THE SENSOR HUB FOR DETECTION OF THE RELATION BETWEEN PHYSIOLOGICAL PARAMETERS AND COLOUR MODIFICATIONS IN TEXT BACKGROUND AND OVERLAY DURING READING IN CHILDREN WITH AND WITHOUT DYSLEXIA

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Doctoral Dissertation
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SENZORSKO VOZLIŠČE ZA ZAZNAVANJE RAZMERJA MED FIZIOLOŠKIMI PARAMETRI IN BARVNIMI SPREMEMBAMI V OZADJU BESEDILA IN BARVNIM PREKRIVANJEM MED BRANJEM PRI OTROCIH Z DISLEKSIJO IN BREZ NJE

Doktorska disertacija

Supervisor: Prof. Gregor Papa

Co-Supervisor: Prof. Tadeja Jere Jakulin

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To the children with dyslexia.

To my husband, family, friends, mentors, professors and colleagues.

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Abstract

The doctoral dissertation discusses the mechanisms of the colours' influence on the reading process and electrophysiological correlates of the reader's condition, considering developmental aspects, graded (level) aspects and gender aspects of tested groups of children and their reading acquisition.

The reading process is one of the most important processes during an individual's maturation. As a complex process, reading involves both cognitive and perceptual abilities. Therefore, we can say that reading skills also affect learning, which depends on a wide range of perceptual and cognitive abilities. In early school-age children, it is not very difficult to determine the reading level. However, it is essential to understand other fundamental emotional and motivational problems caused by specific reading and learning difficulties that could impair overall school achievement (educational outcomes). Reading could also be reflected through the psychophysiological state of the child as a process involving sensory integration, attention, and memory. These basic neural and physiological reading processes can be measured by various BioSignal modes such as electroencephalography (EEG), electrocardiography (ECG), electrodermal activity (EDA), and eye movement.

Numerous studies have examined how coloured backgrounds and overlays can improve the reading process, especially in children with dyslexia and other reading difficulties. It is important to note that colours in the human body elicit an emotional response that physiological parameters can also measure. These parameters are needed to understand better the impact of colours on reading performance and how colours can improve reading. With the dissertation, we wanted to explore, understand and present the relationships between physiological parameters and colour changes of text and background during reading in the context of developmental and various reading disorders (such as dyslexia) in children, which could confirm or refute the hypotheses we set at the beginning of the research.

In three experimental and correlation studies, we evaluated differences in electroencephalography (EEG), heart rate variability (VSU), electrodermal activity (EDA), and eye movement (oculomotor activity) during reading in thirteen different combinations of the text backgrounds and overlays. We used the same design attempt with different combinations of background colours and methodology in all three studies.

The first study results represent the context of developmental differences in reading in children with twenty-six participants (thirteen from the second and thirteen from the third grade of primary school). The second study demonstrates better reading skills from a gender perspective with fifty children (twenty-five girls and twenty-five boys), and the third study demonstrates a correlation of better reading of children with dyslexia relative to particular colour background. The experiment was performed with thirty-six participants (eighteen with dyslexia, eighteen with control groups).

Based on the results of studies and confirmation of seven hypotheses, we can conclude that colour overlays and colour background allowing a better understanding of various aspects of the reading process and improving its skills.

Povzetek

Doktorska disertacija obravnava mehanizme vpliva barv na bralni proces z elektrofiziološkimi korelati bralčevega stanja ob upoštevanju razvojnih vidikov, stopnjevanih (nivojskih) vidikov ter z vidikov spola testiranih skupin otrok in njihovega bralnega usvajanja.

Proces branja je eden najpomembnejših procesov med zorenjem posameznika. Kot kompleksen proces branje vključuje tako kognitivne kot zaznavne sposobnosti. Zato lahko rečemo, da razvoj bralnih veščin vpliva tudi na učenje, ki je odvisno od širokega spektra zaznavnih in kognitivnih sposobnosti. Pri otrocih v zgodnjem šolskem obdobju ni zelo težko določiti stopnje branja, vendar je pomembno razumeti druge osnovne čustvene in motivacijske težave, ki jih povzročajo nekatere težave pri branju in učenju, ki bi lahko poslabšale splošne šolske dosežke (izobraževalne rezultate). Proces branja se lahko odraža tudi skozi psihofiziološko stanje otroka kot proces, ki vključuje senzorično integracijo, pozornost in spomin. Te osnovne živčne in fiziološke bralne procese lahko merimo z različnimi načini BioSignalov, kot so elektroencefalografija (EEG), elektrokardiografija (EKG), elektrodermalna aktivnost (EDA) in gibanje oči.

Številne študije so preučevale, kako lahko barvna ozadja, barvne folije in platnice izboljšajo bralni proces, zlasti pri otrocih z disleksijo in ostalimi težavami pri branju. Pomembno je upoštevati, da barve v človeškem telesu izzovejo čustveni odziv, ki ga je mogoče izmeriti tudi s fiziološkimi parametri. Ti parametri so potrebni za boljše razumevanje vpliva barv na bralno uspešnost in tudi za to, kako lahko barve izboljšajo samo branje.

Z disertacijo smo želeli raziskati, razumeti in predstaviti razmerja med fiziološkimi parametri in barvnimi spremembami besedila ter ozadja med branjem v kontekstu razvojnih in različnih bralnih motenj (kot je disleksija) pri otrocih, s katerimi bi lahko potrdili ali ovrgli hipoteze, ki smo jih postavili v začetku raziskovanja.

V treh študijah, opravljenih z metodama eksperimenta in korelacije, smo ocenjevali razlike v elektroencefalografiji (EEG), variabilnosti srčnega utripa (VSU), elektrodermalni aktivnosti (EDA) in gibanju oči (okulomotorna aktivnost) med branjem, in sicer v trinajstih različnih kombinacijah barv ozadja in folije nad besedilom. V vseh treh študijah smo uporabili enak poskus zasnove z različnimi kombinacijami barv ozadja in metodologije. Rezultati prve študije predstavljajo kontekst razvojnih razlik v branju pri otrocih s šestindvajsetimi udeleženci (trinajst iz drugega in trinajst iz tretjega razreda osnovne šole). Z drugo študijo smo dokazali boljše bralne veščine z vidika spola s petdesetimi otroki (petindvajset deklic in petindvajset fantov) in s tretjo študijo smo dokazali korelacijo boljšega branja otrok z disleksijo glede na določeno barvno ozadje. Eksperiment smo opravljali s šestintrideset udeleženci (osemnajst z disleksijo, osemnajst kontrolnih skupin).

Na osnovi rezultatov študij in potrditev sedmih hipotez lahko ugotovimo, da so na podlagi ustreznih meritev senzorjev barve in barvne podlage tiste, ki omogočajo boljše razumevanje različnih vidikov bralnega procesa ter izboljšanje veščin le-tega.

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Chapter 1

Introduction

1.1 Challenges

One of the most important processes during the maturation of an individual is learning to read. Reading is a complex process involving perception and cognition, which integrates auditory and visual information processing, attention, memory, and language skills [1]. Therefore, reading skills are affected by reading, which depends upon a range of perceptual processes and cognitive abilities. [2]–[4]. Several research studies are dedicated to the reading skills acquisition in children [2], [5]–[7], considering the process of learning to read as one of the fundamental objectives of education of one person. Depending on the individual scope of abilities, children will have different reading skills, while the lack of some abilities may cause their reading performance over time. These differences in reading abilities could be found from biological, neurological factors to the development of the brain system responsible for the reading process [8]. Since reading abilities could impair educational achievements and increase the risk of mental, emotional, and health problems in children [9], it is essential to identify and treat reading difficulties as early as possible.

Developmental dyslexia is manifested in individuals who require special motivation and intellectual effort to achieve fluent reading and it is usually defined as an unexpected difficulty in reading [10], [11]. It is important to assist the needs of the children with reading difficulties with early identification and professional support [12], [13].

It is not so difficult to mark the level of reading at early school age, but it is difficult to understand other problems that cause emotional distress and lack of motivation and usually interfere with overall school achievement [14], [15]. Children usually do not have difficulty in general performance, while they have some types of reading difficulty. Emotional difficulties are common in those children [16], [17]. Most importantly, through early intervention, the risk of these difficulties can be reduced before they appear in the 4th grade. In the neuropsychological and psychological research regarding children the gender differences are widely analysed especially in context of cognitive abilities and learning to read [18]-[27].

Reading involves sensory integration, attention, and memory, which are reflected in the psycho-physiological state of the children engaged during the reading task. These fundamental neural and physiological processes are measurable by different BioSignal modalities such as Electrodermal Activity (EDA), Electrocardiography (ECG), Electroencephalography (EEG), and eye-movement.

When we take into consideration colours-proven relation to emotions [28]-[30], we can measure it as well through the physiological parameters of the human body. Thus, we can make a parallel with the reading process to better understand how colours could change the physiological parameters and improve the reading process by self.

Many studies have reported how colour overlays and background could improve the reading process, especially in children with reading disorders [31]-[36]. The goal of the present research was to understand the relationship between physiological parameters and colour modifications in the text and background during reading in the context of developmental, gender and different reading disabilities (such as dyslexia) of children.

We aimed to address the mechanisms of colours effect on the reading process through electrophysiological correlates of the reader's state while taking into account the developmental, gender, and graded (level of) reading aspects of the reading acquisition.

1.2 Approach and Hypotheses

This research aimed to investigate the effects of colour on the content as a stressor during the reading task. The present study aims to further illuminate underlying physiological and behavioural processes accompanying the reading task in children from the developmental, gender and reading skills perspective.

The hypotheses that are investigated in this thesis are as follows:

H1: The younger children would have more difficulties reading the text on the intense colour background than a pastel background.

H2: The older children would struggle more with any colour except for white.

H3: There are differences among boys and girls in the emotional response caused by colours during the reading task.

H4: Colours could highlight reading differences among girls and boys during the reading task.

H5: The children with good reading skills will be less affected by the change of colour.

H6: The pale colours would facilitate the reading task in children with and without dyslexia, unlike intense colours.

H7: With appropriate set of sensors we can detect the most appropriate colours for each individual.

1.3 Scientific Contributions

This research generates the novel method that combines different modalities (sensors) in one sensor hub, which can simultaneously measure neurophysiological parameters during the reading performance and capture its changes related to different background/overlay colours.

Second, this novel method is applicable to several approaches of understanding the reading process through gender, developmental, and reading grade differences.

Third, the created sensor hub could be used for early dyslexia and other reading disorders prediction, and better understanding of emotional responses during the reading task or other contents such are photo, video or games.

This study is a step towards defining the set of measurements that may enable the quick automatic selection of colour setup that would facilitate the reading task in a specific reader.

1.4 Ethical Issues

The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of the Psychology Department of the University of Niš in the Republic of Serbia (9/2019, 4 September 2019).

1.5 Publications Overview

The Methodology developed in this thesis was incorporated in three different studies in order to better understand colours influence on reading performance in children through following aspects: 1. Developmental differences, 2. Gender differences, 3. Reading difficulties such as dyslexia.

1. The study “The sensor hub for detecting the developmental characteristics in reading in children on a white vs. coloured background/coloured overlays” sheds light on the underlying neural, physiological and behavioural processes accompanying the reading task in children. Moreover, this is an initial step towards the possibility of including colour into reading content to improve reading skills in children at different developmental stages
2. The study “Effect of colours on reading performance in children measured by the sensor hub: from the perspective of gender” is an attempt to present new evidence regarding gender differences in reading skill. This research aims to contribute to the existing body of knowledge on the effect of the text, background and overlay colour according to gender.
3. The study “The Relation Between Physiological Parameters and Colour Modifications in text Background and Overlay During Reading in Children With and Without Dyslexia” presents the first research that explores the impact of 13 combinations of background and overlay colours on the reading performance of children with normal reading skills and children diagnosed with dyslexia, measured by multimodal sensor hub (electroencephalography, EEG; electrocardiography, ECG; electrodermal activity, EDA; and eye-tracking).

1.6 Thesis Overview

Chapter 2 starts by describing the background in the field of reading and learning difficulties, developmental dyslexia and its neurobiological origin, developmental aspects of reading, and gender differences in context of reading performance, which is followed by an explanation of the colour influences on reading performance and emotions. Next, types of used sensors are presented along with Bluetooth sensor network which is used for the data acquisition.

Chapter 3 presents the developed methodology and experiment design for this thesis incorporated in three different studies. This chapter summarizes the performed work in three different studies and publications.

Chapter 4 describes the aim and summary of the contribution of the study “The sensor hub for detecting the developmental characteristics in reading in children on a white vs. coloured background/coloured overlays” published in Sensors journal.

Chapter 5 presents the study “Effect of colours on reading performance in children measured by the sensor hub: from the perspective of gender” published in Plos One journal

Chapter 6 describes the contributions and the study third "The Relation Between Physiological Parameters and Colour Modifications in text Background and Overlay During Reading in Children With and Without Dyslexia" published in Brain sciences journal.

Chapter 7 concludes the different studies in the thesis and provides highlights of the future work.

Chapter 2

Background

2.1 Reading and Learning Difficulties

When a person has a problem in reading words or understanding what they have read, the reading disorders occurs. One type of the reading disorders is dyslexia. The majority of reading disorders are the result of specific differences of brain processing the written words and text. Mostly these disorders are present from the early childhood, but individuals could develop a reading problem in case of brain injury at any age.

Children with reading disorders commonly have problems to recognize words they already learned and understand text they are reading. Usually, they also might be poor spellers.

Reading disorders are not always a sign of lower intelligence or low willing, reading disorders are not a type of intellectual or developmental disorder [38].

The well-known reading disorder is dyslexia. Individuals with dyslexia are ranked with normal intelligence, but their read grade are lower than expected in individuals at the same age.

There are distinct forms of reading difficulties in learning to decode (developmental dyslexia) and learning to comprehend text (reading comprehension impairment). Which of these difficulties will appear, depend on impairments of oral language development. Dyslexia occurs in situation where persisting problems in the development of speech-sound (phonological) skills exists [39].

It is estimated that more than 10 percent of the world population is affected by dyslexia [40]. Dyslexia is a learning disability whose main characteristics are difficulties with accurate or fluent word recognition with the neurobiological origin. It is also characterized by poor spelling and decoding abilities which results in problems in reading comprehension and reduced reading experience [10].

2.1.1 Developmental Dyslexia

Understandings of dyslexia vary according to different theories, but there is a general opinion that children who fail to accurately read, need careful support and monitoring at early school age. The World Federation of Neurology recognizes children with dyslexia as those who, regardless of the standard school curriculum, cannot attain reading, spelling, and writing skills in proportion to their intellectual abilities [13], [31]. At that age, the most effective approach for children with reading difficulties are early identification and professional support which assists their needs [42]-[44]. For example, in Sweden, diagnosing dyslexia in practice is possible only at children age of thirteen [45]. Marking the grade level of reading is not so difficult at the early-school age, but it is difficult to understand other problems which usually obstruct overall school achievements and cause a lack of motivation and emotional distress [46], [47]. Children with dyslexia do not have difficulties in their general performance in other segments of the curriculum. Some of them may also have emotional difficulties [12], [47]. Through early intervention, the risk of those difficulties may be reduced before they emerge in the 4th grade. In the research dedicated to the early indicators of dyslexia, children were monitored from preschool age to the end of the fourth grade of primary school [14], [15]. There are evidences that dyslexia can be prevented and predicted in early school-age children [16], [17], [48]. Understandings of dyslexia vary according to different theories, but there is a general opinion that children who fail to accurately read, need careful support and monitoring at early school age. At that age, the most effective approach for children with reading difficulties are early identification and professional support which assists their needs.

2.1.2 Neurological basis of reading difficulties

Today, scientists are better able to understand the child's nervous system and how it operates in the case of dyslexia using functional neuroimaging [49]. There is good evidence that dyslexia has a neurological basis [50], [51]. Namely, it may be reflected in the psycho-physiological states of the body during the reading task [39].

Reading as a complex skill cause many reasons in children who fail to learn to read. For example, it is investigated that reading difficulties in some children may result from difficulties with processing speed, general language deficit, rapid auditory processing or visual deficits, among other things [9]-[11]. Phonemic awareness is used as one of the best predictors of subsequent reading success and that it is causally related to reading skill.

For better understanding of reading development, reading disabilities and its interventions the neuroimaging techniques have been used. Researchers have found evidence regarding skilled word recognition and its requirement for developing a highly organized cortical system. The cortical system integrates the processing of orthographic, phonological, and lexica-semantic attributes of words [51].

As mentioned above reading involves sensory integration, attention and memory, and those processes may be reflected in the psycho-physiological states of the individual engaged in the reading task. Those states are a result of underlying neural and physiological processes, which are measurable and quantifiable by different BioSignal modalities.

2.1.3 Colour filters and dyslexia

Given that colours can affect the state of our body and emotions [33], this work investigates the relationship between physiological parameters and colour modifications in the text and background during reading in children with and without dyslexia. In order to improve treading skills in children with dyslexia, colours have been used in modulating performance and for other purposes such as increasing reading speed and fluency [34], [52]-[55]. The so-called visual stress syndrome is observed in dyslexic individuals very often [48], but the role of colours involvement during the reading performance remains controversial The concept of colour involvement in reading performance has led to the broadened use of coloured overlays to reduce reading disorders and improve reading skills.

It is reported that symptoms of visual stress are caused by sensitivity to certain light frequencies [59]. In practice, applications of coloured filters have led to the use of lenses and overlays in reading. Coloured overlays filter the light using transparent plastic reading sheets tinted with colour over the text [32],[59]. Many dyslexic subjects reported that coloured overlays can help them with widespread difficulties arising in the reading process [61]–[64].

Moreover, it has been reported, without taking into consideration children with dyslexia, that colour overlays could improve the reading process in school-age children [65]. Furthermore, other scientists [66] have shown that problems caused by dyslexia could be relieved by visual changes in the presentation of the reading text. Other researchers have focused on the visual design of the text on the computer screen, where background and text colour, or font size were adjusted in order to help people with dyslexia [64]–[66]. These conditions have inspired Pinna and Deiana [67], [68] to study how colours could influence reading time and comprehension.

Other studies dedicated to the effects of colour on reading in dyslexic children, showed how the reduction of symptoms in Meares Irlen Syndrome could be possible with the application of colour filters which for visual discomfort reduction [69]. Moreover, coloured filters in the research were considered as an effective intervention for readers with visual stress. It was reported [70], that the reading speed of patients with Meares-Irlen syndrome improved by more than 20% when they wore the selected colour-tinted lenses. By contrasting no filter, yellow and green filter, researchers [71], [72] found that children with dyslexia were fastest and had the shortest fixation time when reading in the yellow and green-filter condition.

We found that Stein [72], [73] in his studies declare that dyslexia is "characterized by poor temporal processing, hence impaired visual and auditory sequencing, that is caused by impaired development of transient/magnocellular (M-) systems throughout the brain" and based on this argument needs to collect evidence not only from psychophysical tests but from electrophysiological, attentional, brain imaging, interventional, eye movement, and genetic findings as well. Aside from the use of colour overlays, it was also found that the use of different background colours [32] increased the reading performance of subjects with dyslexia and has been recommended by the British Dyslexia Association [73].

2.2 Colour Influence on Reading Process

Colours perception is one of the crucial aspects of human vision which trigger brain activity [74], [75].

Colours affect the mood and behaviour of an individual [76], [77]. Red is recognized as colour which produces the highest hazard and blue is linked with peace and calm filings, biologically observed cool light has a larger alerting effect than warmer light as the reddish [66].

Thus, the basic colours in psychology are blue, yellow, red, and green and every visual stimulus process by the human perceptual system contains colour information.

There is some limited evidence that colours may impact the reading process, specifically with early school-age children, and those with reading disabilities [78], [79]. Going back a few decades, the role of colours in reading dates back to 1958. Jansky [52] reported the case of a student with a reading deficit who was able to recognize words printed on yellow paper, but unable to recognize words printed on white paper. Previous studies considered the influence of background, text, or overlay colour on the actual reading process in children [32], [66]. While more recent studies have shown that colours do not influence the reading process and that this could be a placebo [80], others have found that colours may be particularly effective for early readers in school-age children [81].

Regarding the gender perspective and how colours could highlight the differences in males and females, it is found that male subjects prefer blue and green, and females prefer pink and purple overlay colours for reading [82]. Therefore, the effect of colour on the reading process from the perspective of gender have been investigated in the present research [72].

