



# tACS Theta Entrainment Enhances Eye Movements; Implications for Dyslexia and Reading Remediation



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## Abstract

This research investigated the relationship between theta frequency brainwaves and eye movements during reading. Substantial evidence indicates that theta brainwaves support auditory encoding of the linguistic knowledge required for reading, and that this activity is disrupted in dyslexia – a theory called the temporal sampling hypothesis. It has been suggested that theta brainwaves might also be involved in visual processing during reading in a visual correlate to the auditory temporal sampling hypothesis, where sequential eye movements which occur during reading, occur at a theta frequency. It is possible that eye movements provide a rhythmic stimulus which entrains theta brainwave activity in the visual domain, and that poor dyslexia are underpinned by a failure of the brain to synchronise auditory and visual signals at a theta frequency. Eye-tracking data from this study supported the hypothesis that eye movements during normal reading occur at rate consistent with a theta signal, with fixations occurring at a mean frequency rate of 3.4Hz. The study also used transcranial alternating current stimulation (tACS) with the aim of maximising theta activity in the visual domain, and thereby improve the efficiency of eye movements during reading with normal reading adults. Not only did eye movements become significantly more efficient when reading under theta tACS, but the temporal frequency of fixations also increased to just over 5Hz, the same frequency at which tACS was applied. These results provide initial support for a visual correlate to the auditory temporal sampling hypothesis and opens the door for research into brainwave entrainment as a remedial intervention for dyslexia.

**Keywords:** Reading; Dyslexia; Theta; Temporal sampling; Entrainment; tACS; Eye movements

**Abbreviations:** tACS: Transcranial Alternating Current Stimulation; FEF: Frontal eye fields; TSH: Temporal Sampling Hypothesis

## Introduction

Reading is one of the most sophisticated cognitive skills performed by the brain. It requires coordinated and integrated processing in the brain networks responsible for coding auditory and visual stimuli. The linguistic knowledge required to read is gathered via auditory processing of spoken language, while visual networks encode combinations of letters that are captured via rapid, rhythmic eye movements. Both auditory and visual processing are disrupted in dyslexia - a developmental disorder characterised by persistent low literacy that is irresponsive to traditional methods of teaching reading. Children with dyslexia fail to learn to read at an age-appropriate rate, despite normal levels of intelligence and access to education. Unfortunately, the underlying neurobiological cause of dyslexia has yet to be defined, meaning there is not yet a treatment that targets the brain basis of the disorder. A growing body of research in the field of reading and dyslexia indicates that dysfunctional brainwave activity may

be an underlying contributor to the disorder. Studies to date have primarily focused on theta frequency brainwave activity that occurs in the auditory domain when processing of speech sounds, with substantial evidence supporting dysfunctional theta activity in dyslexia. We suggest that parallel theta activity might also occur in the visual domain during normal reading, brainwaves which are disrupted in dyslexia and account for the disorder's visual deficits. To investigate this, we designed a study to examine eye movements that occur during normal reading, as well as the effect that stimulating theta brainwave activity in the visual domain might have on those eye movements.

## Temporal sampling and entrainment in phonological processing

Before a child begins learning how to read, they must have developed an understanding of language in its spoken form.

Each spoken word is a formulation of single units of sounds, or phonemes. For example, /a/, /sh/, /oo/, and so on. The cognitive activity of encoding and making linguistic sense of combinations of phonemes is called phonological processing. A child who has developed a reasonable phonological knowledge can begin learning how individual phonemes map onto their visual representations – letters – and, thereby, begin the process of learning to read.

There is substantial evidence to support temporal sampling and entrainment as the neurological mechanisms by which phonological processing occurs in the brain's auditory networks [1-7]. Phonemes in spoken language occur at a steady, temporal (time-based) frequency of approximately 300 milliseconds (e.g., "the-cat-sat-on-the-hat" = beat-beat-beat-beat-beat at a rhythmic frequency of approximately 300 msec each phoneme). Regularity distinguishes speech-sounds above other haphazard environmental noise and triggers neuronal populations in the listener's auditory pathway to synchronise – or entrain – their firing rhythm to the same phonemic temporal frequency [6-9]. This process is referred to as brainwave entrainment. In other words, auditory neurons 'sample' spoken language at an approximate rate of every 300 milliseconds – the rate of a low-theta frequency band-wave. By synchronising their activity to the same frequency, theta-entrained auditory neurons coordinate the wide-spread network communication required for phonological processing [3].

