Efficacy of neurofeedback and multi-sensory learning in dyslexia

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Auto Train Brain is a neurofeedback and multi-sensory learning mobile application to improve the reading abilities of children with dyslexia. It reads electroencephalography (EEG) signals from 14 channels of EMOTIV EPOC+ and processes these signals to provide neurofeedback to improve the QEEG signals with visual and auditory cues in real-time. In this paper, we used Auto Train Brain to present the first clinical trial that neurofeedback with multi-sensory learning was compared with special education. Auto Train Brain was applied to 16 children with dyslexia with comorbidities 60 times for 30 minutes. 4 participants of the experimental group also received special education. The control group consisted of 14 children with dyslexia without any comorbidities who did not have remedial training with Auto Train Brain, but who did continue special education. The TILLS test, which is a new neuropsychological test to diagnose learning disabilities, was applied to both the experimental and the control group at the beginning of the experiment and after a 6-month duration from the first TILLS test. Comparison of the pre- and post- TILLS test results indicated that applying neurofeedback and multi-sensory learning method concurrently was proven to be feasible for improving the reading abilities of people with dyslexia without comorbidities. In particular, reading comprehension of the experimental group improved more than that of the control group statistically significantly.

Index Terms**—**Neurofeedback, special education, multi-sensory learning, developmental dyslexia, Auto Train Brain, TILLS.

Introduction

Dyslexia is a specific learning disability with neurological roots. It has a prevalence of 10% of children. It is described by difficulties with accurate and fluent word recognition and by poor spelling abilities. These difficulties are due to dyslexic’s deficit in the phonological component of language. Other consequences include problems in reading comprehension and reduced reading experience that can affect the growth of vocabulary and knowledge (Lyon, Shaywitz, & B.A. Shaywitz, 2003). There is a "disconnection hypothesis" for dyslexia, which is due to the defective phonological system because of weak connectivity between anterior and posterior language areas (Paulesu et al., 1996). The reading and spelling abilities of people with dyslexia are lower than their peers.

Neocorticalization, brain parcellation, lateralization, and gyrification are affected by the addition of supernumerary minicolumns within the isocortex (Casanova & Christopher, 2008). Because minicolumns are widespread and many, abnormalities to the basic ontogenetic pattern of minicolumns can result in incredibly significant alterations. The minicolumnopathies change brain volume, gray over white matter ratio, and gyrification (Casanova, Buxhoeveden, Switala, & Roy, 2002). In dyslexia, it is suggested that there is a minicolumnopathy (Casanova et al., 2002) as fMRI studies suggest that people with dyslexia have reduced brain volume, decreased gyrification, and abnormal lateralization and the white matter depth of people with dyslexia are more comprehensive than usual due to the existence of less folding of the cortex rather than its thickness (Casanova, El-Baz, Giedd, Rumsey, & Switala, 2010). Regardless of the underlying structure, the brain has the means to organize itself after birth according to environmental demands. Reading is a culturally developed process throughout the life of a human (Casanova et al., 2010). Changes in reading patterns are the result of the remodeling of corticocortical connections throughout the first few years of life. Minicolumns can provide for "weak linkages," enabling the cortex to adapt to environmental demands without changing the intracortical circuits (Casanova & Christopher, 2008). It also explains how the brain adapts circuits initially established for vision and language into a reading system (Wise et al., 2007). As new connections are acquired, the conjoint activation of neurons triggers the formation of new circuits (Casanova & Christopher, 2008). With brain maturation, bi-hemispheric activation in children is replaced with the activation of a more efficient system within the left hemisphere (Sandak et al., 2004). The shift towards a reading dominance by the left hemisphere is not usually developed in people with dyslexia. Early studies showed that people with dyslexia relied on their right hemisphere for language-related processes (Yeni-Komshian, Isenberg, & Goldberg, 1975). More recent studies have refined this view in favor of a deficit in intra-hemispheric "short” corticocortical connectivity targeting the left angular gyrus (Sandak et al., 2004). The resultant changes in connectivity engender in those so affected the other brain circuit for reading (Simos et al., 2009). The less efficient reading circuit is manifested as weak phonologic processing or awareness. Various researchers have reported that children with dyslexia have slow waves at FC5 and F7, and they do not desynchronize beta-1 activity during a reading task in areas related to Broca's area (FC5; speech production, articulation) and the Angular gyrus (CP5, P3), understanding semantics and mathematics (Klimesch et al., 2001) as well as the left parieto-occipital area (P7, O1) (Rippon & Brunswick, 2000). Children with dyslexia have increased slow activity at the right temporal and parietal (P8 and T8) regions of the brain (Arns et al., 2007). Research has reported that the left temporal region is disrupted (Thornton & Carmody, 2005). Dyslexia may also be comorbid with ADHD, meaning that slow activity in the frontal lobes may be high. There is a symmetric increase in coherence for the delta and theta bands at T3 and T4 and a specific right-temporo central increase in coherence for the alpha and beta bands (Arns et al., 2007). Bi-hemispheric (at T3 and T4) hyper coherence manifests in the delta and theta bands, while hypo-coherence can be found between P7- O1 in the delta, theta, and alpha bands (Coben et al., 2015) meaning that left-hemispheric dominance is not established yet. Therefore, any dyslexia training software should improve the left-hemispheric dominance.

In neurofeedback applications, the user's brain activation is read in real-time to help the user gain control over specific aspects of the activity in his/her central nervous system. Therefore, the user receives direct feedback about their actual brain activation pattern and consequently can learn to gain voluntary control over EEG signals (Ninaus et al., 2013). Neurofeedback is the process of learning to control neural processes via an explicit feedback signal. Real-time feedback of EEG signals to oneself is an approach in which participants can receive direct feedback regarding neural activity, as reflected in the visual and auditory cues. Recent studies have reported success in training participants to manipulate activity in specific target brain regions, and such training can translate into changes in behavioral measures or clinical symptoms. Learned control over a specific region of the brain was shown to lead to alterations in brain networks in the long run (Niv, 2013).

