanding will be signified by the lack of time-locked synchronization and subsequently reduced applications of existing semantic and procedural networks. Talk in the classroom is identified in two processes, Process 1 which is the externalization of the practices and content through talk and Process 2 which is the internalization of talk through working memory for encoding into long term memory.

Current research in science education makes use of three general approaches to present empirical evidence in identifying the relationship between classroom talk and student outcomes. The studies cited in educational research typically consist of case studies of individual teacher-student talk in the classroom (Process 1 focused), intervention-based studies which seek to promote greater talk (Process 1 focused), and relational studies which correlate talk and student outcomes (Process 1 focused). Case studies typically use self-reports, interviews, and observations of teachers trained and encouraged to make use of talk intensive pedagogies (Johnston *et al.*, 2019; Ramli, 2019; Lee et al., 2018). In contrast, intervention studies are typically designed to build effective infrastructures and environments in the classroom which increase talk and thereby increase learning (Chen, 2019; Colley & Windschitl, 2016; Hand et al., 2020). Intervention studies often examine and focus on the specific characteristics of talk and the classroom environment through which to intervene, but they usually do not account for Process 2. For example, the Science Talk-Writing Heuristic is often scaled at various levels from the classroom, school, or district level of implementation with little investigation how individual student differences in cognition (Process 2) may play out and influence outcomes in learning. The final type of study, correlational studies, capture and relate talk to learning as an outcome occurring in natural classroom settings. These studies are often unable to make causal and predictive statements about the effectiveness of talk in the science classroom. An understanding of the mechanisms underlying the production and comprehension of talk would allow for greater ability to predict effects, build interventions, and triangulate self-reports. However, few studies have combined examinations of internalization, talk, and student outcomes. One approach to examination of the three areas of interest, internalization, talk, and student outcomes, is through incorporation of neurological evidence which is well suited to examine Process 2.

1.2. Theoretical Background

Student learning through interactions, applications of semantic networks and application of cognitive resources through verbal communication, i.e., talk, is firmly situated in sociocultural theory and is examined via behavioral processes. A semantic network is a network which represents the relationship between concepts (Benedek *et al.*, 2017). This is often identified as a form of declarative long-term memory while its application of the networks is identified as a function of procedural long-term memory. Sociocultural theory suggests that students develop functional statuses related to learning via two interacting behavioral processes (Samon & Levy, 2020). The first process (Process 1) is through the student's interaction with other people, such as talk, and the second (Process 2) is through internalization of the external information. Process 2 consists of semantic and procedural network application, cognitive system clustering, and cognitive resource recruitment. Internalization is the process by which assimilation of information occurs through the interactions of working memory (applications of semantic and procedural networks) and long-term memory (cognitive resources) with encoding and retrieval occurring as a result (Gilboa & Marlatte, 2017). While the first process (e.g., talk) can be readily observed, the second process (internalization) is not readily and directly examined and is often inferred from the first process. There is agreement that both processes are necessary as researchers have identified that it is the combination of the two processes; the interaction between thought and speech that results in understanding and learning (Kelly, Barr, Church, & Lynch, 1999). It is suggested by Sedova *et al.*, (2019), that the more opportunities a student has to talk with others the more likely they are to learn new content. Thus, talk and language can be used as a tool to increase student understanding and the learning of new concepts. Like other research, the Sedova *et al.*, (2019) study was constrained to examining the talk process only and was not able to establish an underlying mechanism connecting the talk process (Process 1) and the internalization process (Process 2). Thus, the underlying mechanism of action connecting behavior to cognition in the classroom was not examined.

Talk between teachers and students is established through dual participation of a speaker and a listener. The speaker is responsible for the construction of syntax, grammar, and context of the information. Neurologically this occurs through cognition which changes encoded memory to motor intentions, and ultimately execution of vocal patterns which are analyzed by the listener. The listener in this context is responsible for the development of the sound patterns in constituent parts of words (phonemes), words, sentences, and decoding the words into meaning. Advances in the use of neuroimaging and related methods has allowed educational researchers to understand which neural processes are involved in social interactions related to internalization during student-teacher talk. Time-locked synchronization or coupling of neural tissue oxygen demand between the speaker and listener has been repeatedly demonstrated in laboratory settings during verbal communication (Descorbeth *et al.*, 2020; Varga & Heck, 2017; Ahn *et al.*, 2018). Much of the research explaining how speaker-listener coupling occurs has taken place using functional magnetic resonance imaging (fMRI). Listeners' neural activity is illustrated to be coupled with brain activity both with a predictable delay, in real-time, and prospectively (e.g., performing a planned action) due to anticipatory effects by the listener (Redcay & Schilbach, 2019). In addition to the use of fMRI to examine speaker-listener coupling, high-density electroencephalography (EEG) has illustrated non-homologous brain areas couple between the speaker and listener. This means that when a time-locked synchronization occurs, understanding can occur even when the areas of coupling do not overlap between the speaker and listener. The strength of the coupling activity was evidenced by neural responses known as a hemodynamic response. As the complexity of the information increased (words versus sentences versus paragraphs), the intensity of activation also increased so long as understanding was occurring (Van Turennout *et al.*, 1997). While fMRI and high-density EEG are powerful tools to examine underlying neural processes, they are extremely restrictive and unsuitable for use in naturalistic settings such as a classroom or even a simulated classroom. A newer neurological measurement approach which has recently come to the attention of educators is functional near-infrared spectroscopy (fNIRS), which allows researchers to capture some of the information typically found in an fMRI with less invasiveness and the ability to be used in classroom and classroom-like settings.

The ability to examine hemodynamics across multiple lobes in the brain provides information about the cognitive systems used during both the processing of talk information and locations which may couple during talk. Areas of interest include the frontal lobe, parietal lobe, the occipital lobe, and the temporal lobe. The parietal lobe is associated with integration of spatial, sensory, navigation, and symbolic interpretation including written and spoken language, mathematical problems, and long-term memory (Fogassi & Luppino, 2005; Karnath et al., 2001; Wagner *et al.*, 2005). Activations within the parietal lobe may be indicative of understanding of content based upon association of functions and structure. The occipital lobe is primarily responsible for conscious vision, memory retrieval, and object recognition (Bar, 2003; Bladowski *et al.*, 2006; Pins & Ffytche, 2003). The temporal lobe processes auditory information and encodes them into long-term memory for integration (Jenkins & Ranganath, 2010).

