Roman Rosiek

Psychological Methods in Research on Didactics of Physics

Psychological Methods in Research on Didactics of Physics

Uniwersytet Pedagogiczny
im. Komisji Edukacji Narodowej
w Krakowie
Prace Monograficzne 1090

Roman Rosiek

Psychological Methods in Research on Didactics of Physics

WYDAWNICTWO NAUKOWE
UNIWERSYTETU PEDAGOGICZNEGO KRAKÓW 2020

Recenzenci
dr hab. Władysław Błasiak
dr hab. Ewa Dębowska

Projekt okładki
Janusz Schneider

Opracowanie typograficzne, skład
Anna Petiurenko

ISSN 2450-7865
ISBN 978-83-8084-611-1
e-ISBN 978-83-8084-612-8
DOI 10.24917/9788380846111

Wydawnictwo Naukowe UP
30-084 Kraków, ul. Podchorążych 2
tel./faks 12 662-63-83, tel. 12 662-67-56
e-mail: wydawnictwo@up.krakow.pl

Zapraszamy na stronę internetową:
http://www.wydawnictwoup.pl

Contents

INTRODUCTION

The development of electronics, digital technology, and IT tools has been progressing quickly in all aspects of human life in recent years. The significant development and the contribution of physics to the formulation of new items, e.g. semiconductors, new types of data storage, or lasers, has resulted in the miniaturisation of devices, a drop in their cost, and made them more common. This is also the case with modern instruments, both measuring as well as diagnostic and surgical. The widespread development and the possibility of miniaturisation causes extremely advanced diagnostic and measuring devices to be available. Relevant substantive knowledge and practical skills regarding the use of such devices is usually not as widespread. Those who undergo surgery lack this kind of knowledge as well. An example of this are biofeedback centers, which make use of a wide variety of advanced measuring devices for various purposes, while the most important criterion is financial gain. Searching for "biofeedback" online results in advertisements offering participation in sessions that claim to improve eyesight, correct vision defects, cure cancer, or solve sexual dysfunctions. There are also many fields, e.g. detailed didactics, including physics didactics, in which cutting-edge technology use spreads relatively slowly, even though physics and physicists are the basis of technological progress.

The aim of this work is to attempt an adaptation of the newest measuring tools and techniques based on the accomplishments of electronics and medical diagnostics, as well as to present the basic non-invasive methods of measuring human psychophysiological parameters and to attempt an adaptation of these techniques for the purpose of obtaining information related to the cognitive activity of the subjects. The aim of the trials is research related to measuring parameters indicating motivation, focus, stress, as well as to monitoring the task solving strategies of pupils and students. Furthermore, the results are to be used in teaching methodology, especially in physics education, as a supplement of existing methods, such as surveys or observation sheets. This is possible due to the creation of a new cognitive didactics laboratory in the Didactics of Physics Department at the Pedagogical University of Cracow.

THEORETICAL PART

1. CHAPTER – BIOPHYSICAL BASIS

1.1. Cell electrophysiology

1.1.1 The basics of cell electrophysiology

The smallest elementary structural and functional live structures – the cells (from Latin *cellula*) – are the basis of the structure of living organisms. Cells are capable of performing all possible basic life processes such as metabolism, growth, and reproduction. An important determinant of the functioning of the environment of the cell is the cell membrane, which is 10^{-10} m thick (Konarska, 1995). The most important attribute of the cell membrane is its selective permeability. The existence of the semipermeable membrane results in the existence of a charge-concentrating gradient, which is the difference of potentials between the surroundings of a cell and the insides of a cell, equal to approximately -90 mV (negative potential inside the cell). External stimuli in the form of mechanical, chemical, or thermal impulses directly affect the processes taking place on the cell membrane. Reactions based on the effect can be grouped as follows:

– Subliminal – cause only local changes in membrane potential which are quickly resolved,

– Above threshold stimuli – cause a rapid depolarisation of the membrane cell called an action potential, which, e.g. in the case of muscle cells, causes a mechanical contraction.

The most important attributes of cell stimulation (in Augustyniak, 2001) can be described as follows:

1. The cell's reaction to stimuli is an electrical phenomenon and can have mechanical after-effects.

2. The stimulation process is rapid, maintained by positive feedback which is an increased permeability of the cell membrane for Na+ ions occurring after exceeding the threshold potential,

3. If the cell membrane potential is lower than a threshold value, cell reaction to stimuli is not possible. For muscle cells this takes 2 to 3 ms, and for heart muscle cells it can take up to 300 ms.

4. In the repolarisation phase, the cell can once more react to an external stimulus. The bigger the amplitude of the stimulus, the quicker the reaction. In this phase, the cell is a natural transducer converting the amplitude of the stimulus into nerve impulse frequency. The conduction of stimuli is a way of transporting information in an organism. The depolarisation of a cell can be the stimulus for neighbouring cells to depolarise. The condition for stimulus propagation is exceeding the threshold potential value of the neighbouring cells. The following graph depicts the phases of a cells' polarisation and the appropriate threshold values.

1.1.2 Technical difficulties related to non-invasive methods of measuring electrophysiological signals.

The observation and measurement of electric signals generated by the cells in the human body require use of the right methodology. Most commonly, the measurement consists of absorbing the energy of the studied object with the use of appropriate electrodes. In order to minimise the encumbrance of the studied system, measuring devices with the highest possible impedance have to be used. The use of very high-impedance measuring devices demands the use of appropriate electrodes. They are a very important element, connecting the source of ionic current with the electronic measuring system. This is a connection between two types of conduction: ionic (of the cell) and electronic (of the electrodes and the measuring system). High input impedance increases the sensitivity of the measuring system towards external interference, e.g.

[10]

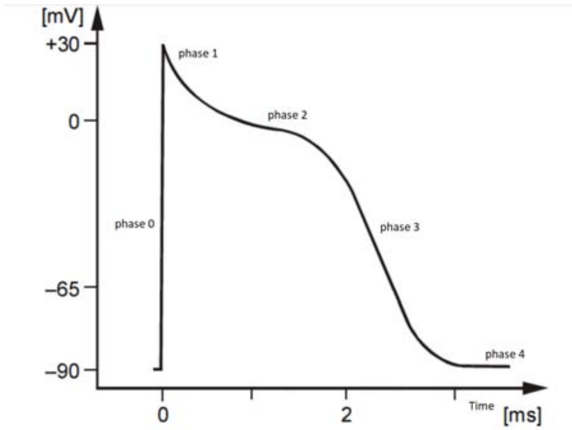


Figure 1: *Membrane potential in the successive stages of cell depolarisation and repolarization (Augustyniak 2001 p. 18).*

ripples of electricity. This type of circuit creates an additional electromotive force described as the contact potential difference. From an electrical point of view, such contact between an electrolyte and metal is a half-cell. The parameters and empirical formula of the electrodes used are an extremely important aspect of the measurement. This issue is the subject of interdisciplinary research. The design and empirical formula of the electrodes are highly protected secrets of many companies specialising in medical diagnostic equipment. Almost all measurements or prolonged signal readings (e.g. EEG or EKG readings) require the specification of the skin – electrode contact impedance. This has to be carried out before starting the measurement. There are high standards regarding the maximum allowed contact impedance. The Polish Cardiac Society allows for a maximum impedance of 10 kΩ for EKG readings. Figure 2 depicts a flow chart of an automatic electrode impedance control system. This method uses damping of signal summation applied of the entry point of the differential amplifier. In case of low electrode contact impedance the signal is identical on both inputs, which means that it will be damped. Any electrode contact impedance change is registered as an increase of the test signal amplitude. A frequency of 800 Hz is high enough to be easily separated from the useful signal which is measured at much lower frequencies.

The depolarisation process is very similar in single cells, regardless of their function, and generates the same potential. However, a much lower potential is registered on the surface of the body. This causes the necessity of using multiple signal sources or averaging the signal due to the existence of elements such as the skin or bones of the head which restrict the measurement possibilities. Despite these obstacles, accurate measurement of specific biopotentials by separate measurements conducted within a defined frequency scope are possible. Table 1 depicts measurements and basic properties of biopotentials.

Aside from appropriate input impedances, interference resistance, high sensitivity, and selective band usage, an important element regarding the use of diagnostic and measuring equipment is the safety of the patient. These devices have complete galvanic separation. Most commonly (which is the case in our equipment as well) optoelectronic

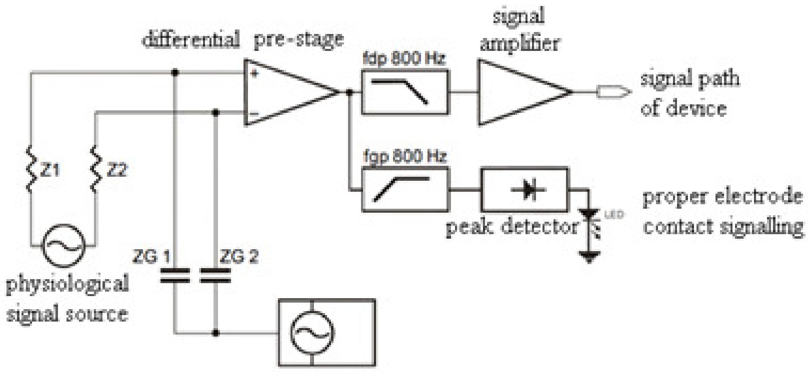


Figure 2: *Electrode contact impedance value monitoring system (Augustyniak 2001 p. 24).*

Table 1. *Biopotentials and their basic properties.*

Signal name	The range of frequency	The range of amplitude
EKG	0,05 – 250 Hz	0,5 – 5 mV
EEG	0,5 – 100 Hz	0,1 – 100μV
EMG	5 – 10 000 Hz	0,05 – 10 mV

connections are used, i.e. opto-isolators or fibre-optic transmission. Earlier solutions were based on magnetic coupling. This did not guarantee full protection against high voltage avalanche breakdowns. Logical protection was used as well in the form of battery power. The equipment used battery power during measurements, but it was impossible to perform measurements while the batteries were being charged. Currently used protection norms are designated as follows: IEC 601-1 (*Medical Electrical Equipment; General Requirement for Safety*), IEC 601-1-1 (*Collateral Standard, Safety requirements for Medical Systems*).

2. CHAPTER – OVERVIEW OF SIGNALS AND METHODS OF PSYCHOPHYSIOLOGICAL MEASUREMENT OF SIGNALS

2.1. Electroencephalography (EEG)

The act of measuring brain activity is called electroencephalography (EEG). In 1929, Hans Berger discovered clinical links between human brain activity and electrical phenomena observed on the surface of the skull (Augustyniak 2001). Measuring the electrical output of brain activity is not a simple endeavour. Among the obstacles are the very small amplitude of the measured signal (usually below 100μV), difficulties related to very high skin and hair impedance, as well as the dispersion and averaging of the signal due to anatomy (e.g. due to bones of the head).

The placement of the electrodes corresponds to the anatomy of brain structures. The international 10-20 system proposed in 1958 has gained widespread acceptance. The following figures depict the placement and description of the electrodes. The symbols are based on Latin names of the regions: F – frontal region, Fp – prefrontal area, P – parietal region, O – occipital region, T – temporal region, Z – middle electrodes, A – ear electrodes, C – central electrodes, Cb – cerebellum electrodes (Augustyniak 2001). The most commonly used solution is the use of the averaged common Goldman electrode, i.e. a point which the potential of is made by averaging the potential of all skull electrodes using 200kΩ resistors. Due to the fact that signals have very small amplitudes during EEG readings, the measurement ends up severely distorted. Undesirable occurrences which distort the signal are one of two types. They can be physiological artefacts due to the functioning of organs and muscles. It is impossible to get rid of this type of interference. The second type of interference are artefacts of technical nature which stem from flaws in the equipment used. The development of diagnostic equipment, the improvement of electrode quality, as well as the usage of substances improving the contact of electrodes minimises this type of interference.

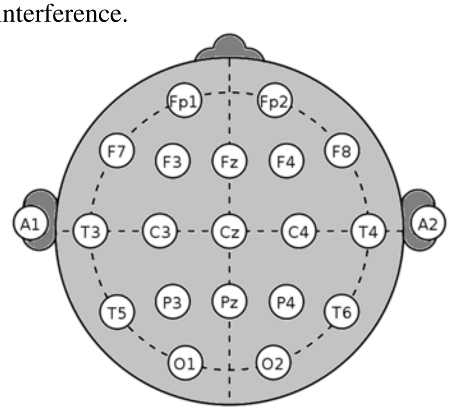


Figure 3: *Placement and nomenclature of electrodes in the 10-20 system.*

2.2. Electromiography (EMG)

The purpose of an electromyogram (EMG) is the measurement and assessment of the electrical activity of muscles. There are two types of muscles in a human body. The first type are smooth muscles. This muscle group is not controlled (in the volitional sense), but governed directly by the autonomic nervous system of the body. The second group are striated muscles. Among them are the cardiac and skeletal muscle tissues. Skeletal muscles are used in expressing emotions, maintaining proper stance, or movement of certain limbs. These muscles connect with the bones via tendons. The muscles in this group usually work in an opposing way, e.g. arm flexion and straightening in which the biceps and triceps are alternately used.

Every muscle consists of thousands of contractile fibres. Fibres are made up of many filaments. There are two types of filaments: actin filaments and myosin filaments. There are areas in which the two types of filaments overlap. Muscle function is related to the overlapping of myosin filament groups. This is depicted in Fig. 4. Every muscle is innervated by motor neurons. The axon of such a neuron branches out multiple times and innervates many nerve fibres. The precision of a muscle depends on the number of neurons controlling its function. One axon can innervate a high number of muscle fibres. A single motor neuron innervates a whole group of muscle fibres. Such a group is called a motor unit. A motor unit may contain from 4 (eye muscles) up to 4000 (posterior) of muscle fibres. Muscle fibres innervated by a given neuron generate action potential which spreads along the fibres, causing a contraction. This neuromuscular connection is called a junction. When a stimulating impulse arrives, acetylcholine (ACh) is released in the synapses. The muscle contraction strength is governed by the number and the frequency of the action potentials arriving at the motor neurons. Muscle movement happens at the cost of the transformation of adenosine triphosphate (ATP into adenosine diphosphate (ADP). ATP reserves stored in the muscle usually suffice for a few seconds of activity, so this process has to be in constant renewal. At medium muscular effort, the source of this energy is the oxidation of glucose.

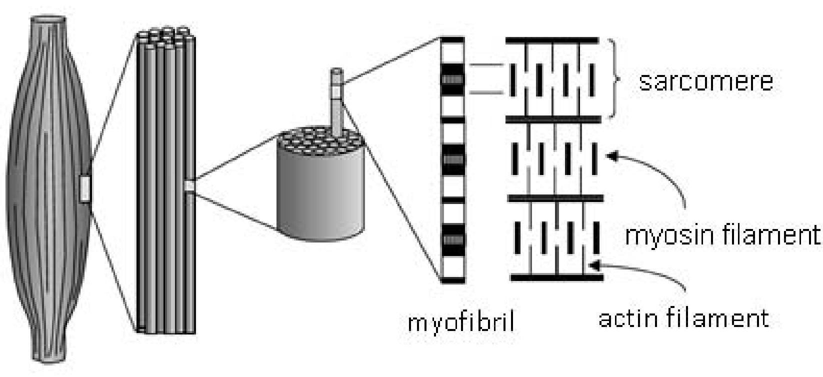


Figure 4: *Striated muscle structure (Jaskowski 2004 p. 101).*

The change of voltage in muscles is related to the change of two important EMG parameters. Both the amplitude as well as the frequency of the measured signal are changed. There is a close link between the strength of the contraction and the frequency of action potentials as well as proportion between the strength of the contraction and the number of innervated muscle fibres.

From a signal measurement method point of view, two types of EMG tests can be distinguished.

1. Measuring the biopotentials above muscle surface with the use of external electrodes.

2. Measuring by inserting puncture electrodes.

The non-invasiveness of the first method is caused by the measurement of only the total and averaged activities of many nerve fibres.

2.2.1 Electromyographic devices

Surface electrodes of varying types are used for EMG readings. They are most commonly silver or chlorosilver (Ag/AgCl) electrodes. Conductive gel is used in order for the impedance value to be less than 5 kΩ.

A typical electromyographic device has the following parameters:

- Very high input impedance. Due to the usage of puncture electrodes in medical tests, impedance of over 1 MΩ is required to counteract their small surface area.

- Wide band of measured frequencies. Usually from 2 Hz to 10 kHz.

- Multichannel capabilities. 64-channel measurements are often carried out.

- Set of anti-interference and signal frequency analysis filters.

Figure 5: *Placement of electrodes for facial electromyography, modified in accordance with Frieldung, Cacioppo 1986. (Sosnowski 1993, p. 149), as well as electrode installation and measurement instructions, laboratory ZD IF at the Pedagogical University of Cracow.*

The main objectives of EMG measurements are cognitive process monitoring and motivation research (Sosnowski 1993). Tytus Sosnowski references multiple electromyography tests which allow for scalable degrees of task difficulty. Those were perceptual tasks (Maspfuhl 1970), (Rimehaugh 1987), as well as linguistic tasks consisting of word recognition (Cacioppo 1985). Cacioppo and Petty and Morris (Cacioppo 1985) consider that EMG activity of mouth regions represent working memory activity. Linguistic tasks influence the increase and decrease in muscle reaction time as measured in the forearm leads. A very interesting phenomenon is the occurrence of so-called private speech (Sosnowski 1993). While reading, problem solving, or using recall, a marginal but measurable electromyographic increase in somatic stimulation is observed, despite the lack of articulated speech. Experiments carried out by Garrity (Garrity 1977), (McGuigan 1978) show that greater stimulation occurs (in Sosnowski 1993):

– in the case of illegible text,
– in poor readers when compared to more skilled ones,
– while doing text reconstruction (facial muscles are stimulated according to the quality of the reconstruction).

Research in the field of motivation (Svebak 1986), (Svebak 1987) shows that people with high task motivation exhibit higher amounts of activity than those with lower task motivation. Research regarding facial muscle activity during positive and negative emotional states conducted by Dimberg, Lanzetta, Cohen, and Thayer (Dimberg 1982), (Lanzetta 1982), (Cohen 1985) showed that the increased activity of the zygomaticus major is related to positive emotions, while an increase in the activity of the corrugator supercilii in the EMG reading is related to negative emotions. Research conducted by McHugo (McHugo 1983), Rief, and Ferstl (Ferstl 1984) allowed for the development of methods for differentiating between positive and negative reactions in test persons. The aforementioned laboratory studies suggest that the methodology of EMG measurements used in physics didactics should easily support and supply a lot of useful information regarding motivation, emotions of students, and the didactic process.

Due to the difficulty in interpreting electromyography readings and the need to conduct them under laboratory conditions, as well as the difficulty in forming conclusions based on short series of readings done on varied groups of people in the ZD IF UP laboratory in Cracow, we use emotion recognition software created by Noldus. It is a specialised software package which extracts the values of six basic types of emotions from a video recording of the face, based on specifically prepared and calibrated databases. The analysis is done similarly to that is done in remote eye tracking, by real-time comparison of specifically made “face maps” with a database containing hundreds of patterns. Due to the fact that the studies still need to be continued and no conclusions can be made on the basis of such a small number of results, they will not be published in this work. The results will be subject of separate works and doctoral theses in the near future.

[16]

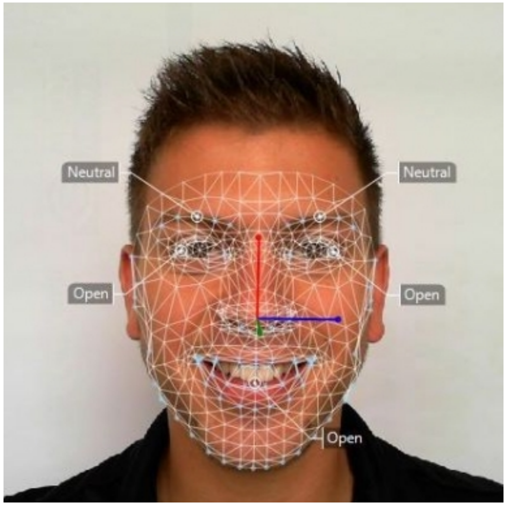


Figure 6: *Working principle of Noldus Facereader software. Retrieved from: http://www.noldus.com/human-behavior-research/products/facereader.*

2.3. Electrodermal activity (EDA)

Electrodermal activity is electrical changes measured on the surface of the skin. Researchers (Sosnowski 1993) distinguish two ways of measuring such activity: endosomatic and exosomatic. The precursors of this method in literature are Tarchanoff, Vigouroux, and Fere (Sosnowski 1993). The endosomatic method consists of measuring the difference in potentials between two points on the body. It is often a measurement of the difference in potentials between a given point on the human body and the reference point. The exosomatic method most commonly measures the differences in electrical conductivity between two points on the body. It is also, rarely, a measurement of resistance (Sosnowski 1993). In specialised literature regarding electrodermal conductivity research, especially in the exosomatic method, units of conductivity called μmho are used. From a physics and SI unit point of view, it might be hard to understand and explain the need of replacing the μS unit of conductivity. A more in-depth analysis of the literature shows that in order to prevent having to remember yet another unit, which is *Siemens*, English-language psychology literature prefers to simplify the notation by assigning the inverse of electrical resistance as electrical conductivity. 1μmho is used instead of $1\mu S = \frac{1}{1\ M\Omega}$. It is the unit of 1 Ohm written "in reverse," which is meant to signify the inverse of electrical resistance. One might think that this stems from the difficulties of introducing and understanding the physical sense of the 1S unit.

In psychology, electrodermal activity is divided into tonic and phasic activity (Venables 1980). Phasic activity consists of short-term changes which are deliberately exposed and controlled by the researcher. Tonic activity indicates a relatively constant and slow change of conductivity.

The measured parameters can be divided by the size of the reaction or the time parameters of the reaction. The basic parameter is the reaction amplitude (a). Time parameters include the latency (b), reaction curve increase time (c), curve decrease/drop time (d). It is often the case that, before the conductivity value can return to the base

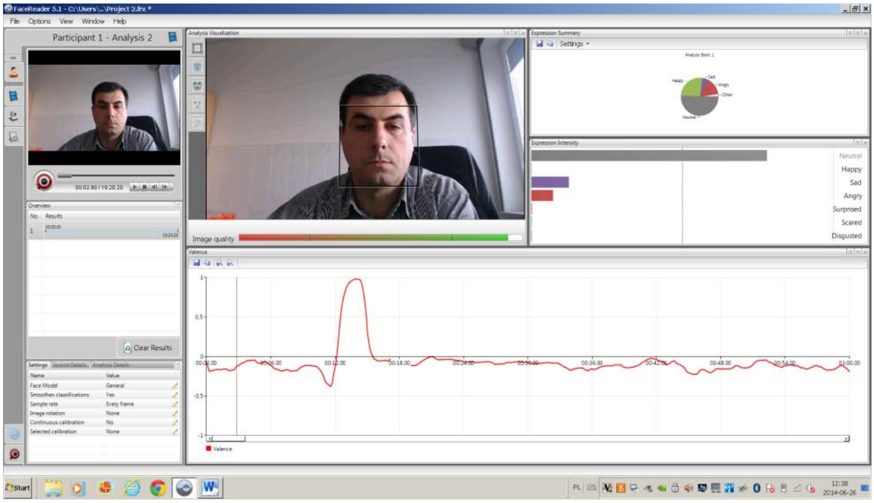


Figure 7: *The main window of FaceReader^{TM} software, Laboratory at the Pedagogical University of Cracow.*

state, another stimulus appears causing yet another conductivity change. Therefore other parameters are often used, such as: curve drop half-time (e), curve drop time constant (f) defined as the time in which 37% of the maximum value of amplitude conductivity is achieved.

Venables and Christie (Venables 1980) define the average values of electrodermal activity parameters for people 5 to 25 years of age reacting to a 90 dB acoustic stimulus as:

- Conductance value: 3.04 μS (1 to 40 μS),
- Skin conductance change amplitude: 0.52 μS (0 to 3 μS),
- Latency: 1.7s (1.3 do 2.5 seconds),
- Curve drop half-time: 4.14 s. (1 to 15 seconds).

Sweat gland activity research (Kuno 1956) showed a significant relationship between hand or foot sweat gland activity and physical stimuli (Fowles 1974), (Grings 1973), (Grings, Dawson 1973). It has been observed that the thermoregulatory activity of these glands becomes dominant in temperatures above 30 ^{o}C (Sosnowski 1993). Many researchers (Edelberg 1972a, 1972b), (Edelberg 1973), (Wilcott 1967) emphasize that increased electrodermal activity happens in stressful conditions (Lewartowski 1990). Psychological stress conditions entail increased energy use and increased heat output of the body, as well as vasoconstriction. Increased sweat gland activity in stressful situations compensates for the decrease in heat dissipation by the vascular system (Coles 1971). A very important factor is the anticipatory nature of EDA changes which precede the occurrence of heat stress (Sosnowski 1993).