In the literature, there is research about using computer-based multi-sensory learning methods to improve the reading and writing abilities of people with dyslexia. According to (Kast et al., 2007) a computer-based multi-sensory learning program strengthens memory via visual and auditory associations between graphemes and phonemes and improves the writing abilities of people with dyslexia. People with dyslexia must learn correspondences between orthographic tokens and phonemic utterances, and they must do this to the point that there is a seamless automatic ‘connection’ between these distinct sensorial units of language. As more senses are involved in the learning process, rapid naming and memory strengthen. Orton Gillingham (O-G) approach, a multi-sensory learning method designed for people with dyslexia, has proven that a multi-sensory approach improves the reading abilities of people with dyslexia (Guyer & Sabatino, 1989). Perceptual learning is defined as an improvement of perceptual skills with practice and has been successfully used for dyslexia (Gori & Facoetti, 2014). People with dyslexia find difficulty shifting their attention between modalities, but such "sluggish attention shifting" is reported only when people with dyslexia shift their attention from visual to auditory modality. Visual-spatial attention shifts rely on the dorsal stream, more specifically on the occipitoparietal areas. Other researchers have suggested that the dorsal pathway might be fed, to a large extent, by the magnocellular pathway. This finding is compatible with the magnocellular deficit theory of dyslexia (Stein & Walsh, 1997) which can account for many of the multi-sensory, uni-sensory and cross-modal processing differences in people with dyslexia (Harrar et al., 2014). Therefore, any dyslexia training software should take into account the asymmetric shifts of cross-modal attention.

Although there has been much separate research about QEEG neurofeedback and multi-sensory learning methods for people with dyslexia, none of the research has combined the best parts of these methods and come up with a seamless, fully automated version of both methods which will provide an effective way of improving the literacy skills of people with dyslexia. Neurofeedback is based on visual and auditory cues, which provides the basis of a multi-sensory approach for those of people with dyslexia who cannot read and write yet. By applying neurofeedback, slow brain waves are reduced to the degree that the brain is ready for learning new information about lexemes and graphemes. Then, an alphabet teaching system that combines lexemes with graphemes should be presented. The system should connect the visual representations of lexemes with phonemes in a seamless way, and this process should be repeated many times as there are cross-modal processing differences of people with dyslexia to make it a permanently acquired ability. Computers can handle repetitive tasks very efficiently and can repeat the same procedure to children with dyslexia. This new solution should provide replicable results and allow an application to any subtypes of dyslexia.

Auto Train Brain is a patented software (patent number: PCT/TR2017/050572) specifically designed for children with dyslexia (Eroglu, Çetin, & Balcisoy, 2018). Within this software application, a system and method for improving learning abilities are proposed (Figure 1). The system relies on a distinctive protocol of multi-sensory learning and QEEG neurofeedback. The main aim is to provide a home-based therapy that improves the reading abilities of people with dyslexia reliably. After applying Auto Train Brain to people with dyslexia 60 sessions, multi-scale entropy of people with dyslexia was improved at all temporal scales and became similar to those of typically developing children (Eroglu et al, 2020). In this study, we would like to investigate whether the improvements in EEG and the complexity will be positively reflected to the TILLS test scores after Auto Train Brain training.

In the present study, we report on a clinical trial in which the effects of QEEG neurofeedback and multi-sensory learning training were studied. The following research question is addressed:

- Does simultaneous neurofeedback training together with multi-sensory learning improve the reading abilities of children with dyslexia who are 7-10 years old?

Our contribution to this research is to investigate the possible positive effects of the Auto Train Brain training and compare the effect size of neurofeedback and multi-sensory learning with that of special education and other proven methodologies for dyslexia in the literature. The primary endpoint of the experiment was set to 60 sessions of Auto Train Brain training to be completed in 6 months when the reading abilities of the experimental group and the control group would be evaluated in terms of the TILLS test descriptive scores. A priori power calculation was not registered. We presented a priori power calculation in the limitations of the study.

Methods and materials

Participants

This was the first clinical trial that investigated the possible effects of Auto Train Brain. The children with dyslexia who voluntarily participated in this study were recruited with advertisements randomly. 36 individuals applied to participate in the experiment (Figure 2). Four of them were excluded due to their ages. 32 participants from Ankara, İzmir, and Kocaeli were included to participate in the experiment. The participants met DSM-V criteria for dyslexia, as assessed by psychologists and psychiatrists beforehand. The child neurologist physically examined the participants who were already diagnosed with dyslexia and approved their participation in the experiment. The participants resided in the different cities of Turkey, and those who would be assigned to the experimental group were expected to come to the Ankara University Faculty of Medicine during the experiment. Therefore, those who resided in Ankara or were willing to come to Ankara were assigned to the experimental group primarily. The experimental group and the control group were matched based on age and the first TILLS test descriptive scores (Table 1,

Figure 2). There were 16 participants with dyslexia (M_{age}= 8.56, *SD* = 1.36) in the experimental group and 14 participants with dyslexia (M_{age}= 8.59, *SD*=0.94) in the control group.

The experimental group had dyslexia, and there were comorbid situations such as EEG anomalies, cerebral palsy, ADHD, and giftedness. The socio-economic situation of the experimental group was low to the middle class; they were mostly residents of Ankara. The experimental group took 60 sessions of Auto Train Brain 3 times a week, 4 of them received special education concurrently.

At the start of the experiment, the control group had 16 participants. However, two of them left the study to get neurofeedback training at a psychiatrist's office. The control group resided in İzmir and Kocaeli; the socio-economic situation of the control group was low to the middle class. The control group was more homogeneous than the experimental group and had dyslexia only. The participants in the control group received special education provided by the rehabilitation centers according to the Special Learning Difficulty Support Training Program, prepared by the Special Education and Rehabilitation Center at the Ministry of Education in Turkey. The support training program includes a) Preparation for learning (300 lesson hours) b) Reading and writing (250 lesson hours) c) Mathematics (200 lesson hours). The control group received 3-hour special education per week during 6 months.