2.3 Sensors

Wireless sensor networks are a technology that is gaining a lot of attention nowadays. The broad spectrum of wireless sensor networks of small devices equipped with sensors (microprocessor and wireless communication interfaces) are already finding use in scientific research, military applications, environmental monitoring, and healthcare [83]. One of the main focuses in this field is the introduction of smart sensor nodes. Small, low-cost and low-power devices are the product of MEMS (micro-electrical-mechanical systems) technology, combined with electric components and wireless communication. They are capable of performing various tasks related to sensing, data processing and wireless communication.

When put together, these devices can make up a well-developed platform that enables many uses in terms of security systems, health monitoring, detection of aerial and hydro chemical agents etc. The main reason for this being the high usability and many integrated sensors.

For the purpose of the present research experiment the sensor hub was developed for data acquisition of the physiological parameters during the reading process.

The goal of the present study was to employ multimodal sensor measurements to examine the influence of the colour of the content on the reading task for children at different developmental stages. More specifically, we have employed measurements of electroencephalography (EEG), eye-tracking, electrodermal activity (EDA) and heart rate variability (HRV) to assess the influence of background and overlay colour on reading performance in school-age children. Through electrophysiological correlates of the reader's state, we aimed to address the mechanisms of colour influence on the reading process.

The sensor hub was composed of an eye-tracking system and a portable multimodal EEG/ECG/EDA system, as presented in Figure 1. For real-time data monitoring and storage two laptops were used: one laptop for eye movement monitoring (with additional external computer monitor and keyboard in front of the participant) and another for EEG/ECG/EDA monitoring.

In the first two experiments regarding developmental and gender differences, real-time data monitoring was performed as in Figure1 where one channel of the amplifier was used for the synchronization with the photosensitive electrode. In the third experiment regarding reading grades (dyslexic and non-dyslexic individuals) the external keyboard was used for the synchronization with the triggers at the space button (marking the signal in both systems/Eye-tracking and Smarting).

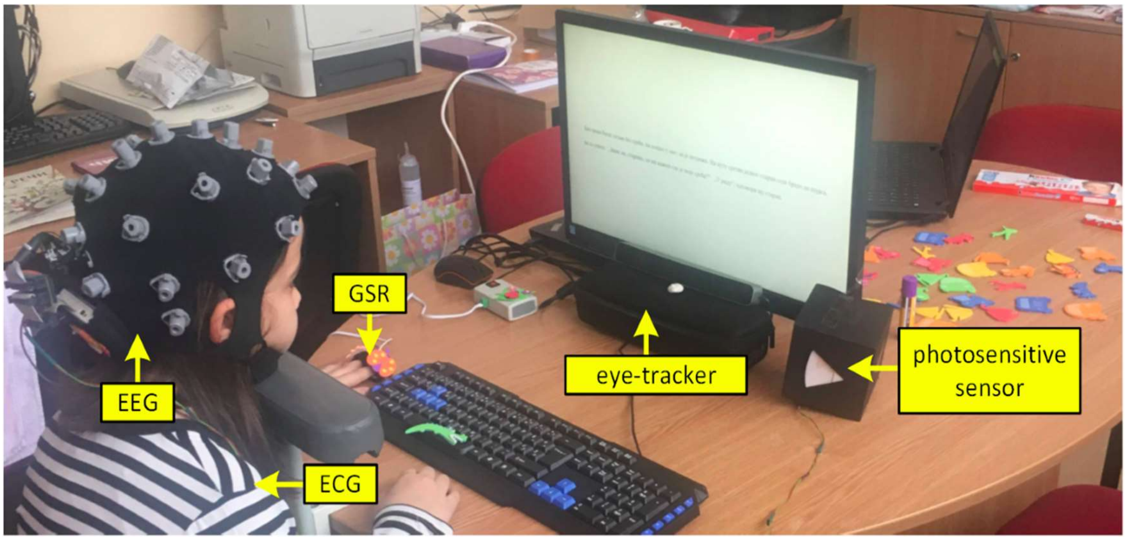

Figure 2.1: Experiment setup: (1) Eye-tracking system; (2) Portable multimodal EEG/ECG/EDA system; (3) Photosensitive sensor for synchronization of multimodal EEG/ECG/EDA system and eye-tracking system.

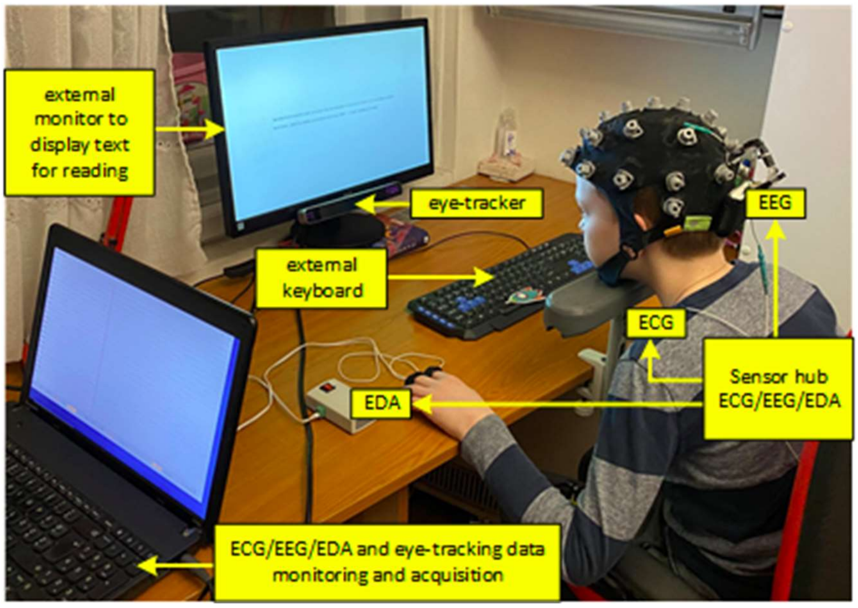

Figure 2.2: Sensor hub ECG/EEG/EDA, computer, screen and eye-tracking system.

Figure 2.2 shows the sensor hub consisted of a portable multimodal ECG/EEG/EDA and eye-tracking system for the acquisition of physiological data during the reading performance.

Real-time monitoring and storage were at one laptop instead of two, which was the case in the previous experiment setup because the system now is synchronized by keyboard stream instead of the photosensitive sensor. In front of every child an an external keyboard and monitor were positioned and connected to the laptop. The sampling rate was set to 250 Hz for EEG/ECG data and 40 Hz for EDA data [84]. The application for data acquisition used Lab Streaming Layer (LSL) for the synchronization between the EDA, EEG/ECG data, and keyboard stream, and stored all data in XDF file format.

2.3.1 Eye-tracking system

In the front of the participants an SMI RED-m 120 Hz portable remote eye-tracker (iMotions, Copenhagen, Denmark) was placed below the computer monitor (it was fixed in place to avoid accidentally moving). For ensuring the same distance of from the monitor and table for each participant an adjustable chinrest was used (the chinrest was 57 cm away from the eye-tracking sensor and 16 cm above the table) as is shown in Figure 2.3. In the experiment the SMI software was used for data collection (iView RED-m) and stimuli presentation (Experiment Centre 3.7).

Figure 2.3: SMI RED-m 120 Hz portable remote eye tracker (iMotions, Copenhagen, Denmark).

2.3.1.1 Eye-tracking measurement

The gold standard of understanding differences in children's reading skills is certainly eye tracking [1], as one of the oldest methods for determining differences in developmental components [7].

Although eye movements have proven the significance for adult reading and cognitive processes understanding, it was rarely used in the case of young readers in the development stage. Using the method of eye movements was historically invaluable for the investigation of the developmental aspects of the reading skills [17].

Analysing the readers' eye movements, it is possible to get an accurate insight into the reading process over time [7]. It is also a helpful tool in understanding underlying interactions between visual and language processing systems and their changes in the developmental aspect. Also, it is shown that eye movements are an important source of information about the development of reading skills [7].

In the present research eye-tracking data analysis and visualization were performed using SMI BeGaze TM 3.7 software (SensoMotoric Instruments, Teltow, Germany).

The selected eye-tracking parameters were: fixation count, fixation frequency (count/second), fixation duration total (ms), fixation duration average (ms), saccade count, saccade frequency (count/second), saccade duration total (ms), and saccade duration average (ms).

2.3.2 Portable multimodal EEG/ECG/EDA system

Electrocardiogram (ECG) and electroencephalogram (EEG) have long been used in conventional science and medicine to evaluate the physiological activities of both the heart and the brain [85]-[90].

The mobile EEG 24-channel amplifier were used for EEG and ECG signals recording (SMARTING, mBrainTrain, Belgrade, Serbia) wirelessly communicating with a laptop via Bluetooth. Twenty-two monopolar EEG channels of Greentek Gelfree-S3 cap (10/20 locations: Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T7, T8, P7, P8, Fz, Cz, Pz, AFz, CPz, POz) were recorded. The ground was located at FPz and FCz was used as the reference site. The surface SKINTACT ECG electrode as one channel of the amplifier (placed in the left chest region, over the heart) was connected to record ECG signal as a reference for heartbeat detection. The resolution of the acquired EEG and ECG signals were 24-bit and 250 Hz sampling rate. The skin-electrode impedances were below the manufacturer recommended value of 1 kOhm, prior to the tests.

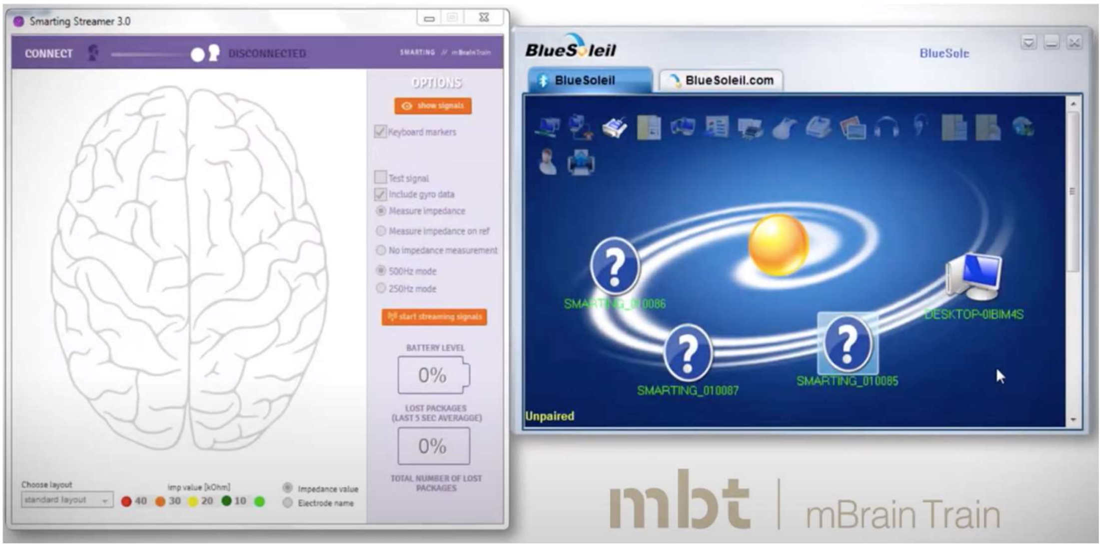

Figure 2.4: SMARTING, mBrainTrain, Belgrade, Serbia.

2.3.2.1 Electroencephalogram (EEG)

EEG was developed in 1875 in order to mark the electric activity of various parts of the brain with the use of electrodes placed on the head [91].

EEG works based on the principle of differential amplification, or voltage differences between different recording points. EEG mostly used a pair of electrodes that compares one active exploring electrode site with a neighbouring or distant reference electrode.

In the present research for each subject and electrode site, the EEG signal was processed in order to calculate the band power in five predefined frequency bands, as follows: delta (0.5-4 Hz), theta (4-7 Hz), alpha (7-13 Hz), beta (15-40 Hz) and whole range (0.5-40 Hz). The median value of the EEG band power (for each frequency band) was determined for 13 time-epochs coinciding with the reading of the content of each presented slide. The median EEG power in each frequency band was calculated by raw continuous signal band-pass filtering (4th order Butterworth filter with cut-off frequencies defined by individual band's frequency range), squaring, segmenting into 13 epochs (determined as time intervals between each slide's onset and offset), and median averaging to a single power value over signal samples of each epoch (i.e., over each slide's duration). The applied processing resulted in 65 median power values (i.e., 13 slides times 5 frequency bands) for each EEG channel of each subject. Median power calculation was applied since it is less likely to be affected by outliers in the EEG power samples that occur with temporary movement artefacts than the mean power.

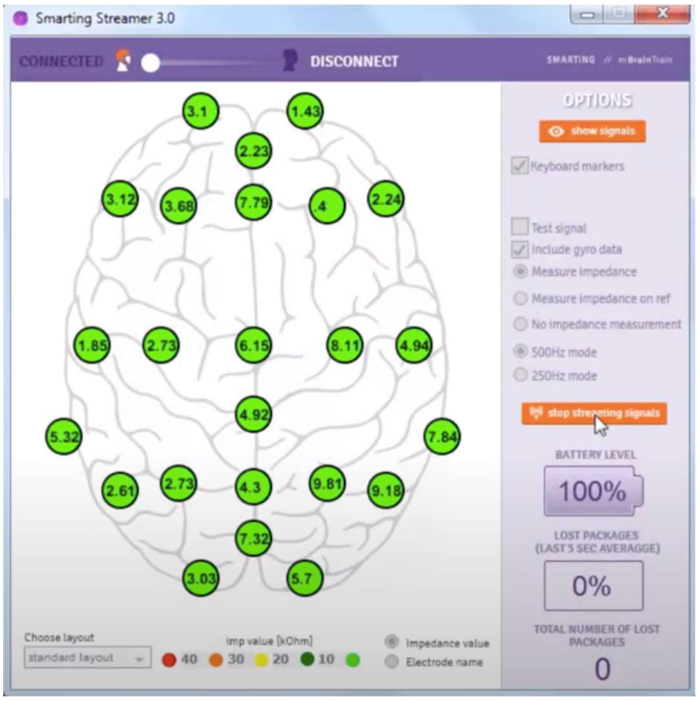

Figure 2.5: EEG cap layout from Smarting streamer 3.0.

2.3.2.2 Electrocardiogram (ECG)

The electrocardiogram records the variation of bioelectric potential in a time that results in the heartbeats. Valuable information about the functional aspects of the heart and cardiovascular system can be obtained through the analysis of the bioelectric signal. Electrocardiogram (ECG) is a clinical tool that monitors heart rate (rhythm), and regularity or irregularity of heartbeats.

ECG was first developed in 1887 and it notes the electric activities from various areas of the heart [85].

2.3.2.3 Heart rate variability (HRV)

Heart rate variability (HRV) is a broadly used physiological parameter that measures changes in the cardiac rhythm through time, and non-invasive assesses the cardiac autonomic nervous system (ANS) [92]. HRV is a reflection of changes of the cardiac sympathetic and parasympathetic branches of the ANS. The number of heartbeats per minute is heart rate, and heart rate variability (HRV) is the fluctuation in the time intervals between adjacent heartbeats [93].

In the present study, the heart activity signal was band-pass filtered using an FIR filter in the range 1-45 Hz (750 points), after which the Pan-Tompkins algorithm [94] for the extraction of heart activity beats was applied. Beat-to-beat intervals (BBI, the time between two successive heart activity peaks) were calculated. Heart rate variability (HRV) parameters [95] were calculated from the BBIs for 13 time-epochs coinciding with the reading of the content of each presented slide (Table 1). The applied processing resulted in 14 HRV parameter values in one subject for each of the 13 slides.

Table 2.1: Heart rate variability (HRV) parameters.

Parameter	**Unit**	**Description**
	Time domain parameters	
Mean RR	ms	Mean value of BBIs
SDNN	ms	Standard deviation of normal BBIs
Mean HR	beats/min	Mean value of heart rate
STD HR	beats/min	Standard deviation of heart rate
CVRR=SDNN/Mean RR	n.u.	Coefficient of variance of normal BBIs
RMSSD	ms	Root mean square of differences of successive BBIs
NN50	beats	Number of successive BBIs that varied more than 50 ms

2.3.2.4 Electrodermal activity

According to Wolfram Boucsein, Electordermal activity (EDA) “was first introduced by Johnson and Lubin (1966) as a common term for all electrical phenomena in skin, including all active and passive electrical properties which can be traced back to the skin and its appendages”[96], [97].

In the present study, we have used a research prototype for galvanic skin response (electrodermal activity, EDA) recording that communicates with a laptop via Bluetooth [84]. The sampling rate for EDA data was 40 Hz. The SMARTING application has Lab Streaming Layer (LSL) compatibility which enabled synchronization between the EDA and

EEG/ECG data within a single file of XDF format [84] that communicates with a laptop via Bluetooth.

The mean value of the EDA data was calculated as a representative value of electrodermal activity for 13 time-epochs coinciding with the reading of the content of each presented slide. The applied processing resulted in 13 mean values for each subject (one mean EDA value per slide).

2.3.2.5 Photosensitive sensor for synchronization of multimodal EEG/ECG/EDA system and eye-tracking system

For the synchronization of electrophysiological recordings and eye-tracking data, one channel of the amplifier was used. A small photosensitive sensor registering the changes on the screen after each slide. Changes of the black and white light on the screen were used (200 ms each) and sent as a trigger for the synchronization of the multimodal EEG/ECG/EDA system and eye-tracking system for each event (slide).

2.3.3 Experiment setup improvements

Real-time monitoring and storage were at one laptop instead of two, as in the earlier experiment design because the system was synchronized by keyboard stream instead of the photosensitive sensor (which were registered colour changes of two subsequent slides and marker the events during the experiment). The laptop was connected with an external keyboard and screen positioned in front of every child.

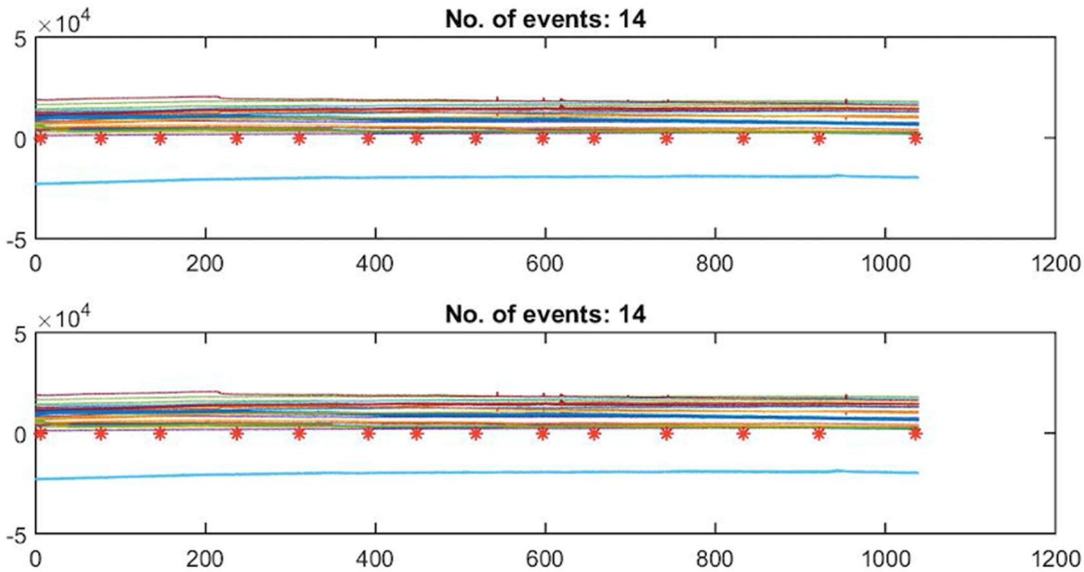

Figure 2.6: Keyboard event marker with the Lab Stream Layer (LSL).

Figure 2.6 shows five streams with the marked events recorded through LSL. The XDF file were exported with MATLAB feature in five streams: Impedance stream, EDA stream, EEG stream, Keyboard stream and Keyboard events.

The ECG data and HRV parameters were calculated from the BBIs with the same 13 time-epochs per each slide of each participant.

Chapter 3

Methodology and Experimentation

The Methodology and Experiment design developed in this thesis was incorporated in three different studies with focus on clarifying the reading differences in children and better understanding of colours influence on reading performance in children.