Figure 8: *Placement of EDA electrodes, Neuroscience Laboratory at the Pedagogical University of Cracow.*

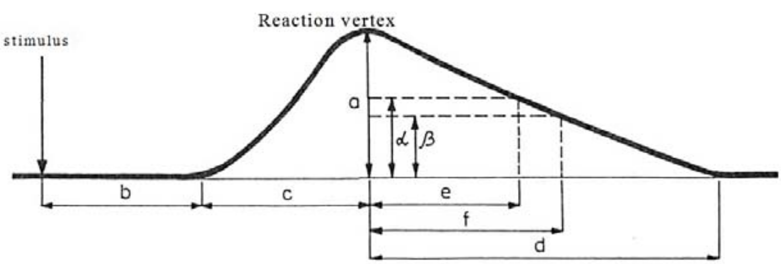


Figure 9: *Basic parameters of electrodermal reactions (Sosnowski 1993, p. 185).*

2.3.1 Electrical skin model

The most popular and illustrative skin models were presented by Montagu, Coles, and Sosnowski (Montagu 1968), (Sosnowski 1993). In this model, the epidermis is regarded as an insulator stretched over the surface of the body. It contains sweat glands, which are regarded as conductive elements. It is assumed that the conductivity value depends on the number and the activity rate of sweat glands. The authors present sweat glands as resistors in parallel, the number of which increases with the activity of the glands.

2.4. Cardiovascular Activity: HRV, PPG

The heart is one of five human organs (alongside the skin, eyes, muscles, and the brain) (Sosnowski 1993) generating electrical signals. On the surface of the heart muscle cell membrane, the electromotive force equals from -90mV (Sosnowski 1993), (Aleksandrov 1983), (Bober 1982) up to -80 mV (Traczyk 1990). The change in heart muscle potential can be measured as the change in voltage on the surface of the skin. The research of Willem Einthoven in 1903 regarding the measurement of the potential generated by the heart is recognised as the starting point of electrocardiography. Electrocardiographic readings are the result of selective measurement of skin surface voltage. The signal shows the changes taking place in the heart during heartbeat (Siddle

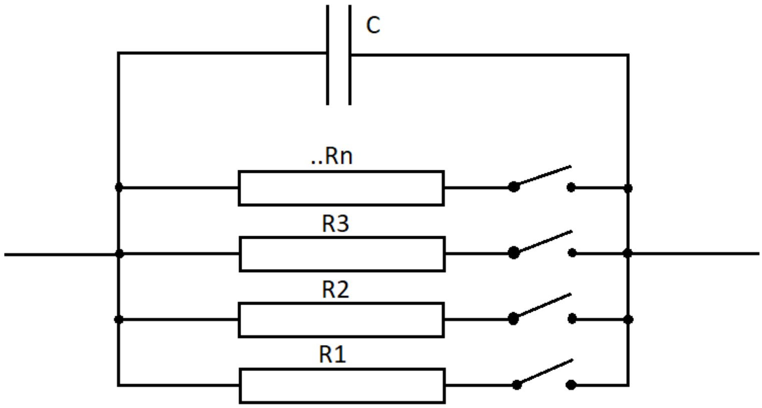


Figure 10: *Electrical skin model according to Montagu and Coles (Montagu 1968).*

1980). Taking into account literature regarding the relationship between blood pressure, heart rate, and blood flow propagation, there have been many reports confirming a close link between heart rate parameters and psychological factors (Flash 1987), (Jacobson 1932). Blix, Stromme, and Ursin (Blix 1974) were the first to show that stressful conditions cause a significant increase in heart contractions. This is often called additional heart rate. Is it also visible in cardiac output (Sosnowski 2002). Many researchers emphasise the relationship between strong cardiovascular reactions and cognitive activity (Jennings 1986). The author describes increased heart rate during cognitive activity, and even bradycardia related to cognitive activity.

M. Coles and Duncan-Johnson (Coles 1975) believes that the value of heart rate increase during information processing is a monotonic function of the difficulty of the perceptual task processed. Weinmann (Weinmann 1989) believes that in the case of difficult tasks, there is a substantial drop in heart rate after an initial significant increase. He argues that this demonstrates giving up in the case of too much cognitive effort. According to other researchers (Carrol 1986), (Carrol 1989), the biggest increases in heart rate during arithmetic task solving were related to difficult, but solvable tasks. In the case of subjective assessments of tasks as difficult and impossible to solve, no change in heart rate was observed (Carrol 1986).

The circulatory system plays a very important role, bringing oxygen, water, minerals and nutrients, enabling the transport of hormones and metabolic breakdown products for all the cells of our body. The operation indicators of cardiovascular system, which are correlated with the nervous system, are the most significant for educational research purposes.

It is important to link the heart activity monitored during specific types of emotional and motivational activities (Acharya 2006). An increase in cardiovascular activity is not only associated with physical activity and movement. The system strongly reacts to any task stimuli, not just those related to physical effort (Sosnowski 1993).

Psychologists studying the responses of the cardiovascular system apply measurement techniques developed in medicine to their field of knowledge (Sosnowski 2002). Carrying out this kind of research involves analysis of the impact of psychological factors on the work of cardiovascular system in healthy people. The basic and widely known indicators which enable non-invasive monitoring of the heart are: the heart rate (pulse), blood pressure and the electrical activity of the heart (ECG).

A very interesting indicator of psychophysiology is blood flow to the chosen parts of the body. Measuring the blood flow to the head and limbs are the most interesting from the point of view of teaching and the most available from the methodological point of view. (Sosnowski 2002), (Goldwater 1987), (Jennings and Wood 1980), (Steptoe 1980), (Steptoe 1984). In terms of possibility of using this type of research in physics education, we are interested in blood flow to the certain areas of the body, for example fingers or carotid arteries. This parameter is often used by many researchers as an indicator of arousal during information processing (Sosnowski 2002), (Hare 1972a,b), (Hare 1973). Many researchers have linked changes in blood propagation in different areas of the body with the level of stress (Allen 1987), (Jennings and Tahmoush 1980), (Johnson 1967).

In our research, we focused on the flow of blood, and analyzed changes in blood flow through a finger. The reason for this type of test is associated with a very small number of artifacts, compared to a traditional ECG, which requires the participant to be motionless for a prolonged period of time while the electrical activity of various muscles of the body are being recorded.

Another important reason for analysis of the blood flow in certain places of the body (BVP) is the view formulated by Sokolow and followed by other research which attempted to verify the idea of the orienting and defensive reactions. This indicator is often used by researchers in relation to changes in the peripheral flow, and used as an indicator of stress or arousal during processing. We use a photoplethysmograph (PPG) as an indicator of BVP (see Fig. 11), which is mobile and ensures simple application.

Figure 11: *Photoplethysmograph. Neuroscience Laboratory at the Pedagogical University of Cracow.*

3. CHAPTER – THE FUNDAMENTALS OF EYE-TRACKING

3.1. Anatomy of the eye

3.1.1 General information

The processing of visual information begins in the eye. The eye, like a camera, consists of a rigid and tight chamber called the *sclera*, whose task is to protect the eyeball from mechanical damage. The front part of the eye comprises an optical system - the equivalent of a lens.

The front-most part of the eye is the *cornea*, which is transparent. The cornea, like the sclera protects the eye from mechanical damage. It constitutes a protective filter and a lens with a fixed focal length. Directly behind the cornea is the pupil, which is a lens opening. The diameter of the pupil (just as the iris of a lens) can change and is adjustable.

An iris serves as an adjustable aperture. One of the most important elements of the eye is the lens, which is varifocal. The lens of the human eye, in contrast to a camera lens, has excellent transparency, which cannot be achieved by camera optical systems despite the use special anti-reflective layers and appropriately chosen materials (Francuz 2013). As already mentioned, the varifocal lens of the eye allows us to see in an aquiline way objects located at different distances.

The method of changing the focal length of the eye is not at all similar to the way the focus changes in camera optical systems. This particular property of a human eye is achieved by changing its shape, more specifically changing the radius of the curvature of the eye lens. The farther away an observed object is, the thinner the lens becomes. For closer objects, the thickness of the lens increases. This property arises because the lens of the eye is fastened to the inner part of the eyeball by ciliary muscles. When these muscles contract, the lens extends and becomes thinner. As the muscles relax the lens becomes thicker in the center. The increase of thickness of the eye lens is connected with increasing refraction angle of light passing through the lens. This special property of the eye is called *accommodation*.

The function of the image sensor is played by the *retina*. It comprises about 70% of the internal surface of the eye. Visual representations of scenes are formed by optical system on the retina of the eye. The image formed on the retina is sharp, real, reduced and reversed because the image formed on the retina is produced by light passing through the varifocal biconvex lens, thus the object is viewed by an observer at a distance more than twice greater than the focal length of the lens. Despite the fact that the image formed on the surface of the retina is sharp and projected by the optical system of the eye on its surface with the same accuracy, we cannot assume that further processing of the whole surface of the retina occurs with the same accuracy. It has been said (Duchowski 2007) that while the eye and a camera have many features in common due to their construction, yet processing of the picture is totally different. First of all, semiconductor imaging sensors convert the image formed on their surface, with the same quality regardless of position. We can talk about the same surface density of the light-sensitive elements and constant values of their parameters, regardless of their location on the surface of the transducer. Fig. 12 shows the view and the construction of a semiconductor imaging sensor.

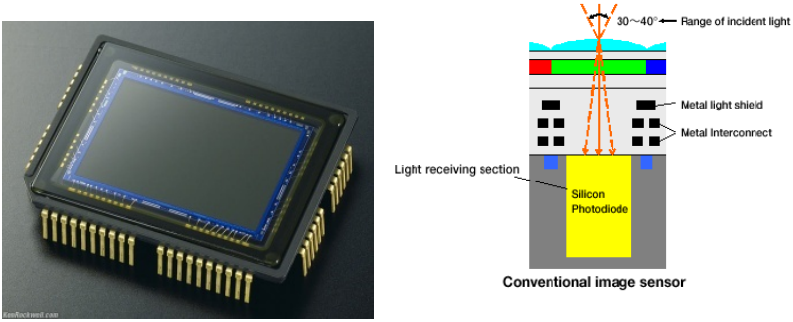


Figure 12: *CCD sensor of Nikon D60 and internal structure of a semiconductor image sensor. Retrieved from: http://www.gizmodo.jp/2013/06/4cmos.html.*

Ocular photoreceptors are not spaced evenly over the entire surface. There are two types of light-sensitive photoreceptor cells used for vision. Their names are rooted in their shape: the cones and the rods. These receptors are very different to each other in sensitivity (responsivity). While working in good lighting conditions (e.g. daylight) the cones take over the dominant role in the creation of image information. These receptors have the ability to properly respond to light of different wavelengths (e. g. in order to distinguish colors). Rods are receptors with significantly higher sensitivity, having the ability to respond to light with a much smaller illuminance. They respond to very small streams of light, but have limited ability to discriminate between colors (differential response to light of different wavelength). The human adult retina contains about 4.6 million cones, according to Curcio at alt. (Curcio, 1990). The receptors are not distributed throughout the retina in a regular way. Their biggest density is located at the intersection of the retina by the visual axis (Francuz, 2013). The visual axis of the human eye is inclined at an angle of about 5 degrees with respect to the optic axis of the eye. This is illustrated in the following figure (see Fig. 14).

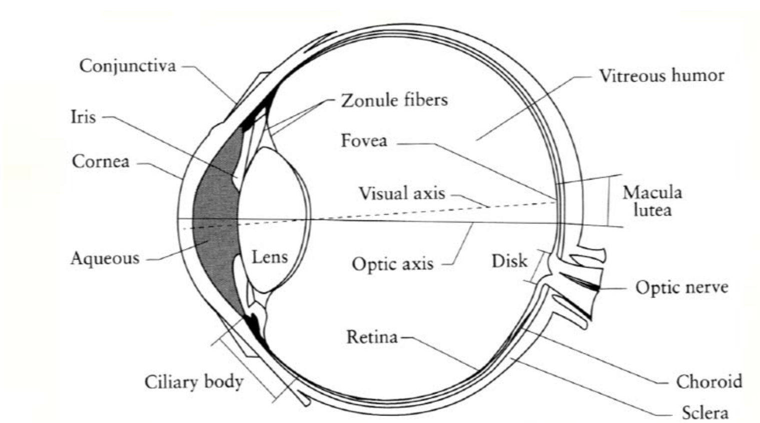


Figure 13: *The structures of the eye labeled (Glassner 1995).*

The area with the highest surface density of receptors is called the macula. It is a small area in the shape of an ellipse, of vertical (minor) axis about 1.5 mm and 2 mm horizontal (major) axis. Its area is about 2.4 mm^2 (Niżankowska 2000). Within this area, the surface density of receptors is also heterogeneous. On an area of about 1 mm^2 called the fovea, particularly at its center point, called the fovolea, the number of cones can reach a value of 324 thousand per 1 mm^2 (Francuz 2013). Peter Francuz estimates that if we built an image sensor of the photographic film frame size of 24 x 36 mm with the same density of photosensitive elements, it would have a resolution of 280 megapixels. Currently, in the most advanced equipment for professional digital photography, for example the H5D Hasselblad (body without optics price is about 40 000 $) with a sensor size of 40.2 x 53.7mm, the manufacturer has achieved 60 megapixels. Mlodkowski (Mlodkowski, 1998) estimates that macular area is 0.3% of the total retinal surface, the fovea area of only 0.1% of the whole retina, having no rods at all. Cones located at the area of macula constitute 1/8 of the total number of cones, which are distributed throughout the retina. About 4 to 5 million remaining cones covers 99.7% of the remaining retinal surface. This is illustrated in the following figure (see Fig. 14 and 15).

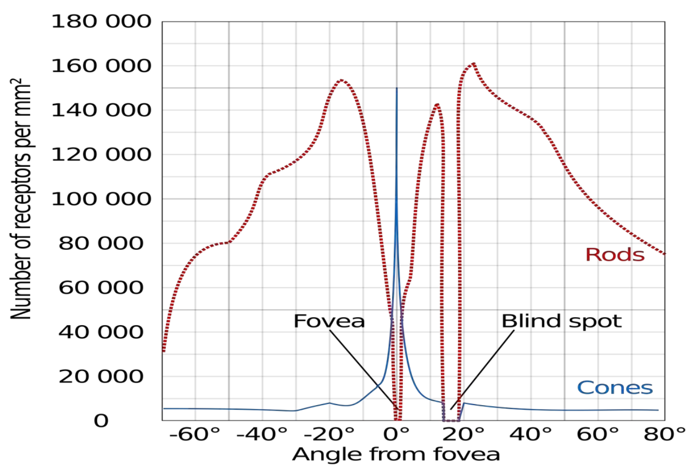


Figure 14: *Distribution of rods and cones along a line passing through the fovea and the blind spot of a human eye, Retrieved from http://en.wikipedia.org/wiki/Blind_spot_%28vision%29.*

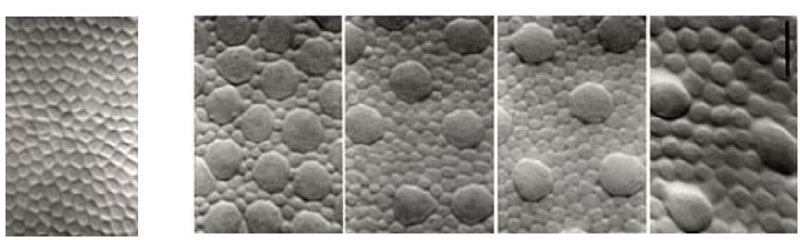


Figure 15: *Microscopic image of a fragment of the retina in the area of macula (left) and with increasing distance from the fovea (Curcio,1990).*

For every 1mm^2 outside the macula there are approximately about 7,000 cones on the retina (Hofer 2009). The consequence of that kind of distribution of receptors on the retinal surface is different spatial resolution of processed images projected on the retina surface by the lens. Much more data reaches the brain from the macula than from other parts of the retina. This allows us to see much more and to process images generated in this area much more precisely.

There are also receptors known as rods at the retina of the eye. Their number (Francuz 2013) varies from 78 to 107 million. It has been said (by Curcio 1990), that the number of rods in the retina of the eye is almost 20 times more than the number of cones. We can conclude on this basis that the retina is better suited for viewing monochromatic images in low light conditions than for colorful scenes under fully lit conditions. Many scientists believe (Francuz 2013), that this is a remnant of the predatory ancestors and their nocturnal activities. Fovea does not contain any rods. They appear only at the edge of the macula. Their number increases with distance from the edge. The largest rods density about 150 thousand per mm^2 can be observed 20 degrees from the fovea (Francuz 2013). Rod density decreases by a factor of two at the edge of the retina. This structure allows our eyes (in poor lighting conditions) to see objects that are located outside the center of our vision. By moving our eyes, we can analyze the shape and details with full resolution. This could be very important for our ancestors while hunting in poor lighting conditions.

It is also worth mentioning about the area of the retina called the blind spot or optic disk. This is a hole with a diameter of about 1.5 mm. In this are the optical nerve and blood vessels, but no photoreceptors. The image projected by the lens of the eye in this area is not processed. The existence of blind spot can be demonstrated by the following experiment:

1. We cover the left eye.
2. We look at the cross.
3. We slowly move the image closer to the face starting from a distanceof about 25 cm.
4. The image disappears at a distance of about 15 cm because at that distance it is in the area of the blind spot.

Figure 16: *The test proving the lack of receptors in the area of blind spot (macula ceca). http://serendip.brynmawr.edu/bb/blindspot/.*

Due to the fact that we have two eyes, deficits associated with the lack of noticing part of the image by one of the retinas are compensated by the other. Since the eyes are spaced apart from each other, different parts of the viewed scene are on the areas of the blind spots in each eye. We can see the full image because the brain receives information from the two retinas. In the brain, by using information from the two retinas, the deficits associated with the existence of blind spots at the retinas are complemented.

3.1.2 Retinal ganglion cells

Accurate analysis of perceived images is possible not only due to the existence of photoreceptor cells, but also specialised neurons (Francuz 2013) - ganglion cells. These cells process four types of information:

- spatial resolution (responsible for visual acuity),
- reacting to changes in the intensity of lighting over time,
- sending information regarding the wavelength of the perceived light,
- sending information regarding the contrast (areas with differing brightness) allowing for the perception of the edges of objects.

An analysis of the anatomy of retinal ganglion cells reveals (in Dacey, 2000) three possible groups. The first group are bistratified ganglion cells. They are distinguished by their small size and a disproportionately high number of branches when compared to their size. The second group are parasol ganglion cells with large cell bodies and a high number of branches. The third group are midget ganglion cells. These cells are characterised by small cell bodies and a small number of branches (i.e. dendritic trees and axon). The size of midget ganglion cells, especially the dendrites, depends on the distance between the cells and the fovea centralis. The farther from the fovea centralis, the bigger and more plentiful the dendrites, which allow for inter-neuron communication.

All neurons also have an axon, a type of branch transporting nerve impulses to other cells. Approximately 770 up to 1.7 million (Jonas 1992) axons of ganglion cells comprise the most important part of the optic nerve. Approximately 80% of all optic nerve axons are midget ganglion cell axons, making them the most numerous. Approximately 90% of information transported through the optic nerve comes from the small cells (midget and bistratified ganglion cells), which makes it fair to say that they are more important than the bigger cells. Small ganglion cells usually connect to photoreceptor cells in the middle part of the retina. It is important to note that they are sensitive to changes in the spatial distribution of the intensity of lighting. This allows for shape differentiation. Another quality of retinal ganglion cells is the ability of reacting in a different way to different wavelengths of light. Nearly all (Dacey 2000) midget ganglion cells react exceptionally well to green and red light. They do not react as well to yellow and blue. This is where bistratified ganglion cells come in. Some cells not only detect different wavelengths of light, but also specialise in detecting the differences in the intensity of lighting (edges) between planes of a similar brightness. This is the domain of parasol ganglion cells. They can detect (Francuz 2013) a 1% to 2% difference in the brightness of adjoining planes. 10-15% differences are identified without any problems (Shapley 1981).

The attributes of cells complement each other: midget ganglion cells react to much larger differences in the lighting of adjoining objects. Midget ganglion cells take up less space in the retina than parasol ganglion cells. The attributes of cells complement each other in the detection of the contours of objects located outside of the fovea centralis and in the spatial relations of perceived objects (Francuz 2013). Worth noting is how quickly nerve impulses are sent out by the cells, which depends on the size of the axons. The velocity is higher for bigger cells with bigger axons. Parasol ganglion cells send nerve impulses out the fastest. The transfer of information is as quick as 4m/sec. (Francuz 2013). This property of parasol ganglion cells lets the observer notice movement and helps notice spatial arrangements as well as assisting in the process of identifying contours.

3.1.3 The analysis and kinds of eye movements

The science regarding eye movement underwent significant changes in the recent years. By the end of the 20th century, eye movement was still very often related to physiological processes, even though hypotheses such as The Eye-Mind Hypothesis (Just 1980) were formed much earlier. These hypotheses were partially rejected by some researchers (Andersson 2004). Studies regarding the confirmation of the existence of a neurophysiological link between eye movement and cognitive functions were also carried out (Soluch 2013). One of the studies was an experiment based on an antisaccade task, testing the processes of making decisions, paying attention, and memory (Everling 1998), (Zee 2004). Currently, eye movement is often regarded in relation to higher mental functions. A practical example of this view is eye tracking, which is regarded as a broad reflection of the relationship between mental and cognitive processes and visual external stimuli (Soluch 2013). Many researchers expand on this reasoning. They believe that eye tracking is a window to the soul, thoughts, and feelings (Holm 2007), (Glimcher 2003). There are many scientific papers about the (currently very popular) opinions and theories regarding the relationship between brain activity, thoughts and feelings and eye activity. One of the most popular and significant works expressing such views is a book called "Eye movements: A window on mind and brain" released in 2007, ed. R. van Gompel (Van Gompel 2007). The 33 chapters and approximately 700 pages contain a description of the theories and studies regarding learning processes, reading, visual processing, eye movement and spoken language processing, and eye movement in reading words and sentences.

In order for an area in one's field of view to be clearly perceived, the eyes are supported by cognitive processes. The attention system is constantly analysing the entire field of view and approximately three times a second decides which object to look at, as well as coordinating and defining the spatial parameters of the movement (Soluch 2013). This is why eye movement has such significance the existence and understanding of human perception. An important element of the description of eye movement, aside from the quantitative aspect, is the description of the mechanisms underlying the completion of the movements. Depending on the duration of eye movement, the saccades can be defined as express (Marek 1995), quick, or slow (Fischer 1987), (Fischer 1995). Express saccades are reflex movements which consist solely of tracking the new object, calculating the parameters, and moving. The average reaction time of such a movement is 70 to 140 milliseconds. Movement quicker than 70 ms does happen (Soluch 2013), but such movement has to be treated as premature, as the conduction of nerve impulses by relevant nerve centres takes longer than that. Since it is impossible for nerve impulse conduction through all the nerve centres to happen so quickly, it means that the movement could not have been caused by an actual stimulus.

Quick saccades happen when attention is not yet drawn, which means that the subject is not processing information regarding the fixation point. The remaining structures are still involved, so it is possible to block the movement. The average reaction time for this type of movement is between 140 and 200 milliseconds (Soluch 2013).

Slow saccades happen after a 200 ms or longer delay from exposure to the stimulus. This type of movement involves all functional structures. Slow saccades involve losing focus of an object, deciding on eye movement, specifying and calculating eye movement parameters and completing the movement. The decision involves solely the part of brain, which has the rarely used potential of intentionally blocking eye movement (Soluch 2013).

A healthy human's eye movements are very complex and consist of many components. Paweł Soluch divides them into convergence, drift, tremor, microsaccades, optokinetic reflex, fluid movement, and rapid movement (saccades). A short description of the eye movement components is shown further in the chapter.

A drift is a slow eye movement shifting in a direction away from the centre of the fixation point. Its role is to prevent the decrease in sensitivity of a receptor (adaptation) under the influence of a constant stimulus. Many researchers claim that this type of movement also compensates for the shadows of blood vessels within the eye, eliminating visual impairment (Sekuler 1994). The role of the drift, as well as the tremor, has not been fully explained yet. Experimental studies consisting of stopping minor movements led to loss of vision (Budohowska 1995), (Sekuler 1994). S. Martinez-Conde states (Martinez-Conde 2004) that the drift has the ability of compensating for the instability of the visual system leading to loss of focus by correcting the fixation point.

Eye tremor is a type of movement with a frequency of approximately 90 Hz, which is not subjectively perceived due to its critical blinking frequency of 25–50 Hz, depending on the physical and mental state of the subject. The critical blinking frequency causes images which change with a frequency higher than 50 Hz to blend. The role of the tremor is unclear. Some researchers relate it to the constant activation of visual neurons (Martinez-Conde 2004). Others consider that it might stem from the low-precision control of the eye by the muscles (Holmqvist 2011).

The next type of movement is the fixation. Fixations happen when the eyes focus on a specific point of vision (Soluch 2013). Fixations are very often treated as a physiological mechanism due to the static nature of the process. An in-depth analysis of fixations shows that they consist of minor movements called the internal fixation movements, tremors, microsaccades, and drifts (Soluch 2013). Even though, based on physiology, fixations are movements, they are also a compensation mechanism. Minor movements are used to widen the field of precise vision, which is why microsaccades are omitted when describing fixations as static processes of stopping the eyes on a chosen fragment of the field of vision, also called visual analysis.

Microsaccades, which are small and quick rapid movements, are a mechanism allowing for the return of the eyes to a fixation point (correctional function stemming from minor eye movements). Due to minor instabilities of the visual system, a mechanism allowing for renewed focus on an observed object is necessary for proper vision (Soluch 2013). There are also papers indicating that microsaccades play a role in distinguishing colour shades (Soluch 2013), (Martinez-Conde 2004).

