Brain Activity of Young and Adult Hebrew Speakers during Lexical Decision Task: fNIR Application to Language

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Abstract. The process of reading activates a large-scale neural network which includes different cortical brain regions. This network is thought to be age-dependent and changes throughout the process of reading acquisition. The frontal lobe is considered to be related to higher, executive, functions. We conducted a functional Near InfraRed Spectroscopy (fNIR) study in order to compare frontal lobe performance during a Lexical Decision Task (LDT) among two different age-groups: children and adults. Data indicated significant differences with age in LDT behavioral performance, and brain activity in the upper left frontal lobe. The young group exhibited slower reaction times and lower accuracy in addition to differences both in the level of blood oxygenation as well in the blood oxygenation timeline. The current study's results suggest 1) the involvement of the frontal lobe during the process of reading and that 2) frontal lobe activity is modified with the age of maturity.

Keywords: Neuroimaging, fNIR, Lexical Decision Task, Developmental language.

1 Introduction

One of the common methods of investigating neural networks related to language is the Lexical Decision Task (LDT) [1-7], which involves the identification of words and pseudowords. It has been suggested that word identification occurs through orthographic processing and pseudoword identification through phonological processing [8]. As such, this task is often used in an attempt to investigate the developmental and impaired aspects of word decoding processes. Previous neuroimaging research suggested that several brain regions are involved in LDT performance, including the superior and the inferior frontal lobe [1, 5, 6, 9]. According to these studies, the superior frontal lobe is involved in the process of decision making [3], where an input from more posterior brain regions involved in semantic information processing (mainly the inferior parietal lobe, specifically the angular gyrus) evokes a positive intra-lexical decision response following a word

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stimulus, or a negative response which is triggered by an extra-lexical temporal threshold [5, 10]. The inferior frontal lobe is thought to be more involved in differentiating between frequent and non-frequent words [6, 9].

fNIR is an emerging, non-invasive brain-imaging technology that allows for the measurement of hemodynamic changes within the brain. It is a portable, affordable, and easy-to-use device that is considered to be more tolerant to movement artifacts as compared to other brain imaging modalities such as electroencephalography (EEG) and functional Magnetic Resonance Imaging (fMRI). Due to these many attractive attributes, fNIR has become commonly used in various areas of cognitive research [5, 11-14]. Specifically, several studies focused on the involvement of the frontal lobe in different aspects of language. For example, Sakatani et al. [15] used near infrared spectroscopy to show the effect of aging on the left prefrontal cortex activity during a series of lingual and memory tasks. Quaresima et al. [14] reported on the involvement of the left Broca in the process of language translation task. Watanabe et al. [16] correlated between language dominance and handedness. In addition, Hofmann et al. [5] used near infrared spectroscopy to demonstrate the involvement of the left superior and inferior frontal lobe in the performance of LDT. Although these studies support the notion that the left frontal lobe is involved in language, the role of the frontal lobe in the process of reading acquisition still remains unclear.

The purpose of the current study was to find whether, and to what extent, the frontal lobe is involved in the performance of the LDT. Specifically, we investigated whether there are age-related differences, in the frontal lobe activation during the performance of the task.

2 Method

Participants: Twenty-two adults (age 25.1±2.48, 9 females and 13 males) and 25 7th grade children (age 12.65±0.467, 13 females and 12 males), participated in the study. All subjects fall into the criteria of a regular reading definition based on Standard Hebrew Reading Test. The decoding score was 92.98±36.52 for word and 47.33±23.40 for pseudowords per minute for the adults and 76.96±21.05 for word and 31.27±10.30 for pseudowords per minute for the young group ($F_{(1,46)}=4.012$, $p<0.05$; $F_{(1,46)}=10.57$, $p<0.01$, for words and pseudowords, respectively). The adults were paid volunteers and the teenagers were compensated with a gift at school. All participants had nonverbal IQs in the normal range (100 and above) as measured by the Raven Standard Progressive Matrices [17]. All participants were native Hebrew speakers from a middle-class background. All subjects were right-handed, displayed normal or corrected-to-normal vision in both eyes, and were screened for normal hearing. None of the participants reported chronic use of medications. Informed consent approved by the University of Haifa ethics committee was obtained prior to each participant's participation in the study.