1. “The sensor hub for detecting the developmental characteristics in reading in children on a white vs. coloured background/coloured overlays”
2. “Effect of colours on reading performance in children measured by the sensor hub: from the perspective of gender”
3. “The Relation Between Physiological Parameters and Colour Modifications in text Background and Overlay During Reading in Children With and Without Dyslexia”

The same experiment design was incorporated in all three studies. All of the participants had the same conditions, and were sitting on a chair at a table in the small classroom or school chamber. In front of each participant were a computer monitor and keyboard. Before the experiment, participants got the instruction from the researcher to read in silence the text from the stimuli presentation on the screen, and to press the space button for the next slide of stimuli presentation. The pseudo randomization was applied in the experiment for the colour background/overlay order, starting always with a referent slide (white background with black text). No other colour was fixed/related to a certain reading context. In this way, no other factors apart from the actual colour would be averaged out (paragraph complexity such as vocabulary, syntax, etc., as well as semantic/affective content).

The experiment starts with the calibration and validation method, after which participants saw the black slide, so the researcher had time to launch the multimodal eye-tracking and EEG/ECG/EDA system and for data acquisition. After the researcher’s instruction, the participant would press the space button on the keyboard and the first slide (stimuli) would appear on the computer screen.

More detailed experiment setup, stimuli, and design are presented in additional articles in chapters 4,5, and 6.

Chapter 4

Study on the Developmental Characteristics

4.1 Introduction

The details of the study on "The sensor hub for detecting the developmental characteristics in reading in children on a white vs. coloured background/coloured overlays" ware published in Sensors journal. It investigates the influence of white vs. 12 background and overlay colours on the reading process in twenty-four school-age children.

The aim of the study was to assess developmental differences between second and third grade students of an elementary school and to evaluate differences in electroencephalography (EEG), ocular, electrodermal activities (EDA) and heart rate variability (HRV) during the reading task in 13 combinations of the text overlay and background colours.

4.2 The Article

sensors

MDPI

Article

The Sensor Hub for Detecting the Developmental Characteristics in Reading in Children on a White vs. Colored Background/Colored Overlays

Tamara Jakovljević [1,*], Milica M. Janković [2], Andrej M. Savić [2], Ivan Soldatović [3], Petar Todorović [4], Tadeja Jere Jakulin [5], Gregor Papa [6] and Vanja Ković [7]

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Abstract: This study investigated the influence of white vs. 12 background and overlay colors on the reading process in twenty-four school-age children. Previous research reported that colors could affect reading skills as an important factor in the emotional and physiological state of the body. The aim of the study was to assess developmental differences between second and third grade students of an elementary school, and to evaluate differences in electroencephalography (EEG), ocular, electrodermal activities (EDA) and heart rate variability (HRV). Our findings showed a decreasing trend with age regarding EEG power bands (Alpha, Beta, Delta, Theta) and lower scores of reading duration and eye-tracking measures in younger children compared to older children. As shown in the results, HRV parameters showed higher scores in 12 background and overlay colors among second than third grade students, which is linearly correlated to the level of stress and is readable from EDA measures as well. Our study showed the calming effect on second graders of turquoise and blue background colors. Considering other colors separately for each parameter, we assumed that there are no systematic differences in reading duration, EEG power band, eye-tracking and EDA measures.

Keywords: sensor hub; reading in children; developmental differences; background colors; overlay colors

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1. Introduction

Learning to read is a complex process involving both perception and cognition, via the integration of visual and auditory information processing and memory, attention and language skills [1]. Therefore, reading is a taught skill depending upon a range of perceptual processes and cognitive abilities affecting learning over time and across development [2–4]. One of the key objectives of early education is the learning of reading, and a number of research studies have explored the process of reading skills acquisition in children [2,5–7]. Depending on their individual set of underlying abilities, children will have different developmental profiles of reading skill obtainment, while weaknesses in some abilities may cause reading impairments over time. Individual differences in the learning of reading may originate from biological and environmental factors, shaping the development of the brain systems involved in the reading process [8]. The current knowledge emphasizes the importance of identifying and treating reading difficulties as early as possible, since they may impair academic achievements and increase the risk of social, emotional and mental health problems in children. More specifically, poor reading skills are shown to be associated with increased risks for school dropout, attempted suicide, incarceration, anxiety, depression, and low self-concept [9].

There is some limited evidence that colors may impact the reading process, specifically with early school-age children, and those with reading disabilities [10,11]. Going back a few decades [12], it has been shown that the role of colors in reading dates back to 1958. Jansky [13] reported the case of a student with a reading deficit who was able to recognize words printed on yellow paper, but unable to recognize words printed on white paper. Previous studies considered the influence of background, text or overlay color on the actual reading process in children [12,14,15]. While more recent studies have shown that colors do not influence the reading process and that this could be a placebo [16], others have found that colors may be particularly effective for early readers in school-age children [17].

As reading involves sensory integration, attention and memory, those processes may be reflected in the psycho-physiological states of the individual engaged in the reading task. Those states are a result of underlying neural and physiological processes, which are measurable and quantifiable by different biosignal modalities. The goal of this study was to employ multimodal sensor measurements to examine the influence of the color of the content on the reading task for children at different developmental stages. More specifically, we have employed measurements of electroencephalography (EEG), eye-tracking, electrodermal activity (EDA) and heart rate variability (HRV) to assess the influence of background and overlay color on reading performance in second and third grade students at elementary school. We aimed to address the mechanisms of color's influence on the reading process through electrophysiological correlates of the reader's state, while taking into account the developmental aspect of reading acquisition.

This study sheds light on the underlying neural, physiological and behavioral processes accompanying the reading task in children. Moreover, this is an initial step towards the possibility of including color into reading content to improve reading skills in children at different developmental stages, and addressing the question, "Why would the effect of text background color (if there is one) vary according to age?" One prediction could be that the younger children would have more difficulties reading the text on the intense color background in comparison to a pastel background. This is because the reading process is still not automated, and so it makes it harder for them to read in such a context in comparison to the older children who are proficient in reading [18–20]. An alternative hypothesis would be that the older children would struggle more with any color except for white, because of the experience they have reading on white as a default background in comparison to any other background that is novel (and distracting) for them [21–23].

2. Materials and Methods

2.1. Participants

Twenty-five healthy participants were randomly chosen from eight classes of the second and third grades of the elementary school "Drinka Pavlović" in Belgrade, respectively. These two age groups were selected intentionally, because children in Serbia start to learn letters in the first grade and the biggest shift in the reading happens between the second and third graders. The reading experience was compatible between the two grade groups, as both of these grades spend equal amounts of time in school (8am–3.20pm) and they finish all their homework at school as well. The participants' (10 boys and 15 girls) ages ranged from 8 to 9 years. The inclusion criteria were that children have no reading and learning disabilities or attention disorders, and have normal or corrected to normal vision according to teachers assessment. Only one child was excluded from the analysis due to the large artefacts in the acquired signals and his data were not used in the statistical analysis.

All the subjects underwent the same experimental conditions and participated individually in the small school classroom during the regular time period of the daily school classes. Each child received a short instruction about the experiment setup and design.

Consent forms were provided through the school director for each child who participated in the study. After the experiment, every child received a small present and diploma for participation in the experiment process.

The ethical committee of the Psychology Department of the University of Niš approved the experimental procedure.

2.2. Experiment Setup

During the experiment, each participant was sitting on a chair at a table in the front of a computer monitor and keyboard. At the beginning of the experiment, participants got the instruction to read quietly for themselves the text from the stimuli presentation shown on the computer monitor, and to press the space button for the next slide of stimuli presentation. The experiment was run applying the pseudo randomization of color background/overlay order, starting always with a referent slide (black text on white background). No other color was fixed/related to a certain text. Therefore, in this way, any other factors apart from the actual color would be averaged out (paragraph complexity such as vocabulary, syntax, etc., as well as semantic/affective content). Details about the "experiment" content are explained in the Section Experiment Design.

During the reading process, physiological data were acquired using a sensor hub composed of an eye-tracking system and a portable multimodal EEG/ECG/EDA system, Figure 1. Two laptops were used for real-time data monitoring and storage: one laptop for eye movement monitoring (with additional external computer monitor and keyboard in front of the participant) and another for EEG/ECG/EDA monitoring.

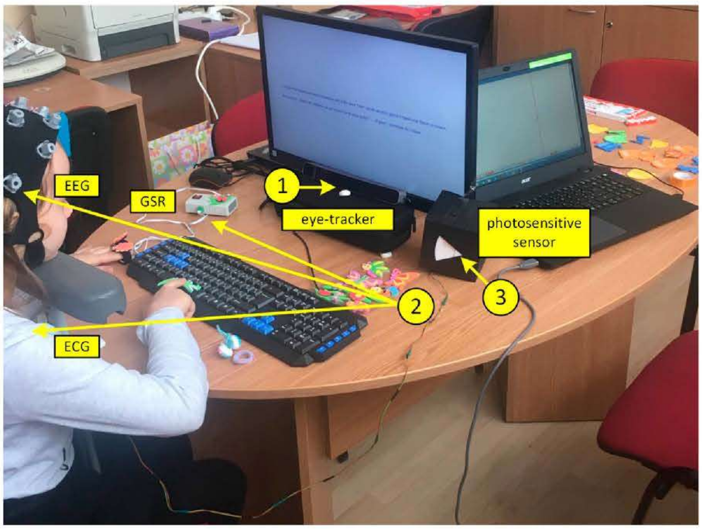

Figure 1. Experiment setup: (**1**) Eye-tracking system; (**2**) Portable multimodal EEG/ECG/EDA system; (**3**) Photosensitive sensor for synchronization of multimodal EEG/ECG/EDA system and eye-tracking system.

An SMI RED-m 120 Hz portable remote eye tracker (iMotions, Copenhagen, Denmark) was placed below the computer monitor in front of the participant, and it was fixed in place to keep it from accidentally moving. An adjustable chinrest was used to ensure the same distance from the monitor and table for each participant (the chinrest was 57 cm away from the eye-tracking sensor and 16 cm above the table) [24]. The SMI software was used for stimuli presentation (Experiment Centre 3.7) and data collection (iView RED-m).

The EEG and ECG signals were recorded using a mobile 24-channel EEG amplifier (SMARTING, mBrainTrain, Belgrade, Serbia) wirelessly communicating with a laptop via Bluetooth. Twenty-two monopolar EEG channels of Greentek Gelfree-S3 cap (10/20 locations: Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T7, T8, P7, P8, Fz, Cz, Pz, AFz, CPz, POz) were recorded. The ground was located at FPz and FCz was used as the reference site. One channel of the amplifier was connected to the surface SKINTACT ECG electrode placed in the left chest region, over the heart, to record ECG signal as a reference for heartbeat detection. EEG and ECG signals were acquired with 24-bit resolution and 250 Hz sampling rate. The skin–electrode impedances were below the manufacturer recommended value of 1 kOhm, prior to the tests.

One channel of the amplifier was used for the synchronization of electrophysiological recordings and eye tracking data. A small photosensitive sensor registering the changes on the screen after each slide was used with the changes of the black and white screen (200 ms each), and it sent a trigger for the synchronization of the multimodal EEG/ECG/EDA system and eye tracking system for each event (slide).

We used a research prototype for galvanic skin response (electrodermal activity, EDA) recording [25] that communicates with a laptop via Bluetooth. The sampling rate for EDA data was 40 Hz. The SMARTING application has Lab Streaming Layer (LSL) compatibility which enabled synchronization between the EDA and EEG/ECG data within a single file of XDF format.

2.3. *Experiment Design*

2.3.1. Stimuli

Participants read a story on the computer monitor. The story was at an adequate level for the second/third grade of elementary school and was selected from the school's literature for the Serbian language course. Participants were unfamiliar with the text used in the study.

The story "St Sava and the villager without luck" was split into 13 paragraphs: the 1st slide was a referent one with a white background with black letters, then there were 6 slides with black letters on red, blue, yellow, orange, purple and turquoise backgrounds, and the next 6 slides were presented in the overlay manner which looks like covering black text on a white background with a colored foil (calculated by the algorithm described in the section *Color Calculation*).

The experiment started with calibration and the validation method would stop on the black slide so the researcher had time to launch the multimodal EEG/ECG/EDA system and eye-tracking system for data acquisition. Next, on the researcher's instruction, the child would press the space button on the keyboard and the first slide with the text would appear on the computer monitor. The participant read text to themselves and then pressed the space button for the next slide to continue the text.

After finishing the test, the researcher posed questions (recommended for exercise in literature after the story) to check whether the children read the text carefully or not.

2.3.2. Color Calculation

All colors (color shades) used for designing the slides (stimuli) were defined within the RGB color model and each individual color was expressed as an RGB triplet ([R,G,B]), where the value of each additive primary color component can vary from 0 to 255. A list of background shades in the slides with colored backgrounds (and black text) with associated numerical values of their RGB triplet is as follows: red ("red", [255,0,0]), blue ("blue", [0,0,255]), yellow ("yellow", [255,255,0]), orange ("orange", [255,128,0]), purple ("purple", [255,0,128]) and turquoise ("turquoise", [0,255,255]. White and black shades were defined by triplets [255,255,255] and [0,0,0], respectively. The RGB components of the background and text in the slides with "overlay effect" were calculated according to the following formula:

$$\text{Overlay Component} = \text{Shade Component} * \text{Opacity} + (1 - \text{Opacity}) * \text{Underlay Shade}$$

where Opacity value was set to 0.5, Shade Component was selected from one of the previously listed background color shades, and the Underlay Shade value was 0 for black and in the case of a white background was 255.

The resulting RGB triplets for the shades of the text and background for slides with overlay effect were as follows: overlay red ("red O", text—[128,0,0], background—[255,128,128]), overlay blue ("blue O", text—[0,0,128], background—[128,128,255]), overlay yellow ("yellow O", text—[128,128,0], background—[255,255,128]), overlay orange ("orange O", text—[128,64,0], background—[255,192,128]), overlay purple ("purple O", text—[128,0,64], background—[255,128,192]) and overlay turquoise ("turquoise O", text—[0,128,128], background—[128,255,255]).

2.3.3. Data Processing

Eye tracking data analysis and visualization was performed using SMI BeGaze ™ 3.7 software (SensoMotoric Instruments, Teltow, Germany). The selected eye-tracking parameters were fixation count, fixation frequency (count/second), fixation duration total (ms), fixation duration average (ms), saccade count, saccade frequency (count/second), saccade duration total (ms), and saccade duration average (ms). EEG/ECG/EDA data were analyzed using Matlab ver. 8.5 (Mathworks, Natick, MA, USA) in the manner described below.

For each subject and electrode site, the EEG signal was processed in order to calculate the band power in five predefined frequency bands, as follows: delta (0.5–4 Hz), theta (4–7 Hz), alpha (7–13 Hz), beta (15–40 Hz) and whole range (0.5–40 Hz). The median value of the EEG band power (for each frequency band) was determined for 13 time-epochs coinciding with the reading of the content of each presented slide. The median EEG power in each frequency band was calculated by raw continuous signal band-pass filtering (4th order Butterworth filter with cut-off frequencies defined by individual band's frequency range), squaring, segmenting into 13 epochs (determined as time intervals between each slide's onset and offset), and median averaging to a single power value over signal samples of each epoch (i.e., over each slide's duration). The applied processing resulted in 65 median power values (i.e., 13 slides $\times$ 5 frequency bands) for each EEG channel of each subject. Median power calculation was applied since it is less likely to be affected by outliers in the EEG power samples that occur with temporary movement artefacts than the mean power.

The heart activity signal was band-pass filtered using an FIR filter in the range 1–45 Hz (750 points), after which the Pan–Tompkins algorithm [26] for the extraction of heart activity beats was applied. Beat-to-beat intervals (BBI, the time between two successive heart activity peaks) were calculated. Heart rate variability (HRV) parameters [27] were calculated from the BBIs for 13 time-epochs coinciding with the reading of the content of each presented slide (Table 1). The applied processing resulted in 14 HRV parameter values in one subject for each of the 13 slides.

Table 1. Heart rate variability (HRV) parameters.

Parameter	Unit	Description
	Time domain parameters	
Mean RR	ms	Mean value of BBIs
SDNN	ms	Standard deviation of normal BBIs
Mean HR	beats/min	Mean value of heart rate
STD HR	beats/min	Standard deviation of heart rate
CVRR = SDNN/Mean RR	n.u.	Coefficient of variance of normal BBIs
RMSSD	ms	Root mean square of differences of successive BBIs
NN50	beats	Number of successive BBIs that varied more than 50 ms
pNN50	%	Percentage of successive BBIs that differ more than 50 ms

The mean value of the EDA data was calculated as a representative value of electrodermal activity for 13 time-epochs coinciding with the reading of the content of each presented slide. The applied processing resulted in 13 mean values for each subject (one mean EDA value per slide).

2.4. Statistical Methodology

The results are presented as count (%), means ± standard deviation, or depending on data type and distribution. The groups are compared using parametric tests and independent samples t tests. All p values less than 0.05 were considered significant. There were no substantial deviations from the parametric testing assumptions. All data were analyzed using SPSS 20.0 (IBM Corp. Released 2011. IBM SPSS Statistics for Windows, Version 20.0. Armonk, NY: IBM Corp.) and R 3.4.2. (R Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/). It is noteworthy that Bonferroni corrections were applied in all the statistical analyses with multiple comparisons.

3. Results

3.1. White (Default) Background—Reading Results

Grade comparisons (second vs. third) regarding the examined parameters for white color only are presented in Table 2. A significant difference was obtained regarding EEG frequency bands (Alpha, Beta and Theta) and ECG parameters (SDNN, CVRR and STD HR). In all other parameters, we observed no significant difference between second and third graders. All EEG power bands are higher in the second grade group (except Delta band), compared to third graders. An opposite trend is shown in the SDNN, CVRR and STD HR parameters, whereby third graders achieved higher scores in comparison to second graders.

3.2. Background and Overlay Colors—Reading Results

In Table 3 we show the overall results which were calculated by subtracting the parameters acquired for the white color from the parameters acquired for each of the background and overlay colors (normalized values). Second and third graders were then compared on each of the parameters measured in the study, namely, reading duration, EEG, eye tracking, EDA and HRV.

The results demonstrated that students in the second grade differed significantly from the students in the third grade consistently on a few HRV parameters, in particular, SDNN (yellow, turquoise and turquoise O), CVRR (for orange, turquoise and blue O), and STD HR (blue, yellow, turquoise, blue O, yellow O, orange O and turquoise O). Besides these differences, significant differences were found in RMSSD (for turquoise and blue O). In each of these cases second grade students scored higher (or positively) in comparison to the third grade students who scored lower (or negatively), which is marked with an orange color in Table 3. Out of all the parameters in the study, only in the case of saccade duration total for the blue O did the third graders score significantly higher than the second graders, which is marked with a green color in Table 3.

In Figure 2, the normalized SDNN, CVRR and STD HR values across grades and colors are presented.

Given that there were no systematic differences across colors in Table 3 for reading duration, eye-tracking, EEG or EDA parameters, for a subsequent analysis all twelve background and overlay colors were averaged together in order to examine the differences between younger and older children.

Grade comparisons (second vs. third) regarding the examined parameters over the averaged scores for all colors together are presented in Table 4. A significant difference was obtained regarding reading duration, and median Alpha, Betha, Delta and Theta power bands, as well as for the whole range, then for fixation duration total, fixation duration average and EDA. In all other parameters we observed no significant difference between second and third graders.

Regarding reading duration, third graders took a significantly longer time to complete the reading. All EEG power bands (Alpha, Betha, Delta, Theta and whole range) as well as EDA were higher in the second grade group, compared to third graders. An opposite trend was found for the eye-tracking measures, whereby both fixation duration total and fixation duration average were higher in the third graders in comparison to the second graders.

Table 2. Reading duration, EEG, eye tracking, EDA and HRV parameters in second and third grade—significant p values are marked as bold.