The socio-economic situation was measured with a survey filled out by the parents of the children. The survey includes questions about education level, income, occupation, and residence.

The Test of Integrated Language & Literacy Skills (TILLS)

The TILLS is a test for assessment of oral and written language abilities in students 6–18 years of age. Published in 2016 (Nelson, Plante, Helm-Estabrooks, & Hotz, 2016), it is unique in the way that it is aimed to thoroughly assess skills such as reading fluency, reading comprehension, phonological awareness, spelling, as well as writing in school-age children. The test is originally developed in English. Turkish Dyslexia Association has translated and adapted it to Turkish. This test has been used for diagnosing learning disabilities. For 6-7 years old children, a TILLS descriptive score of less than 24 indicates learning disability with 84% sensitivity and 84% specificity. For 8-11 years old children, a TILLS descriptive score of less than 34 indicates learning disability with 88% sensitivity and 85% specificity.

The TILLS test has 2 dimensions (language and modality). For listening modality, it has (1) Vocabulary awareness, (2) Phonemic awareness, (6) Listening comprehension, (8) Following directions; for speaking modality, it has (4) Nonword repetition, (3) Story retelling, (13) Social communication; for reading modality, it has (10) Nonword reading, (11) Reading fluency, (7) Reading comprehension; for writing modality, it has (5) Nonword spelling, (12a) Written expressions- Word score, (12b) Written expression -discourse score, (12c) Written Expression – sentence combining score; for Memory, (14) Digit span forward, (15) Digit span Backward, (9) Delayed story retelling subtests. The TILLS descriptive point is the sum of all subtests' scores.

Neurofeedback QEEG data acquisition

Throughout the experiments, the EMOTIV EPOC+ headset was used. The internal sampling rate in the headset was 2048 per second per channel. The EEG data were filtered to remove main artifacts and alias frequencies, then down-sampled to 128 per second per channel. There were 14 EEG channels plus two references, and 128 samples per second per channel were used. Electrodes were placed according to the 10-20 electrode system. Before the training, the calibration of the EMOTIV EPOC+ headset on the participants' scalps was performed with MyEmotiv mobile application; each electrode was made sure to transfer EEG data with high quality. For all analyses in this study, all of the 14-channel EEG data were recorded during the experiments in theta (4-8 Hz), alpha (8-12 Hz), beta-1 (12-16 Hz), beta-2(16-25 Hz), gamma (25-45 Hz) bands. EMOTIV EPOC+ was proven to provide research level QEEG data quality (Badcock et al, 2013).

Neurofeedback treatment protocol and multi-sensory learning method

Auto Train Brain is a mobile application that uses neurofeedback and multi-sensory learning principles. It is used with an EMOTIV EPOC+ headset. It is a non-invasive solution, offers continuous brain performance improvement for both adults and children without any side-effects. It reads QEEG from 14 channels, processes these signals, and provides online, real-time visual and auditory neurofeedback. Within this software application, a system and method for improving learning ability are proposed. The EEG neurofeedback protocol is explained below:

- Reduce theta waves at Broca area in the brain if above the norm threshold;
- Reduce theta waves at Wernicke area in the brain if above the norm threshold;
- Find the channels with the maximum absolute power of theta waves at the left hemisphere and reduce absolute theta; and
- Find the channels with the maximum absolute power of theta waves at the right hemisphere and reduce absolute theta.

A positive reward is a green arrow on the screen, negative feedback is a red arrow and a "beep" sound. With a positive reward, the score displayed on the screen is increased. If the slow brain waves of the participant are above the norm threshold, a red arrow is presented on the screen and the participant is asked to try to turn it to a green arrow. A typical neurofeedback session lasts 20 minutes. After neurofeedback session, a phoneme-grapheme matching alphabet teaching system is presented. One of the significant differences between the currently available neurofeedback systems and Auto Train Brain is that it combines neurofeedback with multi-sensory learning principles. Moreover, the 14-channel neurofeedback protocol is novel.

Study Design, Behavioral Assessments, and Training Sessions

The participants in the experimental group with their parents commuted to the Ankara University Faculty of Medicine 3 times a week. A special room was reserved for the duration of the experiment. In the first interview, all participants filled out questionnaires, and a psychologist applied the 1.5-hour TILLS test to the participants. The experimental group came to the sessions with their parents, while the parents were waiting in the waiting room, only the participant was taken to the room. The psychologist helped the participant to wear the EMOTIV EPOC+ headset and started the Auto Train Brain application on a mobile phone. During the training, each participant sat in a chair and the electrodes were fitted by the International 10–20 electrode system. There were 0.5 meters between the participant and the mobile phone screen. The psychologist just stayed with the participant to make sure the participant was using the mobile app correctly, but no guidance or encouragement was provided. There was no one else in the room and the door of the room was closed. There was a distance of 1 meter between the psychologist and the participant. The participants were able to complete the task with a good concentration. The psychologist in the room was neutral to the participant, not friendly or empathetic. In the first session, the participant was instructed to focus on the arrow he saw on the application screen and, if he saw a red arrow, he was asked to turn it to green with brainpower. No additional information about the experimental procedure was explained to the participant. Before the 10th session, the child neurologist examined the children and checked for any side effects. All participants were given 60 sessions of neurofeedback training during 12 consecutive weeks, 3 times a week, irrespective of the phenomenology, severity, or subtype of dyslexia. A standard neurofeedback protocol for reducing slow brain waves was applied to the experimental group for 10 minutes in the left brain and 10 minutes in the right brain. After neurofeedback, the participants received 10-minute multi-sensory learning of the alphabet with Auto Train Brain. The participants who completed the 60th session, were told that the experiment was completed. An appointment was made for the second

TILLS test exactly 6 months after the first TILLS test. At the end of the 6th month, the TILLS test was performed again.