Dyslexic readers, on the other hand, demonstrate phonological deficits that are believed to be due to shortfalls in auditory processing, such that decreased perceptual sensitivity to sound-segments in language – particularly syllables, stress and the rhythmic timing of speech – results in difficulties coding

language [10-12]. The Temporal Sampling Hypothesis [2,3] proposes that the phonological deficits evident in dyslexia are due to a decreased perceptual sensitivity to phonemes. Neuronal networks responsible for processing sound have difficulty tuning in to the theta frequency of speech. This means that brainwaves in the auditory domain do not have a stable theta rhythm stimulus to entrain to [13]. The hypothesised flow-on effect of a theta deficit in the auditory domain is ineffective phonological processing which contributes to disordered reading [2, 3, 5, 10-14].

There is extensive evidentiary support for the auditory temporal sampling hypothesis. For example, impaired coding of speech-sounds presented at a theta frequency has been demonstrated via EEG in children with dyslexia [15]. MEG recordings have also demonstrated reduced responses to theta frequency auditory stimulus in dyslexic readers when compared to normal readers [13], and phonological tasks (e.g. manipulating sounds within varying digit spans, matching multi-syllabic words for stress patterns) have been associated with significantly reduced EEG theta activity in dyslexic children [16-17]. Consistent with this, a longitudinal study in children with dyslexia found that deficits in phonological awareness and auditory coding persisted across four years when compared to age-matched normal readers [14]. Regarding entrainment, Power and colleagues [18] demonstrated successful theta entrainment to a rhythmic stimulus based on the repetition of the sound "ba.", and Luo and Poeppel [6] confirmed theta brainwave entrainment to speech-sounds via EEG. Furthermore, in the same study theta entrainment correlated with significantly improved speech intelligibility on behavioural tasks. Other experiments have demonstrated that finger-tapping in time with a theta speed metronome beat is impaired in children and adults with dyslexia [19,20], providing support for a theta-entrainment deficit.

**A temporal sampling and entrainment as a basis for visual processing in reading**

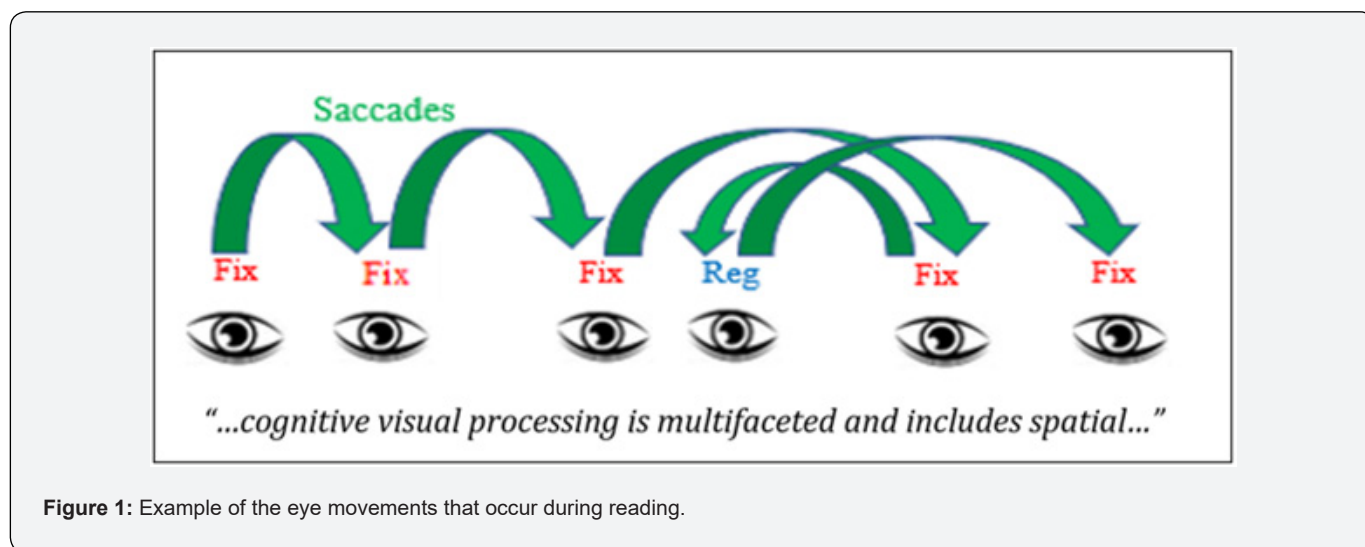


Figure 1: Example of the eye movements that occur during reading.

Given the role auditory temporal sampling plays in phonological processing during reading and dyslexia, we suggest

that a similar action might occur in the visual domain during reading – a visual correlate to the auditory temporal sampling

hypothesis. Visual processing during reading requires rapid serial sampling of text via systematic eye movements [21] in a manner remarkably akin to the temporal sampling of phonemic speech-sounds [22]. When reading English, the eye moves in a linear left-to-right fashion across text, making regular saccades – movements which take approximately 30 milliseconds, and bring a new region of text into the fovea – and fixations – 200-300 millisecond pauses which allow for more detailed analysis of a section of text. Occasionally, the eye moves backward (right-to-left) and re-fixates on a section of text that needs revising for comprehension – this is a regressive fixation [21] (Figure 1).