Parameters	Grade		p Value *
	Second (n = 12)	Third (n = 12)	
Reading duration			
RD (s)	43.38 ± 25.32	49.07 ± 27.63	0.628
EEG parameters (median power band)			
Alpha (μV^2)	13.19 ± 5.15	5.63 ± 4.28	**0.001**
Beta (μV^2)	6.05 ± 2.81	3.33 ± 2.40	**0.018**
Delta (μV^2)	64.45 ± 20.47	71.85 ± 63.54	0.707
Theta (μV^2)	16.07 ± 7.14	8.35 ± 7.67	**0.018**
Whole Range (μV^2)	113.3 ± 38.5	97.2 ± 80.5	0.540
Eye tracking parameters			
Fixation Count	38.25 ± 19.62	35.00 ± 9.66	0.620
Fixation Frequency (count/s)	1.01 ± 0.36	0.99 ± 0.67	0.925
Fixation Duration Total (s)	40.87 ± 25.01	46.22 ± 26.32	0.631
Fixation Duration Average (ms)	1088.2 ± 542.9	1331.5 ± 730.9	0.381
Saccade Count	34.92 ± 19.16	28.70 ± 5.23	0.301
Saccade Frequency (count/s)	0.95 ± 0.38	0.86 ± 0.65	0.686
Saccade Duration Total (ms)	741.3 ± 449.4	680.0 ± 276.7	0.711
Saccade Duration Average (ms)	20.93 ± 2.76	23.22 ± 5.61	0.227
EDA value			
EDA (μS)	9.41 ± 3.49	6.20 ± 4.38	0.060
HRV parameters			
Mean RR (ms)	637.4 ± 59.8	680.5 ± 114.4	0.264
SDNN (ms)	35.14 ± 11.95	66.11 ± 46.15	**0.043**
CVRR (n.u.)	0.06 ± 0.02	0.10 ± 0.05	**0.021**
Mean HR (beats/min)	94.87 ± 8.69	90.26 ± 13.75	0.337
STD HR (beats/min)	5.12 ± 1.54	8.40 ± 3.85	**0.016**
RMSSD (ms)	42.50 ± 17.42	84.94 ± 74.74	0.079
NN50 (beats)	12.42 ± 9.44	19.67 ± 16.43	0.298
pNN50 (%)	23.40 ± 18.34	36.30 ± 25.88	0.236

* independent sample t test.

Table 3. Differences between second and third graders on reading duration, EEG, eye tracking, EDA and HRV parameters (normalized on white color), ($p < 0.05$ is marked with pale orange color, and $p < 0.01$ is marked with dark orange color). The values in the table represent Cohen's D effect sizes.

Parameters	Normalized Values											
	Red	Blue	Yellow	Orange	Purple	Turquoise	Red O	Blue O	Yellow O	Orange O	Purple O	Turquoise O
Reading duration												
RD (s)												
EEG parameters (median power band)												
Alpha (μV^2)												
Beta (μV^2)												
Delta (μV^2)												
Theta (μV^2)												
Whole Range (μV^2)												
Eye tracking parameters												
Fixation Count												
Fixation Frequency (count/s)												
Fixation Duration Total (s)												
Fixation Duration Average (ms)												
Saccade Count												
Saccade Frequency (count/s)												
Saccade Duration Total (ms)								0.9				
Saccade Duration Average (ms)												
EDA value												
EDA (µS)												
HRV parameters												
Mean RR (ms)												
SDNN (ms)			0.6			0.5						0.2
CVRR				0.8		0.6		0.6				
Mean HR (beats/min)												
STD HR (beats/min)		0.2	0.4			0.5		0.2	0.7	0.5		0.3
RMSSD (ms)						0.5		0.3				
NN50 (beats)												
pNN50 (%)												

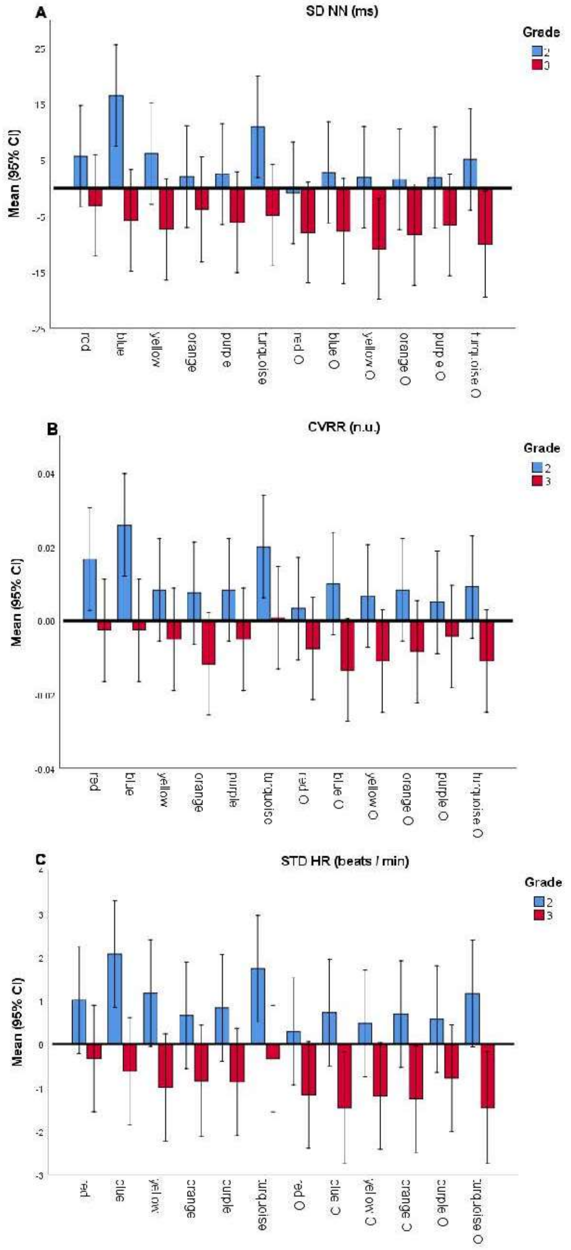

Figure 2. SDNN, CVRR and STD HR by grade and color (normalized on white color). (**A**) Normalized SDNN values (ms), (B) Normalized CVRR values (n.u.) and (C) Normalized STD HR (beats/min). Normalized values of each parameter are calculated by subtracting the parameter value for white background from the values for each of the background/overlay colors. Bar plots show the normalized data for all background and overlay colors (overlay colors labeled with "o" on x-axis), where second and third grader's values are presented with blue and red colored bars, respectively. Error bars denote standard errors of the mean.

Table 4. Reading duration, EEG, eye tracking and EDA parameters in second and third grade across all colors together—significant *p* values are marked in bold.

Parameters	Grade		*p* Value *
	Second (*n* = 12)	**Third (*n* = 12)**	
Reading duration			
RD (s)	42.74 ± 31.81	50.33 ± 27.40	**0.001**
EEG parameters (median power band)			
Alpha (μV^2)	13.50 ± 5.28	4.67 ± 3.20	**0.001**
Beta (μV^2)	6.36 ± 2.90	3.71 ± 4.70	**0.001**
Delta (μV^2)	71.49 ± 37.33	51.23± 48.90	**0.001**
Theta (μV^2)	17.55± 7.88	6.38± 4.75	**0.001**
Whole Range (μV^2)	123.36 ± 54.24	74.45± 61.30	**0.001**
Eye tracking parameters			
Fixation Count	35.14 ± 13.97	36.35± 10.31	0.412
Fixation Frequency (count/s)	1.10 ± 0.89	1.01 ± 0.75	0.372
Fixation Duration Total (s)	40.01 ± 30.71	47.47 ± 25.63	**0.028**
Fixation Duration Average (ms)	1038.49 ± 593.15	1283.29 ± 584.55	**0.001**
Saccade Count	31.31 ± 12.36	30.93 ± 8.05	0.753
Saccade Frequency (count/s)	0.99 ± 1.00	0.89 ± 0.71	0.376
Saccade Duration Total (ms)	662.9 ± 293.4	712.0 ± 273.6	0.147
Saccade Duration Average (ms)	21.65 ± 6.09	22.69 ± 3.88	0.093
EDA value			
EDA (μS)	10.13± 3.25	6.32 ± 3.95	**0.001**

* independent sample t test.

4. Discussion

We have evaluated differences in reading duration, EEG, eye tracking, EDA and HRV parameters in 24 children (12 second and 12 third grade students in elementary school) using simultaneously monitored sensor signals.

The literature regarding EEG power bands (Alpha, Beta, Delta, Theta) has been shown to have a general developmental decreasing trend with increasing age [28–30]. However, in the case of a specific mental activity, such as reading in this study, little is yet known about developmental changes in the contribution of EEG power bands [31]. When kids were given a task to read on a white color (which is a standard and everyday background color), they showed a reduction in Alpha, Beta and Theta power bands with age (Table 2). Given that this is a pilot study in this sense, it remains to be resolved whether this is specifically a developmental trend, or one that has to do with experience, or both in combination. To fully resolve this issue, one would also need to have a much wider range of age groups tested.

A correlation between HRV parameters and age in infants and during childhood, caused by progressive maturation of the autonomous nervous system, is known in the literature [31–34]. However, the impact of age on HRV parameters is more extensive in infancy and the early childhood period (up to eight years) [31]. In this study, participants were 8 and 9 years old, so they were in years of life when the age impact was much less significant on HRV parameters [35]. Consequently, the level of stress in our study was expected (and found) to be lower in the group with a higher strain [36]. Namely, SDNN, CVRR and STD HR were found to be lower in younger children when reading on a white background (Table 2). However, we would not predominantly attribute these findings to the developmental causal factor, but at least to some extent to experience in reading.

This study gives further support to the existing findings that colors may play an important role in the reading process [12,14,15,17,37–41]. When normalization on the white background was performed (by subtracting white from each of the other background and overlay colors), systematic differences (on at least two colors) were found regarding HRV parameters (normalized SDNN, CVRR, and STD HR values), with second graders scoring higher on these parameters (Table 3). The corresponding graphics across colors are presented in Figure 2, where it could be observed that blue and turquoise backgrounds have a calming impact (increasing normalized SDNN, CVRR, and STD HR values) on second graders, which is in accordance with the previous reports [18–20] and partially in accordance with our first hypothesis. No systematic differences were found across colors between younger and older children in reading duration, EEG power band, eye-tracking and EDA measures. This is why, based on the results presented in Table 3, for the following analyses all twelve background and overlay colors were averaged together, and we examined differences between second and third graders in that case (Table 4). Based on the results presented in Table 4, we observed a significant difference across multimodal sensor measurements in terms of reading on background and overlay colors in contrast to reading on the white background color.

The findings concerning reading duration on background and colored overlays showed that the third grade students achieve longer reading durations in comparison to the second graders. This could be explained by the fact that third graders or older children need more time to adapt to unexpected text and stimuli such as color [21–23], which is in line with our alternative hypothesis. Additionally, previous studies have shown that older children are slower in reading than younger children because they demand longer fixation duration and saccades [41–47], skipping words more frequently than younger children [48,49]. Concerning the eye-tracking measures, it was in fact found that third graders have longer fixation duration totals and fixation duration averages in comparison to the second-graders, which is a result that is in line with the above-mentioned assertion that older children take longer to read. This indicates the higher mental load in the reading task in older children.

A similar pattern of EEG results found for the white background was also found for the background and overlay colors. However, the number of parameters that showed a significant difference between second and third graders and significance levels was much more prominent for background and overlay colors in comparison to the white background. The study shows significant differences between the second and third graders in all four EEG power bands (Alpha, Beta, Delta and Theta), as well as in the whole range based on the averaged results from the twelve background and overlay colors.

Similarly, it is important to mention that EDA linearly correlates to arousal and reflects cognitive activity and emotional response [50,51], and it is the most used psychophysiological measure of arousal [52]. The higher the arousal is, the higher the electrodermal activity is. In the present study, it was found to be higher among second graders, from which we conclude that they had a higher stress level.

5. Conclusions

The aim of this study was to assess developmental differences in second and third grade students in elementary school regarding reading on white vs. colored overlay and background, and to evaluate differences in reading duration, and brain, eye, electrodermal and heart activities. Evaluating all the findings and results derived during reading on the white color and all 12 background and overlay colors, we can conclude that there is a decreasing trend with age regarding EEG power bands (Alpha, Beta, Delta, Theta) that is shown in the comparison between second and third grade students. In addition, second graders show lower scores in the reading duration and eye-tracking measures (fixation duration total and fixation duration average), which confirms the (alternative) hypothesis that older children need more time to adapt to unexpected text, and have longer fixation durations on words during reading. Comparing HRV parameters in second and third graders during reading on the white color, we found lower scores in second graders and higher scores in 12 overlays and background colors compared to third graders, especially for the SDNN, CVRR, and STD HR measures. The highest values of normalized SDNN, CVRR and STD HR among students were reached with the turquoise and blue background colors, which could be the result of a calming effect during task performance caused by the background color. Furthermore, we have found that EDA linearly correlates with level of arousal (tension and stress), whereby we have found higher values in younger children. Across single colors and their influences on measures during the reading task, there are no systematic differences in reading duration, EEG power band, eye-tracking and EDA measures, except for HRV measures, as mentioned above.

Thus, the goal of combining different modalities was to find a more objective approach to understanding the developmental differences in children's reading, as well as to understand the contribution of different modalities and combinations of modalities to the process of reading text on a white vs. colored overlay and background.

In the following work, it will be necessary to move forward from group studies to individual studies in order to determine and establish the individual optimal parameters, as well as colors, corresponding to individual differences in the reading process.

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4.3 Summary of Study Results

Evaluating all the findings and results derived during reading on the white colour and all 12 background and overlay colours, we can conclude that younger children have lower scores of reading duration and eye-tracking measures in comparison to the older children, and a decreasing trend with age regarding EEG power bands (Alpha, Beta, Delta, Theta). Further, in younger children (second graders) HRV parameters showed higher scores in 12 background and overlay colours than third grade students. This result is linearly correlated to the level of stress and is readable from EDA measures as shown in the results section. Present research showed the calming effect of turquoise and blue background colours in second graders. Considering the influence of other colours separately for each parameter, we have concluded that there are no systematic differences in reading duration, eye-tracking, EEG power band, and EDA measures among groups.

Chapter 5

Study on Gender-Related Performance

5.1 Introduction

The study “Effect of colours on reading performance in children measured by the sensor hub: from the perspective of gender” evaluates differences in Heart Rate Variability (HRV), Electroencephalography (EEG), Electrodermal Activities (EDA), and eye movement of children during the reading task. Taking into account that colour may affect reading skills, in that it affects the emotional and physiological state of the body, the research attempts to provide a better understanding of gender differences in reading through examining the effect of colour, as applied to reading content. The physiological responses of 50 children (25 boys and 25 girls) to 12 different backgrounds and overlay colours of reading content were measured and summarised during the reading process.

5.2 The Article

PLOS ONE

RESEARCH ARTICLE

The effect of colour on reading performance in children, measured by a sensor hub: From the perspective of gender

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Abstract

In recent decades reported findings regarding gender differences in reading achievement, cognitive abilities and maturation process in boys and girls are conflicting. As reading is one of the most important processes in the maturation of an individual, the aim of the study was to better understand gender differences between primary school students. The study evaluates differences in Heart Rate Variability (HRV), Electroencephalography (EEG), Electrodermal Activities (EDA) and eye movement of participants during the reading task. Taking into account that colour may affect reading skills, in that it affects the emotional and physiological state of the body, the research attempts to provide a better understanding of gender differences in reading through examining the effect of colour, as applied to reading content. The physiological responses of 50 children (25 boys and 25 girls) to 12 different background and overlay colours of reading content were measured and summarised during the reading process. Our findings show that boys have shorter reading duration scores and a longer Saccade Count, Saccade Duration Total, and Saccade Duration Average when reading on a coloured background, especially purple, which could be caused by their motivation and by the type of reading task. Also, the boys had higher values for the Delta band and the Whole Range of EEG measurements in comparison to the girls when reading on coloured backgrounds, which could reflect the faster maturation of the girls. Regarding EDA measurements we did not find systematic differences between groups either on white or on coloured/overlay background. We found the most significant differences arose in the HRV parameters, namely (SDNN (ms), STD HR (beats/min), RMSSD (ms), NN50 (beats), pNN50 (%), CVRR) when children read the text on coloured/overlay backgrounds, where the girls showed systematically higher values on HRV measurements in comparison to the boys, mostly with yellow, red, and orange overlay colours.

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Introduction

In children reading skills progress over developmental stages [1], while learning to read is one of the most important achievements of the early school years [2]. The complex process of reading skill acquisition involves perception and cognition, via integration of auditory and visual information processing, and memory, attention, and language skills [3]. Reading skills depend upon a range of cognitive abilities and perceptual processes that affect learning during development [4–6]. Gender differences in cognitive abilities during development have been widely analysed in neuropsychological and psychological research. However, these differences are still subject to debate [7–11]. Some studies have reported such differences [12, 13], while others report that they are not able to isolate them [14–18]. This implies the need for additional research on gender differences during cognitive development. More generally, in the past decade, the question of whether males and females differ in cognitive ability has been the focus of significant research [19]. While males and females do not differ in general intelligence, which is a general consensus [20], gender differences are commonly observed for more specific cognitive abilities such as visual-spatial ability [21] and language [22]. However, most gender differences are small or trivial (close to zero) in magnitude, explained by the Hyde gender similarities hypothesis (GSH) [15]. The gender gap in reading achievement, which is found cross-culturally, may be one exception to this hypothesis [19, 23, 24]. Hyde [25] concluded that it is "difficult to reconcile" the magnitude of the gender gap observed in reading with that in other domains of verbal ability, which is typically much smaller, as is claimed by Linn [26].

In the developmental context, girls tend to be superior to boys in verbal abilities and linguistic function from infancy through to adulthood, and for this reason gender difference has been investigated in previous studies, reporting greater reading achievements in girls [24, 27], with boys being better in visuospatial tasks involving memory [28]. Female students read more frequently and had a more positive attitude towards reading, resulting in better reading comprehension [29]. Recent research reports a larger Scan Path Length and Saccade Amplitude in female subjects [30]. Also, in tests of early reading ability Harper and Pelletier [31] found no gender differences in children's performance. However, the study employing eye-tracing methodology revealed gender differences in reading abilities indicated by Saccade Duration, Regression Rate, and Blink Rate [27].

Currently there are very few sources that explore the impact of colour on the reading process, specifically with early school-age children [32, 33]. The influence of text-, background-, or overlay-colour on the reading process in children is reported in literature [34–36] but there is no clear consensus regarding this. A recent study reported that colour does not influence the reading process [37], while conversely another has found that colour may be particularly effective for early readers such as school-age children [38]. In the study of visual stress, it is found that male subjects prefer blue and green, and females prefer pink and purple overlay colours for reading [39]. Therefore, the effect of colour on the reading process from the perspective of gender is interesting for further investigation.

Reading involves attention, memory, and sensory integration, which may be reflected in the psycho-physiological state of the individual engaged in the reading task. These processes are a result of fundamental physiological and neural processes, which are measurable by different BioSignal modalities such as Electrocardiography (ECG), Electroencephalography (EEG), Electrodermal Activity (EDA), and eye movement. The goal of the recent study was to incorporate multimodal sensor measurements to investigate the effect of colour on the content within the reading task in children from the perspective of gender differences. We have included measurements of heart rate variability (HRV), EEG, EDA, and eye-tracking to assess the influence of background and overlay colour on reading performance in boys and girls attending the early years of primary school. We aimed to address the mechanisms of colour effect on the reading process through electrophysiological correlates of the reader's state while taking into account the gender aspect of the reading acquisition.

The current research is an attempt to present new evidence regarding gender differences in reading skill. This research aims to contribute to the existing body of knowledge on the effect of the text, background and overlay colour according to gender.

We aimed to investigate the effects of colour on the content as a stressor during the reading task. The present study aims to further illuminate underlying physiological and behavioural processes accompanying the reading task in children from the gender perspective.

Materials and methods

Participants

The study was carried out with fifty healthy participants, boys and girls (25 plus 25) randomly chosen from students in the second and third years (aged 8–10) of primary school "Drinka Pavlović" in Belgrade. Inclusion criteria were that children have normal or corrected-to-normal vision, and no reading and learning disabilities or attention disorders. A typical case for exclusion would be the presence of large artefacts in the acquired signals. However, no such cases were observed in our sample. According to these criteria, no participants were excluded from the statistical analysis.

Children individually participated in the experiment, each under the same experimental conditions: during the school day and in the same small classroom. They received a short instruction about the experiment setup. After they finished the reading test, participants received a certificate and a small present from the researcher. The research process was anonymous and the collected data were anonymised. Only the data regarding the gender and age of the participants were available to the research team. Before starting the experiment, researchers received oral informed consent about the students' participation from the parents at a school class meeting, organised by the school director and the class teacher, which was summarized in the school director's note and delivered to researchers.

The ethical committee of the Psychology Department of the University of Niš (a branch of the Serbian Psychology Association) approved the experimental procedure No 9/2019.