The control group received a TILLS test at the beginning of the experiment and after 6 months. They have not received any training with Auto Train Brain. Instead, they continued special education.

Statistical Analysis

The variables were the TILLS test descriptive scores and the TILLS subtests' scores (pre- and post-treatment) for both the experimental and the control group (Table 2). The statistical analysis was performed with SPSS 22. This study used a randomized controlled pre- and post-test design. This design allows for a multivariate repeated measures analysis of variance that was applied for a comparison of the experimental group and the control group about the subtests of the TILLS test. There were two factors in our experiment, namely time (there were two levels for the factor "time" , the time at which the first TILLS test was conducted and the time at which the second TILLS test was conducted), and the factor "group" (the experimental group and the control group). The significant interaction effects (group X time) were determined. The alpha significance level was set to 0.05 to balance the potential for type I and type II errors. We have checked the normality of data for the TILLS test results (skewness = 0.439, kurtosis = -0.399), and validated that the data were normally distributed. Mauchly's test did not indicate any violation of sphericity.

Results

Multivariate repeated measures of ANOVA indicated that there was no significant group-by-time interaction in the TILLS test descriptive scores [$F_{(1, 28)} = 0.729$, $p = .400$; Table 3]. However, a significant main effect of time was identified for the TILLS test descriptive scores [$F_{(1,28)} = 11.972$, $p=.002$; Table 4]. Between subject groups, the TILLS descriptive scores did not differ statistically significantly [$F_{(1, 28)} = .384$, $p=.540$; Table 4]. We have repeated the analysis excluding the four participants who also continued special education from the experimental group. Multivariate repeated measures of ANOVA indicated that there was no significant group-by-time interaction in the TILLS test descriptive scores [$F_{(1, 23)} = 2.117$, $p= .159$]. However, a significant main effect of time was identified for the TILLS test descriptive scores [$F_{(1,23)} = 5.694$, $p=.0026$]. Between subject groups, the TILLS descriptive scores did not differ statistically significantly [$F_{(1, 23)} = 2.683$, $p=.115$]. Our results indicated that we reached our primary endpoint for this experiment. Auto Train Brain training improved the reading abilities of the experimental group up to the level of the control group who only received special education. The rest of the statistical results about the subtests of the TILLS test which were presented below were secondary.

There was no significant group-by-time interaction in the subtests of phonemic awareness [$F_{(1, 28)}=0.779$, $p=.385$; Table 3], story retelling [$F_{(1, 28)}=0.010$, $p=.920$; Table 3], nonword spelling [$F_{(1, 27)}=0.018$, $p=.894$; Table 3]. However, a significant main effect of time was identified for phonemic awareness [$F_{(1, 28)} =4.749$, $p=.038$; Table 4], story retelling [$F_{(1, 28)} = 6.482$, $p=.017$; Table 4], nonword spelling [$F_{(1, 28)} = 8.660$, $p=.007$; Table 4]. Between subject groups, the scores in these subtests did not differ statistically significantly. Both Auto Train Brain and special education improved phonemic awareness, story retelling, nonword spelling (Table 4). We have repeated the analysis excluding the four participants who continued special education from the experimental group. There was no significant group-by-time interaction in the subtests of phonemic awareness [$F_{(1, 23)} = 0.202$, $p=.657$] and nonword spelling [$F_{(1, 23)} = 0.181$, $p=.674$]. However, a significant main effect of time was identified for phonemic awareness [$F_{(1, 23)} = 4.708$, $p=.041$] and nonword spelling [$F_{(1, 23)} = 4.447$, $p=.046$]. Between subject groups, the scores in these subtests did not differ statistically significantly. Both Auto Train Brain and special education improved phonemic awareness and nonword spelling.

There was a significant group-by-time interaction in the subtests of reading comprehension [$F_{(1, 27)}=5.711$, $p=.024$; Table 3], vocabulary awareness [$F_{(1, 28)} = 4.684$, $p=.039$; Table 3], social communication [$F_{(1, 28)}$ = 5.845, p=.022; Table 3], digit span forward [$F_{(1, 28)}$ = 5.758, p= .023; Table 3], digit span backward [$F_{(1, 28)}$ = 4.443, p= .044; Table 3]. For the experimental group, the simple effect of time in the subtests of reading comprehension [$F_{(1, 14)}$ = 4.98, p=.042; Table 5] was statistically significant. Post-hoc tests indicated that Auto Train Brain training improved reading comprehension statistically significantly more than that of special education. The experimental group progressed from m = 3.06 (SD = 4.22) to 5.20 (SD = 4.41), a 70% improvement, whereas the control group regressed from m = 7.12 (SD = 3.18) to m = 6.36 (SD = 4.22), a -10% improvement (Table 2). We have repeated the analysis excluding the four participants who continued special education from the experimental group. There was a significant group-by-time interaction in the subtests of reading comprehension [$F_{(1, 23)}$ =5.973, p=.023], vocabulary awareness [$F_{(1, 23)}$ = 6.680, p=.017], social communication [$F_{(1, 23)}$ = 6.067, p=.022], digit span forward [$F_{(1, 23)}$ = 4.590, p= .043], digit span backward [$F_{(1, 23)}$ = 5.601, p= .027]. For the experimental group, the simple effect of time in the subtests of reading comprehension [$F_{(1, 10)}$ = 5.252, p=.045] was statistically significant. Post-hoc tests indicated that Auto Train Brain training improved reading comprehension statistically significantly more than that of special education. The experimental group progressed from m = 2.86 (SD = 4.29) to 5.20 (SD = 5.41), an 81% improvement.

For the control group, the simple effect of time in the subtests of vocabulary awareness [$F_{(1, 13)}$ =9.69, p=.008; Table 6], social communication [$F_{(1, 13)}$ =5.430, p=.037; Table 6], digit span forward [$F_{(1, 13)}$ =9.75, p=.008; Table 6], and digit span backward [$F_{(1, 13)}$ =8.576, p=.012; Table 6] were statistically significant. Post-hoc tests showed that special education improved vocabulary awareness, social communication, digit span forward, and digit span backward scores more than those of Auto Train Brain training.