Saccades occur when the eye travels from one location to another, performing rapid visual search and processing of text. When a section of text requires more in-depth cognitive processing the eye pauses in a progressive fixation (Fix). In this example, the saccades are short and progressive fixations occur frequently due to the lexical complexity of the sentence. A regressive fixation (Reg) occurred when the word “multifaceted” needed revising for comprehension of the text.

Pammer [22] suggested that this rhythm of fixations and saccades might enable theta frequency visual temporal sampling of text, stimulating synchronized theta activity in the visual domain. Indeed, physiologically, it is well established that retinal neurons re-set their action potentials with rapid shifts in visual stimuli [23-25]. Significant increases in theta activity have been found to coincide with the onset of sentence reading [26], and correlate with visuospatial processing around the time of saccades [27]. Thus, we suggest that, in a manner that correlates with theta brainwave-enabled phonological processing, visually stimulated theta activity might facilitate the neuronal network communication required for encoding and processing of the text during reading. Such a model fits neatly with the temporal sampling hypothesis of dyslexia, given that eye movements differ significantly in dyslexic readers compared to normal readers.

Children with dyslexia do not demonstrate normal developmental gains in eye movements when reading [28-29]. Typically, as children gain proficiency in reading, they are able to move their eyes more rapidly along a passage of text. Progressive fixations become shorter, saccades travel further, and fewer regressive fixations are required. However, this increased efficiency in eye movements is not evident in dyslexic children [28-29]. Consequently, adult dyslexic readers demonstrate erratic visual search patterns and make more frequent, lengthier fixations [29-32]. Erratic eye movements could mean children with dyslexia have no stable theta stimulus for visual temporal sampling and entrainment. Lack of coordinated brainwave activity might underlie the myriad of visual difficulties children with dyslexia have, including conducting visual search among cluttered environments [33,34], orienting visual attention, coding the temporal sequences of words and letters within words [34-38]. And processing visual stimuli that is of low spatial frequency, such as letters in words [39,40].

### The present study

The purpose of this study was to initiate investigation into the possibility that visual temporal sampling occurs via sequential eye movements during reading. An experiment was designed with two questions in mind: Firstly, could theta frequency fixations be a visual stimulus that entrains theta brainwave activity in the visual domain? To investigate this, a reading with eye-tracking task was designed to record participant’s eye movements during normal reading. It was hypothesised that the frequency rate of fixations would be consistent with temporal sampling of phonemic speech-sounds in the auditory domain – that is, fixations would occur at a theta frequency rate. Secondly, the study was designed to explore whether enhancing theta brainwave activity in the visual domain would increase the efficiency of eye movements during reading. Research into brainwave entrainment as a treatment for neurological disorders has gained increasing momentum over the last twenty years. Positive effects of entrainment have been demonstrated in attentional disorders [41], epilepsy [42], motor control [43], depression [44], Tourette’s syndrome [45], and communication and behavioural difficulties related to Autism Spectrum Disorder [46]. If impaired brainwave activity is indeed an underlying neurobiological cause of dyslexia, the implications for theta entrainment as an intervention for children with reading difficulties is clear. This study was an initial step to evaluate such a possibility. To investigate this the effect of theta entrainment in the visual domain during reading, theta frequency transcranial alternating current stimulation (tACS) was conducted over the frontal eye-fields (FEF). It was hypothesised that this would enhance the efficiency of eye movements during reading by increasing reading speed and shortening the duration of fixations and saccades.

### Materials and Methods

#### Participants

Twenty-six normal reading adults (22 female, 4 male) aged 18-52 years participated in the study. All participants gave informed consent and had no conditions that would exclude them from safely receiving transcranial stimulation. Reading ability was screened using the National Adult Reading Test (NART) [47]. The mean NART error score for participants was 6.48/50 ( $SD = 5.52$ ), which is well below Australian adult population norms ( $M = 19/50$ ,  $SD = 9.04$ ) [48]. Five participants withdrew from the experiment after one session, and four had eye-tracking data that was inadequate for analysis, resulting in 17 participants in the final analysis.

#### Reading task with eye-tracking

The task consisted of 20 presentation blocks plus an additional practice block. Each block comprised of a passage of text approximately 100 words in length, adapted from a variety of reading comprehension books, non-fiction books and magazines. The task was run on a 24-inch desktop monitor using Microsoft

PowerPoint. Static passages of text were presented in black, size 12 Times New Roman font on a white background. A chinrest ensured that participants completed the task while sitting at the same distance (45 cm) and angle from the desktop, resulting in the text of the reading task subtending a visual angle (the size of the text's image on the retina) of approximately  $0.6^\circ$  for each letter, and  $50^\circ \times 15^\circ$  for the width  $\times$  height of the text block.