Procedure

A computer screen and keyboard were placed in front of every child. The participants read the text in silence from the computer screen, as per the instructions from the researcher at the beginning of the experiment. Each of the participants read the story from the stimuli presentation on the screen, pressing the space button to receive the next paragraph on the next slide. The experiment started with the presentation of black text on white background (the referent slide) as children would typically see in daily life. After that, a pseudo-randomised background colour with black text was presented to the children along with an overlay version (marked by O in the further text, e.g. "red O is for red overlay") of the presented slides. The text on each colour/slide was different but was kept in a logical order. Except for the referent slide, no other colour was fixed to any particular stimuli presentation. There are no other factors (semantic or affective content, syntax, vocabulary, or text complexity) that could impact the reading process apart from the actual colour, given that the colours were randomly presented to the participants, rather than being selected.

The experiment design was exactly the same as in [40].

Fig 1 shows the sensor hub which consists of a portable multimodal ECG/EEG/EDA and eye tracking system for physiological data acquisition during the reading task. For data real-

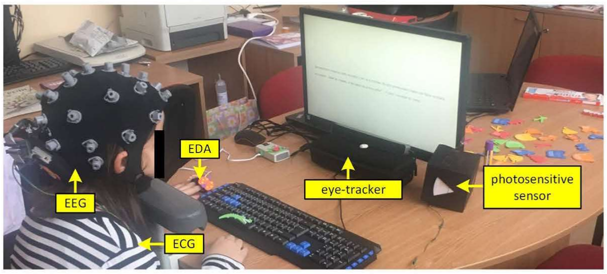

Fig 1. Portable multimodal ECG/EEG/EDA system and eye-tracking system.

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time monitoring and storage two laptops were used, one for the ECG/EEG/EDA system, and one for eye movement signal monitoring (connected with an external keyboard and the screen positioned in front of the child).

A portable remote eye tracker (SMI RED-m 120-Hz, https://www.smivision.com) was mounted in front of the participants and fixed to the screen to secure its stability. In order to ensure that each participant was the same distance from the screen, an adjustable chin-rest was mounted on the table (it was placed 16 cm above the table and 57 cm from the eye-tracking sensor) [41]. For the stimuli presentation SMI Experiment Centre 3.7 was used. An iView RED-m was used for data storage and collection.

The Smarting (mBrainTrain, Belgrade, Serbia) mobile system with a 24-channel EEG amplifier was used for recording EEG and ECG signals, which were communicating wirelessly with a laptop via Bluetooth. In the experiment a Greentek Gelfree-S3 cap with twenty-two monopolar EEG channels was used (10/20 locations: Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T7, T8, P7, P8, Fz, Cz, Pz, AFz, CPz, POz). The FPz electrode was used as the ground site and for the reference site the FCz electrode was used. The ECG signal was recorded by one channel of the Smarting amplifier using a surface SKINTACT ECG electrode placed at the left chest region above the heart. The signals of EEG and ECG were acquired with 250 Hz sampling rate and 24-bit resolution. Prior to the test, the skin-electrode impendence was below the manufacturer's recommended value of 1 kOhm.

For the synchronisation of the multimodal ECG/EEG/EDA and the eye tracking system, one channel of the Smarting amplifier with a small photosensitive sensor was used. This sensor registered the colour changes between two subsequent slides (one black and one white slide lasting for 200 ms each, positioned between two presented slides) indicating the colour changes of the presented slides.

A custom-made galvanic skin response device [41] that sends data via Bluetooth to a laptop was used (sampling rate 40 Hz) for electrodermal activity (EDA) acquisition. EDA data were recorded on the laptop using the Smarting application.

Data processing

BeGaze 3.7 software was used to monitor eye tracking data. Eye tracking analysis included the following parameters: a) Fixation Count, b) Fixation Frequency (count/second), c) Fixation Duration Total (ms), d) Fixation Duration Average (ms), e) Saccade Count, f) Saccade Frequency (count/second), g) Saccade Duration Total (ms) and i) Saccade Duration Average (ms).

EEG/ECG/EDA data were analysed using Matlab ver. 8.5 (Mathworks, USA) in the following manner for each presented slide:

1. EEG data of all subjects was processed offline. EEG signals were band-pass filtered using 4th order Butterworth filter to extract the activity in the following frequency bands: Delta (0.5–4 Hz), b) Theta (4–7 Hz), c) Alpha (7–13 Hz), d) Beta (15–40 Hz) and e) broadband EEG activity (0.5–40 Hz).
   Filtered signals of all subjects/channels were squared and segmented according to the event markers while each epoch was associated with the reading task of one slide. The median value of data associated with each epoch was calculated for obtaining a single band-power value. Median calculation is used to remove impulse-noises associated with movements, blinks and other artefacts that may occur in the EEG during reading within each epoch. Additional visual inspection of power epochs was conducted to ensure that the median values represent the valid quantification of the band-power activity of each epoch.
2. Heart activity beats were extracted using Kubios HRV Premium 3.3.1. software [42, 43]. The beats are detected using the Kubios built-in algorithm based on the Pan–Tompkins algorithm [44]. The period between two beats, so called beat-to-beat interval (BBI), and time domain heart rate variability (HRV) parameters [45], Table 1, were extracted by the same software. Also, the Kubios built-in threshold based artefact correction algorithm was performed (a local average interval of 0.35 s was selected and the detected artefacts were automatically replaced by cubic spline interpolated values within the software).
3. The average value of EDA data was calculated for each slide.

Statistical methodology

Here we present results as percentages, means ± standard deviation or taking into account data type and distribution. We compared groups (boys vs. girls) using a parametric test, an independent samples t-test. All p-values which were less than 0.05 were considered significant. The data were analysed within the SPSS 20.0 software (IBM Corp. Released 2011. IBM SPSS Statistics for Windows, Version 20.0. Armonk, NY: IBM Corp.). The Bonferroni corrections were applied in all the statistical analysis where necessary as a control for multiple comparisons.

Results

Reading results on white (default) background with black text

Gender comparisons (girl vs. boys) regarding the examined parameters for white background only are presented in Table 2. A significant difference has been obtained regarding a single HRV parameter for pNN50 (%), where girls have higher scores in comparison to boys. In all other parameters of EEG frequency bands (Alpha, Beta, Theta, Delta), ECG parameters and Eye tracking measurements, we observed no significant difference between girls and boys.

Table 1. HRV parameters.

Parameter (Unit) / Time domain parameters	Description
Mean RR (ms)	Mean value of BBIs
SDNN (ms)	Standard deviation of normal BBIs
Mean HR (beats/min)	Mean value of heart rate
STD HR (beats/min)	Standard deviation of heart rate
CVRR = SDNN/Mean RR (n.u.)	Coefficient of variance of normal BBIs
RMSSD (ms)	Root mean square of differences of successive BBIs
NN50 (beats)	Number of successive BBIs that varied more than 50 ms
pPNN50 (%)	Percentage of successive BBIs that differ more than 50 ms

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Table 2. Reading duration, EEG, eye tracking, EDA and HRV parameters in girls and boys—significant p values are marked as bold.

Parameters	Grade		p value*
	MALE (n = 25)	FEMALE (n = 25)	
Reading duration			
RD (s)	40.32± 21.64	49.04± 23.49	0. 21
EEG parameters (median power band)			
Alpha	12.64± 8.47	11.99± 6.56	0.76
Beta	5.50± 3.00	5.77± 2.89	0.75
Delta	133.64± 198.80	81.32± 52.95	0.21
Theta	20.31± 28.69	16.19± 9.54	0.50
Whole Range	134.57± 76.02	130.77± 76.62	0.86
Eye tracking parameters			
Fixation Count	39.88± 21.48	37.68± 15.40	0.69
Fixation Frequency [count/s]	1.02± 0.45	0.97± 0.52	0.74
Fixation Duration Total [s]	48.29± 47.98	44.30±22.18	0.72
Fixation Duration Average [ms]	1,120.83± 588.25	1,201.85± 554.00	0.63
Saccade Count	34.68± 11.23	32.32± 14.59	0.53
Saccade Frequency [count/s]	0.95± 0.45	0.86± 0.52	0.53
Saccade Duration Total [ms]	784.50±289.72	722.84±361.63	0.52
Saccade Duration Average [ms]	22.49± 3.75	22.38± 5.59	0.94
EDA value			
EDA (uS)	7.66± 3.71	7.69± 3.61	0.98
HRV parameters			
Mean RR (ms)	664.09± 54.58	673.95± 99.37	0.67
SDNN (ms)	40.37± 19.12	54.34± 36.03	0.09
CVRR (n.u.)	0.07±0.03	0.08±0.04	0.20
Mean HR (beats/min)	90.93± 7.43	90.76± 12.36	0.95
STD HR (beats/min)	5.51± 2.35	6.89± 3.09	0.08
RMSSD (ms)	48.75± 29.40	69.97± 56.33	0.10
NN50 (beats)	11.60±11.75	20.32±17.63	0.05
pNN50 (%)	22.76±17.75	36.78±25.63	**0.03**

Independent sample t test

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Background and overlay colours

In Table 3 a comparison between girls and boys, based on the t-test for independent samples, was obtained on each of the parameters measured in the study, namely: Reading duration, EEG, Eye tracking, EDA and HRV. As is obvious from the table, the girls (coloured in red) scored systematically higher in many of the HRV measurements. In particular for SDNN (ms) they scored higher on yellow, red O, orange O, and purple O; for CVRR they scored higher on yellow, red O, yellow O, orange O and purple O; for STD HR girls scored higher on red, yellow, orange, turquoise, red O, blue O, yellow O, orange O and purple O; for RMSSD they scored higher on yellow, turquoise, red O, yellow O, orange O and purple O; for NN50 they scored higher on red, yellow, orange, turquoise, red O, blue O, yellow O, orange O and turquoise O; and for pNN50 they scored higher on yellow, orange, purple, turquoise, red O, yellow O, orange O and purple O. Boys only scored higher when reading on a purple background for the following eye-tracking parameters: Saccade Count, Saccade Duration Total and Saccade Duration Average (coloured in blue).

Table 3. Differences between girls (marked with red colour) and boys (marked with blue colour) on reading duration, EEG, eye tracking, EDA and HRV parameters ($p < .05$).

Parameters	Normalized values											
	red	blue	yellow	orange	purple	turquoise	red O	blue O	yellow O	orange O	purple O	turquoise O
Reading duration												
RD (s)												
EEG parameters (median power band)												
Alpha												
Beta												
Delta												
Theta												
Whole Range												
Eye tracking parameters												
Fixation Count												
Fixation Frequency [count/s]												
Fixation Duration Total [s]												
Fixation Duration Average [ms]												
Saccade Count												
Saccade Frequency [count/s]												
Saccade Duration Total [ms]												
Saccade Duration Average [ms]												
EDA value												
EDA (uS)												
HRV parameters												
Mean RR (ms)												
SDNN (ms)												
CVRR												
Mean HR (beats/min)												
STD HR (beats/min)												
RMSSD (ms)												
NN50 (beats)												
pNN50 (%)												

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Girls vs. boys across all of the examined parameters over averaged scores aggregated for all tested colours are presented in Table 4. Boys achieved higher scores on a few EEG and eye-tracking measurements, namely: Delta and Whole range EEG band measurements and Fixation Count, Saccade Count and Saccade Duration Total. The girls, on the other hand, scored higher on the Reading Duration and on a few HRV measures, namely: SDNN, STDHR, RMSSD, NN50, PNN50 and CVRR.

Discussion

The Reading Duration, EEG, eye tracking, EDA and HRV parameters were evaluated in 50 children (25 female and 25 male second and third year students (aged 8–10) of primary school) using a multimodal sensor hub. As reading process involves attention, memory, and sensory integration, which may be reflected in the psychophysiological state of the individual engaged in the reading task, the study aim was investigating different BioSignal modalities such as ECG, EEG, EDA, and eye movement during the reading task.

Gender differences in reading are widely reported [2, 19, 24, 27, 46–49], and it was found that motivation, attitudes, and the type of reading task could impact on reading skills in boys

Table 4. Reading duration, EEG, eye tracking and EDA parameters in girls and boys across all colours together—significant p values are marked in bold.

Parameters	Grade		p value*
	MALE (n = 25)	FEMALE (n = 25)	
Reading duration			
RD (s)	41.83± 22.61	48.83± 27.72	**0.00**
EEG parameters (median power band)			
Alpha	11.02± 6.06	10.50± 5.94	0.27
Beta	5.32± 2.61	5.50± 3.82	0.50
Delta	82.90± 81.16	61.04± 38.66	**0.00**
Theta	15.31± 14.16	13.98± 8.35	0.14
Whole Range	116.90± 69.03	103.82± 58.33	**0.01**
Eye tracking parameters			
Fixation Count	39.55± 22.15	35.79± 11.74	**0.01**
Fixation Frequency [count/s]	1.01± 0.48	1.00± 0.82	0.81
Fixation Duration Total [s]	47.49± 39.36	45.22±26.61	0.41
Fixation Duration Average [ms]	1,154.48± 534.75	1,196.31± 554.87	0.34
Saccade Count	34.95± 15.10	30.75± 10.01	**0.00**
Saccade Frequency [count/s]	0.93± 0.46	0.88± 0.87	0.33
Saccade Duration Total [ms]	776.14±441.89	667.28±246.73	**0.00**
Saccade Duration Average [ms]	21.76± 3.27	22.01± 5.27	0.48
EDA value			
EDA (uS)	7.56± 3.24	7.83± 3.64	0.31
HRV parameters			
Mean RR (ms)	656.20± 51.22	662.65± 90.05	0.26
SDNN (ms)	40.08± 16.87	52.59± 29.66	**0.00**
Mean HR (beats/min)	92.00± 7.31	92.10± 11.36	0.89
STD HR (beats/min)	5.46± 1.99	6.90± 2.47	**0.00**
RMSSD (ms)	44.89± 23.32	65.14± 46.05	**0.00**
NN50 (beats)	12.25±10.57	21.51±18.19	**0.00**
pNN50 (%)	21.45±16.03	34.23±24.02	**0.00**
CVRR	0.07±0.03	0.09±0.03	**0.00**

*independent sample t test

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more closely than in girls [47]. It was speculated that the boys' reading performance could depend more on their motivation and attitude. The results of the present study showed that boys had shorter reading duration parameters than girls, but at the same time, they scored higher in some eye- tracking measures, and had longer Fixation Count, Saccade Count, and Saccade Duration Total measurements than the girls, irrespective of background/overlay colour. They also had a longer Saccade Count, Saccade Count Total and Saccade Count Average when reading text on a purple background. Additionally it is reported that males have a more positive emotional response than females during competitive game play [50]. Therefore, here we have taken into account findings that suggest that boys are more motivated to read in new conditions, without teachers' grades/assessments, and have more competitive attitudes in comparison to female students. It has also been reported that male students have poor reading abilities in comparison to girls [27, 51], and therefore make more exploratory eye movements, which consequently result in larger Saccade Amplitudes as we have also demonstrated in the present research.

Regarding the normal maturation processes reflected in the EEG, McCarthy reported [52] that gender differences are equally distributed, while other researchers [53, 54] found that EEG differences between boys and girls suggest earlier maturation in girls [55]. On the other hand, Cohn [56] and Gasser [57] found no differences between boys and girls measurable by EEG. It is also reported that the amount of activity in the lower frequency EEG bands decreases with age, and in higher frequency bands, it increases [58, 59]. The gender differences in EEG are also reported in context of the task performance and cognitive activity. During the task and rest phase, females have a higher EEG power than males [60, 61]. Also, gender differences are frequently reflected in numerous factors, like task and age [62]. Some research shows that in most cognitive tasks including language, there exist inappreciable differences in behavioural output between the genders [16–18]. EEG power and its distribution over a lifetime also varies between the genders [63]. EEG maturation markers increase in faster band activity (alpha, beta) and decrease in slower band activity (theta, delta) [55, 57, 64–66]. In the present study it is shown that boys have higher values of delta band and whole range of EEG in comparison to girls. Clarke et al. report that boys' EEG matures faster than girls' in childhood, but that these differences are eliminated during adolescence. Conversely Gasser et al. [57] declare that there are no gender differences, mostly because of high interindividual variability in the EEG power spectrum. Other authors have found that until the age of 16 the alpha rhythm does not mature [67]. In previous research the delta band was found to be higher in young individuals than in adults because of incomplete cortical maturation, and is typically even higher in children with learning disabilities [68]. These findings are in line with our results, which showed increased Delta and Whole Range EEG bands to be more prominent in boys than in girls, which could be as a result of the faster maturation process in girls. This is in keeping with previously mentioned results showing that boys had a less mature pattern of eye-movements in comparison to girls.

Likewise, electrodermal activity has been used in several studies with the objective of clarifying markers of psychophysiological functioning and children's developmental processes [69, 70].

Several studies supported higher levels of baseline SCL (Skin Conductance Level) [68] and SCL reactivity to stressors [71] in girls in comparison to boys. In the present study we found no evidence of systematic differences between boys and girls for this measurement when reading text on either white or coloured/overlay background.

Physiological mechanisms during adolescence actively and progressively undergo changes. It has been reported that HRV progressively reduces with age, and development during adolescence can be assessed using the heart rate variability (HRV) [72]. HRV can be used to ascertain the evolution of the ontogenetic maturation [73–76]. Moreover, the gender influence measured by HRV parameters was manifested only in young adults and younger adolescents and our study group belongs to the same age category. Research study shows that measurements of HRV depend on the age but not on the gender of healthy children [77]. When different colours of background, text, and overlay were included in the reading process we found significant differences between girls and boys, whereby girls scored higher on HRV parameters. This indicates higher emotional reactions in girls when they read the text on the coloured/overlay background in comparison to the boys. Regarding this result, our findings are compatible with previously reported results showing that girls have higher values on SDNN and RMSSD measurements.

Conclusion

Primarily this research aimed to assess gender differences in the reading process and to contribute to existing research on the effect of text, background and overlay colour according to gender.

Secondly, the aim was also to investigate the effects of colour on the content as a stressor in the reading task. In order to shed light on contradictory reports regarding gender differences in reading skills, present study illuminates underlying physiological and behavioural processes in the reading task in children from the gender perspective. It evaluates differences in reading duration, EEG, ECG, EDA and eye movement measures on both white and 12 different background/text/overlay colours. It was found that boys show shorter reading duration parameters than girls, and at the same time longer eye-tracking measures such as Fixation Count, Saccade Count, and Saccade Duration Total while reading on a coloured background/overlay, whereas they had a Longer Saccade Duration, Saccade Duration Total, and Saccade Duration Average on a purple background. These results partially support our expectation that boys would have more difficulties reading the text when displayed on background/overlay colours. However, they did not have more issues reading on the coloured background in comparison to the white/default background.

Comparing EEG parameters in girls and boys during reading on white background we did not find systematic differences. Observing all the colours together, it is shown that boys have higher values in Delta and Whole Range bands in comparison to the girls. As the Delta Range is higher in young adults, the findings are aligned with previous research where it is shown that boys will have more difficulties in reading tasks because the reading process is still not automated in comparison to the girls. In fact, they have also demonstrated longer Saccade Count and Saccade Duration measurements in comparison to the girls when reading on a purple background. It seems that the colour can really increase the task difficulty for less proficient readers. We did not find systematic differences for EDA measures between boys and girls while reading on white or coloured background/overlay content. However, regarding ECG measures, girls scored significantly higher on HRV measures (SDNN (ms), STD HR (beats/min), RMSSD (ms), NN50 (beats), pNN50 (%), CVRR), in particular on yellow, orange O and red O colours. These findings are also contributable to studies where it is shown that girls have higher values on HRV measures than boys, which is particularly evident from results including the additional effect of colour on the reading process.

Finally, we can underline that colours used as a stressor in a particular reading task could illuminate gender differences, especially in eye-tracking and ECG measures. Boys have shown longer Saccade Count and Saccade Duration in comparison to girls while reading on the purple colour. Boys have shown shorter reading duration than girls on all coloured background/overlay, and longer eye-tracking measures such as Fixation Count, Saccade Count, and Saccade Duration Total. Regarding the ECG (SDNN, STD HR, RMSSD, NN50, pNN50, CVRR) measures, girls scored higher than boys while reading on yellow, orange O, and red O colours. These findings show that colours could be contributing to a better understanding of gender differences and their relation to the context of the reading processes.