No adversity was reported for any of the participants except for short-lived headaches after treatment in rare conditions.

Discussion

Our research indicated that Auto Train Brain improves the reading abilities of children with dyslexia in 60 sessions up to the level achieved by special education in 6 months. So, we find support to our hypothesis. Auto Train Brain and special education improved phonemic awareness and nonword spelling at a similar level. Auto Train Brain improved reading comprehension more than that of special education. Special education improved vocabulary awareness, social communication, digit span forward, and digit span backward more than that of Auto Train Brain which did not cause any side effects on children. Neurofeedback and multi-sensory learning solution are feasible to train children with dyslexia at home reliably. Therefore, we find support to our hypothesis. This is a pilot study with only 30 participants. In the near future, there needs another experiment to be designed for the definitive conclusion.

Our experimental group consisted of children with dyslexia with comorbid situations and the effect size was 0.23 (16 people). When we excluded the subjects with comorbidities and those who also continued special education from analysis, the effect size of Auto Train Brain was increased to 0.66 (6 people). The effect size of Auto Train Brain is larger than that of Orton-Gillingham method and the neurofeedback study (Breteler et al., 2010). The effect size of Auto Train Brain for people with dyslexia without any comorbidities who also continued special education was 0.88 (2 people). These results showed that Auto Train Brain's effect size was the largest for people with dyslexia without any comorbidities who also continued special education (Table 7). This research also revealed that the activity and effectiveness of Auto Train Brain will be carried to a higher level with special training materials to be added to the later versions.

In this research, it is important to reveal that Auto Train Brain is as effective as special education, because the rehabilitation of children with dyslexia with online education at home is paved the way. Due to the fact that rehabilitation centers were closed during the pandemic period, these children could not receive any education for a very long time. Considering that the pandemic may continue in the upcoming period, online education may remain the only training option.

Previous research indicated that people with dyslexia benefit from neurofeedback applications. In the study (Walker & Norman, 2006) the researchers applied neurofeedback protocols to people with dyslexia to decrease delta and theta at Cz, to increase beta-1 at T3, to decrease coherence at delta and theta range and their research showed at least two levels of increase in reading levels. In the study (Nazari et al., 2012) they applied neurofeedback protocols to people with dyslexia to decrease delta and theta at T3 and F7, to increase beta-1 at T3 and F7. They reported no significant changes in band powers, but hyper-coherence in theta and delta bands were reduced as well as reading time and reading mistakes were reduced due to the treatment. Follow up assessments showed that reading improvements remained durable and better. Applying neurofeedback to dyslexia (delta down at T3-T4, beta down at F7 and C3, coherence training in the delta, alpha and beta ranges) was shown useful for spelling but not reading (Breteler et al., 2010) although other previous studies reported increases in raising reading grade levels (Thornton & Carmody, 2005). Coherence neurofeedback training has been performed on the participants with dyslexia: the most common hypo-coherence was the occipitoparietal lobes to the frontotemporal lobes. The second most common hypo-coherence was the parietal to medial temporal connections. Hypo-coherence has been reported on the delta, theta, and alpha bands. Trained with coherence neurofeedback, the reading performances of people with dyslexia improved (Coben et al., 2015). One of the significant differences between the currently available neurofeedback systems and Auto Train Brain is that the latter combines neurofeedback with multi-sensory learning principles. The neurofeedback protocol also has a novel approach; it is applied from 14 channels. Establishing new weak linkages in disconnected areas improves the reading process upon 60 or more uses. In general, the more neurofeedback is applied, the more permanent and positive are the results achieved. Auto Train Brain is designed for use at home reliably, which extends the treatment period for the end-user and makes it more convenient to use for both children and parents.

Limitations of the study

The first limitation of the study is the number of participants (16 participants in the experimental group, 14 participants in the control group). It would have been better if we had more participants in the experiment. We made a priori power calculation to predict the sample size using G*power. We set the effect size as 0.63, that was calculated from the pre- and post- TILLS descriptive scores of the experimental group who did not have comorbidities, set alpha value as 0.05, set power (1-beta) as 0.95, set T-Test and RCT as input parameters. The sample size for the experimental group was calculated as 67, and the sample size for the control group was calculated as 67. So, this study can be considered as a pilot study. In the future, the experiment should be repeated with a larger sample size to make it a definitive study.

The second limitation of the study is the existence of comorbid situations such as EEG anomalies, ADHD, giftedness, and CP in the experimental group. The control group consisted of individuals with pure dyslexia and was more homogenous than the experimental group. For people with dyslexia who had comorbid brain conditions like EEG anomalies and giftedness, the positive effect of Auto Train Brain is limited. Gifted children with dyslexia have less slow brain waves than those of the norm group; therefore, it was hard to apply neurofeedback protocols, since we aim to reduce the slow brain waves down to norm threshold. These results indicate that comorbid brain conditions reduce the positive effect of Auto Train Brain. Auto Train Brain is more effective for people with pure dyslexia, and people with dyslexia and ADHD. The theta/gamma high group of children with dyslexia benefit more. As people with dyslexia who have comorbid brain conditions did not improve much in the experimental group, we can conclude that comorbid brain conditions present in the experimental group compared with pure dyslexia in the control group do not affect the outcome of the experiment.

The third limitation of the study is the possibility of placebo effects. As described by Gaab et al. (2019), children that are given one-on-one interactions and specialized interventions may improve their functioning based solely on the social and environmental impact of those interventions. Because no alternative intervention for the control group was provided, placebo effects may represent a significant source of improvement.

The fourth limitation of the study is that 4 participants of the experimental group also continued special education. We have repeated the statistical analysis by excluding these participants and showed that the results are also valid for this subgroup.