Participants were instructed to read each passage of text silently. To motivate and ensure genuine reading for comprehension, each passage of text was followed by a simple text-related "true or false" comprehension question [28]. The question was asked verbally by the researcher and answered verbally by the participant. A cut-off mark of 90% was set for correct answers as a manipulation check, and no participants needed to be excluded for this reason. A MobileEye XG eye-tracker was used to record participants' eye movements as they completed the reading task.

### Transcranial alternating current stimulation (tACS)

tACS was applied using a NeuroConn DC stimulator to produce neuronal entrainment at a theta frequency over the frontal eye fields; a primary area involved in controlling eye movements [49]. The active electrode was placed over Fp1 and the reference electrode was placed over Cz of the international 10-20 system. Parameters for tACS were set according to guidelines for brain stimulation [50] and previous theta entrainment studies [51,52]. Sinusoidal stimulation at 5Hz with no DC offset and a  $0^\circ$  relative phase was delivered at an intensity range of  $1000\mu\text{A}$ , with impedance kept below  $10\text{k}\Omega$ . Stimulation in the experimental condition was run for nine minutes before participants commenced the reading task. Stimulation continued to be administered throughout the entire task and was terminated on completion of the task. Sham tACS parameters were identical to the stimulation condition, except for the duration of stimulation. Here, tACS was applied for just one minute and then terminated automatically so as not to affect neuronal firing. Most participants feel tingling or other mild sensations at the initial onset of genuine tACS. Therefore, this sham technique mimics the feeling of genuine tACS to prevent participants differentiating between the stimulation and sham conditions [51]. During post-experiment debrief, all participants stated they were unable to distinguish between the sham and actual stimulation conditions. Sessions were conducted a minimum of seven days apart to ensure there were no lingering effects of stimulation from the previous session [50].

### Procedure

Participants attended two sessions; in the first session participants were pre-screened to ensure there were no contraindications to tACS, followed by completion of the NART and a demographic questionnaire. Two saline soaked electrodes were then positioned on the participants' scalp, according to the tACS experimental condition to be run in that session. After

ensuring impedance was below  $10\text{k}\Omega$  and that the participant was not experiencing any discomfort, a timer was set for nine minutes. During this time, the eye-tracking device was set up and calibrated. Each participant received verbal instructions from the experimenter and written instructions on screen before commencing the task. This was a within-subjects design, so the second session consistent of the condition that they had not encountered in session 1. Eye-tracking data was collected in both sessions. The order in which participants completed the experimental conditions was randomised and counterbalanced, and presentations of the reading task versions were randomised and counterbalanced for session and experimental condition. Participants were debriefed at the conclusion of the second session.