Supporting information

S1 Data.
(XLSX)

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5.3 Summary of Study Results

Our findings show that boys have shorter reading duration scores and a longer Saccade Count, Saccade Duration Total, and Saccade Duration Average when reading on a coloured background, especially purple, which could be caused by the type of reading task and their motivation. Thus, boys scored with the higher values for the Delta band and the Whole Range of EEG measures in comparison to the girls when reading on coloured backgrounds, his finding could reflect the faster maturation of the girls. We did not find systematic differences between groups either on white or on coloured/overlay background in EDA measures. The most significant differences arose in the HRV parameters, namely (SDNN (ms), STD HR (beats/min), RMSSD (ms), NN50 (beats), pNN50 (%), CVRR) during the children engagement of text reading on coloured/overlay backgrounds, where the girls showed systematically higher values of HRV measures in comparison to the boys, mostly with yellow, red, and orange overlay colours.

Chapter 6

Study on Dyslexia Influence

6.1 Introduction

The study "The Relation Between Physiological Parameters and Colour Modifications in text Background and Overlay During Reading in Children With and Without Dyslexia" aim to address neurobiological origin of dyslexia and it's relation to the colours. Present research is focused on understanding the relationship between physiological parameters and colour modifications in the text and background during reading in children with and without dyslexia. We have measured differences in electroencephalography (EEG), heart rate variability (HRV), electrodermal activities (EDA) and eye movements of the 36 school-age (from 8 to 12 years old) children (18 with dyslexia and 18 of control group) during the reading task in 13 modifications of background and overlay colours.

6.2 The Article

brain sciences

Article

The Relation between Physiological Parameters and Colour Modifications in Text Background and Overlay during Reading in Children with and without Dyslexia

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Abstract: Reading is one of the essential processes during the maturation of an individual. It is estimated that 5–10% of school-age children are affected by dyslexia, the reading disorder characterised by difficulties in the accuracy or fluency of word recognition. There are many studies which have reported that coloured overlays and background could improve the reading process, especially in children with reading disorders. As dyslexia has neurobiological origins, the aim of the present research was to understand the relationship between physiological parameters and colour modifications in the text and background during reading in children with and without dyslexia. We have measured differences in electroencephalography (EEG), heart rate variability (HRV), electrodermal activities (EDA) and eye movements of the 36 school-age (from 8 to 12 years old) children (18 with dyslexia and 18 of control group) during the reading task in 13 combinations of background and overlay colours. Our findings showed that the dyslexic children have longer reading duration, fixation count, fixation duration average, fixation duration total, and longer saccade count, saccade duration total, and saccade duration average while reading on white and coloured background/overlay. It was found that the turquoise background, turquoise overlay, and yellow background colours are beneficial for dyslexic readers, as they achieved the shortest time duration of the reading tasks when these colours were used. Additionally, dyslexic children have higher values of beta (15–40 Hz) and the broadband EEG (0.5–40 Hz) power while reading in one particular colour (purple), as well as increasing theta range power while reading with the purple overlay. We have observed no significant differences between HRV parameters on white colour, except for single colours (purple, turquoise overlay, and yellow overlay) where the control group showed higher values for mean HR, while dyslexic children scored higher with mean RR. Regarding EDA measure, we found systematically lower values in children with dyslexia in comparison to the control group. Based on the present results, we can conclude that both pastel and intense background/overlays are beneficial for reading of both groups and all sensor modalities could be used to better understand the neurophysiological origins in dyslexic children.

Keywords: dyslexia; reading; children; background colour; overlay colour; text colour; sensors; physiological parameters; EEG; ECG; EDA; eye tracking

1. Introduction

It is estimated that more than 10 percent of the world population is affected by dyslexia. Dyslexia is a learning disability of neurobiological origin whose main characteristics are difficulties with accurate or fluent word recognition. It is also characterized by poor spelling and decoding abilities which results in problems in reading comprehension and reduced reading experience [1]. Developmental dyslexia is manifested by individuals who require special motivation and intellectual effort to achieve fluent reading and it is usually defined as an unexpected difficulty in reading [2,3]. The World Federation of Neurology recognizes children with dyslexia as those who, despite the common school curriculum, cannot attain reading, writing, and spelling skills in proportion to their intellectual abilities [4,5]. Although definitions and understandings of dyslexia vary, there is a general opinion that children who fail to accurately read, need careful support and monitoring at an early school age. At that age, the most effective approach for children with reading difficulties are early identification and professional support which assists their needs [6–8]. For example, in Sweden, children are being diagnosed with dyslexia on average only at the age of thirteen [4]. At the early-school age, it is not so difficult to mark the grade level of reading, but it is difficult to understand other problems which usually impede overall school achievements and cause emotional distress and lack of motivation [9,10]. Children who have this type of reading difficulty do not have difficulties in their general performance in other segments of the curriculum. Some of them may also have emotional difficulties [11–13]. Through early intervention, the risk of those difficulties may be reduced before they emerge in the fourth grade. In the research dedicated to the early indicators of dyslexia, children were monitored from preschool age to the end of the fourth grade of primary school [14]. It is found that indicators of dyslexia can be isolated at preschool age. There is evidence that dyslexia can be prevented and predicted in early school-age children [15–17]. Today, scientists are better able to understand the child's nervous system and how it operates in the case of dyslexia using functional neuroimaging [18].

There is good evidence that dyslexia has a neurological basis [19,20]. Namely, it may be reflected in the psycho-physiological states of the body during the reading task.

Given that colours can affect the state of our body and emotions [21,22], this study investigates the relationship between physiological parameters and colour modifications in the text and background during reading in children with and without dyslexia. It is evident that colours have been used in modulating reading performance in children with dyslexia in order to improve their skills and for other purposes such as increasing reading fluency and speed [23–27]. The so-called visual stress syndrome is observed in dyslexic individuals very often [28,29], but the role of colour involvement during the reading performance remains controversial [30–34]. Recently, this concept has led to the broadened use of coloured overlays to mitigate reading disorders and improve reading. It is reported that symptoms of visual stress are caused by sensitivity to certain light frequencies [35]. In practice, applications of coloured filters have led to the use of lenses and overlays in reading. Coloured overlays filter the light using transparent plastic reading sheets tinted with colour over the text [36]. Many dyslexic subjects reported that coloured overlays can help them with widespread difficulties arising in the reading process [37–41]. Moreover, it has been reported, without taking into consideration children with dyslexia, that colour overlays could improve the reading process in school-age children [42]. Furthermore, other scientists [39,43] have shown that problems caused by dyslexia could be relieved by visual changes in the presentation of the reading text. Based on these studies, others have focused on designs of computer screen texts, where parameters such as background, text colour, or font size have been adjusted in order to help those with dyslexia [44,45]. These conditions inspired Pinna and Deiana [46,47] to study how reading time and comprehension could be influenced by colours.

Other studies taking into account the effects of colour on reading in dyslexic children showed possibilities of reduction of symptoms in Meares Irlen Syndrome by application of colour filters which eased the visual discomfort in these children [48]. Furthermore, coloured filters were then considered as an effective intervention for delayed readers who had experienced visual stress. It was reported [49] that the reading speed of patients with Meares-Irlen syndrome improved by more than 20% when they wore the selected colour-tinted lenses. By contrasting no filter, yellow, and green filter, researchers [50,51] found that children with dyslexia were fastest and had the shortest fixation time when reading in the yellow and green-filter condition.

Recently, Stein [52] came up with the argument that dyslexia is "characterized by poor temporal processing, hence impaired visual and auditory sequencing, that is caused by impaired development of transient/magnocellular (M-) systems throughout the brain," and thus it is necessary to collect evidence not only from psychophysical tests, but from electrophysiological, eye movement, attentional, brain imaging, interventional, and genetic findings as well. Aside from the use of colour overlays, it was also found that the use of different background colours [44] increased reading performance of subjects with dyslexia and has been recommended by the British Dyslexia Association [53].

Reading involves sensory integration, attention, and memory processes which are reflected in the psycho-physiological states of the individual and measurable by different biosignals. Our previous work introduced a sensorhub for measurement of four biosignal modalities and describes the contributions of each modality to understanding of different aspects of neural, physiological, and behavioral processes in children during reading [21].

Based on the previous studies [11,54] and results, the main purpose of the present study is to extend previously established experimental protocol to children with dyslexia and to better understand the neurological basis of this disorder and its relation to colours.

The current study presents the first research that explores the impact of 13 combinations of background and overlay colours on the reading performance of children with normal reading skills and children diagnosed with dyslexia, measured by multimodal sensor hub (electroencephalography, EEG; electrocardiography, ECG; electrodermal activity, EDA; and eye-tracking).

We expected that children with good reading skills would be less affected by the change of colour. We also expected more variation in reading performance with the introduction of coloured elements in dyslexic children. However, in both groups, we expected that cognitive and emotional arousal would vary with the change of colour and that could only be measured by employing fine-grained measurement tools relying on automatic measures of cognitive and emotional engagement in the task. We expected that the pastel colours would facilitate the reading task, unlike intense colours, which we expected would be more challenging both to dyslexic and non-dyslexic children, based on previous reports [44,50,51]. These parameters make it possible to conclude which colours would result with the better focus on the text, which otherwise could not be assessed with rough measures such as reading duration.

This study is a step towards defining the set of measurements which may enable the quick automatic selection of colour setup that would facilitate the reading task in a specific reader.

2. Materials and Methods

2.1. Subjects

Thirty-six participants took part in this study (18 with dyslexia and 18 without dyslexia, matched according to gender and school grade). Children in the control group were randomly chosen from the second to sixth grade (8–12 years old) of three elementary schools in Belgrade. Children with dyslexia were selected from several elementary schools in Belgrade in coordination with a certified speech therapist. The dyslexic children in this study have already undergone adequate speech treatment for dyslexia. All of them satisfied the standard criteria for dyslexia diagnosed by the speech therapist based on three different tasks: speed of reading, accuracy (phonological decoding), and understanding measured on the standardized text adapted for their age in Serbian. In addition, the IQ of children was tested on the Raven's Progressive Matrices and only those who scored higher than 90 IQ were selected for the study.

Every child from the group of dyslexic children was diagnosed with dyslexia by the specialist in the field and was included in the study based on that criterion. Secondly, they needed to have a normal or corrected to normal vision, meaning that they either had no eye-sight problem, or if they did, they had adequate glasses so that they could read the text with no difficulty. In fact, only one child with corrected vision took part in the study. All the other children had no eye-sight difficulties. For the control group of children, the inclusion criteria were that they have normal or corrected to normal vision and no learning and reading disabilities or attention disorders (as assessed by a certified speech therapist or their teachers). The exclusion criterion for both groups was presence of large artifacts in the acquired signals. In our sample, no such cases were observed. Also, no participants were excluded from the dataset for the statistical analysis, according to these criteria. The experiment was conducted in a classroom at the Faculty of Philosophy, University of Belgrade, where children participated individually under the same experimental conditions. Every child had received instructions from the researcher before the experiment (to read in silence, how to position their head at the chin rest, how to look at the external monitor etc.). After the reading test, the participants received a present (sticker and chocolate) and diploma. The collected data were fully anonymized. Only team members had access to the grade and gender of the children participating in the study. The research team collected informed consent from the parents for the children's participation through speech therapists or school directors and teachers.

The experimental procedure was approved by the ethical committee of the Psychology Department of the University of Niš (a branch of the Serbian Psychology Association) No 9/2019.

2.2. *Experiment Setup*

During the experiment, participants were seated in front of the computer screen with a keyboard at the table, placing their head on the chinrest, making sure they were holding the same distance from the monitor. After the participants received instructions from the researcher, they read the story presented on the computer screen in silence. The reading text was selected from the textbook for the third grade, so that it did not contain any of the words that children would not be familiar with. Also, this text was selected because the paragraphs were comparable based on the length and complexity (per slide). Stimuli presentation was launched by pressing the space button (self-paced reading). The stimuli presentation started with a paragraph with black text on a white background (as a referent slide), as school-age children are used to in everyday life. After the referent slide, which would always appear at the beginning of the presentation, the following slides were presented in a pseudo-randomized order of background/overlay colours. Background colours were always presented with black text and overlays according to colour calculation in the section Experiment Design of the previous study [21] (marked by O in further text, e.g., blue O stands for blue overlay). The story was divided into 13 paragraphs/slides, so the text on each slide was kept in the original order but in different colours (in order to avoid the effect of factors such as semantic or affective content, vocabulary, text complicity, or syntax). Thus, we did pseudo-randomisation of the colours so that the same overlay and background/text colour would not appear one after the other, but every paragraph would be seen by different subjects on the different background colour. This way, we made sure that the particular differences, such as word frequency, length of the word, number of words, etc., would be averaged out.

2.3. *Experiment Design*

Experimental design was exactly the same as in the [21] except for the difference laid out in the description of Figure 1 and Data Processing part.

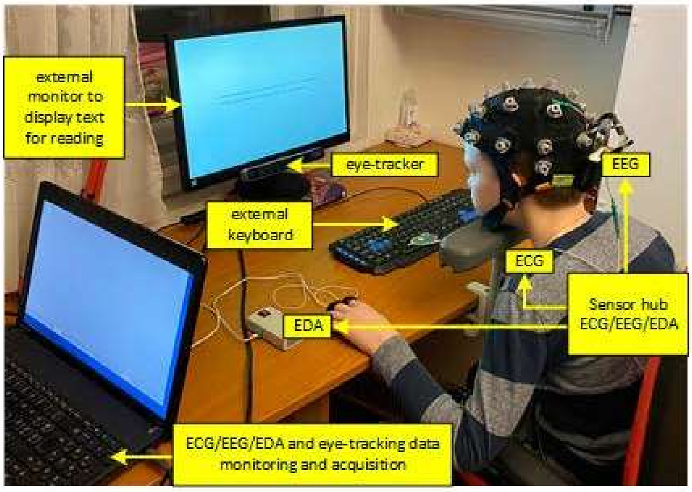

Figure 1. Sensor hub ECG/EEG/EDA computer for data acquisition, external keyboard and monitor, and eye-tracking system.

Figure 1 shows the sensor hub consisting of a portable multimodal ECG/EEG/EDA and eye-tracking system for acquisition of physiological data during the reading performance. A mobile 24-channel EEG amplifier (SMARTING, mBrainTrain, Belgrade, Serbia) was used for EEG and ECG signals recording. EDA recording was performed using a research prototype device [55]. SMI RED-m 120-Hz portable remote eye tracker (iMotions, Copenhagen, Denmark) was used for eye-tracking (9-point calibration was used). The SMI software was used for stimuli presentation (Experiment Centre 3.7), data collection (iViewRED-m), and data analysis and visualisation (BeGaze 3.7). Real-time monitoring and storage were at one laptop instead of two, which was the case in the previous experiment design [22] because the system was synchronized by keyboard stream instead of the photosensitive sensor. The laptop was connected with an external keyboard and external monitor positioned in front of every child. The sampling rate was set to 250 Hz for EEG/ECG data and 40 Hz for EDA data. The application for data acquisition used Lab Streaming Layer (LSL) for the synchronization between the EDA, EEG/ECG data, and keyboard stream, and it stored all data in XDF file format.

2.3.1. Data Processing

(1) Extracted eye-tracking parameters from SMI system were: fixation count, fixation frequency (count/second), fixation duration total (ms), fixation duration average (ms), saccade count, saccade frequency (count/second), saccade duration total (ms), and saccade duration average (ms).

(2) Offline EEG processing was applied on the dataset of all subjects. EEG signals of all subjects and channels were band-pass filtered (4th order Butterworth filter) to extract the EEG activity in the following 5 frequency ranges: (a) delta (0.5–4 Hz), (b) theta (4–7 Hz), (c) alpha (7–13 Hz), (d) beta (15–40 Hz), and (e) broadband EEG activity (0.5–40 Hz).

Filtered signals of all channels were squared and segmented according to the keyboard event markers. Each epoch was associated with the reading of a single slide. For each subject, electrode site, frequency band, and epoch, the median value of filtered and squared EEG was calculated in order to obtain single band-power values for each epoch. Calculating the median band-power over epoch duration is used to remove impulse-noise due to movements, blinks, or other artefacts. Additional visual inspection of power epochs was conducted in order to ensure that the obtained median values represented the valid quantification of the band-power activity. Median power values of each slide/band were normalized by calculating the relative change using the following equation:

$$Pc = (medP - medPt)/medPt \quad (1)$$

where Pc is the measure of power change for each band/slide, $medP$ is the median value of power for band/slide, and $medPt$ the median value of power in frequency band for the whole recording. Measurement unit of $medPt$ and $medP$ is μV^2 while Pc is unitless.

(3) Offline heart-signal processing for extraction of heart-rate variability (HRV) parameters in the time domain: (a) Mean value of beat-to-beat intervals (BBIs), mean RR (ms); (b) standard deviation of normal BBIs, SDNN(ms); (c) mean value of heart rate, mean HR (beats/min); (d) standard deviation of heart rate, STD HR (beats/min); (e) coefficient of variance of normal BBIs, CVRR=SDNN/mean RR (n.u.); and (f) Root mean square of differences of successive BBIs, RMSSD(ms).

(4) The average value of electrodermal activity was calculated for each slide.

2.3.2. Statistical Analysis

Results are presented as count (percent), means ± standard deviation, or median (25–75th percentile), depending on data type and distribution. Parametric tests were used for the analysis of continuous variables with normal distribution, while non-parametric tests were used in analysis with non-normally distributed data. Normality of distribution was explored using descriptive statistics (mean, standard deviation, median, interquartile range, skewness, and kurtosis), tests of normality (Kolmogorov–Smirnov and Shapiro–Wilks), and graphical methods (QQ plot, histogram, boxplot).

When we compared groups by parameters per each colour, the sample consisted of 18 participants × 2 groups (dyslexic vs. non-dyslexic); the majority of samples skewed distribution, and, for that reason, we used the Mann–Whitney U test instead of independent samples t test (Tables 1 and 2).

Table 1. Eye-tracking, EEG, EDA, and HRV parameters in non-dyslexic and dyslexic children; significant p values are marked as bold.

Parameters	**Reading** Non-Dyslexic (n = 18)	Dyslexic (n = 18)	p **Value** *
	Reading duration		
RD (s)	16.4 (11.9–23.5)	54.6 (26.1–70.7)	**0.002**
	EEG parameters (relative band-power) [a]		
Alpha	−5 (−11 to +9)	−3 (−6 to +8)	0.772
Beta	3 (−7 to +13)	6 (−2 to +13)	0.477
Delta	−10 (−17 to +30)	3 (−11 to+18)	0.809
Theta	−8 (−13 to +8)	3 (−7 to +9)	0.296
Broadband	−8 (−14 to +26)	5 (−13 to +17)	0.851
	Eye-tracking parameters		
Fixation count	25 (23–30)	35.5 (29–67)	**<0.001**
Fixation frequency (count/s)	1.5 (1.37–1.80)	1.1 (0.6–1.6)	**0.036**
Fixation duration total (s)	15.1 (10.8–21.6)	48.3 (23.9–59.4)	**0.001**
Fixation duration average (ms)	593.8 (518.2–696.5)	809.7 (575.8–1586.9)	0.071
Saccade count	24 (20–28)	29.5 (25–42)	**0.003**
Saccade frequency (count/s)	1.45 (1.28–1.60)	0.90 (0.50–1.40)	**0.013**
Saccade duration total (ms)	469.7 (434.1–538.2)	736.5 (583.8–1509.7)	**<0.001**
Saccade duration average (ms)	20.1 (18.9–21.7)	23.1 (21.0–33.0)	**0.004**
	EDA value		
EDA (μS)	8.29 (6.04–12.01)	5.67 (4.67–7.47)	**0.012**

Table 1. *Cont.*

Parameters	Reading Non-Dyslexic (n = 18)	Reading Dyslexic (n = 18)	p Value *
	HRV parameters		
Mean RR (ms)	659.4 (596.2–705.5)	693.6 (645.4–759.4)	0.092
STD RR (ms)	39.7 (22.2–57.3)	42.6 (32.5–59.9)	0.631
Mean HR (beats/min)	91.0 (84.4–100.6)	86.5 (79.0–92.9)	0.244
STD HR (beats/min)	6.28 (3.66–7.61)	5.22 (4.47–6.78)	0.988
RMSSD (ms)	50.9 (26.2–77.6)	44.7 (33.5–76.2)	0.527
CVRR=SDRR/MeanRR (ms)	0.08 (0.04–0.10)	0.07 (0.06–0.09)	0.828

Results are presented as median (25–75 percentile). * Mann–Whitney U test (exact p value). [a] EEG parameters are presented as difference from baseline (minus is decreasing trend from thebaseline while plus is increasing trend from the baseline).