1.3. Functional Near-Infrared Spectroscopy (fNIRS)

fNIRS measurements represent the local hemodynamic response directly below the probes. Hemodynamic response is a form of neurocognitive data measuring the oxygenation and deoxygenation of hemoglobin due to neuronal metabolism. The increases in blood flow to tissue demanding a greater supply of oxygen is due to increases in neuron metabolism due to synaptic depolarization related to increases in cognitive activity (Mintun *et al.*, 2001). Each stimulus event is related to neurovascular coupling and leads to a time-dependent outcome. This outcome is consistent with producing a stimulus-neurovascular coupling complex or microstate function called a Hemodynamic Response Function and is related to cognitive function and creates the causal linkage between talk, listening, and the hemodynamic response.

Functional near-infrared spectroscopy is a non-invasive neuroimaging tool which measures the absorption and scattering of near-infrared light (650 nm to 950 nm) to a depth of 10 mm in human tissue. fNIRS has multiple important features which make it an important tool for measuring hemodynamic responses in classroom and classroom-like settings. This is particularly true when contrasted with EEG, magnetoencephalography (MEG) and fMRI. fNIRS is noninvasive and does not require the participant to ingest dye or contrast and is operable by a single researcher. fNIRS does not require the participant to remain immobile. fNIRS is worn on the head and weighs only a few hundred grams. The characteristics of fNIRS as a measurement tool allows placement and study of hemodynamic responses in naturalistic settings which is not possible using other neuromeasurement tools. fNIRS also allows greater spatial resolution than EEG and MEG, though less than fMRI, and has greater signal discrimination between multiple regions.

In summary when comparing fNIRS to other neuroimaging techniques, fNIRS is portable, silent, low power, does not create a high intensity magnetic field, and does not constrict subjects. This makes fNIRS an ideal neuroimaging device for use in classrooms as apart of educational research studies. Importantly, fNIRS has a higher temporal sampling rate (∼10 Hz) than fMRI (∼1 Hz), which helps to prevents the aliasing of higher frequency cardiac (∼0.8–2.5 Hz) or respiratory (∼0.15–0.3 Hz) activity, resulting in a more reliable signal estimation (Lee *et al.*, 2018). Consequently, fNIRS shows great promise for studies aimed at providing further insights into spontaneous brain function and allows integration into science education research.

2. Materials and Methods

This is an observational stimulus response study using neuroimaging data obtained from talk sessions between teachers and students. All procedures performed in this study involved human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments and comparable ethical standards. Informed consent was obtained from all individual participants or their guardians. In addition to hemodynamic response data, the authors made use of content tests and a questionnaire as evidence of student understanding. Combining neuroimaging evidence with assessment data makes it possible to more fully elucidate a mechanism of action linked to teacher-student talk coupling and provide information about Process 2, internalization of talk.

2.1. Participants

Sixteen dyads for a total of 32 participants took part in this study and received no compensation for their participation in the study. The dyads consisted of sixteen elementary teachers and sixteen elementary students randomly assigned to each other but from the same district. The students were aged 9 to 10 and in fourth grade. Teachers were aged 23 to 26 and were all within their first, second, or third year of teaching. Students were sampled from the teachers' classes; however, students were not paired with their own classroom teacher. Teachers and students were selected from school districts located in the Northeastern and Mid-Atlantic regions of the United States. One dyad was excluded from the data analysis due to excessive motion during the session. The excessive motion occurred when the student participant got up from the chair and attempted to write on a white board within the laboratory classroom environment. This reduced the number of dyads to fifteen with a total of 30 participants. An analysis of power suggested that there was a .96 probability of detecting a small effect with 14-dyads. All participants were right-handed and were screened using the Compendium of Neuropsychological Tests (Sherman, Tan, & Hrabok, 2020); no specific neurological (e.g., epilepsy) or mental (e.g., ADHD) differences were noted. In addition, none of the participants had used medications or other items which are known to influence mental alertness and brain activity. Using the National Institutes of Health (NIH) Cognition Measures for ages 7-17 for screening purposes, the researchers determined whether each of the students was on grade level with respect to their ability to read and write (McKenzie et al, 2020). The NIH cognition measures which were used in this study were: (A) the

Flanker Inhibitory Control and Attention test (3-Minutes), with alpha = .92 for this sample, which measures attention and executive function; (B) the List Sorting Working Memory test (7-Minutes), with alpha = .88 for this sample, which examines working memory ability; (C) the Picture Vocabulary Test (4-Minutes), with alpha = .91 for this sample, measuring language ability; and (D) the Oral Reading Recognition Test (3-Minutes), with alpha = .87 for this sample, measuring reading decoding skill and crystalized abilities.

2.2. Conditions

Students, students' parents, and teachers were invited to a university laboratory classroom. The participants were specifically scheduled so only one group was present in the classroom setting at a given time. However, multiple participant sessions occurred during the day. The study protocol was explained to each of the participants and their parents, and assent from the students and consent from the parents and teachers were obtained. Total time spent in the laboratory classroom was 65 minutes. During the session the student was seated at a table and the teacher was seated at another table near the student. The teacher and student could see one another. Both participants were allowed to examine the fNIRS bands, try them on, and ask questions. We also placed the band on their head and let the participants experience what it was like to have the band active and collecting data. During the initial preparation, we also let the participants see what the data looked like that was collected. The bands were then removed, the participants were allowed to move around and see to their comfort needs. When ready, the teacher and student were again seated at their tables. The fNIRS bands were placed on each of their heads and baseline data was collected. Baseline data pre and post task data collection consisted of 5 minutes of data collection with no interaction and no task given. During each of baselines (I and II) the student's eyes were closed. After five minutes the student and teacher were given one of five tasks. The researchers counterbalanced the order of the tasks to ensure that there were no ordering effects. Each task consisted of conditions designed to replicate speaker-listener neural coupling as shown in previous studies (Stephen, Silbert, & Hansen, 2010; Dikker *et al.*, 2014; Hirsch *et al.*, 2018). Counter balanced task presentation consisted of (a) Task 1: *Science Task Fourth Grade*; this task consisted of the teacher reading an unrehearsed summary text of how minerals are identified using tests for physical properties such as hardness, color, luster, cleavage, and streak. The text was an excerpt from an elementary school science textbook, *Inspired Science* published by McGraw Hill. This took approximately six minutes to complete. After the teacher completed the first task, the student and teacher were monitored until their hemodynamic responses measured by the fNIRS returned to baseline. This took approximately six minutes. (b) Task 2: The *Science Task College Level* consisted of the teacher reading an unrehearsed scripted summary text from a college freshman geology text on the use of physical properties to identify minerals using the same physical properties of hardness, color, luster, cleavage, and streak. After completion of the task the students and teachers were then again monitored until their signals returned to baseline. This took approximately six minutes. (c) Task 3: The *Non-Science Task Fourth Grade* consisted of an unrehearsed summary excerpt from *The Hope Chest,* which is non-science text that took approximately six minutes to complete. After completion of the reading the teacher and student were monitored until their signal returned to baseline. (d) Task 4: The *White Noise Task* consisted of white noise played for six minutes as a control condition, controlling for auditory stimulus alone creating the coupling effect. The fifth task (e) Task 5: *Recorded Science Text* consisted of playing a recorded summary text (total time 6 minutes) from a second fourth-grade science textbook which was different from Task 1. The topic covered was how minerals are identified using tests for physical properties such as hardness, color, luster, cleavage, and streak. As with the previous conditions the participants were monitored until their signal returned to baseline. Upon completion of each of the tasks the students and teachers were asked if they did or did not understand the content from each of the tasks and to rate their understanding on a scale of 1 to 4 (1=None of the text; 2=Some of the text; 3=Most of the text; and 4=All of the text). In addition to the rating of understanding, the students took a short five question multiple choice content test on the topics covered in the science texts (using parallel tests for science topics) and a five-question multiple choice test on the topics covered in the non-science text taken after task completion.