### Eye-tracking analysis

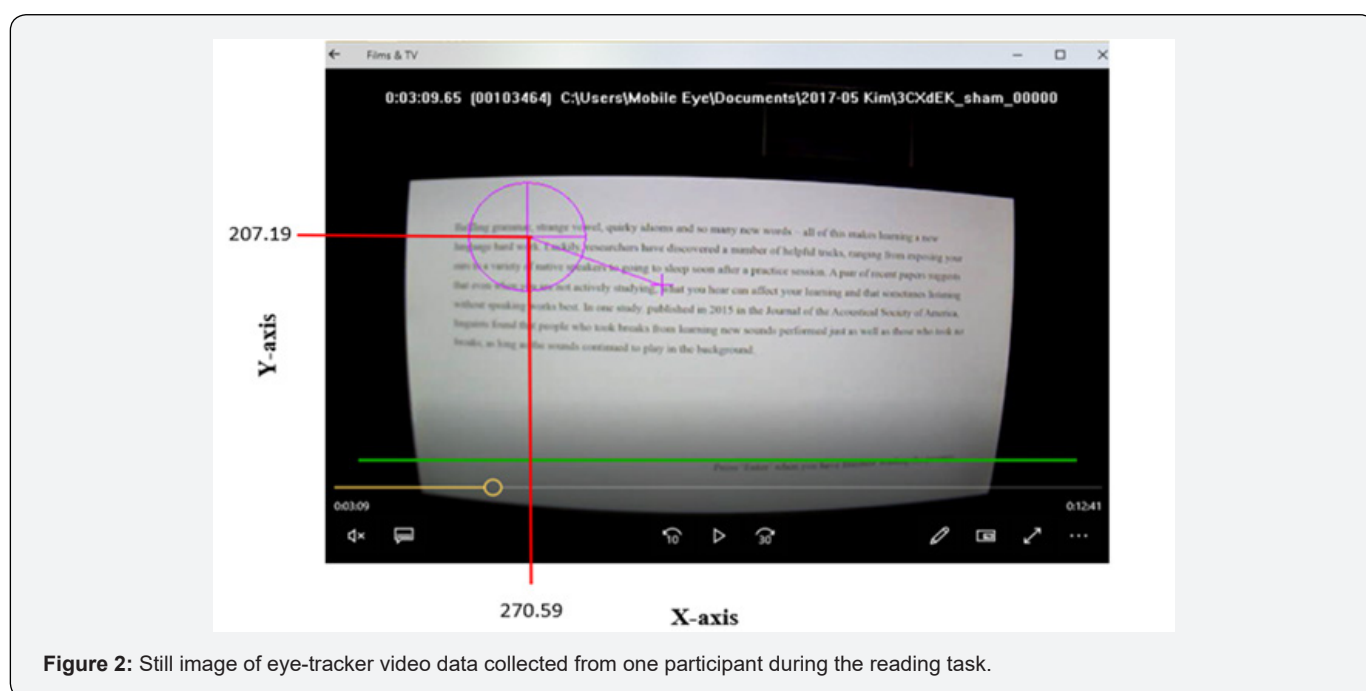
Data produced by the eye-tracker for each experimental session included a video of the participant's eye movements, identifying the eye location with a cross-hair, and a corresponding Common Separated Values (CSV) file – which provided the exact location of the crosshair on the screen at 30 millisecond intervals on an X-Y axis. CSV files were transported into Microsoft Excel, and conditional formatting was used to classify fixations and saccades. Velocity-threshold fixation identification (I-VT) was used to separate fixations and saccades based on their point-to-point, degree-per-second velocities [53]. This method classifies eye movements that are relatively stable (only slight shifts in the X-Y coordinates) to be a fixation. Small velocity shifts during fixations are expected and normal, as the eye never remains completely still, therefore, shifts in velocity that were  $< 100$  degrees/second ( $< 1.0$  shift in X-Y coordinate from one timestamp to the next) were classed as fixations. Fixations that occurred as the eye moved left-to-right along the text were classed as progressive fixations, and fixations that occurred as the eye moved right-to-left along the text were classed as regressive fixations. Shifts in velocity that were  $> 100$  degrees/second ( $> 1.0$  shift in X-Y coordinates from one timestamp to the next) were classed as saccades. As each block of the reading task varied slightly in length, eye-tracking analysis was contained to reading that occurred across the first five lines of text in each block ('Point A' to 'Point B').

To test the hypotheses, eye-tracking data was classified into six variables: Total reading time (TRT), number of fixations per second (Fix.per.sec), number of regressions per second (Reg.per.sec), fixation dwell time (Dwell), saccade length (in time) (Sacc) and frequency rate of fixations (Freq.fix) (see Table 1 for further explanation).

The eye image and scene image are displayed and recorded with resolution  $640 \times 480$  pixels. The crosshairs show the exact X-Y location of the master spot of eye at the 3:09.65min time point during the task. Coordinates of the master spot cluster are provided in a CSV file (Figure 2).

**Table 1:** Eye tracking variables used for data analysis.

Variable	Abbreviation	Description
Total reading time (s)	TRT	Mean reading time from point A to point B across blocks.
Number of progressive fixations per second	Fix.per.sec	Mean number of progressive fixations from point A to point B divided by total reading time.
Number of regressive fixations per second	Reg.per.sec	Mean number of regressive fixations from point A to point B divided by total reading time.
Dwell time of fixations (ms)	Dwell	Mean length of time that the eye remained still on a single point of text (mean [Fix.per.sec + Reg.per.sec]).
Saccade time (ms)	Sacc	Mean time taken for the eye to move from the end point of one progressive/regressive fixation to the commencement of the next progressive/regressive fixation.
Frequency rate of fixations (ms)	Freq.fix	Mean temporal rate at which fixations occurred. This measured eye movements from the commencement time of one progressive/regressive fixation to commencement time of the following progressive/regressive fixation (mean [Dwell + Sacc]).



**Figure 2:** Still image of eye-tracker video data collected from one participant during the reading task.

**Results**

Eye-tracking variables were analysed using IBM SPSS Statistics (2015). Screening for outliers across all variables was conducted using z-score transformations, with an exclusion cut-off of z-score > 3.29 [54]. Only one outlier was identified (in variable Dwell\_sham, z-score = 3.87). However, all other z-score values for this participant were < 3.29, and given the marginal distance from the cut-off mark, it was decided to retain all data for this participant. All variables were normally distributed as assessed using Q-Q plots and Shapiro-Wilk’s tests of normality in the studentized residuals ( $p > .05$ ). The data analysed is presented in Table 2.