Convergence is another essential type of eye movement. The goal of this type of movement is to locate the image perceived in the retina in such a way as to project it onto the novea centralis. This phenomena concerns both eyes simultaneously. Oculomotor contractions direct the visual axis of both eyes to a given point. This mechanism is used by the nervous system to analyse visual depth. Due to the very small angular differences between objects perceived at longer distances, this system works at a distance of up to 5 metres (Cavallo 2001). Paweł Soluch states that this is the only absolute indicator of (Soluch 2013).

Moving the object further away from the eye results in a change in the focus of the lens. Changing the distance of the analysed object causes a change in muscular tension, which in turn changes the radius of lens curvature to achieve a sharp image. Research shows (Levine 2000) that convergence is the sole indicator of distance assessment.

Another type of movement are rapid eye movements. The eye performs them approximately three times a second which is strictly related to the amount of time needed to recognise an object in the fixation point and for planning the next move (Soluch 2013). A number of experiments were carried out, in which the time between two consecutive rapid eye movements was reduced to approximately 70 milliseconds. In order to achieve this result, the whole sequence of eye movements had to have been planned in advance (Loon 2002). Rapid movements are governed by processes taking place in several nervous system structures (Posner 1994). The first element of this process is attention shifting. This means that the analysed field of view fragment stopped being of the highest priority and has been replaced by another. The decision of shifting attention is made by parietal cortex structures (Thiel 2004).

A number of researchers state that eye movement is carried out without engaging attention (Fisher 1993), (Marek 1995), (Pratt 2006). The sudden, unexpected appearance of a new stimulus in the field of view activates the structures of the parietal-temporal-occipital area in the right hemisphere. Frontal lobe structures are in turn responsible for planning the time of the movement, as well as programming it and controlling its direction (Soluch 2013). Merging the information from all these areas is done by the inferior collucilus of the tectal plate (Soluch 2013) and are defined as the final centre of eye movement (Liversedge 2000). Research shows a relationship with the visual areas of the occipital cortex as well as the temporoparietal cortex (Mayer 2004).

The inferior collucilus of the tectal plate transfers information to the brain stem which coordinates the muscles in charge of eye movement. A very important process taking place after carrying out a movement is the suppression of returning attention (Soluch 2013). The goal of this mechanism is to stop the eyes from returning to the point of the previous fixation, which allows for field of view expansion.

Voluntary rapid eye movements can be divided into trailing eye movements and saccades. These types of movements govern actively searching for new information. Saccades are considered to be the fastest type of movement a human body can make and take no longer than 80 ms. Saccades usually happen in-between consecutive fixation points, though it is possible for them to plot a curve, described as a path.

Trailing movements are similar to saccades. They do differ in that they follow a moving object, with the head remaining fairly stationary. The main difference between trailing movements and saccades is that trailing movements are triggered by a moving object entering the field of view. Saccades can happen while observing a uniform structure, e.g. clear skies, or the calm surface of a lake, without any stimulus to follow the position of J. Ross (Ross 1997) proved that the brain centres responsible for engaging and maintaining trailing movements block saccades from happening. In natural conditions, trailing an object entails head movement, as well as, occasionally, correction saccades. These movements work together, which is why their mechanisms are rather complex (Srihasam 2007).

One of the mechanisms ensuring the perception stability of observed objects is the optokinetic reflex. It is a head movement compensation mechanism used to ensure the stability and maintaining the fixation on a given point of an observed area. Another crucial mechanism is the saccadic suppression, which blocks specific groups of neurons responsible for sight in the inferior collucilus of the tectal plate with other areas responsible for rapid eye movement (Lee 2007). This mechanism counteracts the errors in perception caused by how quickly the image is moving. This means that saccadic suppression causes the inability to see parts of the image where the saccade is happening. The typical pre-saccadic suppression causes loss of sight 30–40ms before the start of the saccade, and the post-saccadic suppression takes up to 100–120 ms (Soluch 2013). It can be concluded that humans also experience sight loss for a part of the duration of the fixation, which needs to be taken into account when precisely calculating the fixation time (more precisely, active visual focus) (Holmqvist 2011).

Research into trans-saccadic integration is one of the most often studied problems in perception psychology, for which mostly neuroimaging is used (Soluch 2013). Despite these factors, the trans-saccadic integration is one of the least known mechanisms of visual stability (Soluch 2013). This mechanism is extremely important, as every rapid eye movement significantly changes the image of the world projected onto the retina, which forces the visual system to repeat its analysis of the shapes and features of objects. Due to the trans-saccadic integration, rapid eye movements do not cause visual impairment (Prime 2007). The visual cortex is responsible for the trans-saccadic integration at the brain level (Findlay 2003). The research of D. Melcher (Melcher 2005) proved that the trans-saccadic integration is caused by the cortical representation of space, and not the retinal image. An important element of the trans-saccadic integration mechanism is the analysis of the previous image (Gajewski 2005). A number of studies (Findlay 2003), (Melcher 2009) demonstrated that the attention process and active image processing take part in this mechanism as well. In order to explain this mechanism, visual perception has to be treated as an active way of searching for information, and not as a passive representation of the world.

Although visual attention processes were commonly linked to rapid eye movement mechanisms, the role of trailing eye movement control attention systems is being brought up increasingly frequently (Khurana 1987).

While carrying out their research, S. Hutton and D. Tegally (Hutton 2005) demonstrated the speed and spatial precision of trailing movements caused by performing additional tasks which required attention. They claim that this type of movement does not solely depend on simple nervous mechanisms but, like rapid movement, it is the product of complex cognitive system processes. An important factor of perception processes are their stability mechanisms. Without them, conscious perception of objects during constant body movement would be impossible due to the need to recognise the image anew after every body movement.

Despite a wide scope of interdisciplinary research, we are still unable to draw conclusions on the basis of cognitive processes, relying instead on visual perception research. It is often emphasised that the interpretation of eye movement research results as a stimulus response are imprecise, due to the fact that the complexity of human reaction, as well as the association and categorisation of perceived objects, are not taken into account.

3.2. Methods of eye movement registration. Oculography

The techniques of processing and registering eye movement have been of interest to researchers for many years. The spatial orientation of the eye (Jaśkowski 2004) is of special interest to manufacturers of electronics, medicine, medical electronics, control engineering, and biocybernetics. Various methods of studying the movement of the eye have been used throughout the years (Delabarre 1898, Robinson 1968). The eye has developed a very high movement precision due to the process of evolution. It is moved by three pairs of extraocular muscles which allow for a 90 degree change in position in three degrees of freedom. Its minute moment of inertia (Augustyniak 2001) and soft suspension in the connective tissue to minimise friction allow for a quick change of position and very high rate of angular acceleration. In order to accurately document the movement of the eye, a lot of methods of eye tracking and registration were created. The first research regarding the study and registration of eye movement during reading was published in 1898 (Delabarre 1898, Liversedge 2011). The next figure depicts the apparatus and the original documentation of eye movement during reading.

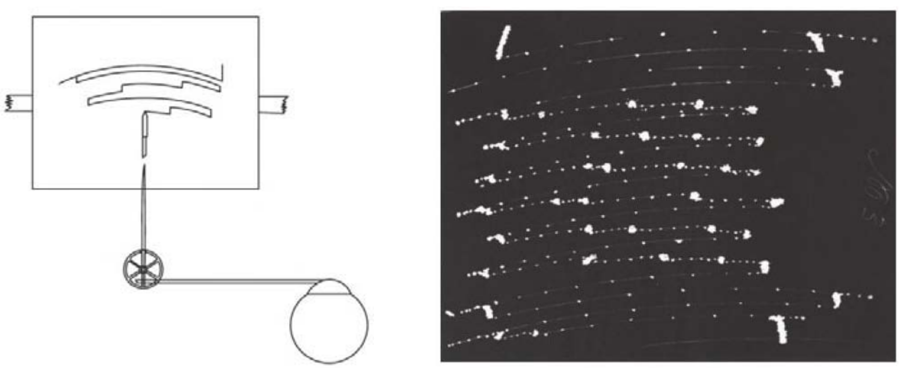


Figure 17: *The apparatus from 1898 for eye movement registration with the use of lever and the original documentation of eye movement during reading (Source: Liversedge 2011, p. 25).*

Table 2 consist the short names and characteristics of types of eye movements.

Table 2. *The kinds of eye movements (Augustyniak 2001).*

Name (a kind of eye movement)	Reason	Aim	Angular speed
SACCADE	A sudden change of the direction of viewing e. g. related to the change of the observed object	Searching of visual attention	Very high, up to 1000 °/s
SMOOTH PURSUIT	Moving of an object being under the observation	Tracking of an object of slow speed	Low, up to 60 °/s
VERGENCE	Change of the angle of the optical axis of the eye depending on the distance of the observed object	Achieving the same target and both-eyed fixation	Very low up to 4 °/s (small amplitude)
VESTIBULAR	Change of head and body position, the vestibular stimulus	Maintaining the same direction of looking independently of the changes in head and body position	High, up to 150 °/s
PHYSIOLOGICAL NYSTAGMUS (miniature movements associated with fixations; Robinson (1968)).	Change of the observed reality – the optical stimulus	Making possible fixation of the eye while a target is moving	Average, up to 80 °/s

Among the methods of acquiring the signal describing eye movement are:

1. Electric methods.
2. Photoelectric methods.
3. Magnetic methods.
4. Video methods.

The electric method of eye movement tracking is based on observations carried out during Du Bois-Raymond's experiments in 1849 (Pearce 2001). They have proven a difference in the scalar potential between the cornea and the retina, which give the eye an electric dipole attribute.

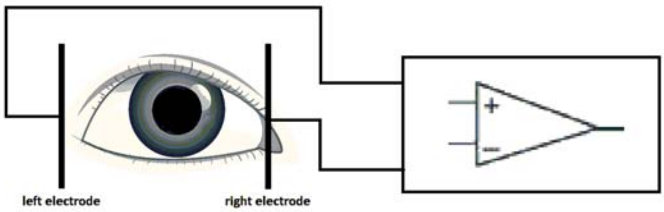


Figure 18: *Arrangement of the apparatus used in measuring changes in eye positioning by using the electric method.*

Piotr Augustyniak (Augustyniak 2001) states that the difference in the scalar potential is approximately 18 to 20mV and approximately 20% of the figure depends on factors such as fatigue, moistness of the eye surface, and lighting. Shifts in the electric field can be seen by eye movement made on the edges of the eye socket (Hulewicz 2005). Due to the presence of vascular tissue as well as other biopotentials, the measured voltage in between the edges of the eye socket is up to $7mV/^{o}$.

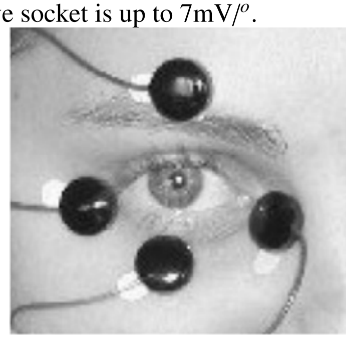
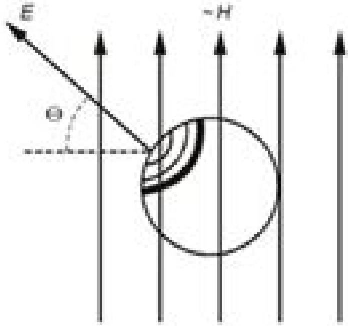


Figure 19: *Method of connecting electrodes used in measuring changes in eye positioning by using the electric method (Augustyniak 2001, p. 69).*

An essential disadvantage of this method is high levels of interference, the amplitude of which often exceeds the value of a useful signal. In this case the source of so much interference, aside from external and bioelectric factors, are the interfaces between the measurement electrodes and the skin. Band filters and DC offset removal are used to eliminate this type of interference.

An important advantage of this method is the possibility of measuring the signal with eyes closed, eliminating fixation. One more important factor is the non-invasiveness of this measurement method.

The magnetic method allows for very precise measurements. The induction loop method allows for recognizing the position of the pupil as accurately as up to 5-10 arcseconds (Soluch 2013), but due to the invasiveness of the method caused by the necessity of inserting a foreign body into the eye, the procedure is discomforting and the experiment must be performed as quickly as possible (it should not take longer than 30 minutes) (Young 1975). One of the most popular methods is the implementation of an inductor located in a specialised contact lens followed by measuring movement in the electromagnetic field. The magnetic method of studying the movement of the eye uses the sources of an external varying magnetic field in which the eye is placed. The signal containing the information regarding eye movement is transported by use of an induction loop mechanically bound to the eye.



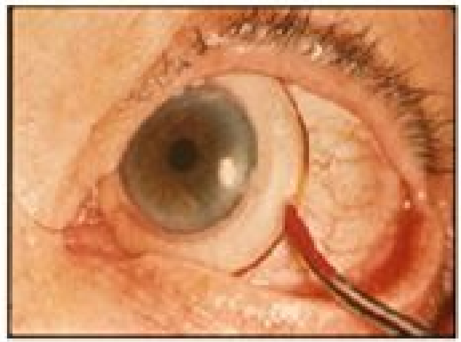


Figure 20: *Physics principle of the measurement of eye movement by use of the magnetic method and the placement of the inductor (source: Augustyniak 2001, retrieved from https://mozyrko.files.wordpress.com/2009/10/cewka-oczna.jpg).*

The signal created in the induction loop consists of a component wave set to the frequency of the external magnetic flux which has its amplitude modulated by the changes in the magnetic flux caused by eye movement. This method also requires specific external conditions in which the eye is to be placed. The magnetic field strength and the frequency of change have to be set properly in order to obtain as precise measurements of eye movement as possible. The next figure depicts the diagram of the measurement system used in the double induction method. A no-outlet closed induction loop is mounted on the eyeball. The movement of the loop bound to the eyeball causes a change in the mutual inductance value of the loops creating the magnetic field. These changes are represented by a phase shift of the voltages measured in the capacitors. The biggest problem of this method is the need to mechanically mount the induction loop on the surface of the cornea. Contact lenses with an induction loop attached to the surface are often used.

Current studies regarding the advancement and modification of this method use more modern methods of wireless signal transfer from the induction loop attached to the contact lens placed on the surface of the eyeball. A huge advantage of this method is that it works with closed eyelids. The transmission of amplitude-modulated eye movement information in a high-frequency range allows for a very high signal-to-noise ratio. It is worth noting that this method allows for the measurement of eye movement in several degrees of freedom, e.g. three mutually perpendicular degrees, even with the eyes closed. Mutually perpendicular magnetic fields with varying frequency values of the changes in magnetic field strength have to be created for this to be possible. An important advantage of this method is the possibility of taking measurements in varying reference systems. Using an external magnetic field allows for the determination of eye direction regardless of whether head movement or eye movement occurred.

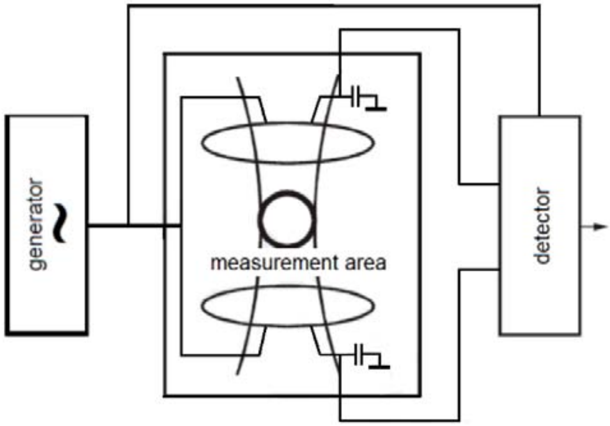


Figure 21: *Diagram of measurement system used for measuring eye movement with the magnetic method (Augustyniak 2001).*

The photoelectric method of measuring pupil movement is based on measuring the differences in the light reflected off the surface of the eye. There are several variations of this method. One of the most accurate methods of measurement uses contact lenses with mirrors attached to their surface. Earlier methods were based on calculating the angle of the so-called first and fourth Purkinje images. They are named after Czech researcher Jan Evangelista Purkyně (Nicholas 2001), a physiologist and histologist who studied the phenomena of reduced colour brightness perception in low light levels (in mesopic vision). He realised that when the eye adapts to twilight vision, light with a short wavelength (e.g. blue or blue-green) is perceived as brighter than light with a long wavelength (e.g. red) (Purkinje 1825). A similar illusion happens when red objects seem to be approaching faster than blue objects of the same shape.

Purkinje images are the reflections on the surface of the eye of a light beam directed at the eye. The principle behind them and the names of the images are depicted in the next figure. A significant obstacle is the fact that the fourth Purkinje image is hard to measure as it is approximately 1% as intense as the first image. A vastly more popular method uses infra-red beam reflections in the iris. Two infra-red LED semiconductors are used to symmetrically illuminate the iris. This is depicted in the next figure. Purkinje images manifest as small white circles near the pupil, which in turn is registered in infra-red light as a black circle in the central part of the eye.

Reflected off the border between the iris and the sclera, the beam is registered by photosensors which measure the reflected light beam. Piotr Augustyniak (Augustyniak 2001) emphasises the low cost of this method and the possibility of using just four photosensors for two-dimensional eye movement measurement instead of the more expensive CCDs (charge coupled devices) in methods based on Purkinje images.

A huge advantage of the photoelectric methods of measuring eye movement is the high accuracy of the measurement.

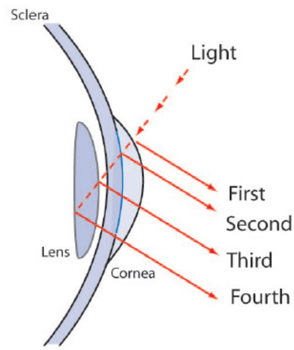


Figure 22: *Light is reflected on the eye and results in various Purkinje images (source: Witzner 2010, p. 487).*

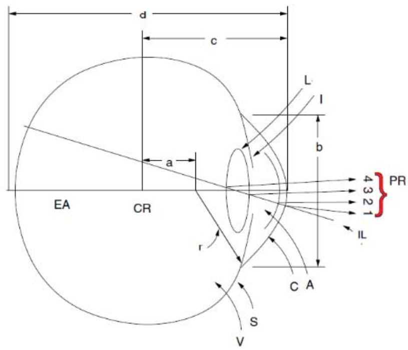
The use of infra-red radiation allowed for measurement precision comparable to electrophysiological methods while retaining low interference sensitivity, especially of the physiologic type. The measured signals are not biological. Another advantage of this method is its non-invasiveness. This allows to use this method not only in clinical practice, but also for the fulfilment of scientific objectives as well as control systems and processes.

The three presented methods are physiological. The following eye tracking method is based on video footage. Before it is presented, the history of eye tracking will be provided.

3.3. History of eyetracking

The Polish term „okulografia” (oculography, optical tracking) is used in Poland interchangeably with the term of English origin: “eyetracking”. According to the authors of the article "Did Javal measure eye movements during reading?" (Wade 2009), Émile Javal Luis, a French physician, who lived at the turn of the nineteenth and twentieth centuries, studied a disorder today called strabismus. He was the first to examine eye movements which occur during the process of reading. Despite the fact that he never defined the concept of eyetracking, he is now widely recognized as its inventor. His research and applications are extensively cited in the majority of articles, books and publications in the field of eye-tracking. Javal used the term "saccades" in the context of eye movements during reading, but they were never measured by him. In 1878 and 1879 he published a series of articles on these processes, therefore the beginning of eyetracking goes back to the year 1878. In the nineteenth century, the research curried out on eye movements were mostly focused on accidental and unconditional movements rather than on the movements that occur during reading. Other researchers - Ermann and Dodge in 1898, watched the eyes of readers using sets of mirrors (Wade 2009). Dodge and others in the early twentieth century recorded the light reflected directly from the eye (Dodge 1900, 1901,1904, 1905, 1906).

Javal discovered a surprising property of the human eye. A human brain does not focus on the whole physically achievable field of view but selects only those fragments that originate from the macula of the retina (in Latin: macula - "spot", lutea - "yellow").



PR – Purkinje reflections: 1 – reflection from front surface of the cornea; 2 – reflection from rear surface of the cornea; 3 – reflection from front surface of the lens; 4 – reflection from rear surface of the lens–almost the same size and formed in the same plane as the first Purkinje image, but due to change in index of refraction at rear of lens, intensity is less than 1% of that of the first Purkinje image; IL – incoming light; A– aqueous humor; C – cornea; S – sclera; V – vitreous humor; I – iris; L – lens; CR – center of rotation; EA – eye axis; a ≈ 6 mm; b ≈ 12.5 mm; c ≈ 13.5mm; d ≈ 24 mm; r ≈ 7.8 mm (Crane, 1994).

Figure 23: *Purkinje images (source: Augustyniak 2001).*

The author of "The History of Eye Tracking Studies & Technology" (Campion 2013) states that, in 1900, the psychologist Edmund Burke Huey built the first device which measured the movements of a human eye - the first eyetracker. This mechanism was unfortunately invasive, because it was necessary to put a lens on the eye to run the research. The eyetracker used a contact lens in which there was a hole for the pupil. Aluminum indicators were connected to the contact lens moving with the eye to track the movement of the eyeball.

Guy Thomas Buswell was the next psychologist who built instruments to measure eye movements. He created the first non-invasive eyetracker. This tool used the light rays that reflect off from the surface of the eye, and then they were recorded with cine film (Campion 2013), (Soluch 2013). Buswell carried out regular tests of reading, as well as examined the processes that occur when viewing (Buswell 1935), (Buswell 1937).

It was the beginning of research with the use of eyetracking. The technology was not quite well developed, but either way Buswell's eyetracker was much more comfortable than the one made by Huey (Buswell 1937), (Campion 2013).

In 1950, Russian psychologist Alfred Yarbus Lukyanovich carried out important and very valuable research on eyetracking. He published a book in 1967 as a report of his research, and the results are widely cited to this day. He described the relationship between fixations and the attention and interest of the examined person (Yarbus, 1967).

Since the beginning of 1970s, the eyetracking research, especially on process of reading, have expanded. The American psychologist Keith Rayner brought major contributions to eye-tracking research, and is considered the most well-known eyetracking researcher (Rayner, 1992), (Rayner, 1998). He worked and conducted his research in a number of American universities. Rayner was the editor of the "Journal of Experimental Psychology" in years 1990 - 1995, as well as the editor of the "Psychological Review" from 2004 to 2010.

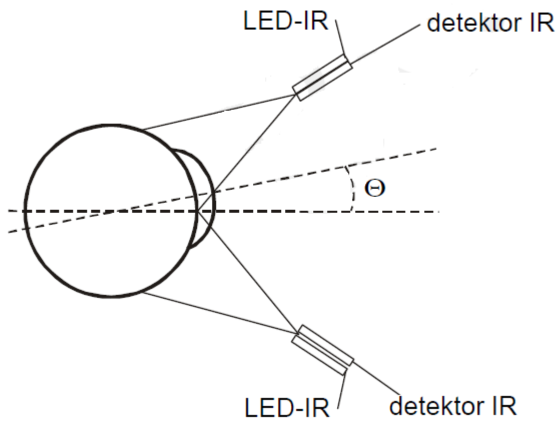


Figure 24: *The principle behind the measurement of eye movement with infra-red radiation in the photoelectric method. (Augustyniak 2001).*

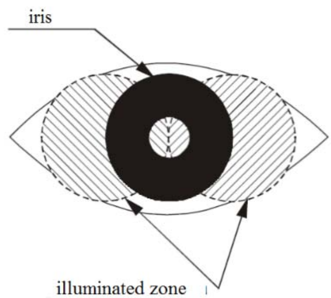


Figure 25: *Method of illuminating the iris with infra-red light in the photoelectric method.*

The author of "The History of Eye Tracking Studies & Technology" (Campion, 2013) writes that in 1980 eyetracking technology was used for the first time to answer questions related to human - computer interactions. Scientists analyzed how to facilitate interaction between the computer command window and a user. It was also investigated how to use advancement in technology and the real-time eye tracking results to help people with disabilities (Deja 2010).

Eye-tracking research is currently carried out in order to make better use of this science. The technology is constantly developing in order to participate in almost all aspects of life (Kurcz 1990), (Liversedge 2011), (Jacob 2003), (Duchowski 2002).

3.4. Video methods of eye movement measuring

3.4.1 Calibration

The aforementioned methods of measuring eye movement have lots of advantages, and, most importantly, do not require any advanced methods of processing analogue signals. Making use of these methods does not entail high costs and the use of digital measuring apparatus. However, in many situations they do not fulfil the expectations of the researchers, e.g. due to the restriction of head movement during the study, or the necessity of carrying them out in laboratory conditions, narrowing down their applicability. Therefore measuring methods based on video recordings of the position the pupil, is usually illuminated by a beam of infra-red light, are used more often. Extremely advanced apparatus and research which can be considered eye-tracking related can be found in works from the sixties, e.g. by Yarbus (Yarbus 1967). The next figure depicts the apparatus used in the sixties.