2.3. Data Acquisition

Data acquisition and visualization occurred using Cognitive Optical Brain Imaging Software (COBI) Studio software version 1.3.0.19. Signal processing and data preparation for statistical analyses was accomplished using the fNIRS Soft Professional 4.10 software. The sampling rate of the fNIRS devices was 4 Hz. Data consisted of fNIRS measurement and imaging data, video, content test scores, and questionnaire results. The video was solely used to determine if there were any irregularities such as large-scale movements during the use of the fNIRS. No irregularities were noted with the exception of the previously mentioned group which was removed from the analysis. The stimulus (talk) was presented to each participant via the teacher and measured as a block of stimulus which was time locked to hemodynamic responses. An example of a block is a unit of measurement performed during the B condition of an A-B-A approach. The B condition contains all measurements performed during that condition and are aggregated together as a moving average. With the A-B-A approach, B is the stimulus. See Fig. 1.

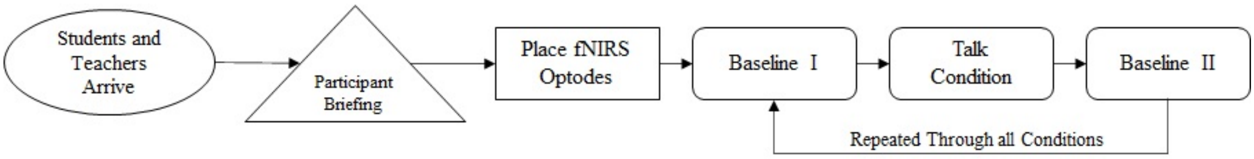

Fig. 1. Flow chart of study activities.

2.4. Data Processing and Data Analysis

As is common in neurological studies, the amount of data was particularly large with over 50,000 data points collected per session. Given the large amount of data and the impact of other physiological processes such as breathing, heart rate, and potential movement, significant data preprocessing is required and was completed prior to full analysis of the oxygenated and deoxygenated hemoglobin concentrations.

2.4.1. Data Preprocessing

Data pre-processing begins with removal of heart pulsations, respiration, and gross movement artifacts (Pinti *et al.*, 2018) using a .14Hz cutoff low pass filter (Nguyen et al., 2018). The .14Hz filtering of the data should result in less than 10% loss of data for each of the fNIRS measures to be consider usable. Data loss from this process in the present study was 7.3%. Extracranial and cerebral contributions to fNIRS signals were separated by means of regression during initial data processing per optode - an optical sensor device which measures the concentration of a substance through changes in wavelengths associated with the substance. There are 54-optodes which collected data associated with the hemodynamic measures in this study. See Fig. 2.

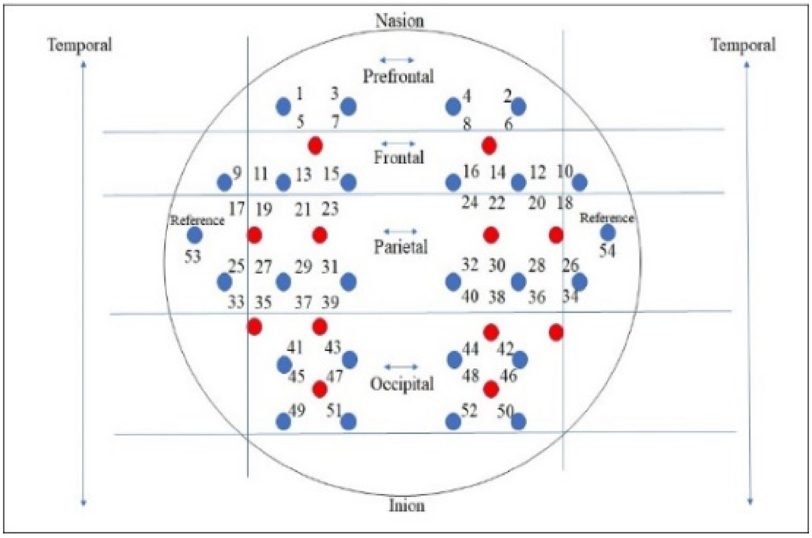

Fig 2. Optode ($n = 54$) and emitter locations.

Even with a loss of data due to movement and filtering, when compared to neurotechnologies such as fMRI, the loss of data is minimal for fNIRS as a neuroimaging technique, given the level of movement associated with classroom activities (Pinti, *et al.*, 2020). Hemodynamic concentration ratios were converted to standardized Z-scores with respect to Baseline I to allow for comparison between individuals and tasks. A moving mean was calculated for each of the participants across each component of the A-B-A sequence during the fNIRS portion of data collection. The calculated moving mean was used to help smooth out short-term hemodynamic response spikes, filter out signal noise, and to ensure that large variations in hemodynamic response did not overweight the analysis. From these moving means, composite values of hemodynamic responses per person and data visualization were created for analysis.