Apparatus: Two computers were employed. The first computer presented the LDT stimuli via ePrime software (Psychology Software Tools, Inc. http://www.pstnet.com) and collected the participants' reaction times. The second computer hosted the fNIR system (fNIR Devices LLC; http://www.fnirdevieces.com). The fNIR device used in this study was composed of two main parts- a head piece holding the light sources and detectors, and a control box for data acquisition with a sampling rate of 2 Hz. The flexible fNIR sensor consists of four light sources and ten detectors designed to image cortical areas underlying the forehead (dorsolateral and inferior frontal cortices). With a fixed source-detector separation of 2.5 cm, this configuration results in a total of 16 voxels. The control box was connected to the computer for data collection and storage which were utilized by the COBI studio software (Drexel University). In order to synchronize the two computers, a COM cable was used to send online event triggers from the ePrime software to the COBI studio software. Matlab software (Version 2010a, The Mathworks, Natick, MA) was used for the signal processing and to prepare data for statistical analysis which was performed using IBM SPSS (Version 18, IBM SPSS Inc., Chicago, IL).

Task: The Lexical Decision Task [18] included 96 trials, of which 48 trials included high frequency words in the Hebrew language [19] and the remaining 48 trials included pseudowords created from the same letters as the real words. The stimuli were presented for 400 ms horizontally in the center of the screen in white on a gray background. Each stimulus was comprised of 4-5 Hebrew letters, each letter one-quarter of an inch (0.6 cm) in diameter. The participants were seated approximately 80 cm from the computer screen and were asked to press with their right hand '1' for word and '2' for pseudowords. The between-trials time interval was set to 10 seconds with a jitter of ± 4 seconds to allow sufficient time for the hemodynamic response to fully evolve [20, 21]. An fNIR resting baseline of 10 seconds was recorded prior to the performing of the LDT, which was used as a reference in the computation of the relative blood oxygenation changes [18].

Behavioral Reaction Extraction: The reaction time of the trial was defined as the time starting from the stimulus onset until participant's reaction is received. Reaction time and accuracy for each trial were first obtained from the LDT log files. Then, for each participant, mean reaction times for words and pseudowords and for correct and incorrect reactions were calculated. Due to the ceiling effect obtained in the LDT, only correct reaction trials were used in the statistical analysis.

fNIR Data Processing and Feature Extraction: Once the heart pulsation, respiration and movement artifacts were removed, fNIR intensity measurements were first converted to relative changes in hemodynamic responses in terms of oxygenated (OxyHb) and deoxygenated hemoglobin (DeoxyHb) using the modified Beer-Lambert law (MBLL) [22]. Note that, since there is an age difference between the two study groups, an age-dependent correction to the path length factor was integrated in MBLL to accurately extract the hemodynamic signals [14, 23]. Then, Oxygenation, which was defined as the subtraction of the DeoxyHb from the OxyHb, was computed. Finally, once oxygenation data epochs were segmented from the stimuli onset to 15 seconds later for each trial, fNIR features such as minimum, maximum and mean value, and time to reach minimum and maximum value, were extracted for each Oxygenation trial epoch, voxel and participant. For the statistical analysis, each parameter was averaged over trials per participant. Noisy segments, which mainly occurred due to movement artifacts, were excluded from the statistical analysis.

Statistical analysis: A series of 2 X 2 mixed model Analysis Of Variance (rmANOVA's) tests were conducted in order to verify age (children X adults) and stimulus-type (word X pseudoword) differences in the research parameters. In addition, in cases where significant age by stimulus-type interaction was found, appropriate t-tests were applied. The rmANOVA was applied separately to different variables including mean reaction time, accuracy, and fNIR features which were obtained from the Oxygenation data of 16 channels. Since fNIR is considered to have a low signal to noise ratio, in order to verify data integrity, in each of the analyses, the fNIR parameters were first tested for normal distribution using the Kolmogorov-Sminrnov test of normality. In cases where the test of normality failed, and outliers were found, the outliers were screened out from the analysis, and then the test of normality was run for the second time.