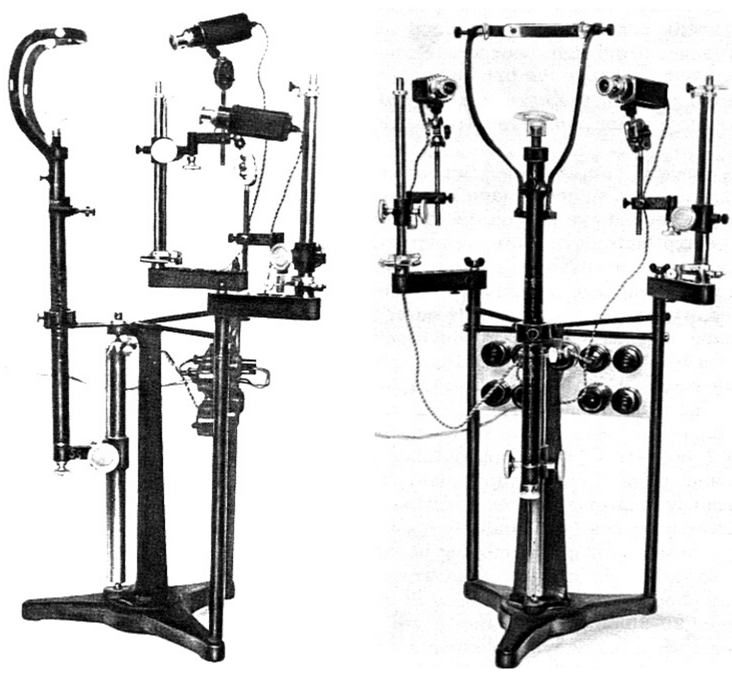


Figure 26: *The apparatus used to register eye movements in in the sixties (source: Yarbus 1967, p. 41).*

In order to minimize the influence of head movement on the measurement of the position of the pupil, a clamp was used to immobilize the head. Modern high-precision research (e.g. laboratory-grade eye trackers) also immobilize the head. In other cases, where different algorithms of calculating the position of the pupil were used, free head movement is possible. The video recording method of measuring eye movement most commonly makes use of cameras and ways of processing videos captured by the cameras. It is usually done in real-time. Modern measuring sets, often called eye trackers, can either be stationary or be mounted on the head of the test person. The working principle of the apparatus is identical. They differ in size and recording speed. The placement of the impressions of light reflected off the cornea in relation to the position of the pupil is the core, and most commonly used, method of measuring pupil movement (Crane 1985, Crane 1994). Remote eye tracking methods most commonly use additional infra-red light sources illuminating the eye for the separation of pupil and head movement. In this situation, the pupil is seen as a black spot with light reflections visible on the surface of the cornea. The image of the pupil and the first Purkinje image are most commonly used for this purpose.

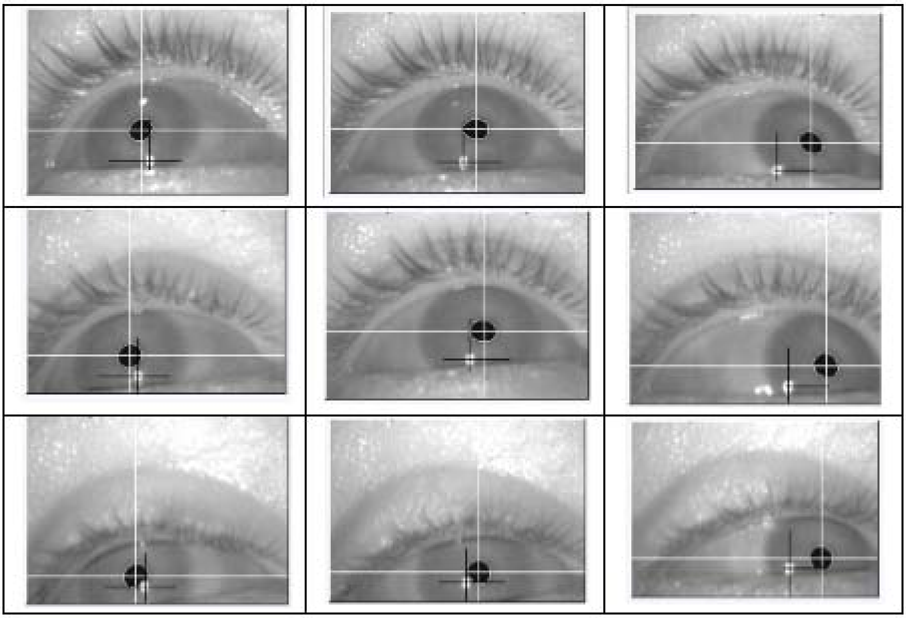


Figure 27: *Measurement of the position of the pupil and first Purkinje image for the left eye of the author using iViewX software while looking at specific parts of the image on screen: UL, UM, UR, CL, CM, CR, LL, LM, LR. (L – left, M – middle, R – right / U – upper, C – central, L – lower).*

3.4.2 Video-oculography

Video-oculography is currently the most popular method of registering the position of the eyes. The following three types of devices, commonly known as eyetrackers, are currently used: *head-mounted eyetrackers* which register the monocular frequency up to 360 Hz (H6, ASL), *remote eyetrackers* operating binocularly up to 500 Hz (RED500, SensoMotoric Instruments) and *ultrafast eyetrackers* requiring stabilization of the head, to measure the monocular frequency of up to 2000 Hz (EyeLink 1000 SR Research). The fixed position of the head-mounted eyetrackers in relation to the eye of the examined person eliminates artifacts connected with head movement. They are comfortable and introduce some flexibility in the experimental environment in relation to the examined person and a monitor which displays images or text. That is also why this type of equipment is often used as a mobile system. The camera and infrared light source is placed in front of the examined eye, above or below it. This is illustrated in the following figure.

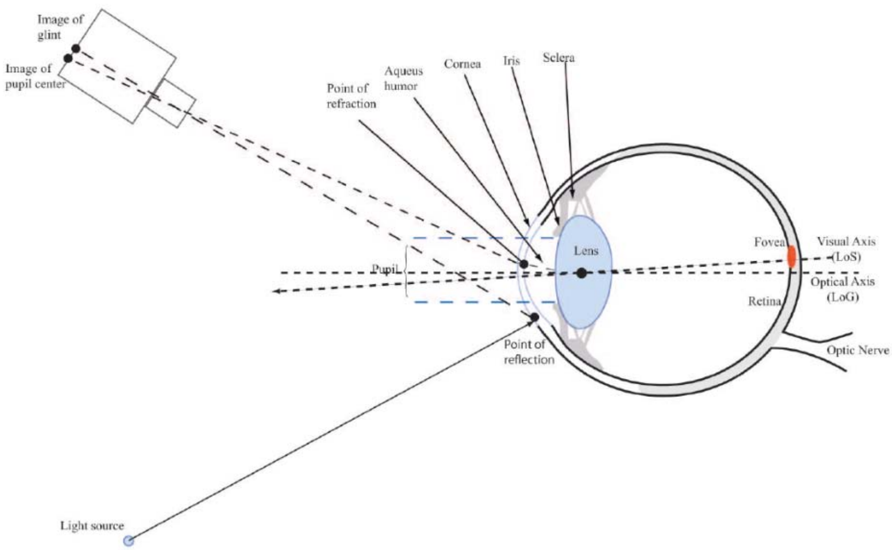


Figure 28: *The operating principle of video-oculography with the analysis of changes in the position of the pupil and the first Purkinje image (source: Witzner 2010).*

In the majority of eyetrackers of this type there is also a scene camera recording a reference image, i.e. the space before the examined person, in order to visualize the results. Video footage from the camera is used for the analysis of results. Scene cameras used a maximum resolution of 640x480 until 2011 (Soluch 2013), when the first commercial head-mounted eyetracker with a scene camera of resolution of 1280x960 appeared. For several years now, thanks to technological advances and miniaturization of electronics, there have been on the market with a built-in eyetracking system, combined with a small mobile recorder device like tablet, smartphone or laptop. The recording speed of these systems is not high, however they have the advantage of a wide range of applicability and usefulness to a very wide spectrum of research. It should be added that for the purposes of research in physics education, faster registration is not necessary. At present the European market is dominated by the following two manufacturers of portable systems: Tobii and Senso Motoric Instruments (SMI), (Soluch 2013), both created in 2011. Their devices are interesting for several reasons.

Tobii developed a system of active markers, placed in the test environment, which communicate with the eyetracker during the experiment. As a result it is possible to automatically track the areas of interest during the analysis. Tobii glasses examine one eye and operate at a speed of 30 Hz (Soluch 2013). Until now the manufacturer has not specified the accuracy at which the location of the pupil is measured.

The company SMI provides software to semi-automatic data aggregation and determination of dynamic areas of interest without the use of markers. The functionally important feature is the binocular measure which allows compensation for the parallax error (Soluch 2013). The manufacturer specifies that the SMI glasses system records the location of the pupil with a frequency of 30 Hz for each eye with a maximum deviation of 0.5° measurement and a spatial resolution of 0.1°.

Figure 29: *Tobii's mobile system.*

Remote eyetrackers use cameras and infrared lights typically located above or below the source of stimulus, which is typically the monitor of the computer to which the eyetracking interface is attached. Most manufacturers enable the use of that kind of eyetracker with other video sources, e. g. screen projector or a TV set, with the use of a special base fixed to the interface.

Remote eyetrackers are sensitive to movement of the head. If the person moves relative to the equipment, it is necessary to perform a calibration every several minutes. However, they are the most comfortable and the most friendly devices to use. Remote eyetrackers work by recording changes in the position of eyes with frequencies from 30 Hz to 500 Hz, using the techniques of monocular and/or binocular measurement. The spatial resolution declared by manufacturers depending on the generation of devices is from $0.1°$ to more than $1°$.

Ultrafast devices are the last group of eyetrackers. They have an eyetracking interface placed at the source of the stimulus or close to the eyes of the examined person. They also require use of a special rack (tower-mounted), in which the head of the examined person is immobilized. This allows the elimination of movement of the head and associated artifacts. Theoretically, it would be possible for systems with a speed above 200 Hz to register microsaccades. In practice, however, these are the ultrafast systems that are used to conduct experiments on microsaccade registration (Martinez-Conde 2009).

It is also worth mentioning that, with the increase in interest of research using functional magnetic resonance imaging (fMRI), there are more and more devices for studying eye movements on the market which are able to work in a magnetic field. The video-oculography tools which give the possibility of stimulus registration together with imposition on this image any eye movements measurement are still slow. A lot of them record images at a speed of 50 Hz-60 Hz (Soluch 2013).

With the growing popularity of eyetracking and evolution in the field of electronics and digital technology the various methods of measuring eyeball movement are being rapidly developed. Because of the ease of application and the availability of methods the

Figure 30: *The Tobii TX300 remote Eye Tracker. Retrieved from: www.tobii.com.*

video-oculographs are the most popular and the most widely used devices. It should be also noted that we observe more and more often attempts to use video cameras, webcams and devices embedded in smartphones. Although the precision of such measurements is often limited only to the movement that could control the mouse pointer, or typing on the virtual keyboard,I believe that the use of this type of equipment, e. g. in smartphones, will be very important in the teaching of physics, for example to monitor eye movements of many students in the classroom, in the conditions of natural experiment. At present, the use of this technology is becoming very useful for people with disabilities, with reduced mobility. This is also a new service for users of modern smartphones. At the moment, there are several solutions provided by phone manufacturers. LG and Samsung are competing with each other in developing the methods of visual control of smartphone applications. Samsung Galaxy S4 has a built-in visual control applications, which is called Smart Scroll^{TM}. The manufacturer describes them as follows:

> "*The Smart Scroll feature uses the front camera to sense when you are looking at your device, and it scrolls through content such as lists, webpages, and messages based on the angle you hold the device*." (Smart Scroll, http://phoneprob.com/what-is-the-smart-scroll-feature-on-my-samsung-galaxy-s4/).

There are also universal software projects to visual control of mobile devices. Umoove company advertises its products as:

> "*Umoove is the first ever, pure software, face and eye tracking, for any mobile device. No extra hardware needed. A unique technology (20 filed patents so far), built from ground up, that has attracted the attention of many of the biggest companies in the world. With simple app downloads, any device can*

Figure 31: *The High Speed Eyetracker SMI 1250 Hz in Neurodidactics Laboratory at the Pedagogical University of Cracow, Institute of Physics.*

> *become capable of seeing the user and looking him in the eye opening new possibilities in many markets (Gaming, Advertising, Sports, Wearable AR/VR etc.) but especially healthcare where looking at the user's eyes is a window to diagnosing their brain activity. Things like ADHD, concussions, strokes, autism, Parkinson's and more can all be seen through the eyes. This means that with no extra hardware any mobile can become an advanced medical device diagnosing and tracking brain activity, dramatically impacting major healthcare markets. Umoove is focused on driving its own in house product, uHealth, an eye tracking based therapy app, for tracking and improving attention and focus. As well as, continuing to form partnerships with others utilizing the Umoove technology in Healthcare and other spaces*"'. (source: http://www.umoove.me/about.html)

There are also open source solutions for PC hardware similar to Opengazer. We can mention for example one of them – the software provided by Szymon Deja, a student of AGH in Cracow (Deja 2010). The software is distributed under the Creative Commons Attribution Non-Commercial license. The following is an excerpt of the software description:

> "*GazePointer is an open source application that uses an ordinary webcam to estimate the direction of your gaze. This information can then be passed to other applications. For example, used in conjunction with Dasher, GazePointer allows you to write with your eyes. GazePointer aims to be a low-cost software alternative to commercial hardware-based eye trackers*." (http://sourceforge.net/projects/gazepointer/)

[44]

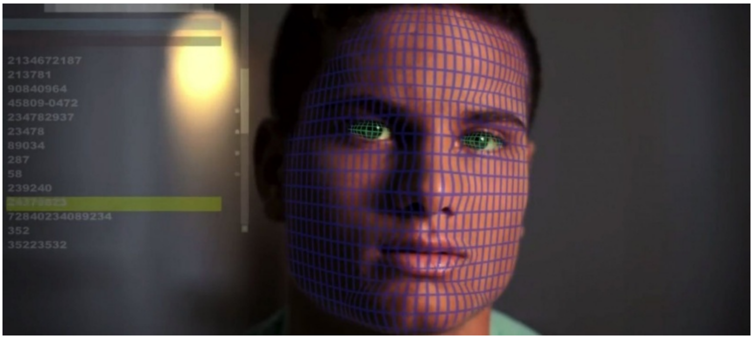


Figure 32: *The way of working the Umoove software for visual controlling the mobile devices software. Source: http://www.umoove.me/about.html.*

The figure below, shows an example of visually controlling the game "Fruit Ninja" using GazePointer software.

Figure 33: *Using the GazePointer software. Retrieved from: http://gazepointer.sourceforge.net/.*

3.4.3 Perception of the environment by human senses

The human senses are responsible for our human existence and, above all, our current knowledge of the world. Early as in the in primary school textbooks of nature the attention is drawn to the fact that a human being communicates with the world via the sense of sight, hearing, taste, smell and touch. The senses are our “window on the world”.

It is the sense of sight that gets the majority of information across from the environment to the brain. It is estimated that out of all human senses, eyes present approximately80% of stimuli (Biecek 2014), (Zając 2003).

That is the reason why for the development of didactics of science it is so important to understand the mechanisms of perception that are governing the processes of learning and information processing.

Learning in general, including science learning is strongly connected with perception and processing of stimuli reaching us from the environment. Therefore the majority of our research projects focus on examining the activity of the eyes of pupils and students during the process of problem solving (Błasiak 2013), (Błasiak 2014).

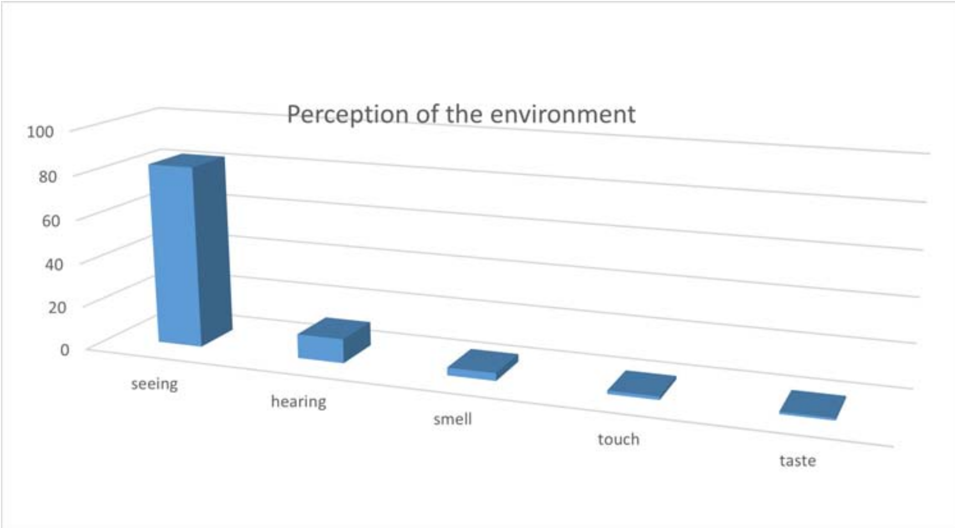


Figure 34: *The comparison of perception of the environment by human senses.*

3.4.4 Methodological issues connected with eyetracking measurement

Most of the eyetrackers used today make use of infrared light to track eye movement. This is why a number of researchers, basing on their experience, recommend using fluorescent lighting in rooms where research is being carried out due to the minimal amount of infrared light emitted. During our remote eye tracking experiments we noticed that darkened rooms are to be avoided, as the pupil size is too big to be properly tracked in these conditions. The contrast levels of the image of the eye filmed by the devices' cameras change as well. This greatly influences the quality of the measurements. Artefacts are observed which are related to errors in iris size measurement, as well as the image of the iris merging with eye edges and eyelashes. When carrying out research using eye tracking devices, consideration should be given to reducing the amount of sunlight, especially if this would otherwise reach the eye tracker or the face of the subject. It is also important to make sure the eye tracker is stable. If a mouse and keyboard are to be used during the study, proper placement is vital. They should be placed in such a way so that the subject does not need to move during usage and that the peripherals do not cause any additional vibrations. Choosing the right number of calibration points is also very important (Duchowski 2007). Increasing the number of calibration points greatly influences measurement precision.

There are also many factors which cannot be predicted or controller during the study, regardless of whether a stationary or mobile system is used. The lack of total control can prevent carrying out the measurement or interfere with the results. Paweł Soluch (Soluch 2013), based on Holmqvist (Holmqvist 2011), gathered all the crucial factors and created the following groups:

1. Obscuring too much of the surface of the eyeball, caused physiologically by a drooping eyelid, and functionally by e.g. laughter or insufficient room lighting conditions.

2. Interference caused by makeup (particularly mascara), glasses, contact lenses, or dry eyes;

3. Interference caused by bifocals;

Losing the image of the eye caused by head movement or mouse and keyboard usage.

3.4.5 Eyetracking description of eye movements

Many different parameters are used in order to accurately describe eye movement during eyetracking measurement of situations such as chart analysis, problem solving, or reading.

The definitions for the most important of them are pointed below according to M. L. Lai., M.-J. Tsai at alt (Lai 2013):

1. AOI – Static or dynamic area of interest.

2. Gaze duration – Total fixation duration within a word or an AOI,

3. Average fixation duration – Mean of fixation duration on each AOI. (i.e., Gaze duration mean)

4. First fixation duration – Time spent on the first fixation

5. Time to first fixation – Time spent from stimuli onset to the first fixation arrival

6. Revisited fixation duration – Sum of revisited fixation durations within an AOI

7. Proportion of fixation duration – Proportion of time fixated on an AOI compared to the total fixation durations or total reading time of a whole task

8. Saccade duration – Sum of saccadic time spent within an AOI

9. Total reading time – Total time spent for a reading task or spent within an AOI

10. First pass time – Time spent for the first entering of an AOI until leaving

11. Re-reading time – Sum of revisited time spent within an AOI

12. Spatial Fixation position – Location of a fixation

13. Fixation sequence – Sequence of fixation allocations on AOIs

14. Saccade length – Distance between two consecutive fixations

15. Scanpath pattern – Pattern of fixation sequences

16. Count Total fixation – Total number of fixations counted in an AOI or in a task

17. Average fixation count – Average fixation count on each AOI

18. Revisited fixation count – Sum of revisited fixations count within an AOI

19. Probability of fixation count – Probability of fixation count within an AOI compared to the number of fixations overall
20. Saccade count – Total number of saccades counted within an AOI
21. Inter-scanning count – Number of fixation transactions between AOIs
22. Total fixation duration – Total time spent on fixations

4. CHAPTER – EYETRACKING RESEARCH

4.1. Review of selected eyetracking research

Paweł Soluch, based on Rayner, separates the development of eye tracking into three phases (Soluch 2013) According to Rayner, Javal begun the first phase by studying text perception. From 1879 to approximately 1920 (Rayner 1998). The second phase continued this topic of research. From approximately the 1950s onward, not many studies were carried out. One of the more important studies of the time were eye movement measurements done by Buswell (Rayner 1998). Works of art were presented to the subjects during the experiment. While presenting works of art to approximately 200 people, the instructions given were being changed. The conclusions contain the following: "Eyeball movement is subconsciously adjusted to the needs of the attention system" (Duchowski 2007). This type of research is currently the domain of P. Francuz (Francuz 2013).

Similar studies in Raynor's second phase of eye tracking development were carried out by A. L. Yarbus (Yarbus 1967). He studied the visual processes taking place while observing both simple and complex stimuli, such as: moving objects, optical illusions, text. He proved that the human eye both voluntarily and involuntarily concentrates on either elements of an object or whole objects which could convey important information critical to the task at hand. It can be said (Soluch 2013) that the time spent focusing on a specific part of the image gives an indication of the importance of the information contained therein from the point of view of the subject. The duration and the sequence of fixations can help in determining and analysing thought processes (Soluch 2013).

The third phase of the development of eye tracking, also the most dynamic, began in the mid-70s of the 20th century (Soluch 2013). The rapid development of eye tracking was set in motion thanks to the development of electronics and computer techniques. The introduction of previously unavailable modern technology allowed for increasingly accurate measurements of eye movement. The methods became less and less invasive and increasingly precise, and, most importantly, easier to use. The most important factors were the development of digital electronics and how increasingly widespread computer use became, mostly in regards to data acquisition. Using computers for later stages of research, i.e. processing and analysis of the increased quantities of gathered data was an important milestone. One of the most often studied topics were visual attention processes (Soluch 2013). There was a number of previously unknown mechanisms observed while carrying out experiments for visual attention process analysis. One of them is the saccadic suppression, which decreases the stimulus sensitivity of the visual system during rapid eye movements. Another mechanism is that the fixation time is relatively comparable to the duration of a saccade for a given type of perceived stimulus. For silent reading, visual searching, or e.g. writing, the duration of a saccade is approximately 5° (Soluch 2013). It was observed that the average fixation time differed between subjects, but remained the same across multiple studies for a specific type of stimulus (Abrams 1972), (Abrams 1989). Saccade and fixation times rely on many more factors than just the type of stimulus. Both physiological mechanisms as well as cognitive processes can influence saccade and fixation times.

Another mechanism described by Paweł Soluch is saccade latency, defined as the time from the appearance of the stimulus to the eye movement trigger. The latency exceeds 150ms, even when carrying out almost automatic processes, e.g. reading (Soluch 2013). In several years of saccadic latency research, several important factors influencing saccadic latency have been established (Rayner 1996). It has been proven that cognitive processes increase latency (Deubel 1995). Most importantly, independent decision-making processes responsible for eye movement programming were discovered (Soluch 2013). A relationship between saccadic latency and precisely locating the target to which the eye is guided has been found (Nazir 1991). Lack of visibility, e.g. the disappearance of the target before turning attention to it, has been found to decrease latency (Ross 1997), (Kingstone 1993). Giving instructions regarding the intensity of the subject's attention while solving a task has been found to increase latency (Kowler 1995). Among educators dealing with eye tracking, a lot of attention is given to image, diagram, and chart analysis, as well as reading. One of the most often cited works regarding eye tracking is a collection of theories and overview of studies assembled by K. Rayner (Rayner 1996). It can be stated that eye movement directly represent the processes of not only language processing, but also illustrations and chart analysis, which are closely associated with teaching physics. The most interest in this field is in understanding relationships between the methods of chart or diagram analysis, or reading comprehension, and eye movement. Most studies show that the comprehension of a sentence or a diagram is almost instantaneous (Soluch 2013).

Several models of eye movement for reading processes and image analysis have been proposed. One of the best known and popular models is the E-Z Reader model created by: E. D. Reichle, A. Pollatsek, D. I. Fisher and K. Rayner (Reichle 1998). It is depicted in the next figure.

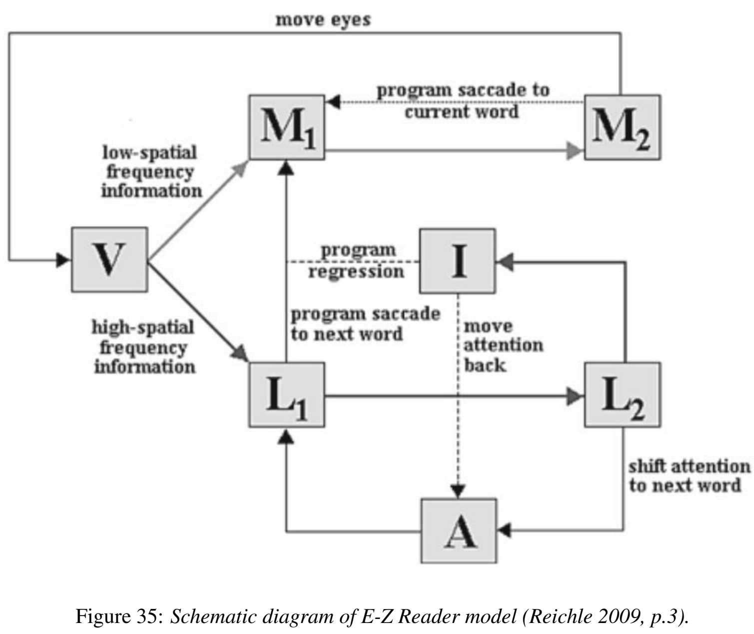


Figure 35: *Schematic diagram of E-Z Reader model (Reichle 2009, p.3).*

[50]

In the Figure 35 one of the models of the reading process is shown as a schematic diagram of E-Z Reader 10. (A) means assumption about attention, (I) - postlexical integration. The thin solid arrows indicate obligatory transitions between components. The thick arrows indicate how information flows between the model's components. The thin dotted arrows indicate probabilistic transitions.