2.4.2. fNIRS Data Analysis

Mixtures of general linear models (MGLMs) were used for analysis of the data from this project (Friston, Harrison, & Penny 2003). A mixture model is a probabilistic causal modeling approach used to represent the presence of subpopulations in the data. This allows us to answer Research Question 1. In this case, the researchers were interested in the subpopulation of optodes which exhibit activations above baseline. During functional brain studies, it is common to use general linearized models such as MGLMs to detect differences between tasks and baseline (i.e., Baseline I, Stimulus Task, Baseline II or A-B-A). In other words, the linear assumption is that each time the task occurs, the brain changes by the same amount without saturation effects or interactions between trials and talk conditions. This was examined using the statistical program R 3.3.1 with the ***mixtools*** package. A mixture model will determine if there are overall differences between each of the conditions as a function of optode detection of hemodynamic response (Boisgontier & Cheval, 2016). This approach allows the researchers to examine which optode/s illustrated greater response and is important for each condition. Once each optode of significance is identified, the optode was mapped to the location on the brain based upon its emitter and detector placement. The combination of optode activations are the patterns of data inputs into the artificial neural networks in time sequence to model whether or not coupling is present. Correlational analysis was conducted between outcomes on the tasks and the students' assessment of their comprehension of the topic. Estimated models used a maximum likelihood approach with an Expectation-Maximization (EM) algorithm using R with the ***mixtools*** package. The selected model used to identify the optodes of significance illustrate the lowest Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) equal to 801.1 and 819.7 respectively.

2.4.3. Artificial Neural Network Development (ANN)

The goal of the analysis of the computational model was to evaluate the multiple network weightings from the modeled interactions between the speaker and listener. The results of this computational model answer Research Question 2. In answering Research Question 2 the aim is to identify the models with highest accuracy and most generalized fit that would predict the test data from the training data with the lowest error. To find the architecture that illustrates the best data fit and conceptual fit, multiple metrics were used in the form of Conforming Capability and Generalizing Capability (Conforming = Mean of Mean Squared Errors of training data ($M\mathrm{MSE}_{\mathrm{tr}}$).+ Mean of Mean Squared Errors of test data ($M\mathrm{MSE}_{\mathrm{tst}}$) and Generalizability = $M\mathrm{MSE}_{\mathrm{tst}}$ - $M\mathrm{MSE}_{\mathrm{tr}}$. Analysis of stability used the standard deviation of the mean squared error (*SD*MSE) and variations, i.e., rival model architectures, which still met conceptual requirements, when the highest standard deviations are removed. In this light the most generalized architecture would have the closest training and testing data comparison of optode means. As identified by Testolin & Zorzi, 2016 and Tan *et al.*, 2019, ANNs have been used extensively to model cognitive functions and classify outcomes with good results. The ANN used in this cognitive computational model is an error back propagation model and the Levenberg-Marquardt algorithm which adaptively varies the parameter updates and splits updating between the use of a Gauss-Newton updating procedure and a Gradient Decent procedure (Andrychowicz *et al.*, 2016). The key concept in this approach is that the recurring connections allow previous inputs to influence unit outputs.

The neurons within the most complex ANN model in this study is estimated to have six distinct layers and 13 nodes representing each of the areas covered by the fNIRS optodes (See Fig. 3). The layers are input, hidden 1 (Prefrontal), hidden 2 (Fontal), hidden 3 (Parietal), hidden 4 (Occipital) and output. The topology is organized in a form known as a Multilayer Perceptron and is commonly used in cognitive science and neuroscience for the modeling of cognitive functions related to long term and working memory or the internalized processes (Process 2) associated with talk (Owen *et al.*, 2005; Maldonato *et al.*, 2018). The input layer provides no computational function but distributes the stimulus. The hidden layers represent the cognitive processing units and the output layers consist of the output probabilities associated with coupling or not coupling between the speaker and listener. The ANN in this study was designed using R 3.3.1 using the ANN package. The proposed method uses a K-fold cross validation which divides the data set into k-number of similar sizes randomly drawn data segments. The segments or folds are used for both training using speaker data and testing using listener data. Comparison of training to predict testing data in ANNs is a common validation approach. Cross-validation using K-fold as an approach has successfully been used in fields such as engineering (Wijayasekara et al., 2011). However, to generate a more generalized model, this method uses one segment of the data for validation and two segments for training. In this way the dataset is divided into three segments containing response data for use in developing the cognitive computational model. Link weights initially consist of randomly weighted values ranging between $\Omega = \pm 2$ (Gallant, 1993). Range limitations ensure that the propagation potentials do not become too large and result in the selection of one dominating node. This sets the conditions for the computational experiment (comparison) examining coupling or non-coupling between speakers and listeners during the tasks.

3. Results

Examination of the data suggests that speaker-listener coupling occurs between students and teachers during successfully understood talk. Fig. 1 provides and map of the optode (blue) and emitter (red) locations for both the speaker and the listener. Based upon the optode map in Figs. 3 and 4, the optodes which show the same activation between the speaker and listener when time-locked -six seconds- from the onset of speaking or listening. Values are expressed as percentages of overlap in a bar graph. Optode maps illustrate areas of hemodynamic response (green optodes). This means that the coupling was present in the speakers' and listeners' brain activity relative to the moment the speaker began to produce vocalizations. In consideration of this, it can be concluded that the listeners' neural activity mirrors the speaker's neural activity with a consistent (across all participants) delay of six seconds. The delayed response is attributed to the speaker's inducement of mirrored activity observed in the listener's neural activity during comprehension. This shows that the coupling was apparent when the teacher and student communicated successfully, i.e., when the talk was understood. Examination of content tests results also supports this; the fourth grade non-science text (α=.89, *M*=4.1/5.0), the fourth grade science text (α=.84, *M*=3.6/5.0), and the college science text (α=.82, *M*=1.2/5.0) illustrate that each of the listeners understood (>80%) the content of the fourth grade texts but not of the college text. Differentiation of levels of understanding are based upon scores on the three content tests (non-science text test, 4th grade science text test, college text test) that the students took. Content tests were parallel and cover the same concepts discussed during the readings.