3 Results

The comparison of behavioral responses and fNIR features between the two age groups (children and adults) and stimuli (word and pseudoword) revealed both group differences as well as stimulus-dependent differences.

3.1 Behavioral Reaction Results

Reaction time (Fig. 1a): Results revealed a significant group effect ($F(1,37)=21.35$, $p<0.001$). The younger group exhibited a slower reaction as compared to the adults. A significant stimulus-type effect ($F_{(1,37)}=22.21$, $p<0.001$) was also obtained. Both groups exhibited a slower reaction time to the pseudoword stimulus as compared to the word. No group and stimulus-type interaction was found ($F_{(1,37)}=2.80$, $p=0.103$).

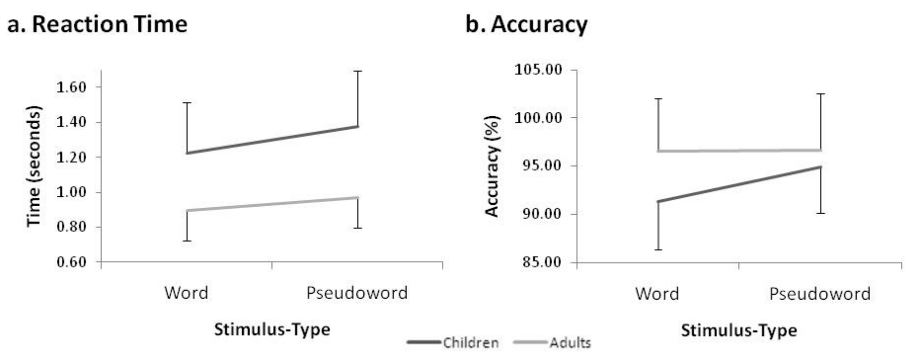

Fig. 1. The children (dark line) and adults (light line) mean (a) reaction time and (b) accuracy performance in LDT. Error bars represent group's standard deviation.

Accuracy (Fig. 1b): Data indicated a significant group effect ($F_{(1,35)}=29.143$, $p<0.001$). The adult group obtained higher accurate reactions as compared to the younger group. A significant stimulus-type effect ($F_{(1,37)}=8.686$, $p<0.01$) was also found, for both groups accuracy was higher for pseudowords as compared to words. Furthermore a significant group by stimulus-type interaction ($F_{(1,37)}$=7.38, p=0.01) was also found. The interaction stems from lower accuracy rate in words ($t_{(35)}$=-5.24, p<0.001) and not for pseudowords ($t_{(35)}$=-1.925, p=0.062) among the younger group.