Table 2. Differences between dyslexic and non-dyslexic children on reading duration. EEG, eye-tracking, EDA, and HRV parameters, ($p < 0.05$ is marked with peach colour where dyslexic children scored with higher values and green colour where non-dyslexic children scored with higher values). The reported statistics is based on Mann–Whitney U test.

Colours	Red	Blue	Yellow	Orange	Purple	Turquoise	Red O	Turquoise O	Blue O	Orange O	Purple O	Yellow O
Reading duration (ms)	0.002	0.008	0.004	0.001	0.002	0.002	0.001	0.002	0.002	0.001	0.002	0.001
Fixation count	0.001		0.002	0.046	0.001	0.010	0.001		0.015	0.024		0.001
Fixation frequency (count/s)	0.008	0.005		0.041	0.018	0.003	0.026	0.011	0.011	0.046	0.016	0.010
Fixation duration total (ms)	0.002	0.016	0.004	0.001	0.002	0.002	0.001	0.031	0.003	0.002	0.005	0.001
Fixation duration average (ms)	0.058	0.043			0.043	0.005	0.050		0.058	0.050		0.025
Saccade count	0.018		0.005		0.001	0.057	0.002		0.049			0.001
Saccade frequency (count/s)	0.008	0.004		0.020	0.004	0.003	0.036	0.009	0.011	0.015	0.013	0.004
Saccade duration total (ms)	0.001		0.003	0.058	0.001	0.025	0.001		0.010	0.023	0.056	0.001
Saccade duration average (ms)	0.020	0.015	0.021	0.052	0.001				0.034	0.031	0.040	0.004
Alpha												
Beta					0.010							
Delta												
Theta								0.004			0.048	
Broadband					0.012							
GSR (uS)	0.029	0.053		0.038	0.022	0.057	0.041		0.049		0.053	0.035
Mean RR (ms)					0.047			0.040				0.027
STD RR (ms)												
Mean HR (beats/min)					0.047			0.040				0.027
STD HR (beats/min)												
RMSSD (ms)												
CVRR = SDRR/MeanRR (ms)												

Data of measurements when all colours were gathered and the sample consisted of 18 participants × 13 colours × 2 groups (dyslexic vs. non-dyslexic) had a normal distribution with a sufficient number of samples. In this situation, we used an independent samples t-test (Table 3).

Additionally, in each group, separately, we compared measurement of each parameter on every single colour to white (difference between 12 colours and white colour) using paired-samples t-test (for differences with normal distribution) and Wilcoxon Signed Ranks test (for differences with non-normal distribution) (Supplementary Table S1).

This is an exploratory study that included several different sensor measurements (eye-tracking, EEG, EDA, HRV) for a better understanding of the neurophysiological origin of dyslexia and its relation to colours. No sample size prior to the study was calculated. Due to the pilot nature of the study, no p-value adjustment for multiple outcomes was applied.

Table 3. Reading duration, HRV, eye-tracking, and EDA parameters in non-dyslexic and dyslexic children across all colours together (18 × 13 colours = 234 readings); significant p values are marked in bold. In Table 3, all the colours were averaged together and compared between the two groups on each measure.

Parameters	Reading		p Value *
	Non-Dyslexic (n = 18 × 13)	Dyslexic (n = 18 × 13)	
	Reading duration		
RD (s)	21.63 ± 15.30	49.20 ± 29.81	**<0.001**
	EEG parameters (relative band power)		
Alpha	2.5 ± 12.2	1.8 ± 11.4	0.529
Beta	−0.9 ± 16.5	5.1 ±27.5	**0.005**
Delta	5.9 ± 38.1	9.1± 47.5	0.415
Theta	2.7± 15.0	2.2± 16.4	0.735
Broadband	1.1 ± 29.1	6.2± 36.2	0.101
	Eye-tracking parameters		
Fixation count	27.20 ± 08.50	45.29 ± 29.59	**<0.001**
Fixation frequency (count/s)	1.53 ± 0.54	1.15 ± 0.70	**<0.001**
Fixation duration total (s)	20.16 ± 14.57	43.57 ± 27.02	**<0.001**
Fixation duration average (ms)	697.20 ± 297.21	1108.41 ± 786.90	**<0.001**
Saccade count	24.33 ± 7.85	35.63 ± 23.65	**<0.001**
Saccade frequency (count/s)	1.37 ± 0.52	0.97 ± 0.69	**<0.001**
Saccade duration total (ms)	517.22 ± 189.82	1122.51 ± 1514.83	**<0.001**
Saccade duration average (ms)	21.34 ± 3.51	27.82 ± 12.11	**<0.001**
	EDA value		
EDA (μS)	8.86± 3.77	6.30 ± 2.36	**<0.001**
	HRV parameters		
Mean RR (ms)	652.47± 96.37	690.61 ± 75.06	**<0.001**
STD RR (ms)	44.79 ± 37.31	47.49 ± 20.25	0.331
Mean HR (beats/min)	93.54 ± 11.94	87.89 ± 9.47	**<0.001**
STD HR (beats/min)	5.70 ± 3.07	5.96 ± 2.09	0.283
RMSSD (ms)	54.21 ± 48.26	56.71 ± 31.06	**0.001**
CVRR=SDRR/MeanRR (ms)	0.07 ± 0.04	0.08 ± 0.02	**<0.001**

* Independent sample t test. Results are presented as mean ± standard deviation.

All p-values which were less than 0.05 were considered significant. The data were analysed within the SPSS 20.0 software (IBM Corp. Released 2011. IBM SPSS Statistics for Windows, Version 20.0. Armonk, NY, USA: IBM Corp).

3. Results

3.1. White (Default) Background—Reading Performance Results

Reading performance (non-dyslexic vs. dyslexic) and physiological parameters measured by the sensor hub on a white background colour are presented in Table 1. For all of the eye-tracking measures, we have found a significant difference between groups, except for the fixation duration average. Dyslexic children showed significantly higher scores in comparison to non-dyslexic children in all eye-tracking measures, except for fixation frequency and saccade frequency. A significant difference was also observed with the EDA parameter, where non-dyslexic children had higher values in comparison to dyslexic children. In all HRV parameters, we observed no significant difference between dyslexic and non-dyslexic children. In mean HR and STD HR, non-dyslexic children achieved higher values, while dyslexic children showed higher scores in all other HRV parameters. Regarding EEG power bands, we found no significant differences between groups. In all EEG measures, dyslexic children showed higher values. Due to the distortion of the normal distribution of the data, the parameters are presented as medians and interquartile range and compared using a non-parametric alternative to the t test, the Mann–Whitney U test.

3.2. Modifications in Background and Overlay Colours—Reading Performance Results

In Table 2, we show median values for the overall results for each parameter per single colour. Dyslexic and non-dyslexic children were compared on each of the parameters, namely, reading duration, eye-tracking measures, EDA, HRV, and EEG parameters. The results show that children in the dyslexic group differed significantly from the children in the control group consistently on the all eye-tracking measures, except on a few single colours for a few measures, namely fixation count (blue, turquoise O, purple O), fixation frequency (yellow), fixation duration average (yellow, orange, turquoise O, purple O), saccade count (blue, orange, turquoise O, orange O, purple O), saccade frequency (yellow), saccade duration total (blue, turquoise O), and saccade duration average (turquoise, red O, turquoise O). We observed significant differences between groups on EDA measure in all colours except yellow, turquoise O, and orange O. Children from the control group scored higher across the EDA measure. Regarding HRV measures, we observed significant differences between groups in mean RR (purple, turquoise O, yellow O) where dyslexic children scored higher and in mean HR (purple, turquoise O, yellow O) where the control group scored higher. Children with dyslexia showed significant increase of the beta band-power on purple and theta band-power on purple O colour in comparison to the control group, while the control group showed significant increase of the theta band-power on turquoise O colour.

Further on, for abetter overview, we showed a visual comparison between the two groups on every background/overlay colour for EEG (alpha, beta, delta, theta, broadband) in Figure 2; reading duration and eye-tracking measurements (fixation count, fixation frequency, saccade count, saccade frequency) in Figure 3; EDA in Figure 4; and HRV (mean RR and mean HR) in Figure 5.

More detailed analysis regarding comparisons of all the background/overlay colours with white across all of the parameters for both groups separately can be found in the Supplement.

Reading performance and physiological parameters comparisons (non-dyslexic vs. dyslexic children) over the average scores for all colours together are presented in Table 3. A significant difference was obtained regarding all eye/tracking measures, reading duration, and median beta power band, as well as for EDA, mean RR, mean HR, RMSSD, and CVRR. We observed no significant difference between non-dyslexic and dyslexic children in all other measures.

Dyslexic children demonstrated longer time duration for the reading performance in comparison to non-dyslexic children (control group). They also showed a higher fixation count, fixation duration total, fixation duration average, saccade count, saccade duration total, and saccade duration average, while the control group showed higher scores of fixation frequency and saccade frequency. Children with dyslexia also showed increased in all of the EEG bands except theta band in comparison to the control group. EDA was higher in the control group as well as mean HR, while all other HRV parameters were higher in dyslexic children.

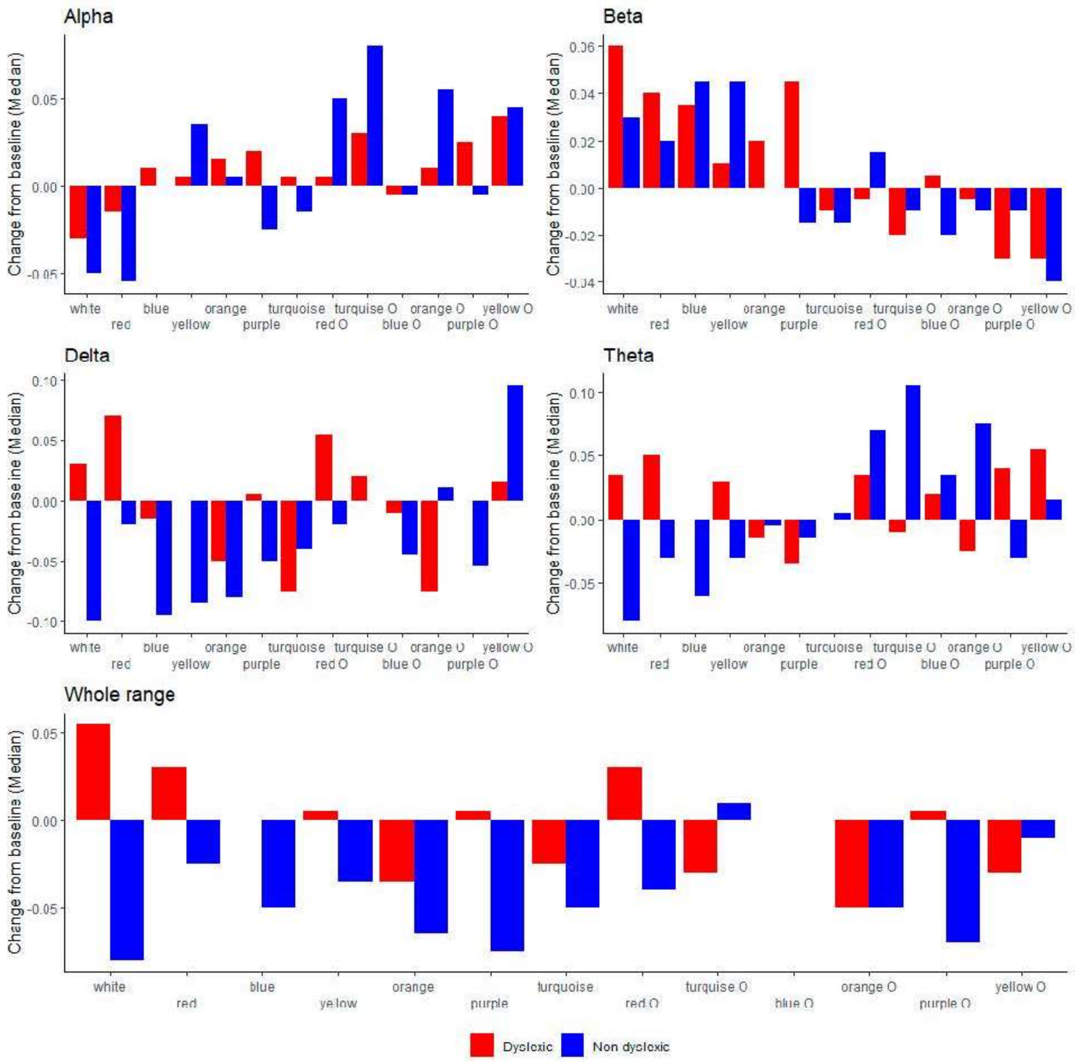

Figure 2. EEG (alpha, beta, delta, theta, broadband) between dyslexic and non-dyslexic children on every background/overlay colour.

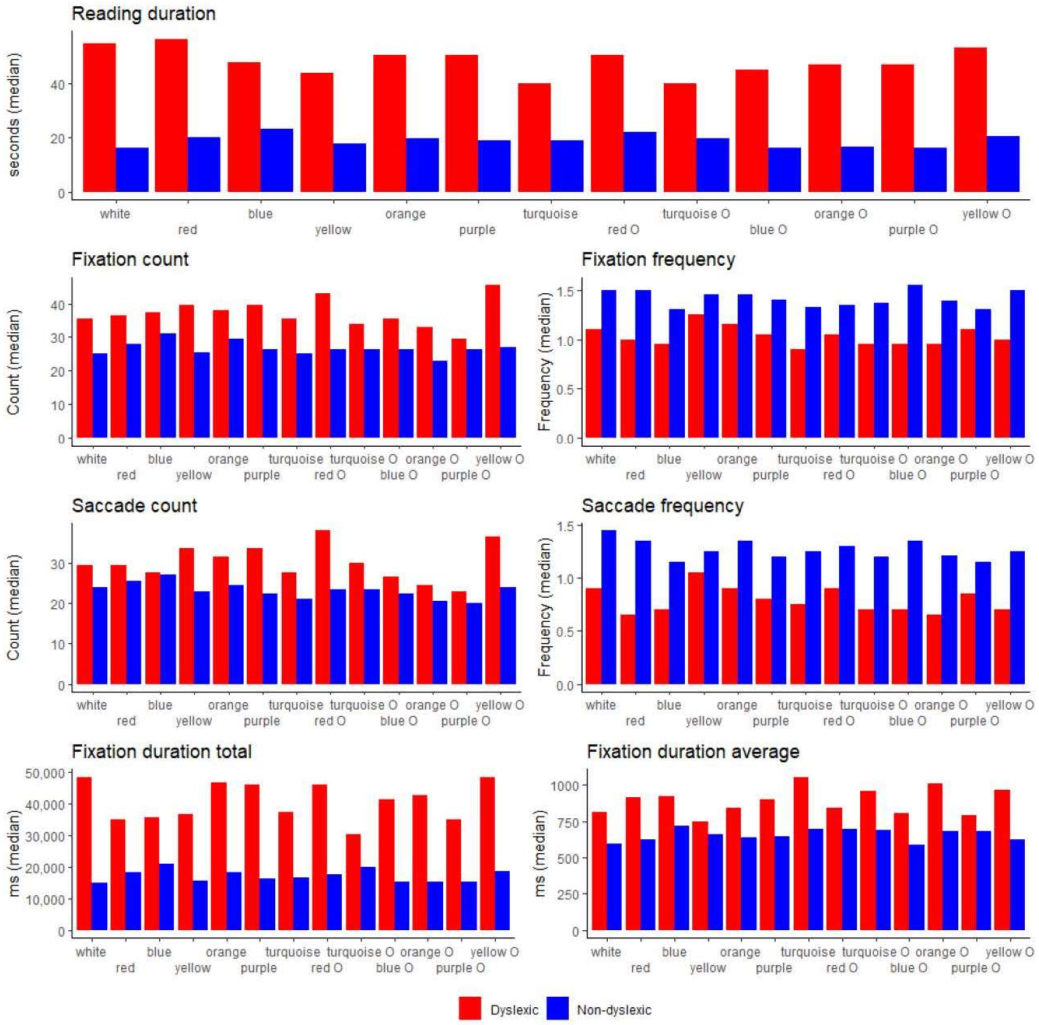

Figure 3. Reading duration and eye-tracking measures (fixation count, fixation frequency, saccade count, saccade frequency, fixation duration total, fixation duration average) between dyslexic and non-dyslexic children on every background/overlay colour.

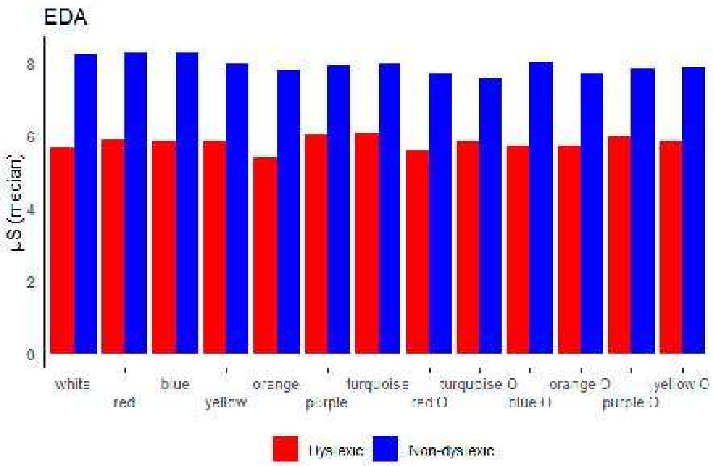

Figure 4. Electrodermal activity (EDA) between dyslexic and non-dyslexic children on every background/overlay colour.

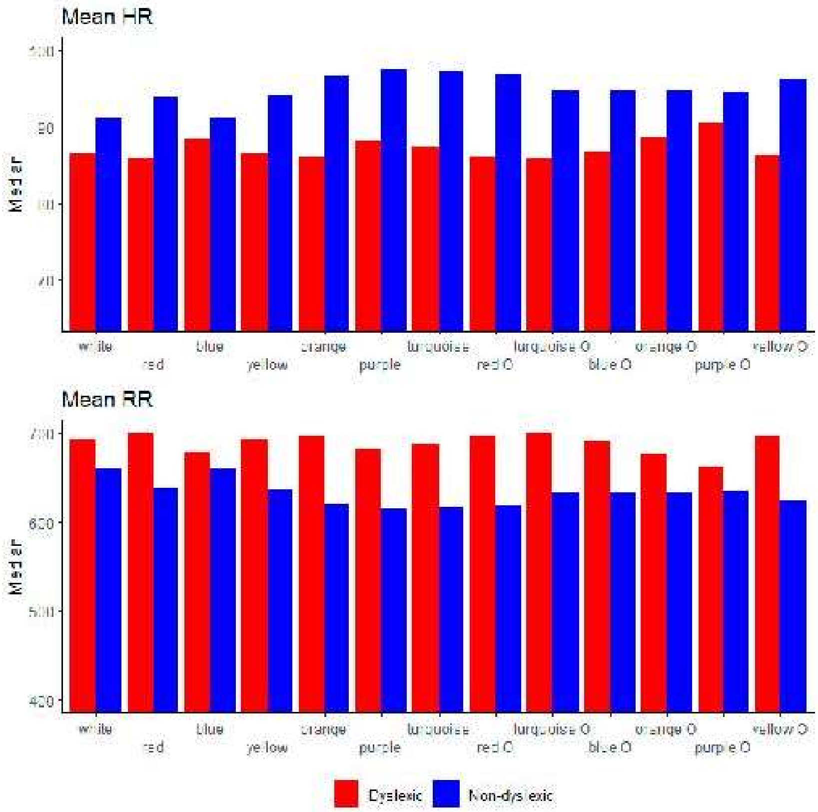

Figure 5. HRV parameters (mean HR, mean RR) between dyslexic and non-dyslexic children on every background/overlay colour.