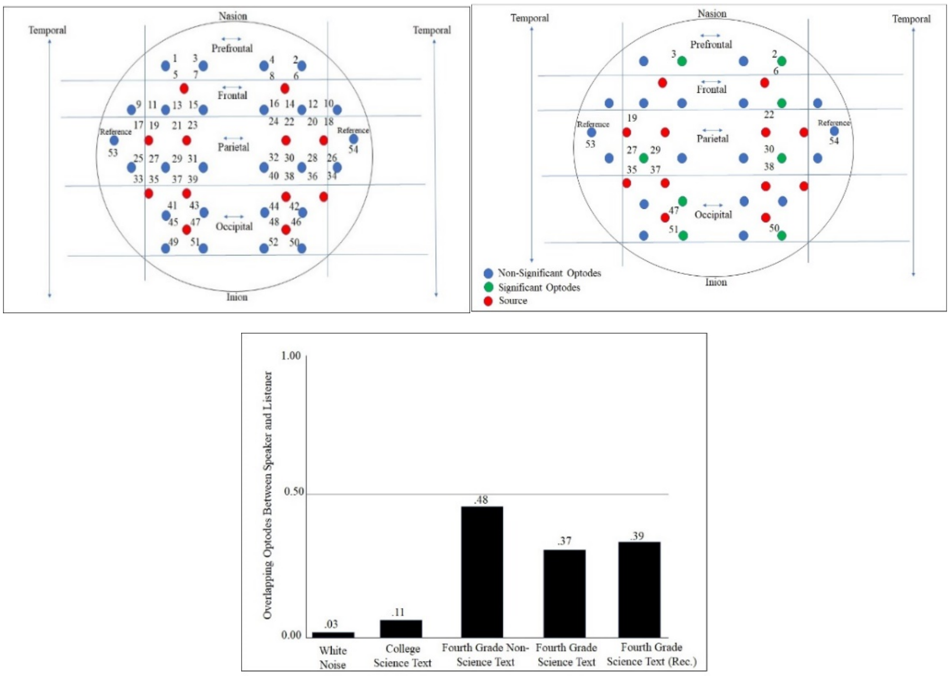

Fig. 3. Optode and emitter locations for reference (**Left**), optodes of significance illustrating speaker-listener coupling (**Right**), graphical comparison of overlapping optodes by condition (**Bottom**).

Speaker-listener coupling may or may not be restricted to similar areas of activation (shown in Fig. 2). Studies have illustrated that the hemodynamic response of listeners can be offset not only by specific times but can also be anticipatory and activated prior to vocalization by the speaker (Silbert, *et al.*, 2014)). Examination of these effects occurred using mixtures of general linear models and artificial neural networks. Using these combinations of techniques, it is possible to examine the combinations of speaker-listener couplings which result in a specific time-locked shift illustrating that the speaker preceded the listener (illustrated by positive values) or listener preceding speaker through anticipation (illustrated by negative values). The anticipation effects were unexpected and beyond the scope of this study but may be examined in later studies. For the 4th Grade non-science text, the 4th Grade science text, and the recorded 4th grade science text, each text shows significant signal response at 6-seconds (Fig. 4) with no signaling before interactions and signal drop off occurring after interactions. Significant coupling illustrated by hemodynamics responses across these three conditions is seen in the prefrontal and parietal locations. The net areas of activation shown in Figure 3, include the sensory, linguistic and extralinguistic areas (Mahl *et al.*, 1964). Based upon structural and functional aspects of the brain, the locations of activations seem consistent with areas of expected neural coupling and understanding of content. No significant speaker-listener coupling was evidenced in conditions in which understanding did not seem to occur (white noise and college science text).

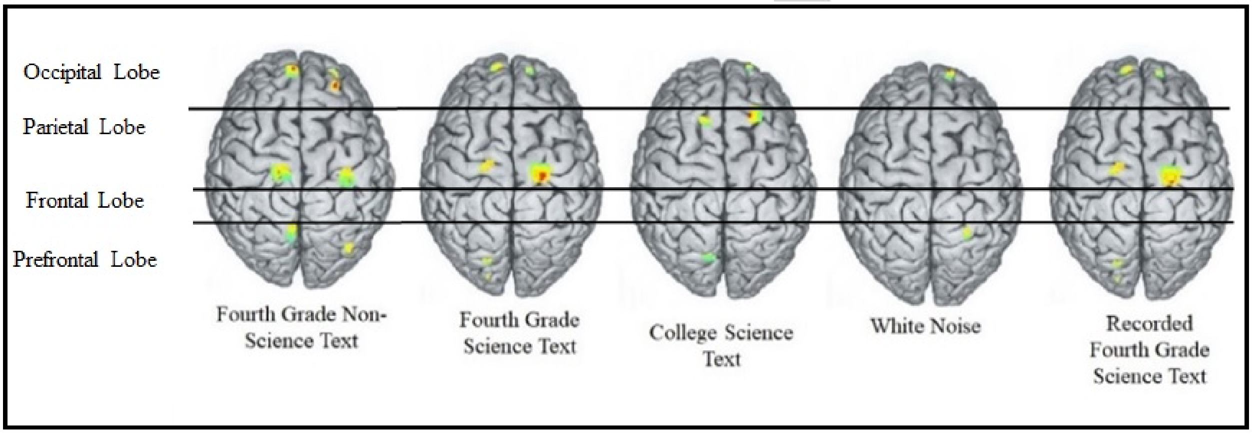

Fig. 4. Locations of speaker listener coupling across participants and conditions. ***Note:*** Displayed colors illustrate hemodynamic responses above baseline (Green: low, Yellow: moderate, Red: high), frontal view.

Further examination of the data to understand the presence or absence of coupling was illustrated through comparison of mean activation times across listeners as a group, speakers as a group, and speaker and listeners as a group. Results indicate that coupling did not occur in listener groups and speaker groups. Meaning comparisons of listener-listener coupling, and speaker-speaker coupling did not illustrate a significant difference in time shifts related to average hemodynamic response; $t_{Listener}(28) = .984$, $p = .167$ CI95% = −.129 − .350 and $t_{Speaker}(28) = .537$, $p = .298$, CI95% = −179 − .299. In contrast speaker-listener coupling illustrated statistically significant differences in time $t_{S\text{-}L}(28) = 6.45$, $p < .001$, CI95% = 5.01 − 6.98. This indicated significant non-synchronism (i.e., uncoupled) between listener and listeners and speakers and speakers, providing evidence for the speaker-listener coupling. The strength of the coupling increased as the text complexity decreased, i.e., as the listener understanding increased. For example, the fourth-grade non-science text illustrated the greatest level of coupling while the college text and the white noise condition illustrated the weakest coupling. The coupling occurs despite the presence of electronic recording devices. Examination of the correlation between strength of coupling and content test results illustrated statistically significant positive relationships across all conditions $r(14) = .81$, $p < .001$. In addition, questionnaire results illustrate that higher ratings of understanding of the texts by the student was related to the intensity of the coupling response $r(14) = .84$, $p > .001$.