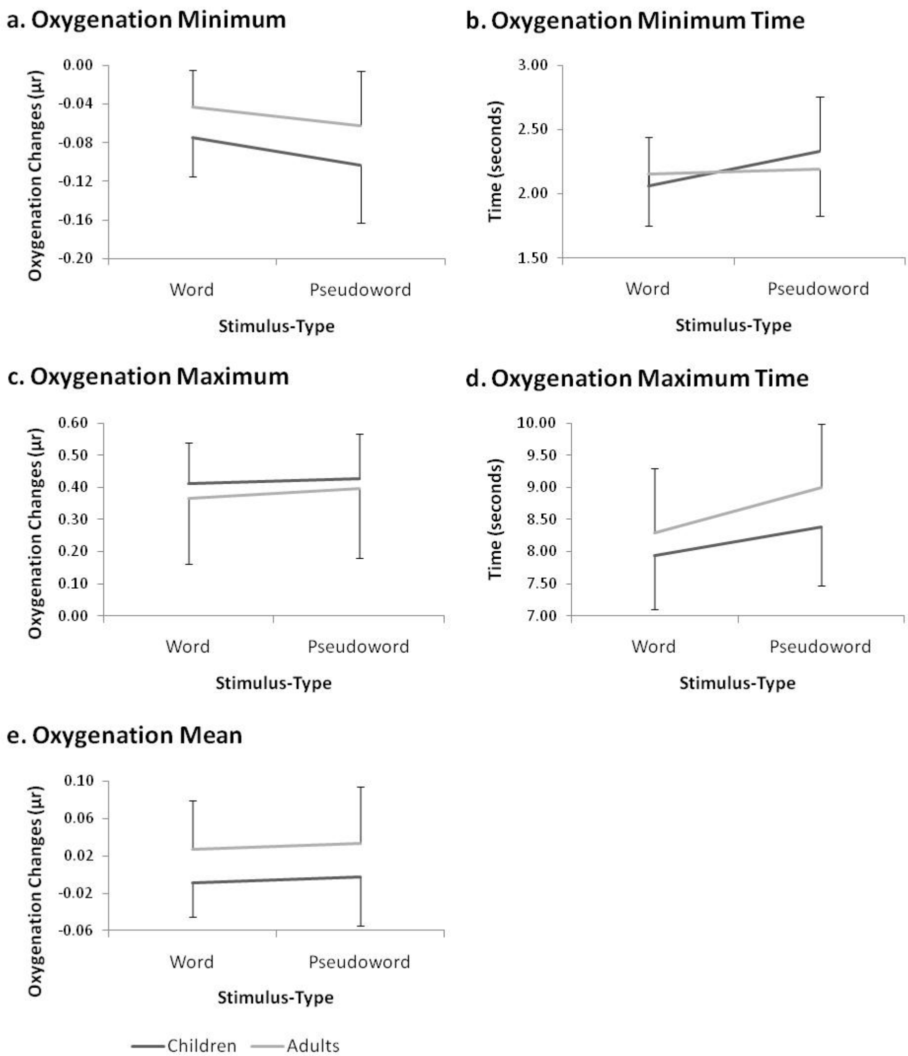

Fig. 2. The children (dark line) and adult (light line) Oxygenation results measured at Channel 3. Error bars represent group's standard deviation.

fNIR Results: The statistical analysis on the features extracted from oxygenation data epochs within the time interval of 15 seconds following the stimulus onset revealed that stimulus-type and age effects were found mainly in Channel 3 which is located in the upper side of the mid-left frontal lobe. Fig. 2 presents the results for the fNIR analysis.

Minimum value of Oxygenation (Fig. 2a): Data revealed significant group effect ($F_{(1,33)}=9.522$, $p<0.01$). The children exhibited a larger decline in the value of the Oxygenation as compared to the adults for both words and pseudowords. A significant stimulus-type effect was also found ($F_{(1,33)}=4.139$, $p=0.050$). For both groups a lower minimum value was found under the pseudowords condition as compared to words. No group and stimulus-type interaction was found ($F_{(1,33)}=0.181$, $p=0.673$).

Minimum-time in which the Oxygenation signal reached its lower value (Fig. 2b): revealed a non-significant group effect ($F_{(1,36)}=0.094$, $p=0.760$), non-significant stimulus-type effect ($F_{(1,36)}=2.278$, $p<0.140$), and no group by stimulus-type interaction ($F_{(1,36)}=1.394$, $p=0.245$).

Maximum value of the Oxygenation signal (Fig. 2c): revealed no significant group effect ($F_{(1,37)}=0.552$, $p=0.462$) and stimulus-type effect ($F_{(1,37)}=1.800$, $p=0.188$) as well as no group by stimulus-type interaction ($F_{(1,37)}=0.231$, $p=0.634$).

Maximum-time in which the Oxygenation signal reached its maximum value (Fig. 2d): indicated a significant group effect ($F_{(1,37)}=4.650$, $p<0.05$), the children reached the maximum value of Oxygenation faster as compared to the adults. In addition a stimulus-type effect was also obtained ($F_{(1,37)}=8.370$, $p<0.01$) where both groups exhibited a longer time to reach the maximum Oxygenation value under the pseudowords condition as compared to the word. No group by stimulus-type interaction ($F_{(1,37)}=0.432$, $p=0.515$) was found.

Mean Oxygenation value (Fig. 2e): Data revealed a significant group effect ($F_{(1,32)}=10.077$, $p<0.01$) where the adults group showed a higher mean value of Oxygenation. No stimulus-type effect ($F_{(1,32)}=0.253$, $p=0.619$) or group by stimulus-type interaction ($F_{(1,32)}=0.000$, $p=0.992$) were found.