Due to the fact that the model mostly describes reading processes, it will be presented without being described in-depth, as this description is included in the works of E. D. Reichle et al. (Reichle 1998), (Reichle 2009), which is why an in-depth analysis of this model will also be omitted.

Despite so many studies being carried out, the individual components coordinating the processes of text analysis and visual content are still unknown. Research into the processes of visual content analysis and of reading shows several important mechanisms. One of the most important mechanisms is how often word fixation time results in shortening the saccades (Soluch 2013). It has been discovered that reading aloud as well as listening combined with paying attention to the text being heard results in longer word fixations than silent reading (Soluch 2013). M. A. Just and P. A. Carpenter (Just 1980) noted longer fixations on less frequently used words as compared to those that are more common. A more in-depth study revealed that this effect wears off as the word is used more and more frequently in a short fragment. When a rarely used word is noticed for the third or fourth time, there no longer is a difference in the fixation time between this word and words which occur more often in the language (Clifton 2007). A similar phenomena occurs in relation to knowledge of terms (Soluch 2013) – the clearer a word is for the reader, the shorter the fixation time (Chaffin 2001). Word fixation time is also determined by the predictability of the word, based on the context of the preceding words (Soluch 2013). This effect has been described by S. F. Ehrlich and K. Rayner (Erhlich 1981). Further research has shown that the more predictable the words are, the more often they are omitted during reading (Rayner 1996). These factors are also directly related to the effect of processing a word based on the age one has learned the word (Soluch 2013). The later one has learned a word, the slower the processing will be, which means that the fixation will also take more time (Juhasz 2005). The same goes for the complexity of a word – the more complex it is, the longer it is being registered by the visual system (Soluch 2013). Literature on the subject contains descriptions of experiments related to the perception of visual scenes, illustrations, and works of art (Francuz 2013). While the models of reading perception are already known, no such models exist for visual scene perception processes. The gaze plots of reading are strictly defined. There are no such relations in the case of visual scene perception. The gaze plots can be vastly different, even in the case of analysing the same image. Changes in the instructions also influence visual processing (Soluch 2013). A number of researchers (Yarbus 1967) have shown that fixations on a given area are strictly related to the task at hand and most often stem from the need of acquiring the information stored in that area.

Another finding is that the understanding of a chart or image improves with subsequent fixations (Loftus 1981). It is likely that basic information regarding the visual scene is registered and processed based on the first fixation (Soluch 2013). This is a vague concept due to the limitations stemming from the physiology of vision. This is caused mostly by the fact that the area of sharp vision is in close proximity to the fixation point due to the size of the macula (Rayner 1992). If an element of the image is important, the fixations are going to be moved to that element due to the perception process mapping fixations to significant areas of the image.

From the point of view of analysis of the process of illustration and visual scene perception, not only is the number of fixations and their duration crucial, but their sequence is as well. This is particularly significant in practical applications of such studies in physics education. A number of studies have shown a similarity between the duration of an image element fixation and the duration of a word fixation. If an element does not seem out of place and is understood, it reduces fixation time (Henderson 1998). It is also worth noting that the field of eye tracking in marketing research and website usability testing is in rapid development, though most of the companies ordering such studies are not interested in publishing the results or describing the methodology used. Paweł Soluch demonstrates one of the few examples of commercial research being available for the reader on the website of the Nielsen Normal Group. The work described the methodology of usability research with the use of eye tracking (Pernice 2009). The Physics Education Division was able to acquire experience in using eye tracking equipment thanks to the Cracow-based Edisonda company, who provided the equipment and test laboratories they used in their research on usability free of charge for physics education research. The value of using eye tracking in physics education as well as marketing research is determining the areas of attention – the elements which attract the attention of the average pupil or student, the legibility of textbooks, the effectiveness of marketing materials or product packaging, etc. This type of research is conducted in laboratories with the use of a monitor, television set or a projector. Though the most valuable research is conducted in a natural environment – in classrooms, lecture halls, shops, sports grounds, or on the street, using mobile devices. It is once again worth noting that eye tracking research has been experiencing a renaissance since the 1980s. It is more accessible, and the results are more useful in education at the school and university level

4.2. Review of selected eyetracking research in education

4.2.1 General overview on the basis of Lai et alt

Modern eye tracking research most often concerns eye-brain relations. More specifically, on researching the cognitive processes influencing eye movement and parameters. This is done by the measurement of parameters such as: the number of fixations, the duration of fixations, the number of saccades and their dynamic parameters, the gaze plots, the width of the pupil, and the number of blinks.

The use of state-of-the-art technology allows for researching reaction times, areas of interest, problem-solving strategies, or mistakes made while solving tasks. Even though as recently as 15–20 years ago eye movement was associated exclusively with physiology and not higher-level physical functions, eye tracking is now considered a precise reflection of interactions between cognitive processes and external visual stimuli (Soluch 2013). A number of researchers believe that eye tracking is a window to the soul, thoughts, and feelings (Holm 2007), (Glimcher 2003). A direct reflection of this belief is a 2007 book edited by R. van Gompel et al. called Eye movements: A window on mind and brain. (Van Gompel 2007). Earlier on, there were such hypotheses as e.g. The

Eye-Mind Hypothesis (Just 1980) which were subsequently modified (Anderson 2004). Multiple studies regarding the confirmation of the existence of a neurophysiological link between eye movement and cognitive functions were also carried out (Soluch 2013). Eye tracking research is associated with research regarding attention processes, memory, and decision making (Everling 1998), (Zee 2004). Despite such a vast number of studies and methods of neurophysiological analysis of the connection between cognitive processes and eye movement, it is worth noting that is it still impossible to analyse specific cognitive processes, as only visual perception research is possible. Eye movement is very often described in literature as lacking precision or accuracy. The most commonly given reason is that the complexity of human reactions and the experiences of the individual influence the categorisation of perceived objects (Soluch 2013).

The use of eye-tracking technology for analysis of the learning process has become more and more widespread in recent years. The use of such modern methods has already lived to see even partial summaries. Lai, Tsai, Yang, Hsu, Liu, Lee et al. (Lai et al. 2013) reviewed, for example, papers included in the Social Science Citation Index from 2000 to 2012. The authors selected 81 papers dedicated to the use of eye-tracking technology in research related to the analysis of the learning process, describing 113 studies carried out in this period of time. The content analysis allowed the authors to distinguish the following themes of studying eye movements and learning:

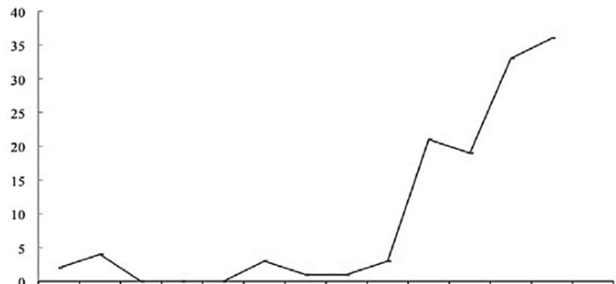
- Patterns of information processing
- Effects of instructional strategies
- Reexaminations of existing theories
- Effects of learning strategies
- Individual differences
- Patterns of decision making
- Social cultural effects

This article also refers to this mainstream, especially to two of the areas mentioned above. They are "individual differences", which are discussed in 7 works from this period, and the "effects of learning strategies", analyzed in 9 works. According to Lai et al. (Lai et al. 2013) both themes were raised simultaneously in 3 works. One of them is the article "Visual attention for solving multiple-choice science problems: An eye-tracking analysis" (Tsai et al. 2012), to which I strictly refer in this work.

Apart from the studies outlined in the review, it is worth mentioning others which have not been specified there. We chose selected research from the current decade relating to didactics of physics and mathematics because of the theme of our research. Research on didactics of physics are described e. g. by Madsen, Larson, Loschky, & Rebello (2012); Madsen, Rouinfar, Larson, Loschky, & Rebello (2013) and Smith, Mestre, & Ross (2010). Issues concerning the use of eye-tracking as a method to study cognitive processes related to learning mathematics were analyzed inter alia: Chesney, McNeil, Brockmole,

& Kelley, (2013), Merkley & Ansari (2010), Moeller, Klein, Nuerk, & Willmes (2011); Schneider, Maruyama, Dehaene, & Sigman (2012) and Susac, Bubic, Kaponja, Planinic, & Palmovic (2014).

In the figure 36 the diagram illustrates the very rapid development of research using eyetracking for exploring learning.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Sum of 2009-2012
Effects of instructional strategies	0	0	0	0	0	0	0	0	0	4	10	4	8	26
Patterns of information processing	2	2	0	0	0	1	1	0	3	8	7	18	11	44
Patterns of decision making	0	0	0	0	0	0	0	0	0	0	1	0	2	3
Individual differences	0	0	0	0	0	0	0	0	0	1	0	6	8	15
Reexaminations of existing theories	0	1	0	0	0	2	0	0	0	6	0	0	5	11
Effects of learning strategies	0	1	0	0	0	0	0	1	0	2	1	3	1	7
Social/Cultural effects	0	0	0	0	0	0	0	0	0	0	0	2	1	3
—Total	2	4	0	0	0	3	1	1	3	21	19	33	36	109

(Note: Ten studies discuss two learning themes, so the total number is 123 (113 + 10)

Figure 36: *Number of studies with respect to each learning theme from 2000 to 2012. (Lai et al. 2013, p.97).*

The authors (Lai 2013) indicate a very wide range of use eyetracking in educational research. Below graphic description of bridging framework between eye movements and learning.

In Poland, there is a group of several people who use eye-tracking in studies related to e.g. teaching methodology, appeal of works of art, effectiveness of websites, linguistics, traffic hazard evaluation, or marketing. In recent times, Poland has seen a rapid increase in the scope of the usage of such methods as well as in the number and quality of studies conducted in these fields. These studies include world-renowned experts in the field of eye tracking, such as Andrew Duchowski from Clemson University.

The first country-wide Polish Eye-Tracking Conference took place in 2012 at the John Paul II Catholic University of Lublin, the second one in 2013 at the University of Warsaw, and the third one in March 2015 at the University of Social Sciences and Humanities in Warsaw.

Research in the fields of the didactics of physics, mathematics, IT, and biology are conducted by the Cognitive Didactics Research Group at the Faculty of Mathematics, Physics and Technical Science of the Pedagogical University of Cracow. The researchers from our Cognitive Research Group participate in these conferences as well.

The inspiration to form the Group were the works of the team of Adrian Madsen and his co-workers at Kansas State University. He e.g. worked on recognising the differences in physics task solving strategies between experts and novices (Madsen 2012).

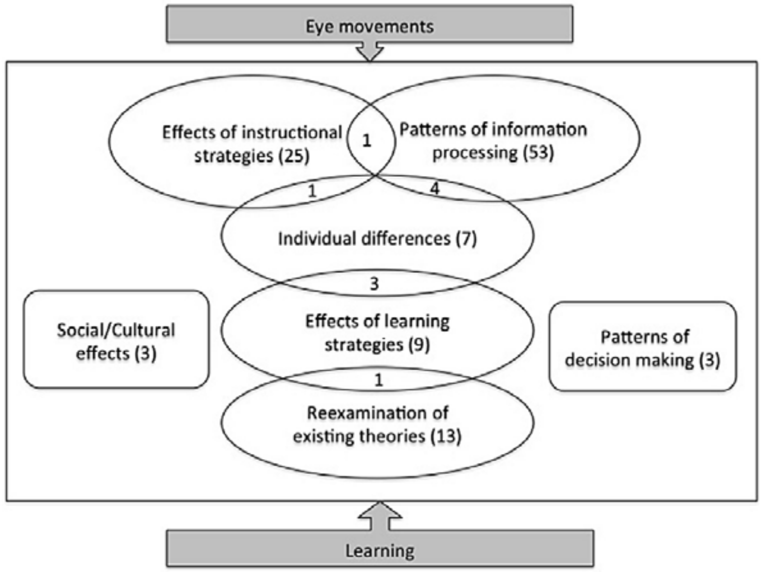


Figure 37: *Bridging framework between eye movements and learning. (Lai 2013, p. 95).*

4.2.2 Pupillometric hypotheses in education

The neural efficiency hypothesis states that the more intelligent people process information and solve problems in a more effective and less mind-straining way than those who are not as intelligent (Davidson 2000), (Haier 1992), (Hendrickson 1982), (Schafer 1982).

This hypothesis is reinforced by psychophysiological research regarding pupil reactions. The widening of the subject's pupil while solving a cognitive task is the psychophysiological measure of strain due to analysis and data processing. The wider the diameter of the pupil, the bigger strain due to information processing or mental effort (Beatty 1982).

Ahern and Beatty (Ahern 1979) have also shown that a relationship exists between the reactions of the pupil and the cognitive abilities of the subjects. They have shown that the pupil changes of students while performing multiplication were negatively correlated with their cognitive abilities. This means that students with a lower Scholastic Aptitude Test (SAT) score had wider pupils while performing multiplication than students who had a higher score. This result is compatible with the neural efficiency hypothesis.

Traditional testing methods, such as observations and surveys, can be supplemented with non-invasive methods of monitoring the psychophysiological parameters of the subjects. The changes of such parameters could be interpreted as an indicator of not only the motivation behind making a mental effort, but also stress levels and the emotional strain related to solving tasks (Madsen 2012).

The research part of this study will contain the results of puppilometric studies which make use of eye tracking technology. This methodology is not yet widespread in research related to physics, crafts, or mathematics education, as well as other specialised types of didactics in Poland (Błasiak 2013). This allows for a chance to assist education, especially in areas which are commonly regarded as difficult (Błasiak 2013).

This part of the experiment is an attempt to document both the search for additional tools of assessing the motivation of students, as well as the research for the possibility of using psychophysiological parameters as indicators of a subjective assessment of the difficulty of the tasks being solved by students.

4.2.3 The hypotheses of Daniel Kahneman

Daniel Kahneman is a leading psychologist, researcher of thinking traps, and the winner of the 2002 Nobel Memorial Prize in Economic Sciences. He believes that the human mind uses two radically different strategies for decision-making. The first one makes use of the rapid System 1, while the second one uses the careful and precise System 2. This division is not a representation of the structure of the brain, rather being a simplified way of describing decision-making. "System 1 works in a rapid and automatic way, with no or minimal effort, and these decisions are not made consciously. System 2 separates the necessary attention between tasks which require mental effort, such as e.g. complex calculations. The activity of System 2 is often related to a subjective state of focus, free choice and conscious action" (Kahneman 2011). Most cognitive distortions are related to the subconscious System 1. The decisions it makes are based on a scarce amount of information. System 2 requires a substantially larger mental effort than System 1. Kahneman believes that the rapid but lazy System 1 has a tendency to provide intuitive answers which are not based on contextual analysis, but on other stimuli which govern our attention (Błasiak 2014). Eye-tracking studies which monitor the amount of time and the physiological parameters responsible for cognitive strain and motivation, as well as eye tracking measurements of the strategies and errors made while solving tasks allow to verify this model.

EMPIRICAL PART

5. CHAPTER – AIMS, METHODOLOGY

5.1. The aim and motivation behind the empirical research

The general aim of the conducted empirical studies was researching the usefulness and the scope of the applicability of psychophysiological methods in physics education, as well as creating a methodology for psychophysiological data analysis in didactics of physics.

The analysis of the available literature regarding this topic, as presented earlier in this work, proves that there is a very solid theoretical foundation binding the psychophysiological parameters with the motivation of tested individuals for attempting problem solving, as well as the subjective assessment of its level of difficulty, the level of cognitive load, and the stress accompanying difficult situations. All of these relations were researched and described in-depth in laboratory conditions, although not in the context of physics education. The development of electronics, the miniaturization of measuring equipment, and the increasing availability of immensely precise measuring methods allows for the adaptation of such research in the context of physics education. One of the most important aspects is the use of previously unavailable methods, e.g. eye-tracking.

In conclusion, the aim of the studies carried out in laboratory conditions and described herein is to answer the following research questions:

Q1. Are psychophysiological methods such as HRV, IBI, BVP, S.C., RESP, EEG, or remote eye-tracking readings usable in didactics of physics?

Q2. What psychophysiological parameters could both be easily measured and be able to best show the cognitive activity of a student while solving a physics-related task?

Q3. What is the relation between eye tracking parameters and psychophysiological indicators describing breathing and heart rate, and the motivation, cognitive load, and stress levels of students while solving physics-related tasks?

Q4. Do eye-tracking parameters allow for a better description of physics-related problem solving strategies and for finding the reasons behind the mistakes made during task solving?

Q5. What are the advantages, disadvantages, and technical constraints of particular methods used in research on didactics of physics?

Q6. What practical conclusions can be drawn from the research? Which of the methods are worth it to be adapted for physics education research for the purposes of simultaneous monitoring of sizeable groups of students in conditions natural to the students, i.e. classrooms and lecture halls?

5.2. Layout of the research

The studies presented in this work were carried out in five phases, which is shown in the Fig. 38. The scheme describes the following information about all of the experiments:

1. Method used for the research

2. Number of study participants

3. Level of the research sample
4. Number and kinds of research tasks
5. A kind of questionnaires (if used)

The subjects were not to be limited in regards to time used for task and problem solving in any of the studies.

Figure 38: *Layout of the empirical part of research.*

6. CHAPTER – EXPERIMENT 1. EYE-TRACKING RESEARCH COMBINED WITH SIMULTANEOUS MONITORING OF PSYCHOPHYSIOLOGICAL PARAMETERS.

6.1. Apparatus and tools used for the research

6.1.1 Measurement of eye-tracking parameters

Hardware

The study was carried out in a professional laboratory made available for the study by the Edisonda company, where commercial marketing-specialised eye tracking research takes place. The SMI Red 250 eye tracker was used for this study.

Figure 39: *Eyetracker RED 250, retrieved from http://www.smivision.com.*

This eye tracker is characterized by its accuracy: High Accuracy: 0.4°, Spatial Resolution (RMS): 0. 3°. The SMI Red device was integrated to a 22" monitor, 60 cm away from the face of the subject. The research was carried out in consistent lighting conditions and recorded pupil movement and the subjects' faces during the analysis and solving graphical problems and physics tasks. In order to allow for the coupling of the images of the face with pupil movement, the face and facial expressions of the subjects were recorded with HD cameras for further analysis. In order to carry out the experiment, iViewX together with SMI ExperimentCenter software were used to control the equipment.

Software

The software SMI Experiment Suite^{TM} 360 was used, in which specific parts of the research were carried out by the following applications:

Design - SMI Experiment Center^{TM},

Recording - SMI iView X^{TM},

Analysis - SMI BeGaze^{TM}.

> *The SMI iView^{TM} X focuses on versatility and flexibility for the sake of superior results. Built as a software platform, the design concept provides the unique feature to connect with various camera interfaces such as remote and contact-free systems (SMI iView^{TM} X RED), mobile head-mounted systems (SMI iView^{TM} X HED), high speed and ultra-precise systems (SMI*

iView™ X Hi-Speed) and many more. Dealing with sampling rates from 50Hz up to 1250Hz, detecting eye movement events from visual fixations up to micro-saccades, providing live viewing of tracking and gaze overlays, synchronizing with other equipment, recording eye tracking video on the fly – SMI iView™ X delivers on the promise. (http://smivision.com)

The next figure depicts a window of the iViewX software used for equipment supervision and control during the experiment.

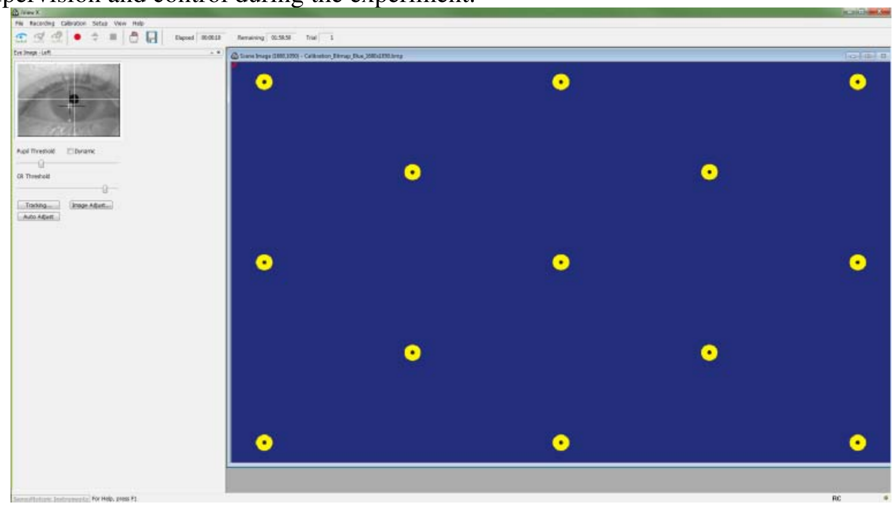


Figure 40: *iViewX software.*

Figure 40 depicts a window of Experiment Center software used to control the course of the experiment alongside the user interface showing the arrangement and method of displaying stimuli in the form of multimedia, the reaction to which is recorded.

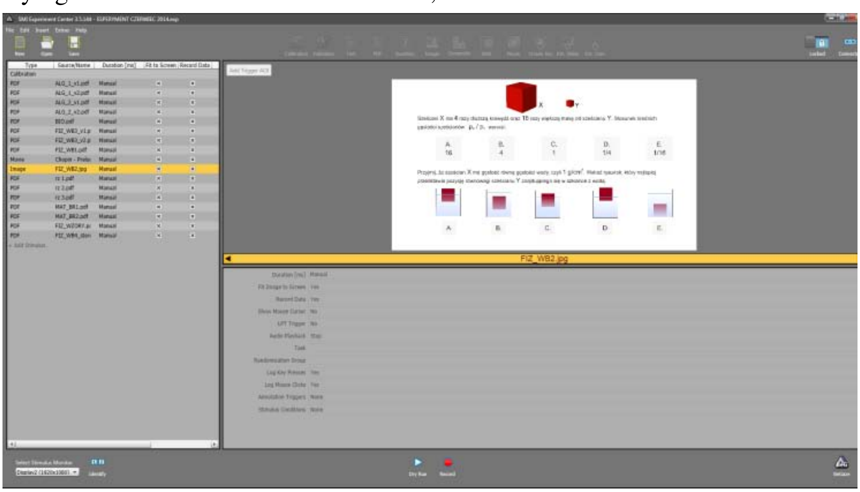


Figure 41: *Experiment Center software.*

SMI BeGazeTM software uses data from the experiment saved on a hard drive by way of streaming to obtain information regarding a vast number of parameters crucial to a comprehensive assessment of the eye and brain activity of the subject. A number of them are to be listed hereafter:

- dwell time,
- blink count,
- fixation count,
- fixation frequency,
- fixation total,
- fixation duration average,
- fixation dispersion average,
- scanpath length,saccade count,
- saccade velocity, saccade velocity average,
- saccade latency,
- pupil size and many others.

SMI BeGazeTM software allows for the visualisation of results by way of

- The so-called individual and collective heat maps,
- Time charts of gaze plots,
- Key performance indicators of the subjects' eyes on areas of interest on the screen displaying the content of the task,
- Or a so-called "AOI Sequence Chart," which shows the precise (with an accuracy of several milliseconds) sequence of the subject's performance on particular areas of interest.

Examples of such visualisation will be presented further.

An in-depth description of the specialised software used to create, supervise, and analyse the results of eye-tracking experiments (containing such software as: SMI iView X^{TM}, SMI Experiment Center^{TM}, SMI BeGaze^{TM} and Analysis Software) is delivered at the SMI website and contains about 1500 pages. Which is why it will be skipped here.

A description of the encoders and electrodes used is contained in the annex, which is why it will also be skipped.

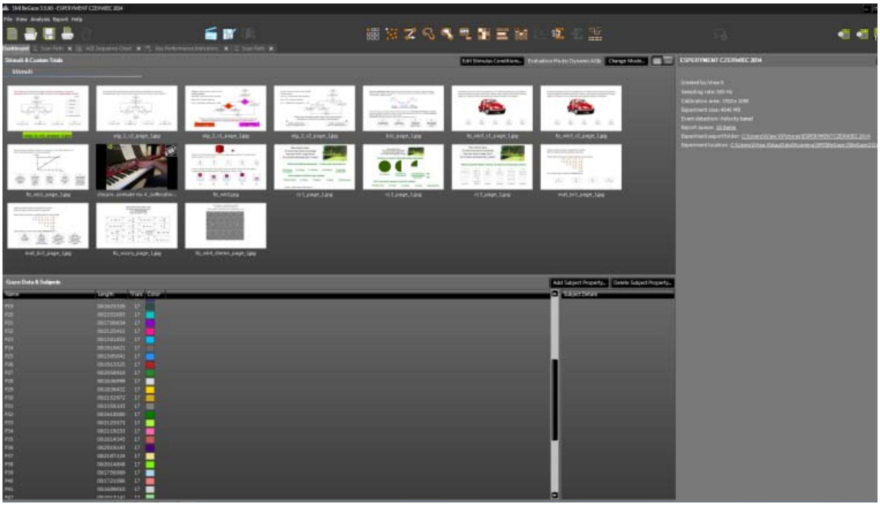


Figure 42: *BeGaze software, main window.*

> *SMI BeGaze™ provides quick and comprehensive analysis and visualization of eye tracking data and stimuli. SMI BeGaze™ greatly simplifies monocular and binocular tracking data analysis by structuring the information on stimuli and subjects, as well as displaying the results as meaningful graphs and visuals – all in one advanced application.*
>
> *SMI BeGaze™ provides the full spectrum of visualizations for gaze plots (scan path, bee swarm) and attention maps (focus map, heat map). Visualization parameters can be modified "on-the-fly". Visualizations can be exported as video (AVI) or bitmap for documentation, presentation etc.*
>
> *(smivision.com)*

6.1.2 Measurement of biophysical parameters

Hardware

During the course of this experiment, selected biophysical parameters were measured alongside eye movement.