Future work will include adding special education practices to Auto Train Brain (especially memory, listening and speaking exercises, and vocabulary awareness) and introduce new games for improving the cognitive abilities that currently neither Auto Train Brain nor special education touches (such as writing words and sentences). Moreover, future work can address whether using Auto Train Brain will help improving other brain conditions like dysgraphia, dyscalculia, dyspraxia, anxiety, autism, and mental retardation.

Conclusions

Methodologically, this attempt was a pilot randomized and controlled study. Technology developments provide an interesting vehicle for delivering interventions and, although further research is needed, combined 14-channel neurofeedback and multi-sensory learning method can improve the reading abilities of children with dyslexia. Currently, Auto Train Brain provides a training that is as effective as special education for children with dyslexia. During the pandemic period, the rehabilitation centers were closed and children with dyslexia couldn’t get any special training. Taking into consideration that pandemic may continue in the coming period, Auto Train Brain can be used as a home-based, online special training solution that was scientifically proven for children with dyslexia. This study has also revealed some implications for future research. New games that improve memory, listening, speaking and vocabulary awareness may be added to Auto Train Brain to increase efficacy. Technology-based therapies provide an innovative mix of technology and psychological treatments.

Competing interests

The authors declare the following financial interests which may be considered as potential competing interests. Auto Train Brain has been developed at Sabancı University laboratories. This work has led to the formation of a company aimed to make Auto Train Brain available to users (www.autotrainbrain.com).

Ethics approval and consent to participate

All the participants gave their informed consent after the experimental procedure was explained to them by guidelines set by the research ethics committee of Sabancı University, and the protocol of the study was approved by the Ethics Committee of Yeditepe University and the clinical trial was registered to the Turkey Pharmaceuticals and Medical Devices Agency (Nbr: 71146310-511.06,2.11.2018).

Availability of data and material

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability

None.

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This is the first research conducted in Turkey in which children with dyslexia between 7 and 10 years old have been treated with the mobile phone software. Participants were recruited from TV advertisements and were referred by child neurologists. We are especially grateful to the families who participated in this study; without their dedication and support, we may not have completed it.

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Figure 1: The usage of Auto Train Brain

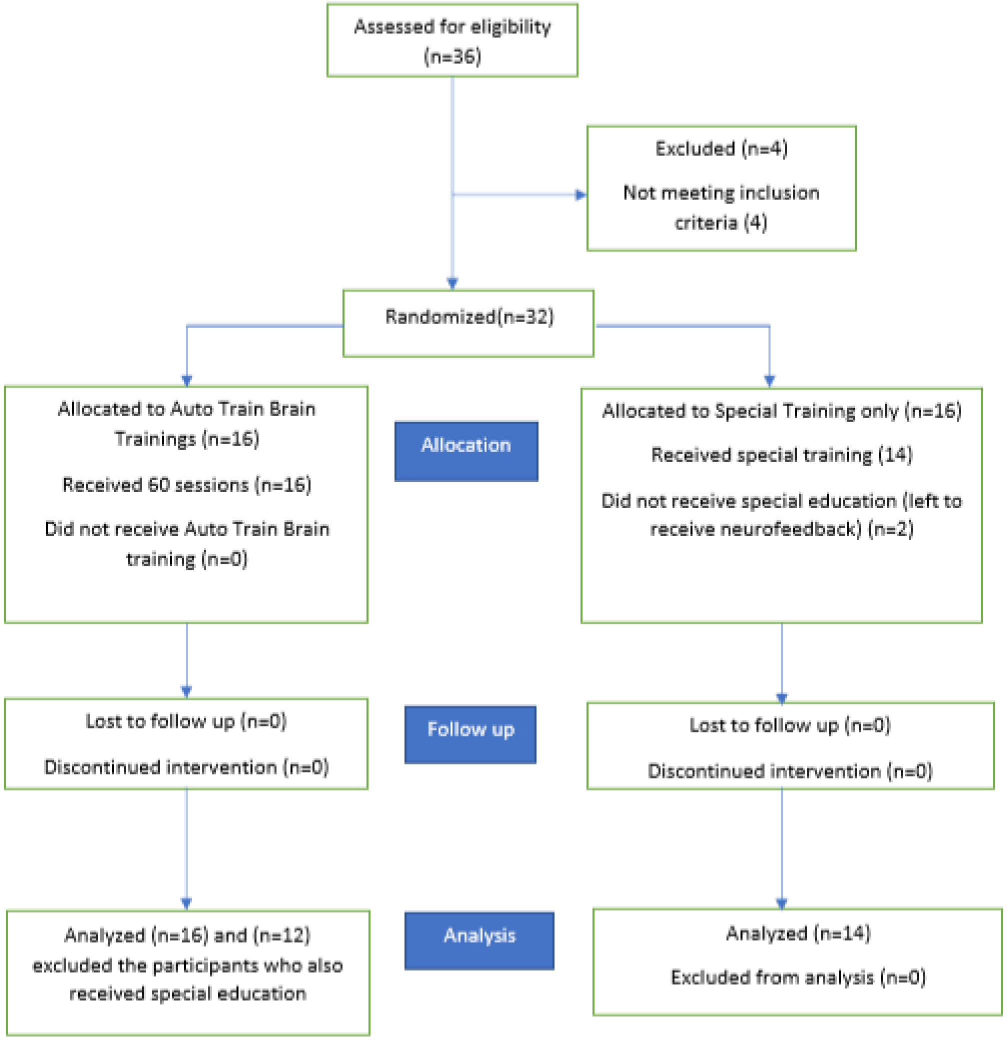

Figure 2: The CONSORT flow diagram for the study presented in this paper.