Computational Results

Computational modeling was used to answer Research Question 2. To understand the systemic recruitment, networking, and clustering of cognitive resources the authors developed a computational model of speaker listener coupling using an artificial neural network (ANN). The ANN layers were modeled into distinct layers (Fig. 3). The topology of the speaker listener coupled models is organized into a multilayer perceptron and is commonly used in neuroscience for the modeling of cognitive function (Lopez et al., 2016). The input layer functions to disperse the stimulus data. The hidden layers are conceptually the cognitive systems for the processing of the speaker verbal stimuli by the listener. The output nodes are interpreted as probabilities of coupling related to the speaker text condition. Trained ANN results suggest that computationally modeled, speaker-listener cognitive processing, successfully predicts the coupling phenomena and the systemic network components which will couple. Table 1 illustrates ANN outputs for the selected model and the closest rival models. The model selected for use in this study illustrated the lowest conforming score and the highest generalizability score. In addition to the conforming and generalizability score, the author examined the changes in variance between the test data model and training model.

Table 1. Model and Rival Model Comparison.

Model	Condition	Conforming	Generalizability	Δr^2
Model 1	4th Gr Non-Sci	.58	.07	−.08
Model 1a	Rival 4th Gr Non-Sci	.62	.05	−.22
Model 2	4th Gr Sci	.86	.11	−.05
Model 2a	Rival 4th Gr Sci	.99	.07	−.14
Model 3	Col Txt	.59	.08	−.07
Model 3a	Rival Col Txt	.66	.04	−.10
Model 4	White Noise	.26	.12	−.02
Model 4a	Rival White Noise	.38	.09	−.03

Table 2 illustrates information related to ANN model outputs for each of the conditions. Training data results show that the highest level of coupling occurs in the 4th grade non-science text .68. The model also illustrates a significant predicative value of .84. Review of Table 2, illustrates that the trained ANN model is not as predictive of output states, e.g., *coupling* or *not coupling*. Although there is a reduction in the model ability to predict, the loss is not substantial ($F(3,12) = 2.18$, $p = .143$, $\alpha = .05$). The chi-square was not significant and thus the models predict coupling responses. Changes in root mean square error (RMSE) average + 0.02 (slight increase), but the change lacks significant differences when compared. Correlation coefficients average a high level of correlation ($r_{Mean} = .87$) providing evidence of a strong association between the training and test models. An overfit penalty of .05 was used during model development to reduce misspecification errors (Borra & Di Caiccio, 2010).

Table 2. Neural Network Output (Training Set | Test Set).

Network Characteristic	Probability of Coupling		Probability of Not Coupling		R-Sqr		RMSE		Mean Abs Error		Generalized R-Sqr		Correlation Between Models
4th Gr Non-Sci	.68	.66	.29	.27	.86	.84	.09	.09	.08	.06	.91	.89	.90
4th Gr Sci	.55	.51	.38	.37	.87	.86	.06	.07	.05	.04	.94	.88	.89
College Text	.39	.38	.59	.52	.85	.82	.06	.08	.09	.07	.87	.84	.86
White Noise	.06	.08	.64	.61	.89	.87	.07	.09	.06	.05	.90	.87	.84

The strength of cognitive activations across specific areas of the brain between speaker and listener are represented in the diagram as node weights (Fig. 4). This provides an illustration of how the stimulus data (talk) moves within the modeled areas. In addition, Figure 4 also illustrates the relative complexity of the coupling interactions. The 4th Grade Non-Science Text illustrates the greatest systemic complexity while the White Noise condition and the College Text illustrate the least complexity in terms of the cognitive network complexity and resource recruitment. The differences may result from a more robust semantic network and potentially more engagement with the non-science text versus the other conditions. In addition, the Parietal Lobe seems to illustrate the greatest response to coupling and is often most present when understanding occurs. This may be as a result of the functions of the parietal lobe associated with the interpretation and integration of sensory information to form singular coherent perceptions for further processing, manipulation of objects mentally and physically, automaticity in arithmetic, spelling and the components of language via declarative memory along with attention and decision making about internal representations (Mountcastle, 1995; Wagner, 2005; Karnath et al., 2001; Fogassi & Luppino, 2005; Bzdok *et al.*, 2016; Dieterich & Brandt, 2018). While the parietal lobe illustrated the greatest response the area illustrating the next most significant hemodynamic response was the pre/frontal lobe which is implicated in working memory, plaining and movement from Process 2 (Internalization) to Process 1 (Externalization).

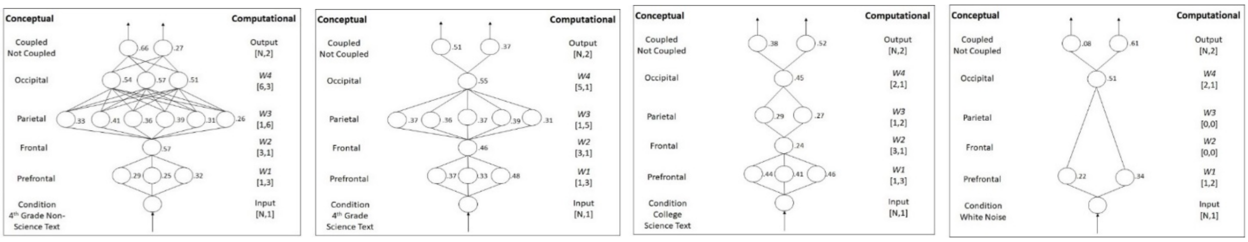

Fig. 5. Artificial neural network models of speaker-listener coupling.