**Total Reading Time (TRT)**

Responses in the TRT\_stim condition, was significantly faster ( $M = 20.97$  seconds,  $SD = 5.25$ ) than TRT\_sham ( $M = 24.36$  seconds,  $SD = 6.92$ ),  $F(1, 15) = 17.38$ ,  $p < .001^*$ ,  $partial \eta^2 = .53$ ,  $Cohen's d$

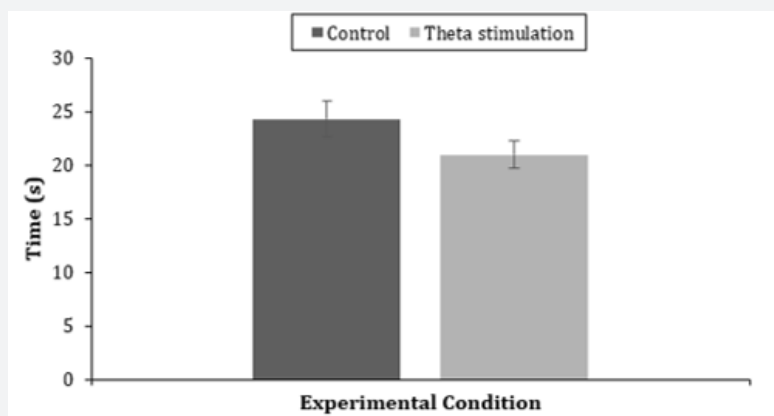
$= .55$ . There was no effect between experimental condition and order of session on TRT,  $F(1, 15) = .71$ ,  $p = .41$ ,  $partial \eta^2 = .04$ . Therefore, consistent with the hypothesis, TRT was faster under theta stimulation regardless of what order the experimental conditions were presented, refer to Figure 3.

**Examination of effects of covariates on total reading time**

Next, the data was examined to assess whether the significant difference in TRT was influenced by the covariates of participant age or reading ability (NART score). A new dependant variable was created using the difference between the mean TRT for control condition and the mean TRT for theta stimulation condition for each participant (TRT\_dif). A higher TRT\_dif indicated a greater effect of theta stimulation on TRT (i.e., faster reading time compared to the control condition).

**Table 2:** Means, Standard Deviations and Ranges for Eye-tracking Variables.

Variable	Mean	Std. Dev.	Min.	Max
Total reading time (seconds)				
Theta stimulation	20.97	5.25	10.22	29.26
Control	24.36	6.92	11.69	38.41
Progressive fixations (per second)				
Theta stimulation	2.09	0.82	0.06	3.1
Control	2.54	0.63	1.42	3.46
Regressive fixations (per second)				
Theta stimulation	0.97	0.45	0.21	2.04
Control	0.94	0.37	0.51	2
Fixation dwell time (milliseconds)				
Theta stimulation	0.15	0.02	0.12	0.2
Control	0.25	0.31	0.14	1.47
Saccade length (seconds)				
Theta stimulation	0.05	0.02	0.02	0.07
Control	0.04	0.01	0.02	0.06
Fixation frequency (milliseconds)				
Theta stimulation	0.19	0.03	0.15	0.24
Control	0.29	0.32	0.17	1.53
N = 17				



**Figure 3:** Mean difference values representing total reading time (TRT) (s) for sham and theta stimulation experimental conditions.

Regression models for TRT\_dif were created for each covariate to determine whether they had any effect on TRT. Separate models were utilised due to the small number of participants. Firstly, a regression model was run for Age. There was independence of residuals as assessed by a Durbin-Watson statistic of 2.12. The data was screened for outliers by checking the standardized residuals for values greater  $\pm 3$  standard deviations, and no outliers were detected. Residuals were normally distributed as assessed by visual inspection of a normal probability plot. Results showed that Age accounted for merely .9% of variability in TRT\_dif with

adjusted  $R^2 = -5.7\%$ . A one year increase in age was associated with a non-significant decrease in TRT\_dif of .05 seconds  $t(16) = -.37, 95\% C.I [-.31, .22] p = .72$ . The overall regression model was also non-significant,  $F(1,16) = .14, p = .72$ .

A regression model was similarly run for TRT\_dif and NART errors. There was independence of residuals as assessed by a Durbin-Watson statistic of 2.02. There were no outliers  $\pm 3$  standard deviations, and a P-P plot showed approximately normal distribution of residuals. The results showed that reading ability

accounted for just 1.8% variability in TRT\_dif with adjusted R2 = -.047%. An increase in NART score by one error was associated with a non-significant decrease in TRT\_dif of .07 seconds,  $t(16) = -.53$ , 95% CI [-.36, .21],  $p = .62$ ). The overall regression model was also non-significant,  $F(1,16) = 4.26$ ,  $p = .61$ .