Table 1: *Demographic information about the experimental (n=16) and the control group (n=14)*

Participants	Comorbidity	Spec.Edu.	Gender	Age	C-section	Breastfeeding	Left hand	SES	TILLS pre	TILLS post
Experiment1		YES	F	9	NO	0	YES	Low	40	46
Experiment2	ADHD	YES	M	7	NO	3	NO	Low	20	32
Experiment3	EEG abnormality	NO	M	9	NO	30	YES	Low	20	10
Experiment4		NO	M	10	NO	4	NO	Low	16	24
Experiment5		NO	M	10	YES	6	NO	Middle	15	19
Experiment6	ADHD	NO	M	7	YES	6	NO	Middle	13	18
Experiment7		YES	M	9	YES	18	NO	Low	11	24
Experiment9		NO	M	7	NO	30	NO	Middle	20	35
Experiment8	CP, gifted	YES	M	8	YES	13	YES	Middle	42	45
Experiment10		NO	M	10	NO	24	NO	Middle	9	13
Experiment11	Gifted	NO	M	8	YES	30	NO	Low	41	40
Experiment12		NO	M	11	NO	24	NO	Low	4	4
Experiment13	EEG abnormality	NO	M	9	YES	0	NO	Low	21	19
Experiment14		NO	M	6	NO	6	NO	Middle	15	23
Experiment15	Gifted	NO	M	9	NO	6	NO	Middle	30	26
Experiment16	EEG abnormality	NO	M	8	NO	24	NO	Low	7	8
Control1		YES	M	8	YES	6	NO	Middle	15	30
Control2		YES	M	9	NO	24	NO	Middle	23	31
Control3		YES	F	8	YES	9	NO	Low	28	33
Control4		YES	M	9	YES	6	YES	Low	14	19
Control5		YES	F	7	YES	19	YES	Middle	5	34
Control6		YES	M	7	NO	7	YES	Middle	9	17
Control7		YES	M	10	NO	6	YES	Middle	24	24
Control8		YES	M	9	YES	24	NO	Middle	30	33
Control9		YES	M	10	YES	0	YES	Middle	34	31
Control10		YES	M	10	YES	24	NO	Low	22	34
Control11		YES	F	8	YES	12	NO	Middle	32	33
Control12		YES	M	9	YES	9	NO	Middle	30	33
Control13		YES	F	9	YES	4	YES	Low	18	15
Control14		YES	F	8	YES	6	NO	Low	15	16
Experiment		YES:4	Female:1	*M*=8.56	NO:10	*M*=11.1	YES:3	Low:9	*M*=20.25	*M*=24.12
		NO: 12	Male:15		YES :6		NO:13	Middle:7		
Control		YES:14	Female:5	*M*= 8.59	NO:3	*M*= 13.9	NO:8	Low:5	*M*=20.88	*M*=27.36
		NO :0	Male:9		YES:11		YES:6	Middle :9		

Table 2: *Pre- and post- TILLS test results for experimental group and control group*

	Control group (n=14)				Experimental group (n=16)			
	pre-scores		post-scores		pre-scores		post-scores	
TILLS	M	SD	M	SD	M	SD	M	SD
Descriptive scores	20.88	8.67	27.36	7.44	20.25	12.02	23.88	8.63
Vocabulary awareness	5.00	2.09	7.57	2.71	5.19	3.35	5.75	2.61
Phonemic awareness	4.82	3.83	7.43	4.78	4.94	4.09	5.88	4.63
Story retelling	4.29	1.90	5.43	3.11	4.88	2.39	6.06	3.13
Nonword repetition	6.76	4.21	7.79	5.28	4.00	3.93	4.88	5.12
Nonword spelling	6.53	3.94	8.21	3.36	6.87	3.66	8.67	3.81
Listening comprehension	5.59	3.62	6.86	4.02	3.75	3.66	4.94	3.88
Reading comprehension	7.12	3.18	6.36	4.22	3.06	4.22	5.20	4.41
Following directions	8.06	3.90	9.07	4.03	8.63	4.81	9.19	3.95
Delayed story retelling	4.76	1.44	5.79	3.64	5.06	2.32	5.38	3.61
Nonword reading	8.00	3.59	9.21	3.19	6.27	4.65	7.47	3.11
Reading fluency	0.41	0.80	0.29	0.61	0.53	0.99	0.60	0.59
Written expression -Disc.	3.00	2.06	2.14	1.96	2.87	2.50	3.67	2.96
Written expression -Sen.	4.88	5.02	3.79	1.76	4.60	5.00	5.07	1.70
Written expression – Words	2.71	3.50	2.21	3.29	3.27	4.03	2.80	3.90
Social communication	3.12	2.20	5.21	3.51	5.31	4.11	5.00	3.42
Digit span forward	8.18	2.46	9.71	3.12	5.63	2.31	5.88	3.09
Digit span backward	7.41	3.00	9.71	3.22	7.00	3.04	7.06	3.11

Table 3: *Repeated measures of ANOVA results, multivariate tests (group X time), interaction effects*

TILLS	Wilks' Lambda	F	Hypotheses df	Error df	Sig.	Eta
Descriptive points	0.975	0.729	1	28	0.400	0.025
Vocabulary awareness	0.857	4.684	1	28	0.039*	0.143
Phonemic awareness	0.973	0.779	1	28	0.385	0.027
Story retelling	1.000	0.010	1	28	0.920	0
Nonword repetition	0.998	0.06	1	28	0.809	0.002
Nonword spelling	0.999	0.018	1	27	0.894	0.001
Listening comprehension	0.999	0.015	1	28	0.903	0.001
Reading comprehension	0.825	5.711	1	27	0.024*	0.175
Following directions	0.992	0.237	1	28	0.63	0.008
Delayed story retelling	0.980	0.584	1	28	0.451	0.020
Nonword reading	0.993	0.188	1	27	0.668	0.007
Reading fluency	0.997	0.091	1	27	0.766	0.003
Written expression -Disc.	0.906	2.791	1	27	0.106	0.094
Written Expression – Sen.	0.980	0.556	1	27	0.462	0.020
Written expressions- Word	0.992	0.226	1	27	0.638	0.008
Social communication	0.827	5.845	1	28	0.022*	0.173
Digit span forward	0.829	5.758	1	28	0.023*	0.171
Digit span backward	0.863	4.443	1	28	0.044*	0.137

*$p < 0.05$.