FlexComp Infiniti^{TM} encoder was used for this purpose. The equipment recorded all psychophysical parameters with a frequency of 2048 samples per second.

Recorded were:

1. Changes of skin conductance (EDA) - to measure the conductivity of the skin, the electrodes were mounted on the fingers of left hand (Sosnowski, 1993).
2. The blood volume pulse (BVP) and heart rate (HR) was measured. The sensor (plethysmograph) was placed on a finger of the non-dominant hand.
3. Respiration rate and respiration amplitude, using the resistive sensor placed on the chest.

To ensure the safety of the subjects and full galvanic separation from the energy grid, data was transferred using the optical path. Optical fibre connected the encoder to the computer recording the data. Bluetooth-based Neurobit Optima4 encoders were also used. This allowed for the computer recording the data to be placed up to 10 m away from the subject.

Figure 43: *Encoders used in the study.*

Software

The next figure depicts a window of *Thought Technology* software in an open-session mode designed specifically for this experiment. The charts depict a 30-second snippet of one of the studies. The upper charts depict the BVP showing the relative values of the volume of blood flowing through the finger as well as IBI (pulse). The middle chart shows skin conductance differences. The lower charts depict the changes in breath amplitude and the average number of breaths depicted as number of breaths per minute.

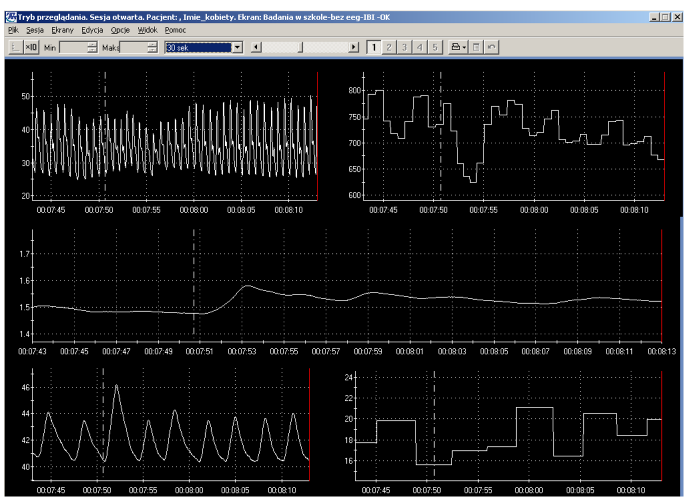


Figure 44: *Thought Technology in open session mode, during registering the data during our experiment.*

An in-depth description of the technical parameters of the encoders and electrodes used is contained in the annex, which is why it will be skipped here.

6.2. Aims of the study, the research sample and tasks

The aim of the study was a very broad eye-tracking study of high school students and the recording of selected physiological reactions during the course of solving tasks. The aim of the study was, specifically, to get to know and record task-solving strategies, and to assess the usefulness and the scope of the applicability of monitoring psychophysiological parameters for the assessment of the motivation and cognitive strain of students during physics-related task solving.

This stage of the study was conducted among a selected group of 38 high school students of the “university class” attending VII LO (high school, ages 16 – 18) in Krakow. The crucial science classes, especially classes in physics, for the students are conducted by academic teachers and researchers in the field of didactics of physics, mathematics, and computer science, working at the Pedagogical University of Cracow. A substantially extended teaching program of selected science subjects, especially in physics, is provided for these students. Some of the classes are held in laboratories at the University. Moreover, due to several years of work with these students, their intellectual capacity, cognitive abilities, and the level of motivation was well known to experimenter.

It was assumed that if the students are motivated but are not moving around, any possible increased energy expenditure will be mainly a result of cognitive strain, which can manifest with a change in the amplitude and frequency, both respiratory and heart. Additionally, in the case of high levels of motivation, readiness, and involvement in task solving, the frequency and amplitude of the measured parameters can change by means of the standard deviation of pulse and the respiratory frequency. Visible changes in electrodermal conductivity were also expected.

This study, as mentioned earlier, involved monitoring blood volume pulse – BVP, heart rate variability – HRV, and electrodermal activity – EDA.

The research question involved assessing whether motivated learners exhibit higher intellectual effort by monitoring the changes in the aforementioned parameters.

In order to achieve this result, a study was created during which the students alternately solved tasks related to physics which were displayed on screen. The students were tasked with picking one of the available answers to each task by using the mouse. There was no time limit for analysing and solving the tasks.

The tasks solved by the students were separated by musical interludes (Frédéric Chopin – Prelude in E minor, Op. 28, No. 4). The students were asked to stop thinking about the tasks during the interludes and to try and relax while listening. The duration of the interlude after every task was 2 minutes and 40 seconds.

An interview was carried out with every student before, during, and after solving the tasks, the aim of which was to assess their current well-being and stress and motivation levels.

The study also involved eye tracking measurements as well as recording the behaviour and facial expressions of the subjects. The theoretical research tool in the form of questions and tasks is presented in a schematic below. It consisted of the following 16 slides:

- slides 1, 2, 3, 15 – questions on participants’ interest in physics (with value ratings from 0 to 10),
- slides 4, 6, 8, 10, 12,14 – problems in physics,

- slides 5, 7, 9, 11, 13 – video with music for relaxation,
- slide 16 – text: “Thank you for participatiing in the research”.

The content of the tasks is contained in the annex. The figure below illustrates the layout of the tasks in the study. The content of particular tasks is contained in the annex.

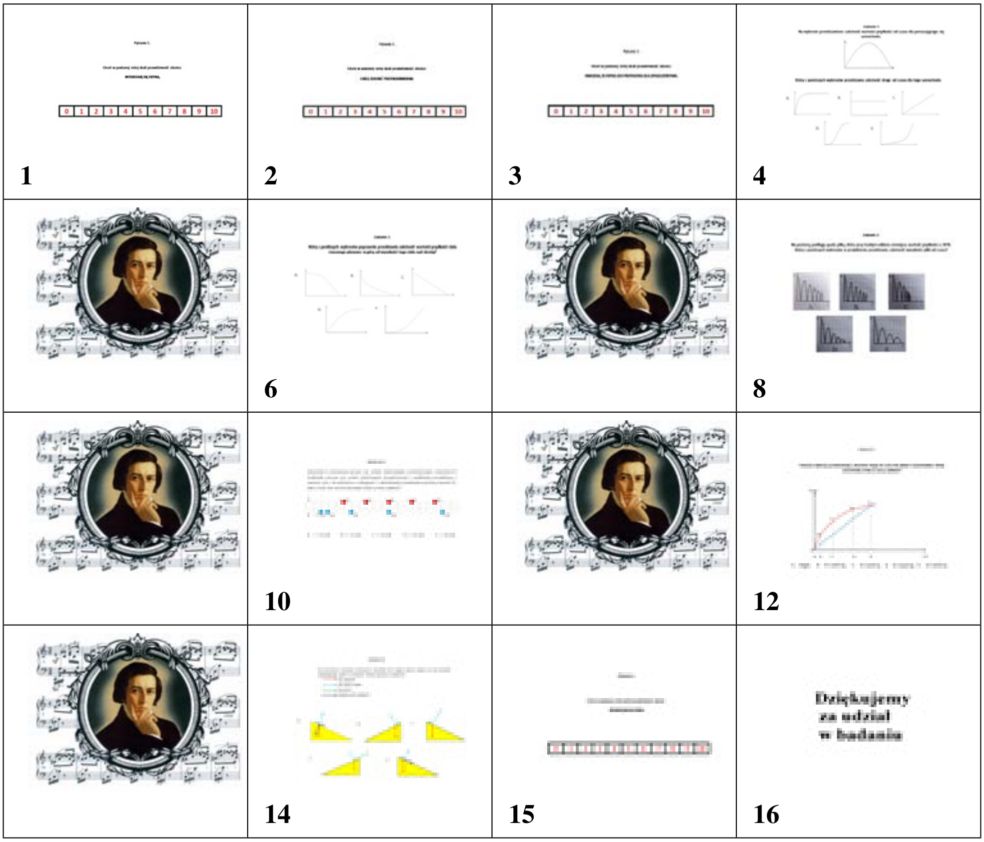


Figure 45: *The layout of the tasks in the study.*

6.3. General remarks regarding the methodology of the analysis of the acquired psychophysiological data

Due to the fact that there was no time limit for solving the tasks, it is not possible to directly compare or overlap the parameter changes of selected subjects. Additionally, a sampling rate of 2048 samples per second as well as recording 14-bit values for every channel, for every person, generated an enormous amount of data which cannot be cited here.

The analysis of the results is carried out under the assumption that, if it is possible to show the relation between the changes of the aforementioned physiological parameters and intellectual effort, then forfeiting the analysis of temporary values and instead presenting the average values will result in a deliberate resignation of a precise description of these changes.

By consciously committing to this simplification, it was assumed that, if it were possible to show these changes in the average values, then an in-depth analysis of temporary values would result in even larger values of these changes and the usefulness of this type of research. It is obvious that by forfeiting averaging in the case of, e.g., choosing a fragment of footage consisting of solving a task related to decision making while analysing eye tracking measurement, the footage will result in having access to data containing even larger values of potential physiological parameter changes.

In order for the comparison of physiological parameter changes of multiple students who solved the same tasks at different paces to be possible, the average values of a given parameter were calculated during the course of the activity, e.g. solving a task, or listening to music.

An in-depth proposal of the methodology of group result analysis, specifically prepared and used for the analysis of the results of the aforementioned empirical studies is shown in paragraph 6.4.1 below.

6.4. Case study – results and analysis

Due to the fact that individual reactions differ in this study and that there is a vast amount of recorded data for all of the 38 subjects, the case study will involve the presentation and analysis of the results of the physiological reactions of one student: Student X.

6.4.1 Blood volume pulse – student X

Figure 46 presents a parameter called the blood volume pulse (BVP). The optical monitoring of the blood vessels of a finger gives information regarding blood flow. The amplitude of a reflected infra-red signal is proportional to the amount of blood located underneath the sensor. The values on the vertical axis are in arbitrary relative units. This allows for control over multiple parameters which provide information regarding e.g. heart rate. ECG (electrocardiography), while more sensitive and accurate as a methodology, is deliberately neglected, as this method is very sensitive to interference signals originating from the muscle activity of the subject. Additionally, the ECG methodology recommends recording the signal in the vicinity of the heart, on the chest. Due to the fact that this would necessitate intruding on the intimacy of the students which could cause additional stress or objection, this methodology is not used here, replaced by a small device called a plethysmograph mounted on one of the fingers on the left hand.

The chart depicts the average BVP values calculated while the student is solving tasks or listening to music. The calculated BVP average provides information regarding the average amount of blood flowing through the finger during the course of the task. Every activity on the horizontal axis is assigned an average BVP value on the vertical axis. In the case of the subject of the case study, the largest amount of blood flow occurred while observing slide no. 3.

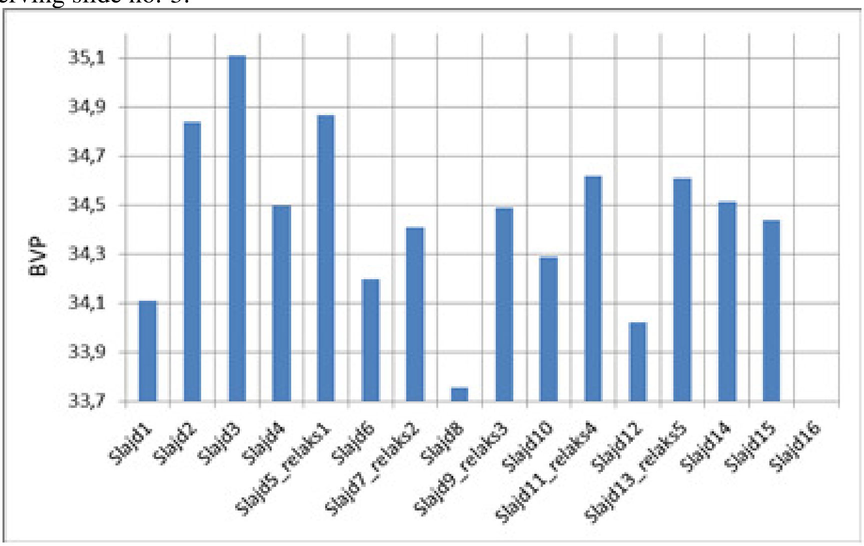


Figure 46: *Blood volume pulse. Student X.*

An analysis of the chart shows a modulation of the average amount of blood flowing through the finger over the course of solving subsequent tasks. The lowest values were recorded while solving the task provided on slide no. 8. There is a noticeable decrease in the average amount of blood flowing through the finger over the course of solving all physics-related tasks. They appear on slides 4, 6, 8, 10, and 12. There were no noticeable changes in BVP while solving task no. 14, which shows that the student was not making a comparable intellectual effort. This is confirmed by an eye tracking analysis of the subject working on the task, showing a very short amount of time spent on analysing the content of the task provided on slide no. 14. This can be interpreted in two ways. Either the student guessed the answer, or knew the task beforehand.

Answering questions regarding interest in physics (slides 1, 2, 3, and 15) and listening to music (slides 5, 7, 9, 11, 13) does not require high levels of cognitive strain, which is why an increase in the average amount of blood flowing through the finger is observed at these times.

These changes can be explained by the fact that the variations of structure of blood vessels, particularly arteries, is closely related to nervous system stimulation. The nerve centre located in the medulla oblongata (Sosnowski 2012) keeps all of the blood vessels shrunken to approximately half their diameter. The degree of stimulation of the sympathetic autonomic nervous system leads to the constriction of blood vessels, which results in lowering the amount of blood flowing through that particular area. The relaxation of blood vessels results in a decrease of the level of stimulation. According to Tytus Sosnowski, maximum stimulation occurs for tasks the difficulty of which is subjectively assessed as average.

The level of cognitive strain and intensive thinking are an enormous influence on the stability of heart rate frequency. It was decided to assess whether it would be possible to observe the average changes of blood flowing through the body (or in this case, the finger) while solving tasks or relaxing.

This required averaging the standard deviation value of the BVP during the course of activities such as listening to music, solving tasks, or answering questions related to the subject's interest in physics. The calculated value is presented on the vertical axis as a point assigned to a particular activity presented on the horizontal axis.

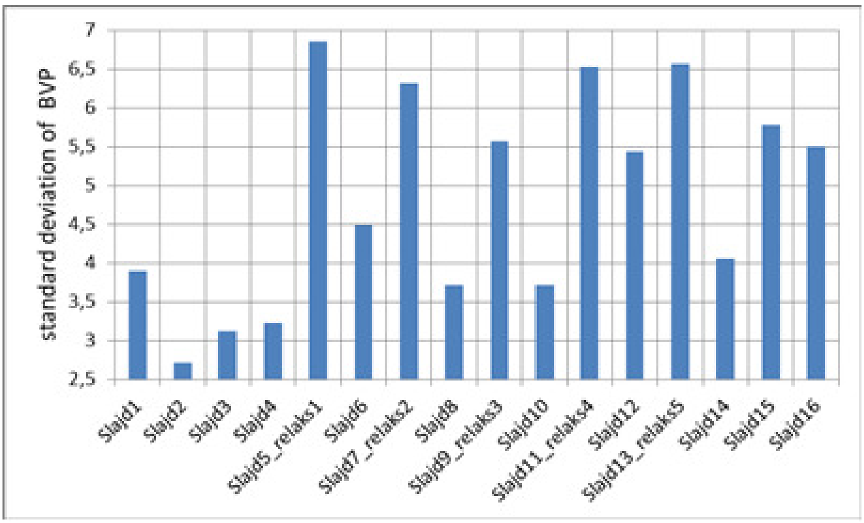


Figure 47: *Standard deviation of blood volume pulse. Student X.*

Analysis of the chart above shows that the highest average values of the standard deviation of BVP are observed while relaxing, listening to music. This is in line with expectations and theoretical knowledge. It means that during this time, the blood flow through the blood vessels of the finger of the student is at its most irregular. This means the student was relaxed and less focused. A much higher level of stability of the average amount of blood flowing through blood vessels is observed while solving problems which require significant cognitive train – tasks contained on slides no. 4, 6, 8, 10, and 12. Despite the lack of significant changes of the average BVP value while solving the task contained on slide 14 shown on the previous chart, which might lead to mistaken conclusions, an analysis of the standard deviation of BVP shows a change in the standard deviation value of BVP. This is a sign of the cognitive strain of the student also being present while solving the task contained on slide 14. The fact that the standard deviation value of BVP at the beginning of the study (slides 1 to 4) is very small may be indicative of the student being highly focused. It can also indicate stress, although high levels of stress would entail vasoconstriction. Analysis of the chart above (Fig. 46: Blood volume pulse. Student X) shows that this is not the case.

6.4.2 Inter-beat interval (IBI) – student X

The basic parameter used to describe heart rate is the pulse. The parameter the changes of which are illustrated on the next chart is called the inter-beat interval (IBI), In other words, it is the time measured in milliseconds between two heartbeats calculated by implementing specialised algorithms analysing BVP changes. Similarly to previous instances, the average IBI value was calculated while the subjects were solving tasks, listening to music and answering questions related to their interest in physics. The average IBI values are presented as points assigned to particular activities.

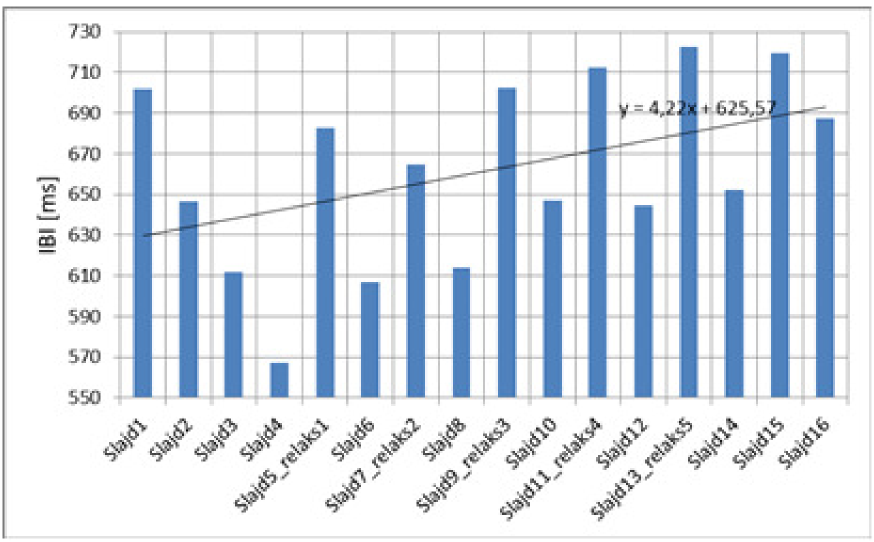


Figure 48: *Inter - beat interval, student X.*

An increase in the average IBI value can be observed over time during the study. It can be assumed that the tasks which require cognitive strain and problem solving will be related to fatigue and an increase over time in the body's need for oxygen and nutrients. The chart shows the opposite. Over time, the pulse of the subject was decreasing. While solving the task contained on slide 4, the average pulse of the subject was approximately 110 heartbeats per minute, whereas while looking at slide 15, the pulse was approximately 84 heartbeats per minute. An analysis of the average IBI values shows a relation. While the student is solving tasks related to cognitive strain and high levels of focus, the pulse increases. A substantial increase in the average amount of time between subsequent heartbeats of the subject is observed while listening to music. The line aligned by the least squares method has a positive gradient (a = 4.22). This could mean that the subject was very focused and motivated to complete the tasks before starting to do so. This could also be an indicator of stress before the study.

The following chart depicts the changes in the average standard deviation values of IBI. The heart rate of the student is at its most regular when solving tasks requiring focus and high cognitive strain. This relates to the tasks on slides 4, 8, 12. Slightly less so on slides 6, 10, and 14. The most irregular pulse of the student was related to leisure activities, i.e. listening to music.

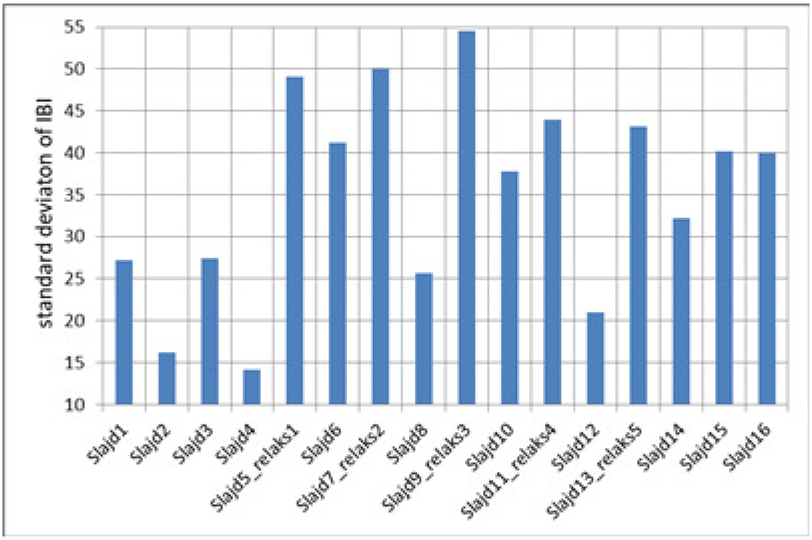


Figure 49: *Standard deviation of inter-beat interval, student X.*

6.4.3 Respiration – student X

Respiration amplitude was measured using a chest strap respiration monitor SA9311M (see: Annex). An increased need for nutrients and significant effort are related to an increased need for oxygen, which should entail an increase in not only the frequency, but also the amplitude of breathing. The following chart depicts an analysis of the change in the average values of the (relative) amplitude of breathing while the student is solving subsequent tasks. Extreme values cannot be assigned to activities related to task solving or relaxation.

Although the average amplitudes of breathing while solving tasks cannot be assigned to any particular activities of the subject, it was evaluated how respiratory amplitudes change while consecutive tasks are being solved by the subject. It can be noted that solving physics-related tasks results in a slightly higher regularity of respiratory amplitudes.

Respiratory frequency changes are one of the simplest indicators of the body's need for oxygen and nutrients. It could be speculated that solving subsequent tasks and cognitive load would be related to elevated needs of the subject's body for oxygen, which would result in an increase in respiratory frequency. The chart shows the opposite. The line aligned by the least squares method has a negative gradient (a = -0.36). This means that the respiratory frequency of the subject decreases over the course of the

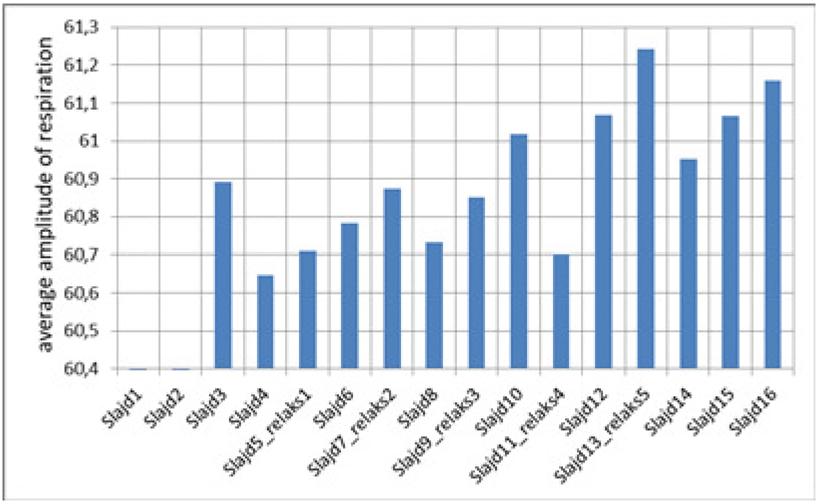


Figure 50: *Amplitude of respiration, Student X.*

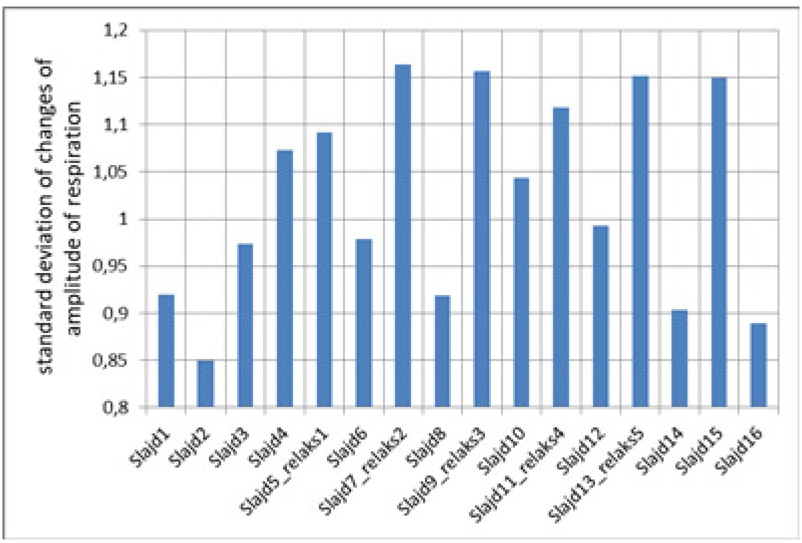


Figure 51: *Standard deviation of amplitude of respiration, Student X.*

experiment. Small, "localised" decreases in the average values of respiratory frequency can be observed during relaxation, whereas an increase can be observed during task solving. High values of respiratory frequency before and at the beginning of the study, decreasing over the course of the study, coupled with low values of respiratory amplitude values can be signs of the student being stressed at the beginning of the study and getting more comfortable over the course of the study (Sosnowski 2002).