As the regression models for age and NART errors were non-significant, they were not used to make any further predictions about the data and were not included as covariates for any of the other eye-tracking variables.

### Analysis of Progressive Fixations

The mean number of Fix.per.sec\_stim ( $M = 2.09$ ,  $SD = .82$ ) was

.45 progressive fixations per second less than the mean number of Fix.per.sec\_sham ( $M = 2.54$ ,  $SD = .63$ ). This difference was significant at 0.5,  $t(16) = -2.26$ , 95% CI [-.86, -.03],  $p < .05^*$ , Cohen's  $d = .55$ , indicating that theta stimulation significantly decreased to the number of progressive fixations per second compared to the control condition.

### Analysis of Regressive Fixations

The mean number of Reg.per.sec\_stim ( $M = .97$ ,  $SD = .45$ ) was only .03 regressive fixations per second less than the mean number of Reg.per.sec\_sham ( $M = 0.94$ ,  $SD = .37$ ). This difference was not significant;  $t(16) = .25$ , 95% CI [-.20, .26],  $p = .77$ . These results are represented in Figure 4.

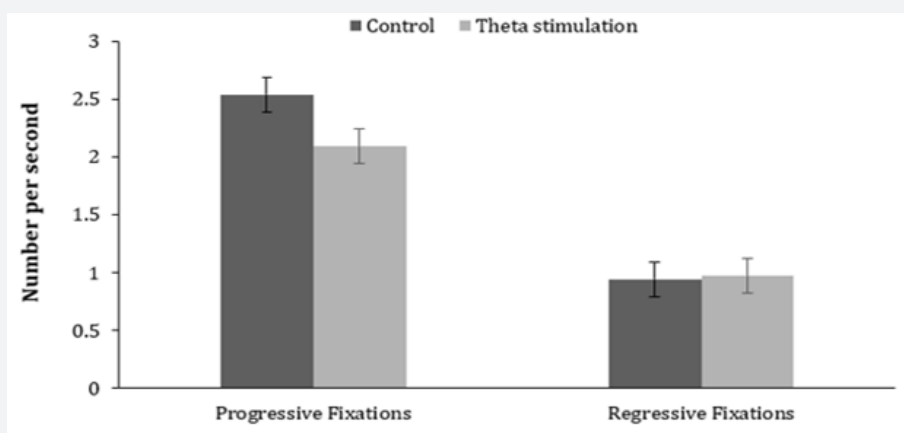


Figure 4: Mean difference values (number per second) for progressive fixations and regressive fixations.

### Analysis of Fixation Dwell Time

Mean Dwell\_sham was 0.25 seconds ( $SD = 0.31$ ). This was .10 seconds shorter than Dwell\_stim ( $M = .15$ ,  $SD = .02$ ). This difference was significant  $t(16) = -16.63$ , 95% CI [-.12, -.08],  $p < .001^*$ . Effect size calculated by Cohen's  $d = 4.14$ , meaning there was just over 4 standard deviations difference in fixation dwell time between reading in the sham condition and reading in the theta stimulation condition.

### Analysis of Saccades

The average saccade length for Sacc\_stim was 0.045 seconds (45 milliseconds) ( $SD = .02$ ), compared to mean Sacc\_sham of 0.039 seconds (39 milliseconds) ( $SD = .01$ ). This difference was not significant  $t(16) = 1.7$ , 95% CI [-.005, .014],  $p = .107$ .

### Analysis of Frequency Rate of Fixations

Lastly, the temporal frequency rate of fixation occurrence was analysed for each condition. Mean Fix.frequency\_sham was 0.29 seconds ( $SD = .32$ ). This means that during the control condition, fixations occurred at an average rate of 290 milliseconds, which equates to 3.4Hz (low theta). Comparatively, the average temporal

frequency rate of fixations under theta stimulation was 190 milliseconds ( $M = 0.19$ ,  $SD = 0.03$ ), which equates to 5.3Hz (theta).