Table 4: *Repeated measures of ANOVA results, within subject effects (time) and between subject effects (group)*

	Within subject effects					Between subject effects				
TILLS	F	Hypo. df	Error df	Sig.	Eta	F	Hypo. df	Error df	Sig.	Eta
Descriptive points	11.972	1	28	0.002**	0.300	0.384	1	28	0.540	0.014
Vocabulary awareness	11.121	1	28	0.002**	0.284	0.595	1	28	0.447	0.021
Phonemic awareness	4.749	1	28	0.038*	0.145	0.461	1	28	0.503	0.016
Story retelling	6.482	1	28	0.017*	0.188	0.694	1	28	0.412	0.024
Nonword repetition	1.353	1	28	0.254	0.046	4.259	1	28	0.048*	0.132
Nonword spelling	8.66	1	28	0.007**	0.243	0.076	1	27	0.785	0.003
Listening comprehension	3.422	1	28	0.075	0.109	2.421	1	28	0.131	0.08
Reading comprehension	1.059	1	27	0.313	0.038	3.725	1	27	0.064	0.121
Following directions	2.043	1	28	0.164	0.068	0.074	1	28	0.787	0.003
Delayed story retelling	1.94	1	28	0.175	0.065	0.002	1	28	0.968	0
Nonword reading	1.497	1	27	0.232	0.053	2.633	1	27	0.116	0.089
Reading fluency	0.012	1	27	0.914	0	0.426	1	27	0.519	0.016
Written expression -Disc.	0.059	1	27	0.81	0.002	0.592	1	27	0.448	0.021
Written Expression – Sen.	0.006	1	27	0.941	0.000	0.297	1	27	0.590	0.011
Written expressions- Word	1.461	1	27	0.237	0.051	0.056	1	27	0.815	0.002
Social communication	3.536	1	28	0.07	0.112	1.288	1	28	0.266	0.044
Digit span forward	10.361	1	28	0.003**	0.27	13.392	1	28	0.001*	0.324
Digit span backward	5.058	1	28	0.033*	0.153	3.652	1	28	0.066	0.115

$^{*}p < 0.05$. $^{**}p < 0.01$.

Table 5: *Repeated measures of ANOVA results for the experimental group, the simple effect of time*

TILLS	Wilks' Lambda	F	Hypotheses df	Error df	Sig.	Eta
Descriptive scores	0.768	4.533	1	15	0.050^{*}	0.232
Vocabulary awareness	0.924	1.226	1	15	0.286	0.076
Phonemic awareness	0.863	2.372	1	15	0.144	0.137
Story retelling	0.819	3.304	1	15	0.089	0.181
Nonword repetition	0.764	4.623	1	15	0.048^{*}	0.236
Nonword spelling	0.74	4.916	1	14	0.044^{*}	0.260
Listening comprehension	0.897	1.723	1	15	0.209	0.103
Reading comprehension	0.737	4.985	1	14	0.042^{*}	0.263
Following directions	0.951	0.775	1	15	0.392	0.049
Delayed story retelling	0.973	0.423	1	15	0.525	0.027
Nonword reading	0.918	1.258	1	14	0.281	0.082
Reading fluency	0.999	0.012	1	14	0.914	0.001
Written expression -Disc.	0.942	0.859	1	14	0.370	0.058
Written expression -Sen.	0.959	0.604	1	14	0.45	0.041
Written expression -Words	0.984	0.234	1	14	0.636	0.016
Social communication	0.979	0.319	1	15	0.580	0.021
Digit span forward	0.958	0.652	1	15	0.432	0.042
Digit span backward	0.999	0.011	1	15	0.918	0.001

$^{*}p < 0.05$. $^{**}p < 0.01$.

Table 6: *Repeated measures of ANOVA results for the control group, the simple effect of time*

TILLS	Wilks' Lambda	F	Hypotheses df	Error df	Sig.	Eta
Descriptive scores	0.647	7.106	1	13	0.019^{*}	0.353
Vocabulary awareness	0.573	9.688	1	13	0.008^{**}	0.427
Phonemic awareness	0.835	2.562	1	13	0.133	0.165
Story retelling	0.804	3.172	1	13	0.098	0.196
Nonword repetition	0.984	0.210	1	13	0.655	0.016
Nonword spelling	0.774	3.802	1	13	0.073	0.226
Listening comprehension	0.885	1.683	1	13	0.217	0.115
Reading comprehension	0.918	1.163	1	13	0.300	0.082
Following directions	0.916	1.190	1	13	0.295	0.084
Delayed story retelling	0.904	1.384	1	13	0.260	0.096
Nonword reading	0.974	0.351	1	13	0.564	0.026
Reading fluency	0.984	0.210	1	13	0.655	0.016
Written expression -Disc.	0.847	2.349	1	13	0.149	0.153
Written expression -Sen.	0.985	0.196	1	13	0.665	0.015
Written expression -Words	0.883	1.728	1	13	0.211	0.117
Social communication	0.705	5.430	1	13	0.037^{*}	0.295
Digit span forward	0.571	9.750	1	13	0.008^{**}	0.429
Digit span backward	0.603	8.576	1	13	0.01^{*}	0.397

$^{*}p < 0.05$. $^{**}p < 0.01$.

Table 7: *The comparison of the effectiveness of the dyslexia training programs in the literature*

Dyslexia training program	Effect size	Dyslexia	Comorbidity	Group size
AutoTrainBrain with special education	0.88	Yes	No	2
AutoTrainBrain	0.66	Yes	No	6
Orton Gillingham	0.43	Yes	No	77
Special education	0.35	Yes	No	14
Neurofeedback (Breteler et al., 2010)	0.3	Yes	No	19
AutoTrainBrain	0.23	Yes	Yes	16