4. Discussion

The intent of this study was to examine talk in a semi-naturalistic, education setting and the existence of a linkage between speaker, listener, and understanding of the texts used during classroom talk. Results from this study suggest a strong relationship develops as a teacher and a student interact; this relationship can be characterized as speaker-listener coupling. Importantly, this relationship is illustrative of why talk is central to science education and education in general. Increases in the number of opportunities linking speakers and listeners increases the complexity of networks and recruitment of cognitive systems, engagement of long-term memory (e.g., semantic and procedural networks), working memory (e.g., cognitive resources) and other cognitive systems used for understanding (Silbert *et al.*, 2014). Educational outcomes in science are attributed to the quality of classroom talk and evidenced in the recruitment of cognitive systems as understanding occurs. Neural coupling provides an explanation and testable mechanism for why understanding occurs. This also provides an explanation and evidence as to why underlying mechanisms of talk and interactions are important but not fully understood through examination of talk (Process 1) only. This study can be seen as a contribution towards the support of classroom talk and its underlying premises by examining and providing evidence for Process 2; internalization. This study may also promote further research into the exploration of how individual interactions between persons (speakers and listeners) via talk patterns can be perceived and are influenced by individual cognitive differences. The recruitment and application of long-term memory based cognitive resources such as semantic and procedural memory typically results from individual background knowledge. The background knowledge may assist in an explanation of why individual students respond differently to talk. Talk acts as an external stimulus triggering specific cognitive priming (Lamb et al., 2015). The cognitive priming promotes prior knowledge activation and may facilitate integration of the information associated with the talk. Meaning individual sematic and procedural network recruitment and their application is deeply dependent on prior knowledge and experience with topics used for talk accessed in working memory and indicated by pre/frontal lobe hemodynamic response. Awareness of how talk and memory interact can lead to greater understanding of talk pedagogy impacts and how individual students process information during talk sessions. This may lend to the potential of individualized instruction which can be built upon existing and nascent sematic networks for application. Meaning the intensity of neural coupling can provide information about the effectiveness of talk in activating prior knowledge. Assessments and curriculum designed with an eye toward coupling as a means to examine Process 2 may provide much greater individualized instruction.

Importantly, delayed speaker-listener coupling may also be used not only in face-to-face approaches but in synchronous and asynchronous online instruction. Our findings suggest that interactions between recordings and listeners via electronic means can lead to coupling and promote the use of specific clusters of cognitive resources and networks. This may be because listening (even delayed or secondary) to more skillful and experienced speakers can produce positive learning outcomes when structured appropriately. Importantly secondary and delayed speaker-listener coupling outcomes are on par with outcomes when speaker-listener coupling is delayed, see Figures 1 and 2. In addition to person to person coupling, coupling has been documented between a speaker and listener when the speaker is an audio recording (Perez et al., 2017). The use of audio recording is an attempt to understand delayed speaker-listener coupling. Delayed speaker-listener coupling occurs when the speaker encodes information onto a medium (in this case a digital audio file) for a listener to access later.

The results of this study suggest that it is useful to attend to, not just the level of interaction between a speaker and a listener, but also to the complexity of the talk and to individual neurocognitive response patterns of individual students. An important consideration in the translation of this work to classroom practice is to more clearly identify specific individual behaviors in the classroom that are linked to neural coupling and provide a window into student understanding. Cognition is highly variable and individual speaker-listener coupling may provide insight into how to best serve all students. This would further link talk Process 1 and Process 2. Unlike previous studies in education examining the role of talk alone, the authors of this manuscript examined the specific neurological relationships between speakers and listeners and the neurological effects associated with understanding and lack of understanding when the interactions occur. In other words, this study provides a marker, based upon neuropsychological data for when internalization happens. Results suggest that both Process 1 and Process 2 activities are needed to create successful learning through talk. It may be Process 2 (semantic and procedural network application, cognitive system clustering, and cognitive resource recruitment) aspects which help to strongly promote learning. Deficiencies in Process 2 result in a lack of understanding as illustrated with the college level text. As talk in many cases is foundational to learning in science the ability to internalize the talk seems to be the limiting factor in learning as is shown by examining the activities of the parietal lobe in this study by condition. Results illustrate that activity in the parietal is seen in talk sequences which there were both self-reported as understanding and have assessment evidence for understanding by the listener. The possible positive outcomes resulting from student talk interaction within the classroom is predicated on the notion of continuous interactions in which, the student works in conjunction with their teacher and as a collective interaction resulting in the acquisition of new knowledge and development of novel sematic and procedural networks via talk (Process 1 and Process 2) (Sizemore *et al.*, 2018). Coupling between speaker and listener may act as the cognitive mechanism of action in which the more advanced person or teacher (the speaker in this case) becomes cognitively available to the other members of the group the listener or student. The availability of the concept allows the listener to observe, rehearse, and encode new information via working memory and long-term memory and promote internalization (McDonald, 2020).

The coupling acts as a cognitive primer and may act to generate complex coordination of behaviors between speakers and listeners seen in learning (Hasson & Frith, 2016). These complex behaviors are intended to promote the use of specific cognitive resources. The practices and activities of science are similar in this respect. There are growing bodies of evidence that suggest that coupled systems such as those discussed in this study become coupled regardless of the intent to couple. At a deeper cognitive level, the coupling acts as a cognitive priming mechanism as suggested by Lamb *et al.*, 2015. However, while Lamb's work was explanatory in relation to learning behaviors such as engagement and critical thinking in the classroom, it lacked an underlying neurological mechanism to explain why cognitive priming occurred. This study suggests that speaker listener coupling helps to facilitate the cognitive priming by reducing a listener's degrees of cognitive freedom. Through cognitive priming the listeners degrees of freedom for response are reduced and responses become more ordered and complex but simultaneously focused thus promoting specific use of cognitive resources (Lamb et al., 2016; Lamb *et al.*, 2019). This translates to observed outcomes in which the speaker benefits from listening to their active speakers (Brothers, *et al.*, 2019). This work supports work conducted by Sedova *et al.*, 2019 which found that students had more positive outcomes on assessment when the class as a whole illustrated a greater overall level of talk which is accessible. This is further supported by the strong linkage between individual speaker and listener participation and their individual achievement on the content tests. From this it is possible to say that a high frequency of coupling is closely aligned to understanding and is linked to better student results. The findings from this study are in line with findings previously outlined by the studies of Webb *et al.* (2014) and Ing *et al.* (2015), illustrating that speaker listener coupling affects different students in similar ways, depending on the complexity of the network they are able to form during internalization (Process 2) see Figure 3. This may result from structural and functional aspects of the human brain which are specifically used to address socialization within the human experience. This may also point to a need to examine coupling not just as a dyad of speaker and listener but as information producer and consumer in modes such as writing. For example, one study found that as the complexity of the information increased (paragraph versus sentences versus words) the intensity of hemodynamic activation also increases so long as understanding was occurring (Rohdenburg, 1996; Guinote, 2007; Federmeier *et al.*, 2020). This indicates that the ability of the participant to apply the semantic and procedural network is of importance in other forms of coupling as well and may point to a general need for coupling to occur if one is to understand. This taken in conjunction with the more robust network (See Figure 3) for non-science text and a less robust network for the science text may suggest that there is a need to emphasize a transitional approach to academic and discipline specific language because the semantic network and related resources may not be present or able to be applied (transferred) from the non-science text to the science text.