4 Discussion

Overall, the behavioral results of the current study demonstrate an advantage of the adults in their performance of the LDT in terms of accuracy and reaction time as compared to the 7th graders group. Moreover, fNIR results reveal evidence for both the involvement of the left frontal lobe in the performance of the LDT as well as age related differences in terms of cortical oxygenation.

By using fNIR and behavioral measures the current data indicated a clear developmental trend in accuracy and reaction time as well as brain activity in the left frontal lobe during performance of LDT tasks. Compared to the adults, the young population exhibited significantly slower reaction time (Fig. 1a), and lower accuracy (Fig. 1b), for both words and pseudowords. Furthermore when performing the LDT the young population showed a higher decline in the upper left frontal lobe Oxygenation value (Fig. 2a), a faster Maximum-Time (Fig. 2d) and an overall lower mean Oxygenation value (Fig. 2e). The Oxygenation minimum value obtained shortly after the stimulus onset represents a fast reduction in the amount of oxygen in the sampled voxel [20, 21]. This was previously suggested to be related to an initial consumption of oxygen reserves within the voxel by its local neurons. Thus, it can be suggested that the lower minimum Oxygenation value during LDT performance that was exhibited by the younger group may represent higher neural activity in the upper left frontal lobe. Support for this notion can be also seen in the fact that the maximum value of Oxygenation emerge faster among the young participants and may represent a faster inflow of oxygenated blood into the sampled voxel. In sum, the longer processing time, higher rate of errors and the upper left frontal lobe activation seen in the fNIR parameters during the LDT among the younger readers as compared to the adults may suggest that the young group may need to invest more effort in an attempt to process the LDT. Although the young readers who took part in this study were all non-disabled readers at the beginning of secondary school and their reading performance was within the normal range it seems that for this population the process of distinguishing between words and pseudowords has not yet fully automatized and requires more mental effort than for mature readers.

Our data indicated that the young group of readers exhibited significantly more errors when processing words as compared to the adults and no significant differences were found between the two groups in pseudowords accuracy. However, for both groups reaction time for pseudowords was slower than for words. Mounting evidence suggests that LDT represents processing of the orthographic (words) and the phonological (pseudowords) routes in reading [8]. Based on the dual-route theory [8], it can be suggested that pseudowords identification is based on the slower sequential phonological route [2]. However, it is conceivable that by the time a reader reaches secondary school, after more than six years of print exposure, the identification of pseudoword patterns becomes more precise and almost similar to a mature reader. However, recognition of real word relies on the identification of its orthographic pattern and on the retrieval of its exact meaning from the mental lexicon. It seems that more than six years of print exposure and reading practice is needed in order to bring the brain circuitry to automatic activation. This notion might be more pronounced in reading Hebrew, as the Hebrew script has two forms, i,e., pointed Hebrew (in shallow orthography) for 1^{st}-5^{th} graders and un-pointed (deep orthography) scripts from 5^{th} grade onwards. It is conceivable that the members of the younger group in the current study, who were in 7^{th} grade, did not yet fully mastered reading in deep orthography and, as a result, exhibited a higher number of errors when identifying words.

Finally, the results of the current study support the notion that the upper left frontal lobe takes part in the process of lexical decision [5]. It was previously shown that the upper left frontal lobe is involved in decision making [3, 24]. It has neuronal connections with more posterior brain regions [25], which were suggested to be involved in semantic information processing [5, 10]. According to the Multiple Read-Out model [10, 26], a lexical decision can be made when the semantic information process leads to a positive intra-lexical trigger or a negative extra-lexical trigger. The relatively lower level of minimum Oxygenation value under the pseudowords condition suggests a higher level of oxygen consumption at the beginning of the information processing, that is, higher effort was made in the pseudoword condition. In addition, the relatively slower fresh blood inflow under the pseudoword condition, also suggests that the pseudoword information processing required more time than the word information processing. Overall, the fNIR results were in line with the behavioral results where a significant stimulus-type effect was found in both reaction time and accuracy, indicating longer and more complex information processing for pseudowords as compared to words.

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