The next attempt at analysing breathing-related parameters aimed at assessing whether breathing regularity could be a cognitive strain indicator. The average standard deviation values of respiratory frequency during solving subsequent tasks and relaxing

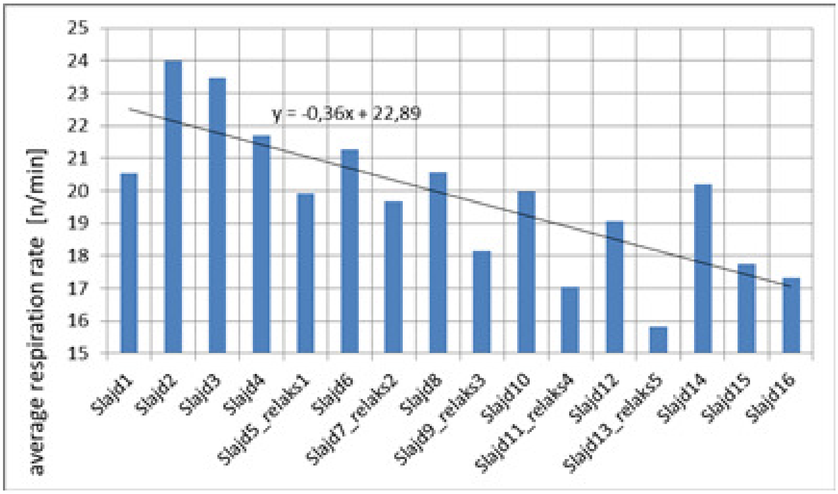


Figure 52: *Respiration rate, Student X.*

were calculated. Graph in the Figure 53 shows these values. The highest irregularity of breathing is observed during listening to music. Solving tasks is related to very regular breathing - slides 4, 6, 8, 10. In an interview conducted after the study, the student said that after completing the task contained on slide 10, he was intensely contemplating on the result while listening to music.

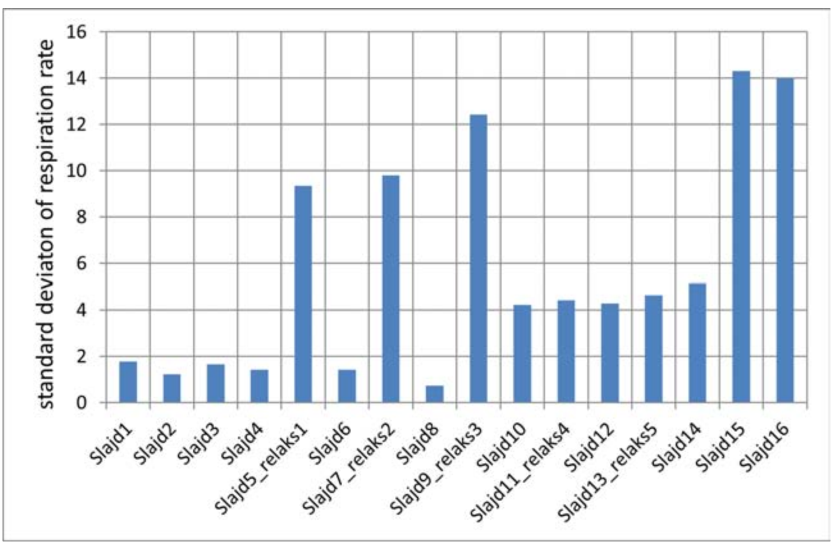


Figure 53: *Standard deviation of respiration rate, student X.*

6.4.4 Skin conductance – student X

An analysis of the average values of electrodermal conductivity shows minor local minima of the average value of conductivity measured during relaxation. It can be observed that the subject exhibited minor increases of the average values of electrodermal conductivity while solving tasks requiring cognitive load.

Despite the ease of measuring electrodermal conductivity, the analysis and interpretation of data is very troublesome. This is mainly due to a lack of a solid theoretical basis and its applications which could be used for meaningful interpretations (Sosnowski 1993).

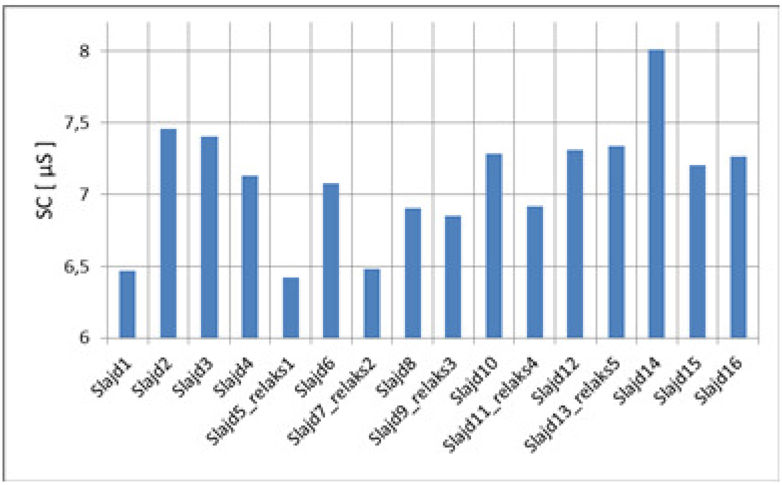


Figure 54: *Changes of the skin conductance, student X.*

An in-depth analysis of the values of electrodermal conductivity and the rate of changes shows a very high rate of changes and their high amplitudes. Which is why it can be assumed that calculating the average values of conductivity for longer intervals will entail a loss of the important information this parameter contains.

The following charts depict instantaneous values of electrodermal conductivity of the subject in particular timeframes of the study. Due to repeating tendencies of changes during both relaxation and task solving, only selected fragments are shown. Additionally, the timeframes were intentionally narrowed in order to even more precisely show the nature of the changes and the pace of the local changes of the S.C. parameter.

The above charts clearly show a fast pace of instantaneous changes of the measured values.

An analysis of the graphs also shows a very interesting relation. The gradient of the line aligned by the least squares method for the graph of the skin conductance of Student X is positive while solving tasks (is it respectively: 0.02; 0.01; 0.04) and negative while relaxing (-0.02; -0.01). The graphs concern timeframes which illustrate the nature of the changes and their pace. A hypothesis can be put forward (which would be worth verifying on a larger group) that studying the monotonicity of a function describing the values of the S.C. parameter could allow for ascertaining the moment when a student is making a decision.

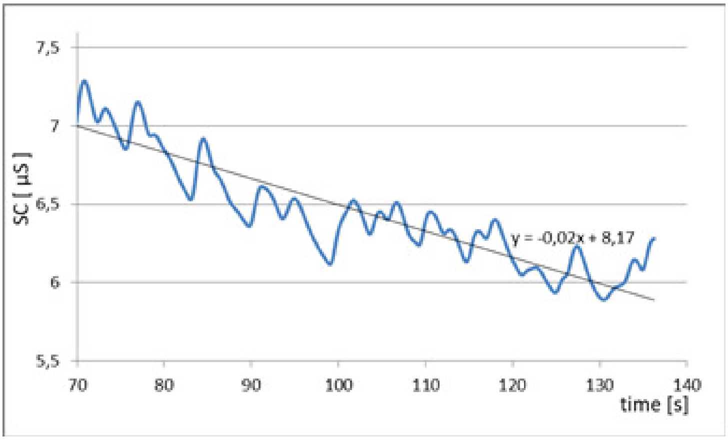


Figure 55: *An excerpt of the graph of S.C. changes for Slide 5 –relaxation 1, Student X.*

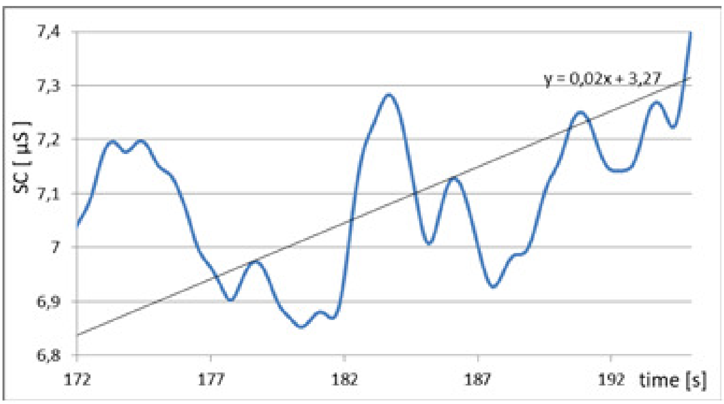


Figure 56: *An excerpt of the graph of S.C. changes for Slide 6 – physics problem, Student X.*

6.4.5 Conclusions

The aforementioned analysis suggests that another interesting research problem in physics education, based on the analysis of the skin conductance parameter, is studying the relation between the value of a gradient of an assigned line with a declared level of stress, motivation and a subjective cognitive strain assessment of the difficulty level of the physics-related tasks being solved.

It is worth it to verify the hypothesis that studying the monotonicity of a function describing the values of the S.C. parameter could allow for ascertaining the moment when a student is choosing an answer.

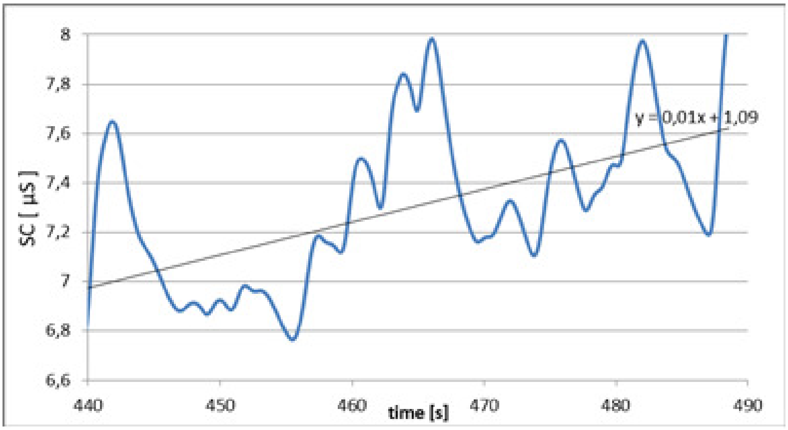


Figure 57: *An excerpt of the graph of S.C. changes for Slide 10 – physics problem, Student X.*

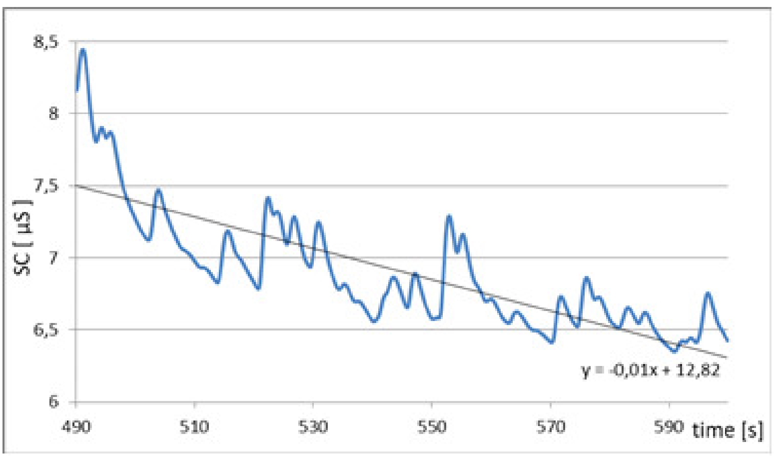


Figure 58: *An excerpt of the graph of S.C. changes for Slide 11 –relaxation 4, Student X.*

6.5. Data analysis for groups of participants

6.5.1 Developing a methodology for group data analysis

The method of biophysical parameter analysis shown above seems the most obvious and correct, as the pace of the changes, as well as their amplitudes, levels, and the type of reaction to stimuli are individual attributes of every person.

As the aim of this study was to assess whether the proposed methods of measurement will find use in practice, at school, during lessons or lectures, one more goal was set regarding an attempt of developing a methodology to analyse group data and finding a way of presenting and analysing data which would allow for comparing the reactions of selected students during task solving.

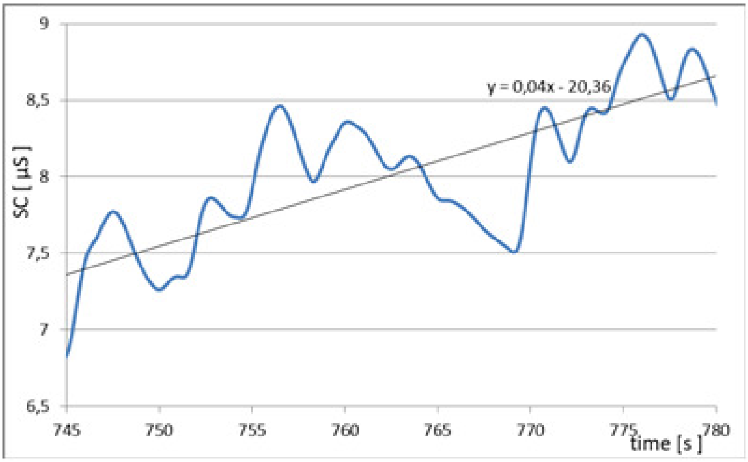


Figure 59: *An excerpt of the graph of S.C. changes for Slide 14 – physics problem, Student X.*

The following group analysis methodology was developed:

1. The average value of the measured parameter was calculated for every type of activity separately, i.e. average values for solving physics-related tasks, followed by listening to music, and answering additional questions (related to interests and career plans related to science).
2. For every person, the average value of the measured parameter over the course of the study was calculated.
3. The relative values of the changes of the measured parameter were calculated as the difference between the average values measured over the course of the task and over the course of the whole study, when compared to the average value of the whole study.
4. The result was given as a percentage.

This form of presentation of the changes of individual values of specific parameters measured for every subject allowed for the creation of a comparison and a summary of the values of relative changes.

6.5.2 Inter-beat interval (IBI)

Graph 60 depicts the relative changes of the average value of the pulse interval for the entire group of students. It is one of the parameters that is easy to measure. An analysis of the IBI changes of the whole group shows an increase of the values of the pulse interval during relaxation and answering questions which did not require a significant intellectual effort.

Solving physics tasks is related to a decrease in the pulse interval, which means increased heart rate. They appear on slides 4, 6, 8, 10, 12, and 14.

Frequency changes of the heart rate of the subjects were also studied. Tytus Sosnowski (Sosnowski 2002) claims that heart rhythm is very stable in task-related situations, such as focusing and solving tasks. It was decided to ascertain whether it would be possible to measure the changes in the stability of heart rate frequency while solving physics-related tasks. The following graph depicts the relative values of the standard deviation of the IBI parameter for a group of subjects. It clearly shows

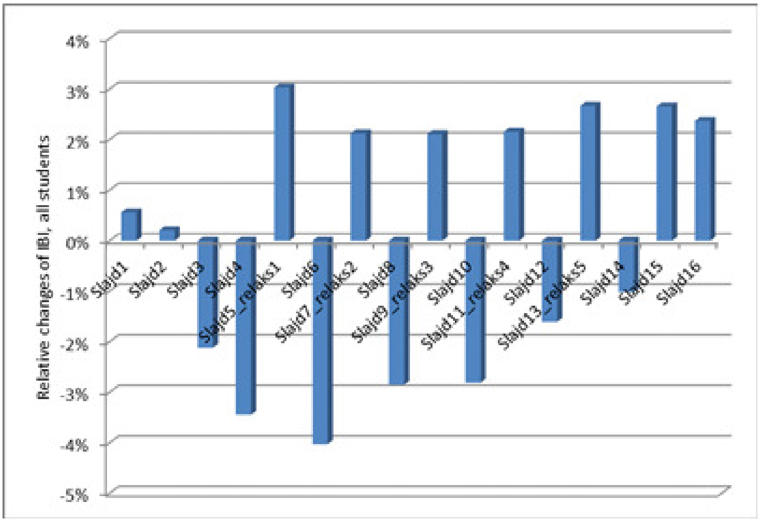


Figure 60: *Relative percentages of IBI changes for the whole group of students.*

a decrease in heart rhythm during relaxation and solving easy tasks. Solving physics tasks entails an increase in heart rhythm, which demonstrates in a decrease in the standard deviation value of IBI.

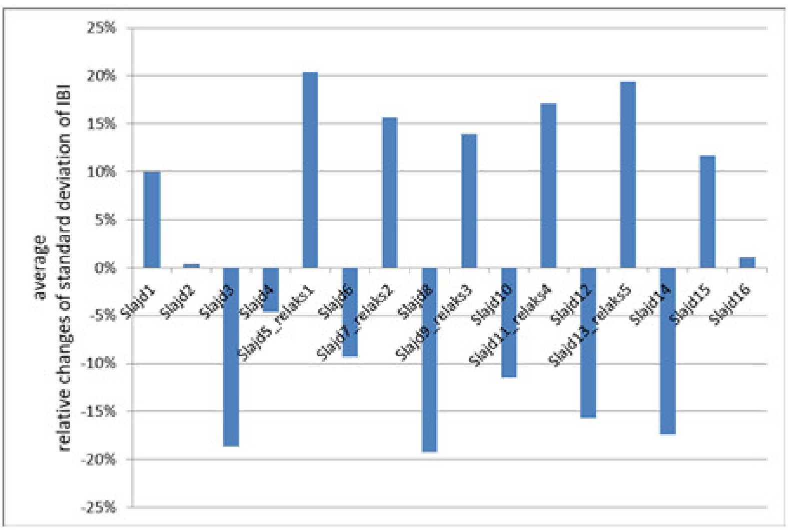


Figure 61: *Relative changes of the standard deviation of IBI for the whole group of students.*

6.5.3 Respiration

Both effort related to muscle activity as well as brain activity are dependent on an increased need for nutrients and oxygen. Everyone knows that movement and running increases the demand for oxygen, which results in an increase in respiratory frequency and amplitude. Knowing that the subjects were asked to not move and only solve tasks during the study, it can be assumed that the increased demand for nutrients will be related to intellectual strain.

Before the study was carried out it was assumed that the respiratory frequency and amplitude of students making an actual effort in solving the tasks will increase over the course of the study due to the effort being made. The following graph presents the results obtained. An analysis of these results shows the opposite of what was assumed. Over the course of the study, the respiratory frequency and amplitude of the subjects decreased. An in-depth analysis of the shape of the graph illustrating the changes in the respiratory frequency and amplitude shows a conclusion that the type of task being solved does not significantly influence the temporary average values of these parameters. Over the course of the study, the average values of the amplitude and frequency of breathing of the whole group decreased as well. The breathing of the subjects became shallow and faster.

As mentioned above, attempts were made at assessing whether the regularity of breathing can be an indicator of cognitive strain. The average standard deviation values of respiratory frequency and amplitude during solving subsequent tasks and relaxing were calculated for the whole group. The following graphs present these values. An analysis of the data contained therein shows that both the value of the average respiratory amplitude and frequency of the group decreased over the course of the study. Solving tasks requiring high amounts of cognitive strain did not result in a temporary increase of these values. The obtained results suggest that over the course of the study, there is a decrease in the respiratory amplitude of the subjects (it is more shallow). An analysis of the average values of the respiratory frequency shows that students breathed less frequently over the course of the study.

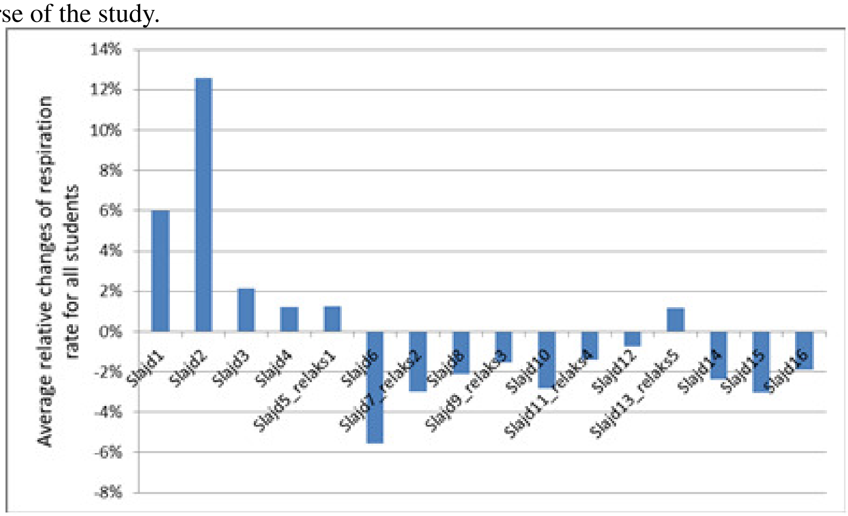


Figure 62: *Average relative changes of respiration for the group of students.*

Tytus Sosnowski (Sosnowski 1993) claims that both the heart rate frequency and respiratory parameters stabilise while focusing, solving tasks or experiencing intellectual strain. According to Sosnowski, breathing gets shallow and measured while solving difficult tasks. In order to verify the hypothesis regarding the changes in respiratory rate

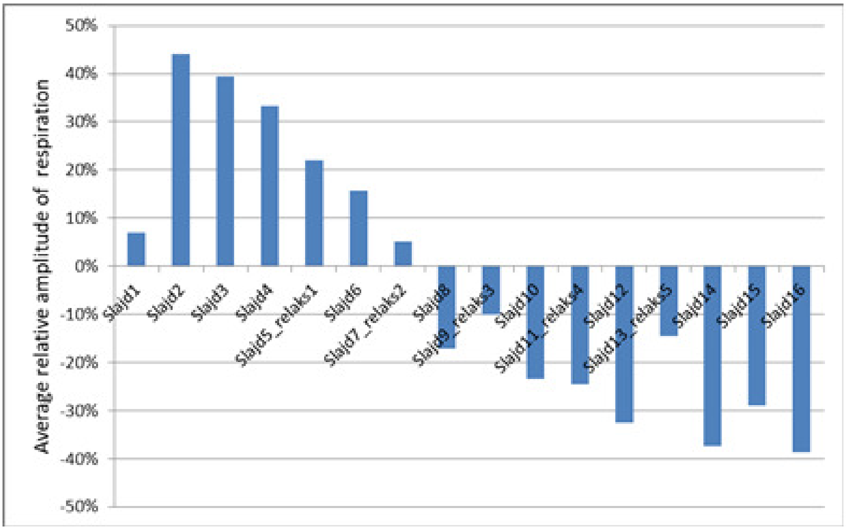


Figure 63: *Average relative changes of respiratory amplitude of the whole group of students.*

stability during solving physics tasks, an attempt was made at analysing the changes of relative standard deviation values of both the respiratory amplitude and frequency of the subjects. The following two graphs depict the results.

The highest respiratory irregularity of the group is observed during listening to music and solving easy tasks, which was also the case when the parameter changes of one particular student were analysed before. Solving physics tasks is related to very regular breathing. Slides 4, 6, 7, 10, 12, and 14 contain tasks during which the subjects exhibited the most stable respiratory frequency and amplitude.