4. Discussion

4.1. Summary

In the 36 children (18 dyslexic and 18 control group), we evaluated the relationship between physiological parameters and colour modifications in the text, background, and overlays during reading performance regarding reading duration, eye-tracking, EEG bands, EDA, and HRV parameters using simultaneously monitored sensor signals. The findings of the present study regarding reading duration on different background and overlay colours, as well as on white background with black text, show that there is a significant difference between groups. Firstly, dyslexic children took longer to read the text. Concerning the eye-tracking measures, we found significant differences between groups in all measures except fixation duration average for reading on white background with black text. Dyslexic children showed higher values for fixation count, fixation duration total, fixation duration average, fixation duration average, saccade count, saccade duration total, and saccade duration average, while non-dyslexic children scored higher on fixation frequency and saccade frequency, which is in agreement with the previous studies [56–60] where it was reported that dyslexic children have longer fixation duration, reading time, and saccade duration. It was also found that the control group scored higher on fixation frequency and saccade frequency in reading on white as well on coloured background/overlay, which is aligned with previous research where it was reported that typical readers simultaneously process the number of letters and adapt to them according to the task, while dyslexic children only process a few letters during the reading task [61–63]. Furthermore, older or better readers need more time to adapt to an unexpected text [64,65].

4.2. EEG Parameters

In the literature regarding EEG power bands (alpha, beta, delta, theta, and broadband activity), it is reported that dyslexic children have an increasing trend or disrupted oscillations in the range of delta and theta, and specifically increasing beta [66–70]. Regarding the broad band activity, it was reported that this measure could be used for distinction between dyslexic children and individuals with normal reading abilities [70]. In the present study, we found no significant differences in EEG bands between groups during the reading task on white background with black text, where dyslexic children showed an increasing trend in all EEG measures in comparison to the control group. Considering the reading performance in all colours together, we found significant increase values in the beta band-power in dyslexic children in comparison to the control group.

The present study gives further support to the reports in which it was found that colours have an important role in the reading process [23,31–37,41,44,46–48,71–73].

Regarding EEG, it was shown that during the reading on purple background colour, children with dyslexia had a significantly increasing trend of the beta and broadband activity and significantly increasing trend in the theta band while reading on purple overlay, which is aligned with previous studies [60,67,69]. The control group of children scored with increasing values of theta band on turquoise overlay colour in comparison to the group of dyslexic readers.

4.3. Eye-Tracking Parameters

The results of the present study regarding eye-tracking measures and reading in colours affirmed the previous study [44] where it was reported that the third colour from the selected colour set with the shortest reading duration in individuals with dyslexia was yellow, as is confirmed in the present study; however, our study shows that the first colour with shortest reading duration is turquoise and the second turquoise O, which is opposite to the previous study, where the first was peach and the second orange. Our study shows that the red colour has the longest reading duration in dyslexic children, followed by red O and yellow O. Regarding the control group, they scored with the shortest reading duration with violet O, blue O, and orange O, while the longer reading duration was recorded on blue, red O, and yellow O. The overall results regarding eye-tracking measures and reading in colour are aligned with the studies [35,74] where it was reported that influence of colours and coloured overlays is minimal for the readers with dyslexia regarding reading duration, except for the yellow and turquoise and turquoise O, as was previously reported [50,51]. Furthermore, the study confirms that there are systematic differences between groups on the white, single colours and all colours together, whereas the control group showed significantly higher values on the fixation frequency and saccade frequency, as was previously explained [61–63], while dyslexic children scored higher in all eye-tracking measures except for a few, namely fixation count (turquoise O, purple O), fixation duration average (orange, purple O), saccade count (blue, orange, turquoise, purple O), saccade duration total (blue, turquoise O), and saccade duration average (turquoise, red O, turquoise O).

4.4. EDA

Regarding electrodermal activity, it is important to mention that EDA is linearly correlated to arousal and reflects emotional response and cognitive activity [75,76], and it is one of the most-used psychophysiological measures for definition of stress level [77]. High electrodermal activity reflects a high level of stress. The present study reports that in both situations, reading on white and coloured overlays/background children with dyslexia scored significantly lower in comparison to the group of non-dyslexic children, as was also reported in previous studies [78,79]. TEDA measure could be used to distinguish children with and without dyslexia, and we can conclude that the control group had a higher stress level or emotional response to the colours, which is aligned with the report where it was found that good readers need more time to adapt to a new form of text [64,65] which may produce an emotional response in such situations [78–80]. Regarding additional colours, we have found that the EDA measure was significant in all colours between groups, except for orange, turquoise O, and orange O, which could confirm the previous reports that pastel colours have a calming effect [81,82].

4.5. HRV Parameters

A relationship between HRV parameters and modification in the text background and overlay in children with and without dyslexia is reported in the present study. During the reading on the white background with black text, which is typical for school-age children, we found no significant differences between dyslexic and non-dyslexic children. Our result gives further support to the previous studies where researchers reported that there is no systematic difference between dyslexic and non-dyslexic subjects regarding the HRV analysis [78,83]. However, considering all colours together during the reading task and physiological responses, we found systematic differences between dyslexic and non-dyslexic children in a few HRV parameters, namely, mean RR, mean HR, RMSSD, and CVRR. Dyslexic children have higher values in all named measures except mean HR, where the control group showed a higher score, which could also be related to the level of stress and aligns with the EDA measure, where the control group also showed higher scores [81,84,85]. Mean HR was significantly higher in the control group than in the dyslexic group for purple, turquoise O, and yellow O, where dyslexic children showed significantly higher values of mean RR. Regarding emotional response in dyslexic individuals [79], the level of arousal in our study was expected and found to be lower in the group with dyslexia, which is reflected also by the mean HR and mean RR measures on the single colours [84] and confirms the hypothesis where those measures could be beneficial for distinction between dyslexic and non-dyslexic individuals.

4.6. Colours Impact on Overall Measures

The aim of this study was to better understand the relationship between physiological parameters and colour modifications in text background and overlay during reading in children with and without dyslexia. The group of 36 school-age children (18 with and 18 without dyslexia) read the text on white and 12 background and overlay colours.

The study evaluated differences between groups in the reading duration, EEG, HRV, EDA, and eye-tracking measures. Based on the findings, we can conclude that there are systematic differences between groups regarding reading duration and eye-tracking measures, whereby dyslexic children scored higher in overall results except for fixation frequency and saccade frequency, which is in line with the previous studies. Regarding single colours, where dyslexic children showed the shortest time duration to finish the reading task, we have found that reading on turquoise and turquoise O background colour was the easiest for them. In the third place was the yellow colour, which was also reported before [45]. Further, we have observed significant differences between groups regarding EDA measures, where the control group has higher values in comparison to the dyslexic one, which confirms the finding of the previous studies as well. Looking into the relation between single colours and EDA, we have observed no significant differences in orange, turquoise O, and orange O colours. Regarding HRV parameters, we found no significant differences in most HRV measures, which aligns with the previous studies, except for the mean HR, where the control group scored higher and which is related to the EDA and stress level as well. Also, systematic differences of the HRV measures were found in single colours for mean RR and mean HR in purple and turquoise O, where the control group scored higher on mean HR and dyslexic group on mean RR. In the previous literature, it was reported that a broadband EEG could be used for the distinction between dyslexic and non-dyslexic individuals. We found significant differences in the two groups on the purple colour, where dyslexic children showed an increasing trend, as well in the beta band for the same colour. Differences in brain waves between dyslexic and non-dyslexic children were explained in previous literature also by increasing of the beta band and oscillations in delta and theta bands. We have found significant differences between groups for turquoise O colour for the theta band, where the control group achieved higher values.

When compared across world languages, the main similarity found for dyslexia was the reading speed deficit (particularly in transparent orthographies [86], sometimes accompanied with other marks, such as a greater deficit for non word reading in comparison to the word reading, as well as an extremely slow and serial phonological decoding mechanism) in German and English [87] and frequency, orthographic neighbourhood size, and word length in Spanish and English [88], which leaves us with no clear sign of the underlying mechanisms of dyslexia. This is why some researchers have urged the identification of a robust sensory marker of phonological difficulties which would allow "early identification of risk for developmental dyslexia and early targeted intervention" [89], as well as the need to understand the pathophysiological visual and auditory mechanisms that cause children's phonological problems [52]. Our study gives further support to the findings regarding reading duration in dyslexic children. However, it goes a step further in uncovering the cognitive and emotional patterns in dyslexic children through the implementation of a sensory hub developed for this study.

5. Conclusions

The goal of the study was to understand colour influence in reading performance and its relation to neurophysiological responses. By combining different modalities, we attempted to find a more objective approach to distinguish children with dyslexia from those without, in order to facilitate prevention through early detection or finding beneficial colour setup which could improve their reading performance. Based on the present findings, we can conclude that turquoise background, turquoise overlay, and yellow background could be beneficial for children with dyslexia and that all presented measures (eye-tracking, EDA, HRV, EEG) could be beneficial for the purpose of better understanding of the neurophysiological origin of dyslexia in children.

We believe that this is only the beginning of this line of research. The next step would be to try to adjust the preferred colour for each individual child, given that we found a large individual variation in the data set presented in this manuscript. By doing so, we would hope to make reading easier for children with reading difficulties and for the dyslexic children. Also, we plan to run machine-learning algorithms in order to assess which of all parameters (combinations of parameters) that were measured in this study give the best prediction of a particular child belonging to the dyslexic or non-dyslexic group. This would be very valuable for both prevention and early detection of dyslexia.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/brainsci11050539/s1, Table S1. All background/overlay colours compared with white colour for each parameter in the groups (dyslexic with orange colour; non-dyslexic with green, $p < 0.05$).

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6.3 Summary of Study Results

Findings of the present research showed that the dyslexic children have longer eye-tracking measures, namely reading duration, fixation count, fixation duration average, fixation duration total, and longer saccade count, saccade duration total, and saccade duration average while reading on white and coloured background/overlay. We found that beneficial colours for dyslexic readers are turquoise background, turquoise overlay, and yellow background. While using these colours, children with dyslexia achieved the shortest time duration of the reading tasks.

Considering other parameters, dyslexic children have higher values of beta (15-40 Hz) and the broadband EEG (0.5-40 Hz) power while reading in one purple background colour, and increasing theta range power while reading on the purple overlay. We have observed no significant differences between HRV parameters among groups on white colour, except for single colours (purple, turquoise overlay, and yellow overlay) where dyslexic children scored higher with mean RR, and non-dyslexic group with higher values of mean HR. Observing EDA measure, we found systematically lower values in children with dyslexia in comparison to the non-dyslexic group. Based on the results of the present study, we can conclude that both pastel and intense background/overlays are beneficial for reading of dyslexic and non-dyslexic groups, and all sensor modalities could be used for better understanding of the neurophysiological origin of dyslexia in children.

Chapter 7

Conclusions

This thesis addresses the problem of combining different sensor modalities in order to synchronously measure changes in the physiological parameters during the reading performance in children. The aim of the thesis and the three research studies (developed on the same methodology design) was to investigate the effects of colour on the reading content as a stressor during the reading task. This thesis illuminates underlying physiological and behavioural processes in reading performances in children especially from the developmental, gender and reading skills perspective in children.

4.1 Hypothesis Validation

In order to validate the thesis hypotheses, we applied the designed method to three studies regarding children reading performance differences in perspective of maturation, gender and reading disabilities. We have applied the proposed method in three different studies to better understand the role of the colours, and how they contribute to the illumination of the underlying problems. We have addressed the 7 hypotheses in this thesis.

The first two hypotheses H1 "The younger children would have more difficulties reading the text on the intense colour background in comparison to a pastel background" and H2 "The older children would struggle more with any colour except for white" were investigated in the first study "The sensor hub for detecting the developmental characteristics in reading in children on a white vs. coloured background/coloured overlays ". In the research both hypotheses were confirmed, where is was found that older children struggle more with the colour changes of reading content, and need more time to adapt to unexpected text, while younger children showed the fastest reading abilities during the reading task. At the same time, younger children showed a calming trend while reading on pastel colours, and shorter reading duration in comparison to the older ones, which goes aligned with the first hypotheses.

In the second study "Effect of colours on reading performance in children measured by the sensor hub: from the perspective of gender" we have investigated the next two hypothesis H3 "There are differences among boys and girls in the emotional response caused by colours during the reading task" and H4 "Colours could highlight reading differences among girls and boys during the reading task". The research extremely confirmed both hypothesis with findings that girls have shown higher values of HRV parameters (SDNN, STD HR, RMSSD, NN50, pNN50, CVRR) on warm colours yellow background, orange and red overlay during the reading process, and more expressed emotional responses than boys. Findings regarding reading differences among girls and boys goes aligned with the fourth hypothesis where girls showed a longer reading duration, and longer eye-tracking measures (except for Saccade Count and Saccade Duration on purple background colour), which confirms that colours could be used as a stressor for illumination of the reading differences in perspective of gender. This finding also goes aligned with the H2, where older children struggle more with the unexpected text, the same is with the comparison of the boys and girls, where boys have proven slower maturation progress than girls, which is shown also in the case of the reading performance in colours.

In the third study "The Relation Between Physiological Parameters and Colour Modifications in text Background and Overlay During Reading in Children With and Without Dyslexia" we aimed to address the three hypothesis H5 "The children with good reading skills will be less affected by the change of colour", H6 "The pale colours would facilitate the reading task in children with and without dyslexia, unlike intense colours", and H7 "With the appropriate set of sensors we can detect the most appropriate colours for each individual". The findings of the present study confirmed the H5, H6, and H7 hypotheses. Compared to dyslexic individuals, good readers showed less oscillation in reading performance than dyslexic children, who were more affected by colour modification of the text. At the same time, pale colours address better reading performance and reading duration of the reading task than intense colours in both groups, which is shown in the results and confirms the H6. Colours shown a significant role in understanding the differences between dyslexic and non-dyslexic children during the reading performance and underline the neurophysiological basis of dyslexia, which is measurable by difference sensors, and confirmed through a chosen set of measurements (EEG, HRV, EDA, and eye-tracking).

Finally, when we summarize all the findings from three studies and evidence for seven hypotheses, we can conclude that based on adequate sensor measurement, colours should be used to better understand the different perspectives of the reading process in children and the use of the reading process and skills improvement.

4.2 Summary of Contributions

A novel method that combines different sensor modalities in one system (sensor hub) for the simultaneous monitoring of the neurophysiological parameters during the reading performance.

This thesis generates three models of the sensor hub usage with the same method, which capture changes of the human body parameters (brain waves, heart rate, electrodermal activity, and oculomotor movements) relevant for memory, attention, mental, and emotional engagement during the reading task in different background/overlay colours.

This novel method showed applicability on several approaches of understanding of the reading process through gender, developmental, and reading grade differences.

The created sensor hub could be beneficial for being a better understanding of emotional responses during the reading task or other contents such are photos, videos, or games. The emotional response in children and adults is measurable through selected set of sensor modalities and their reactions which are sensitive to the colour modifications, as is shown in the results, where the pale colours cause the calming effect on the reader's state.

This method could be used for early dyslexia and other reading disorders prediction and prevention, especially with the further data calcification which will accelerate the process of understanding relation of the particular parameters and colours in every user, or understand a specific combination of the dyslexic individuals during the reading task in a specific colour.

This thesis is a fundament for defining the set of modalities that may enable the faster and automatic selection of the colours that would facilitate the reading performance in a specific reader.

4.3 Limitations

The findings of the thesis were conditioned by the experimental setup in the three performed studies. The experimental setup has demand the same experimental conditions for every participant. The first two studies experiment was conducted in a small school chamber during the regular class period of the day. In the third experiment the biggest challenge was sample size, and finding the participants with dyslexia. Second, problem with the Covid-19 pandemic, has slow down the research progress. In order to better understand the neurophysiological basis of dyslexia it is necessary to work with a wider number of the participants in order to develop algorithms for early prediction of dyslexia.

The benefit of colour on reading performance in children with dyslexia were conducted on the group level, and it needs validation on the individual approach in the future.

4.4 Future Directions

‘Although there are opposite opinions regarding dyslexia treatment and colour influence on the reading performance [80], [81] the usage of colour lenses, overlays are widespread in the practice. The colour therapy nowadays is increasingly represented in treatment of different psychological, emotional and visual problems, as well as in the treatment of the reading disorders [67]-[72], [98].

As dyslexia has a proven neurophysiological basis, it is important to develop a proven set of modalities that will help predict dyslexia in school-age children. This approach will avoid a number of other difficulties such emotional, motivational, and learning are. Firstly, it is important to move from group studies to the individual, and to develop a system which will be able to detect the right colour for each individual based on their physiological response during the reading test. Secondly, it is important to develop a prediction model for early dyslexia prediction and prevention. The kind of system will be useful for psychologist and language expert in elementary and high schools, as well as in private expert practice.

4.4.1 Individual approach

In the following work, as is discussed above it will be necessary to move forward from group studies to individual studies in order to determine the individual set of parameters, as well as colours, which will address individual differences in the reading process.

The most of the reading and learning difficulties mainly depend on an individual set of underlying abilities in children [8], [14], [99]. Children also have different developmental profiles of reading skill obtainment, while weaknesses in reading abilities may cause their reading impairments over time.

Individual differences in the reading and learning abilities in children may originate from biological to the environmental factors. These factors shape the development of the brain systems which is involved in the reading process [8]. Also, these factors may be reflected in the psycho-physiological states of the child engaged in the reading task. When we include a colour influence and its effect on the psycho-physiological changes of the human body it is also necessary to determine the individual sets of the parameters which address the readers needs and helps them in their skills improvement.

It is also found that colours may be especially effective for early readers and school-age children [81].

Today knowledge asserts the importance of identifying and treating reading difficulties as early as possible, since they may deteriorate academic achievements and increase the risk of emotional, social, and mental health problems in school-age children.

4.4.2 Early prediction and prevention of dyslexia

At the school-age the most effective approach for children with learning and reading difficulties are experts support and early problem identification which address their needs [14], [99], [100]. As we have explained previously in Sweden, children are being tested and diagnosed with dyslexia on at the age of thirteen [44].

Early indicators of dyslexia were monitored from preschool age to the end of the fourth grade of elementary school in the research dedicated to the children with dyslexia in Republic of Serbia [101]. The research confirms the statement that dyslexia indicators can be isolated at preschool age. There are also other evidences that dyslexia can be predicted and prevented in early school-age children [16], [48], [99]. Today, science enable better understanding the child’s nervous system with different approaches and modalities which will help early intervention and risk reduction.

The development of machine learning algorithms is one solution that could affiliate reading disorders as dyslexia is [102]-[104].

This thesis is a fundamental step toward defining the right set of measurements that will automatically (with machine learning algorithms) select colours that facilitate the individual reading and he/her reading abilities, in order to improve their conditions and reading skills.

Appendix A

Features

A.1 Statistical Features

1. Mean
2. Standard deviation
3. p Value
4. 25th quartile
5. 75th quartile

A.2 Eye-tracking Features

1. Fixation count
2. Fixation frequency (count/second)
3. Fixation duration total (ms)
4. Fixation duration average (ms)
5. Saccade count
6. Saccade frequency (count/second)
7. Saccade duration total (ms)
8. Saccade duration average (ms)

A.3 HRV Features

1. Mean RR(ms)
2. SDNN (ms)
3. Mean HR (beats/min)
4. STD HR (beats/min)
5. CVRR=SDNN/Mean RR (n.u.)
6. RMSSD (ms)
7. NN50 (beats)
8. pNN50 (%)

9. RD (s)- Reading duration

A.4 EEG Features

1. Alpha (μV2)
2. Beta (μV2)
3. Delta (μV2)
4. Theta (μV2)
5. Whole Range (μV2)-Broadband

A.5 EDA Features

EDA (μS)

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Biography

The author of this thesis Tamara Jakovljević (1989) was born on April 21, 1989 in Valjevo, Republic of Serbia. She finished her master studies at Faculty of organizational science University of Belgrade in 2014 grate honor.

She started her doctoral studies at the Jožef Stefan International Postgraduate School in Ljubljana, as a scholar of the AD Futura Fund of the Republic of Slovenia. Her doctoral dissertation is multidisciplinary research in the field of sensory technologies, dedicated to the development of the sensor-hub for detection of the colour influence on reading in children with reading difficulties, such as dyslexia. During the multidisciplinary work, she surrounded herself with prominent professors from Slovenia and Serbia in order to help the educational process in children by early detection and prevention of Dyslexia.

Her research work has been presented at several international conferences and published in three international journals. She is the part of the team and startup Baby FM that won three international prizes (Local Imagine IF program, Innovation forum-Cambridge, Raising starts-Swiss Government and Science-Technology Park Belgrade, and RIGFyouth-Skolkovo innovation center Moscow).

She believes that her doctorate thesis will be the fundament for establishing the system for individual colours treatment for reading improvement in children and people with dyslexia.