One area of weakness in this study is that authors did not specifically isolate levels of reasoning associated with the text. Levels of reasoning in this context refers to the underlying working memory tools used to "understand" and process the text. As such the authors are unable to isolate the role of reasoning within the coupling. A second area of weakness is that this study only examined coupling occurring between persons of significantly different levels of understanding. Levels of understanding may play a role in how well speakers and listeners couple with one another. It may be necessary to have a significantly different level for understanding resulting in new semantic networks. The differences in the levels of coupling between the college text and the fourth-grade text provide a window into the possible role of levels of understanding. Our analysis indicated that there was a relationship between those conditions that coupled, the conditions that coupled had better results on a content test illustrating that coupling may be a key factor in the outward behavior of understanding. In addition, the networks illustrated in the computational aspect of the study are significantly more complex when compared to those networks without coupling. The complexity also illustrates the relative level of sustained activity associated with the interaction between the speaker and listener. While talk is essential in this process; the listener is also an essential non-passive component which must be considered. The more opportunities for speaker listener coupling to occur can result in better encoding in long term memory and manipulation in working memory. The ability to identify both the physical action of coupling between speakers, listeners, and the behavioral characteristics of coupling may assist in educator evaluation of student understanding in science. Using approaches predicated on neural coupling, it may be possible to distinguish between students who participate effectively in discipline-specific discourse such as scientific argumentation, and in the general acts of learning through talk. It may even be possible to treat curriculum developers as "speakers" and teachers or students as "listeners" of curriculum materials and potentially predict levels of understanding based upon coupling. Though this will require much more research on the effects of delayed speaker listener coupling.

This work may also help to explain why reading to students by teachers helps to promote learning. The degree of speaker listener coupling may also help to explain why some silent students are able to be successful despite not interacting. Under speaker listener coupling, the speaker may couple with multiple listeners intentionally or unintentionally as coupling is a basic neurological process and fundamental to learning. While the level of engagement is not directly measured it is assumed that coupling only occurs between speakers and listeners attending to one another. It is possible to concluded that even the students who did not speak would be engaged and therefore able to benefit from the whole-class discussion.

5. Conclusions

Neural responses by the listeners and resultant decisions in the classroom are influenced by social signals, what to attend to, and expressions by the speaker. Speaker listener coupling may neurologically occur from responses in the parietal lobe as illustrated in the computational model and a study by Smirnov *et al.*, 2019. Moreover, after working toward learning outcomes, parietal lobe brain activity in the speaker predicted the listeners learner behavior, responding even before the listener was able to complete a content test. A first step toward modeling the way in which two individuals accurately combine information that they communicate with each other was made via the use of computational models using machine learning as the basis. This study revealed that sharing information resulting in understanding among the speaker and listener improved performances whereas information in which understanding did not occur worsened performance.

Shared externalized environments and interactions promotes specific neural responses and behaviors. While aspects of the learning environment are determined by the physical environment, other aspects are determined by the classroom community as it establishes behaviors that shape and constrain the actions of each interacting member. Coupled brains create new knowledge, integrate practices and content, and verbal and nonverbal communication systems which are constrained at two levels the environmental level and the speaker listener level. Speaker listener coupling may also provide a window into talk internalization (Process 2). Studies in neural coupling suggest that social institutions such as schools could not have emerged without brain-to-brain coupling and the basis of teaching and learning may in part rest on this foundation. The simplicity of brain-to-brain coupling as a reference system may simplify understanding of behaviors seen in the classroom by illustrating governing interactions that operate among speakers and listeners shaping one's learning in science.

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Appendix: Explanation of Hemodynamic Responses

This fNIRS experiment is based upon specific observed modulations of a systemic hemodynamic responses of the brain resulting from talk interactions between teachers and students. Hemodynamic responses as measure via the fNIRS are highly correlated with BOLD signals in fMRI studies and is observable as a result of talk occurring between the two participants (Indefrey, 2018). Neurocognitive data in the form of hemodynamic response signals are time-locked information related to the stimulus based upon oxygenated and deoxygenated hemoglobin. The fNIRS device can detect and localize distinct levels of oxygenated hemoglobin based upon the absorption and reflection of infrared light by hemoglobin within range of specific detectors. Absorption of light by a chromophore such as hemoglobin can be described using the Lambert-Beer Law. While this law was originally intended to describe levels of absorption in a transparent non-scattering medium, modifications (corrections) for scattering associated with a biological tissue are incorporated for the computations in this study. This factor is known as the Differential Pathlength Factor. By quantifying the oxygen independent optical losses due to absorption and scattering, the optical density of the oxygenated and deoxygenated hemoglobin chromophore can be related to a change in concentration. It is the ratio of the changes of concentration between oxygenated and deoxygenated hemoglobin which is of interest in this study. The sum of the oxygenated and deoxygenated hemoglobin is a measure of the total blood volume in the tissues of the brain. A scattering medium makes it possible to measure the absorption from a source with a parallel detector in large areas of tissue through bone and muscle. Due to the differences in optical properties of oxygenated hemoglobin, deoxygenated hemoglobin, and surrounding tissue, the proportion of each hemoglobin form dictates the behavior of the light. Signals with higher amplitude or higher concentrations of oxygenated blood will have brighter visualizations. These visualizations are often characterized with dull orange illustrating low levels of activation through bright yellow and red illustrating high levels of activation. In terms of neural coupling (speaker listener coupling), fNIRS allows the isolation of specific areas of neurocognitive responses which can be compared across speakers and listeners, listeners and listeners, and speakers and speakers. These isolated hemodynamic responses can also be characterized as strongly time-locked by 6-seconds to the onset of talk by the speaker and coupled to the talk stimulus from the speaker (Butler, Kiran, & Tager-Flusberg, 2020).

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