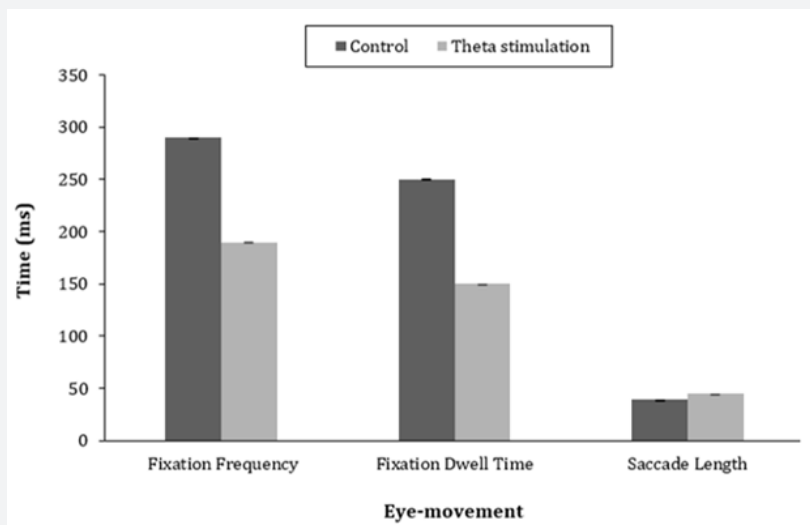
A one-sample t-test was run to test a hypothesis of no difference between the conditions,  $t(16) = -13.93$ , 95% CI [-.10, -.07],  $p < .001^*$ , Cohen's  $d = 3.46$ . Thus, the significant decrease in temporal frequency rate of fixations between the control and stimulation conditions was over 3 standard deviations. These results are represented in Figure 5.

### Conclusion

This study was designed to investigate a hypothesised relationship between theta frequency brainwaves and eye movements during reading. Building on the auditory temporal sampling hypothesis (TSH) [2], it was suggested that visual temporal sampling and entrainment might also be involved in cognitive processing during reading. We hypothesised that eye movements during normal reading – specifically fixations – would occur at a theta temporal frequency rate. We also aimed to open investigation into the possibility of brainwave entrainment as a treatment intervention for dyslexia. We hypothesised that providing theta stimulation (tACS) over the frontal eye-fields

(FEF) would improve the efficiency of eye movements during reading compared to a control condition (sham tACS). Overall, the data supported both hypotheses, indicating that the eye

movements and visual cognitive processes involved in reading may indeed be associated with theta frequency brainwaves in the visual domain.



**Figure 5:** Mean difference values for control and theta stimulation experimental conditions for variables fixation frequency (ms), fixation dwell time (ms) and saccade length (ms). Standard errors are represented in the figure by the error bars attached to each column.

Firstly, fixations during normal reading occurred at a low-theta temporal frequency of 3.4Hz. This lends preliminary support to the idea that eye movements during reading may provide a theta frequency stimulus that triggers theta temporal sampling and entrainment in the visual pathway – a correlate to the auditory temporal sampling hypothesis.

Secondly, despite participants being normal readers without dyslexia, applying theta stimulation over the FEF significantly increased the efficiency of eye movements during reading. Fixations decreased in both number and dwell time, without incurring a cost to comprehension or causing an increase in the need to regressive fixations. Total reading time was also significantly faster under theta stimulation. Although there was no significant change in saccade time, considering the aforementioned changes, it follows that the eye must have travelled a greater distance during saccades in order for readers to cover the same amount of text in a significantly shorter time. Thus, it is feasible that saccades under theta stimulation were more effective in visual search and scan processing. The temporal frequency of fixations increased to just over 5Hz, still within the theta band range, and most remarkably, the same frequency at which tACS stimulation was applied. It is possible that eye movements during reading did synchronise with the transcranial stimulation. In order to confirm this, future experiments would benefit from introducing EEG monitoring that can time-lock fixations observed on eye-tracking to changes in EEG activity. Importantly, the increased efficiency in eye movements did not incur a cost to comprehension. It is possible, therefore, that maximising theta activity in the frontal

eye fields increased the effectiveness of cognitive processes such as visual search, attention, feature binding and spatial coding during reading. We believe that this result points to brainwave entrainment as a potential remedial intervention for dyslexia.

The next step in researching a visual correlate to the auditory temporal sampling hypothesis is to investigate theta entrainment in the visual domain in readers with dyslexia. Compared to normal readers, people with dyslexia have erratic non-linear eye movements when reading, including longer fixations and an increased number of regressive fixations [21]. It is therefore expected that dyslexic readers would not have the stable theta temporal frequency rate of fixations found in normal readers in this study. Building on the auditory temporal sampling hypothesis, dyslexic readers would lack a stable theta frequency visual stimulus to entrain theta brainwave activity in the visual domain. This in turn could account for the deficits in visual processing during reading that is seen in dyslexic readers. Regarding brainwave entrainment as a possible remedial intervention for dyslexia, we do not endorse the use of tACS for use with children [55]. Rather, we suggest that future research investigates the use of sensory entrainment as opposed to electrical stimulation. Visual entrainment via the use of flashing light stimuli presented at a frequency of interest has been evidenced by EEG and MEG [56-60]. Combining reading exercises with this type of visual brainwave entrainment in dyslexic readers could be a way of priming neuronal networks in the brain to be optimally receptive to reading.



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