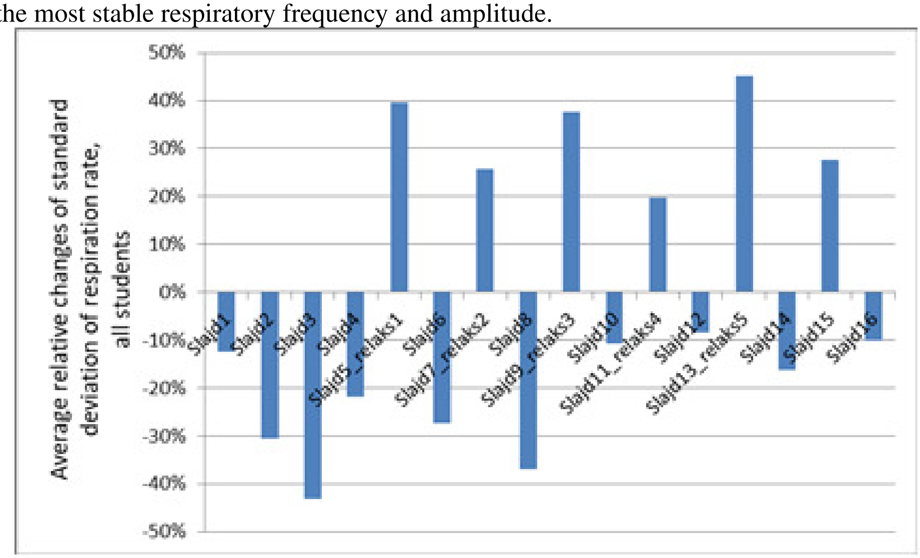


Figure 64: *Average relative changes of standard deviation of respiration rate for all students.*

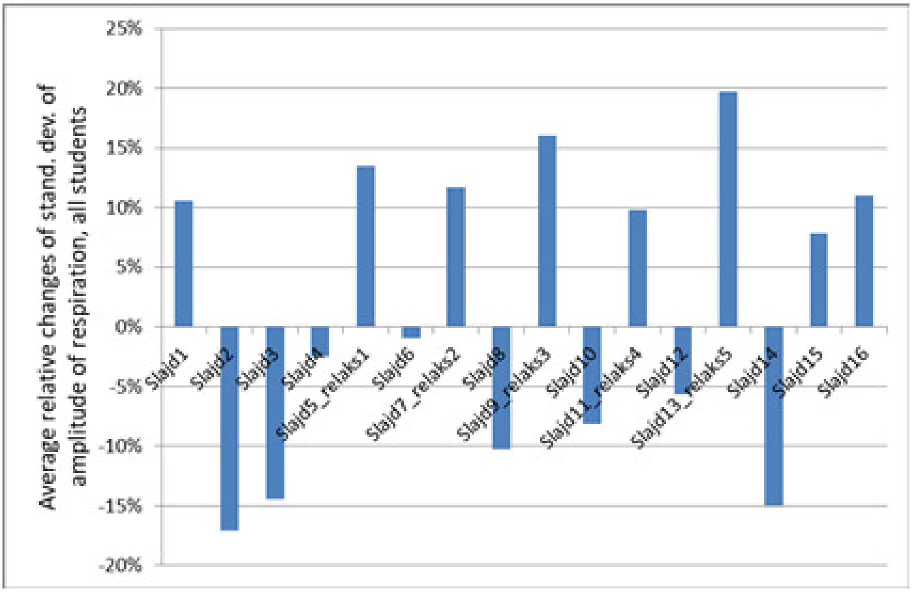


Figure 65: *Average relative changes of standard deviation of amplitude of respiration for all students.*

6.5.4 Blood volume pulse

Many researchers claim that elevated stress levels result in vasoconstriction, (Blix 1974), (Sosnowski 1993), (Carrol 1989), (Weimann 1989), (Sosnowski 2002), Vasoconstriction can entail a reduction in the volume of blood flowing through the limbs. Seeing as using a plethysmograph monitors the propagation of blood and its flow through the blood vesselsof the fingers of the left hand of the subjects, it was attempted to check whether it would be possible to use this device to measure the differences in the volume of blood flowing through the finger of the subjects during task solving. Since it is possible to monitor the pulse, and studying the changes in the frequency values of the pulse to measure the cognitive strain of the subjects was proven useful, it was attempted to assess whether it would be possible to obtaina similar result by measuring the changes in the volume of blood flowing through the fingerof the subjects during task solving.

The average BVP standard deviation value was calculated for this purpose. The following graph depicts the average relative changes in the volume of blood flowing through the fingers of the subjects during task solving. Though there are visible differences e.g. during listening to music, they are too minor to base any conclusions on.

As there were visible changes observed among the subjects in heart rate stability during relaxation and solving physic tasks, it was attempted to assess whether these changes can be similarly measured by studying the standard deviation of BVP observed for specific tasks. The following graph presents the relations. Due to the way the blood flows through blood vessels, their elasticity, disrupted blood propagation through the body due to limb movement, and breathing, the existence of artefacts was assumed. It was assumed that the signal will contain more interference and that the obtained graph can be slightly malformed when compared to the graph depicting the standard deviation of IBI.

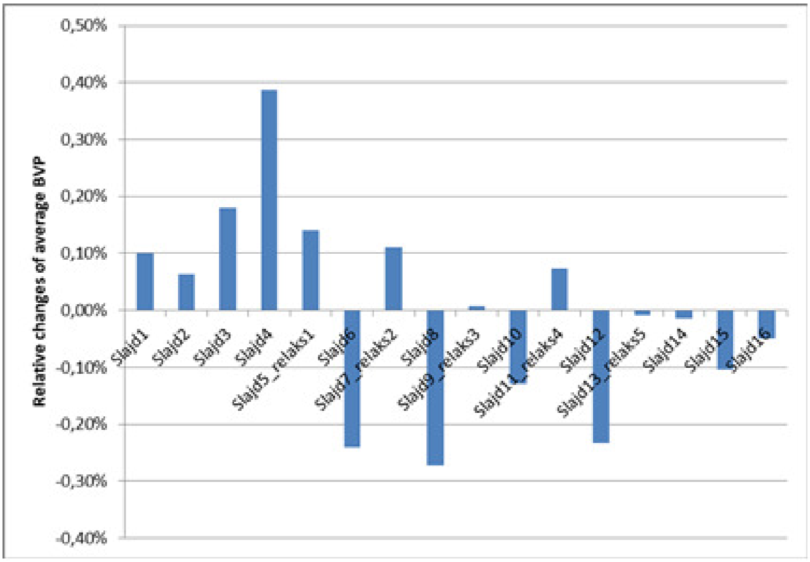


Figure 66: *Relative changes of average BVP for all students.*

Despite the complete change in the approach to using the BVP parameter for heart rate irregularity analysis during subsequent task solving, it can be observed that the highest level of heart rate irregularity, which entails irregular blood flow per unit time, is observed in subjects during listening to music.

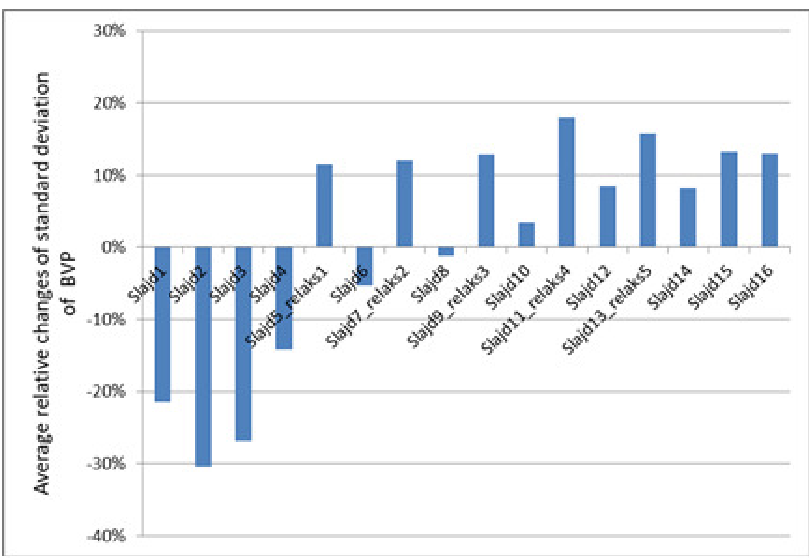


Figure 67: *Average relative changes of standard deviation of BVP for all students.*

6.5.5 Electrodermal activity – skin conductance

Due to the nature and the pace of the changes of electrodermal conductivity of particular subjects, it was initially planned to bypass the analysis and averaging of these values along with a discussion of the results of the whole group, as it seemed to be a methodological mistake which would not result in any useful information.

Though the analysis of the average value of relative electrodermal conductivity values for the whole group of subjects shows a surprising result. A comparison of the shape and the tendencies of change in the graph below (Fig.68.) with the changes in the amount of blood flowing through the finger shown on the graph depicting the relative average changes of BVP shows some similarities.

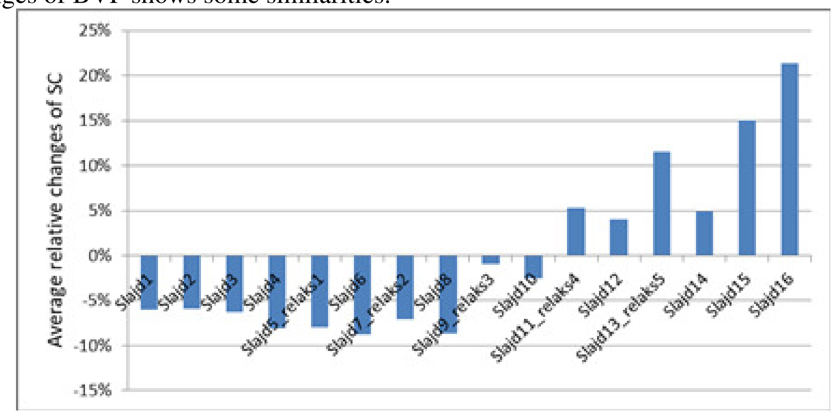


Figure 68: *Average relative changes of skin conductance for all students.*

Although due to very complex psychological mechanisms, interpreting these changes is very difficult. EDA obviously does not exhibit any situational specificity. This means that different quality stimuli can facilitate the same reaction in the subjects as the changes in conductivity would be the same, differing possibly in intensity. According to Edelberg's hypotheses (Edelberg 1970), (Edelberg 1972), a sharp drop in electrodermal conductivity can suggest task readiness, while a slow drop would mean a defensive reaction.

Undoubtedly, the results obtained in this study allow for the proposal of multiple hypotheses, e.g. regarding the relation between S.C. during physics task solving and the declared stress levels of subjects, the relation between the measured electrodermal conductivity and the amount of blood flowing through the blood vessels of the hands of the subjects measured by use of BVP, as well as fatigue during task solving, and the motivation for solving them. This, however, will require further, more in-depth studies on a bigger study group.

6.5.6 Conclusions

Despite a number of restrictions stemming from the calculation of average values, which omits a lot of important information regarding individual changes, the usefulness of this method has been demonstrated in the context of simultaneous monitoring of a larger group of subjects and the possibility of drawing conclusions based on the average values of the reactions of a group of people in real-time.

[82]

These conclusions can be facilitated for future use in physics education. A good example would be a lecturer being able to measure cognitive strain and stress in real-time. This could be possible by creating dedicated software which would analyse and visualise data in real-time. Such an implementation of these methods coupled with PRS (Personal Response System) devices created by one of the authors would allow for immediate reaction and modificationof lecture scenarios, adapting them to the needs of the group while the lecture is still ongoing, as opposed to a significantly delayed reaction in the case of interviews and surveys.

7. CHAPTER – EXPERIMENT 2. ELECTROENCEPHALOGRAPHIC MEASUREMENTS

7.1. Aims of the research

This stage of research consisted of monitoring, measurement and an in-depth analysis by EEG measurements of the frequency and amplitude changes of brainwaves.

The aim of this study was to assess the individual electroencephalographic reactions of students, i.e. monitoring their brain activity, during task solving and relaxation. An attempt was made to get to know the specifics of EEG measurements and adapt such measurements to school conditions.

Assuming the selected study group consisted of talented individuals with an aptitude for science, it was attempted to assess whether this type of measurement could acquire data related to stress, signs of fatigue, or differentiate between levels of cognitive load during task solving.

An additional assumption was assessing and acquiring the optimal value of focus time while solving tasks with the difficulty level tailored to the particular age group.

7.2. Hardware

Research was carried out entirely in Neuroscience Laboratory at the Faculty of Mathematics, Physics and Technical Sciences at the Pedagogical University of Krakow. The room was furnished with specialised furniture, especially the chair which was designed to ensure a high level of comfort of the subjects during the experiment and allow for the body to be in such a position that muscle activity would be reduced to a minimum. Additionally, the room also had air conditioning and modified temperature stabiliser systems. Proper humidity had to be maintained in order to minimise the amount of necessary blinking. This is a very important factor in the quality of the EEG signal. The study made use of a 32-channel EEG device made by Mitsar along with a 32-electrode headgear with passive gel electrodes mounted.

7.3. Software

The study made use of WinEEG software made by Mitsar. This software, aside from advanced brainwave spectrum analysis capabilities, contains an electrode impedance control module. To ensure proper signal quality during the study, the impedance value of the electrode – skin contact was set to not exceed (...) The manufacturer states that these types of electrodes coupled with a low impedance value of the electrode – skin contact do not require the measurements to be taken in a Faraday cage. For constant electrode impedance control, a built-in WinEEG module was used, which not only illustrates the way of mounting the electrodes, but also constantly controls the impedance level of every electrode. The electrodes were mounted in accordance with the 10-20 system described in the theoretical part of this work.

The figure below depicts the window of the WinEEG module controlling the impedance value of selected electrodes and illustrating the placement.

Figure 69: *EEG Mitsar.*

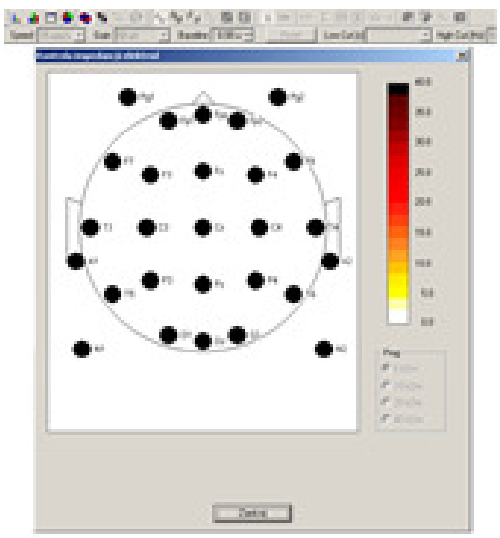


Figure 70: *EEG electrode impedance control – WinEEG software.*

Due to the need of maintaining the lowest possible impedance values of the skin-electrode contact, the study made use of specialised conductive gel for EEG electrodes while maintaining constant control over the impedance levels of every electrode.

Figure 71: *Preparing for the study, applying gel to the electrodes, the way of mounting the headgear in order to restrict the movement of the students.*

The window shows an example EEG measurement recorded during the study.

Due to the very high sensitivity and requirements of the quality of the signal, the subject had to remain still, try not to speak, and also swallow and blink as rarely as possible.

7.4. Sampling, research problems, organization and conduct of the study

In Experiment 2 participated 36 high students attending the "university class" at the VII LO in Krakow who took part in Experiment 1. They had to indicate using the mouse click the correct answers of physics problems, which were shown at the computer screen separately.

Aside from the electroencephalographic measurement, every subject took part in an detailed interview, the aim of which was to assess the well-being of the students, as well as their feelings, a subjective assessment of the difficulty level and their motivation. There was no time limitfor solving particular tasks. Every student was free to take as much time as they needed. After an approximately 30-minute preparation coupled with the interview, every subject was to solve a series of physics tasks separated by two-minute music segments, during which they were asked to relax and cease thinking of the tasks and how to solve them.

The figures below depict the slides containing the tasks. After every task, the students listened to a Chopin prelude.

7.5. Methodology of result analysis

Seeing as the study, including preparation time, took approximately an hour, swallowing, blinking, or doing minor movements could not be avoided. This generated a vast amountof artefacts in an EEG reading. Despite a very thorough artefact correction process as well as the usage of a specialised software module for artefact removal, interference related to these types of situations could not be avoided.

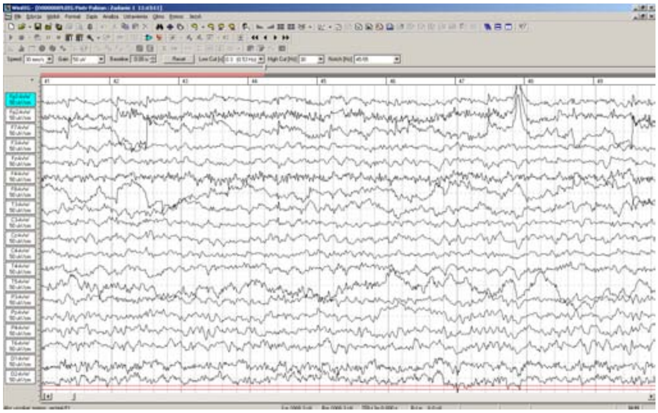


Figure 72: *Window of the WinEEG brainwave measurement software, coupled with an excerpt of the measurements of one of the students.*

As an example of how much interference can muscle activity cause, examples of artefacts caused by blinking are presented below.

Due to the specificity of the EEG signal and the presence of artefacts, presenting average values is omitted from here on despite a very thorough correctional procedure. Thirty-second fragments of brainwave readings without artefacts were chosen for brainwave analysis related to subject activity. The fragments in question were chosen by how well they describe the analysed activities, i.e. during relaxation time, the most suitable fragments were in the second half of the reading, and during task solving the fragments were located between the 40% and 80% points of the total duration time of task solving.

The analysis of the usefulness of this tool in physics education was planned in the methodology of the case study. Qualitative methods are fully justified in terms of studies making use of EEG measurements due to the individual differences theory (Strelau 2006) and a very wide scope and specificity of the reactions of the subjects.

Presented below is a fragment of the study results analysis which shows a possibility of using EEG devices in physics education. As mentioned above, the study made use of EEG signal strength analysis expressed graphically in a logarithmic scale.

The subjects were to answer questions displayed in front of them by choosing one of the possible answers with the mouse. It is worth noting that this was the only possible wayof responding to the questions in the study due to the least amount of muscle activity as possible, which would generate the least amount of artefacts in the EEG reading. A specially-designed Visual Basic application recorded which answer was chosen along with the response time, which was not limited, and proceeded to display the next image.

The measured EG signal was subject to processing in such a way as to select two frequency bands.

The alpha waves are neural oscillations in the frequency range from 8 to 13 Hz. It was assumed in accordance with the facts stated in the theoretical part of the work, that they correspond to states related to a lack of increased intellectual activity and can be signs of losing focus or fatigue.

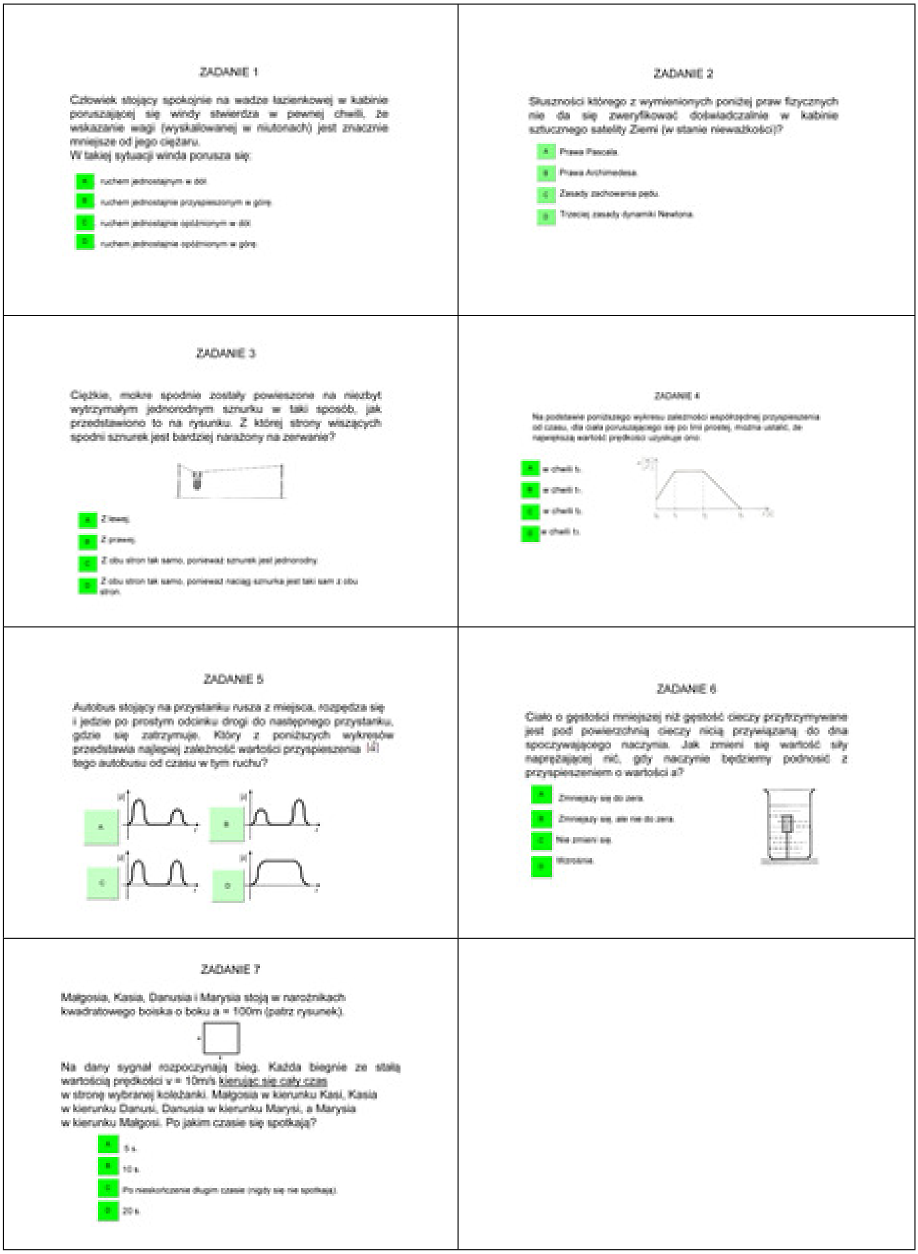


Figure 73: *The research physics problems.*

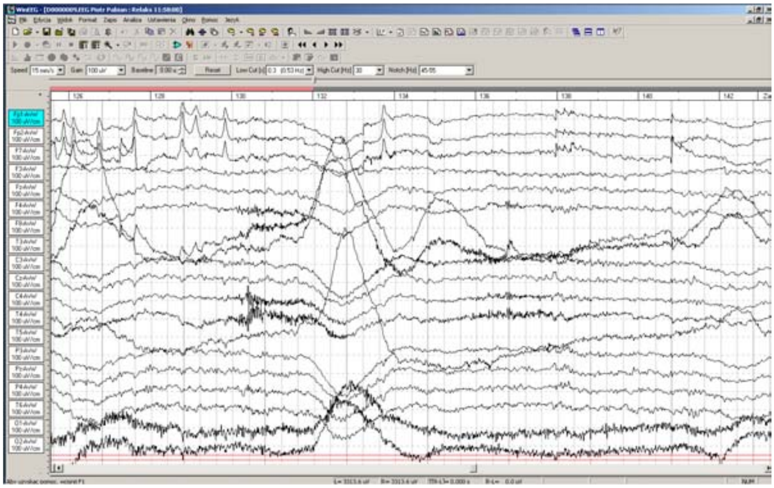


Figure 74: *Example of artefacts in an EEG reading caused by blinking.*

The beta waves band is separated into the following sections: low beta waves (12-15 Hz), proper/middle beta waves (15-18 Hz) and high beta waves (19 Hz and up). Beta waves are linked to wakefulness and focus. Low beta waves are linked to effort, and high beta waves to tension, fear, stress, and anxiety. Beta waves occur during focus, when the brain is set on consciously receiving external stimuli with all senses. This type of neuronal activity is a part of everyday activity of the cerebral cortex of a human, as well as sensory perception and mental effort. Small-amplitude beta waves occur during focus, when the brain is set on consciously receiving external stimuli with all senses. This shows involvement of the cerebral cortexin cognitive activity. A decrease in alpha wave amplitudes often occurs as well, defined as an alpha block, and is most often a sign of focus or sensory stimulation.

7.6. Results and their analysis – case study

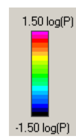
The following graphs show the study results of Student Y during solving physics tasks alternately with listening to a fragment of Frédéric Chopin's Prelude in E minor, Op. 28, No. 4 for 2 minutes and 40 seconds. These graphs are a visualisation of brainwave amplitudes. They are grouped in such a way as to first present a comparison of the changes of brainwave amplitudes of the subject during task solving and during relaxation involving listening to music immediately after giving an answer to a particular task.

The table below depicts time spent on solving particular tasks and the answers chosen by the student.

Table 3. *Time spent on solving the tasks and the answers chosen by the Student Y.*

Task Number	Time of work	Answer
1	4 min 15 sec	D
2	2 min 20 sec	A
3	3 min 40 sec	A
4	1 min 50 sec	D
5	7 min 10 sec	C
6	2 min 20 sec	D
7	4 min 10 sec	C

EEG spectral power map for frequency bands of selected brainwaves.

Key: *Value of brainwave signal expressed as a logarithm of the signal power value.*	

Work on Task 1

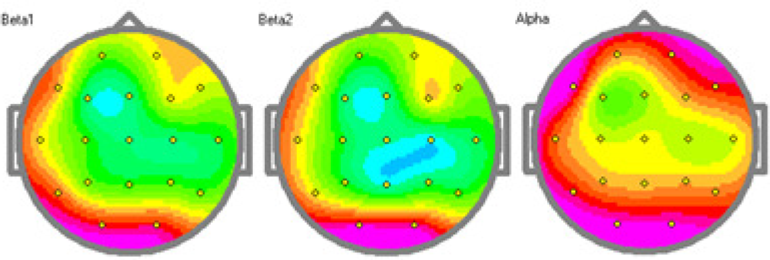


Figure 75: *Alpha, beta 1 and beta 2 brain waves signal while solving Task 1.*

While solving task no. 1, there are big amplitudes visible in both alpha and beta wave ranges of the EEG measurement. A clear interpretation would be challenging without the additional information regarding the subject gathered during the interview. The approximately 30-minute preparation consisting of attaching the electrodes and injecting them with conductive gel using a syringe with a thick needle was unpleasant to the subject and caused discomfort. The student was stressed, which he indicated during the interview. High values of alpha wave amplitudes in the frontal region could stem from artefacts caused by blinking despite thorough correction. Approximately four minutes have passed before the student chose an answer. The answer chosen was option D.

Relaxation after Task 1

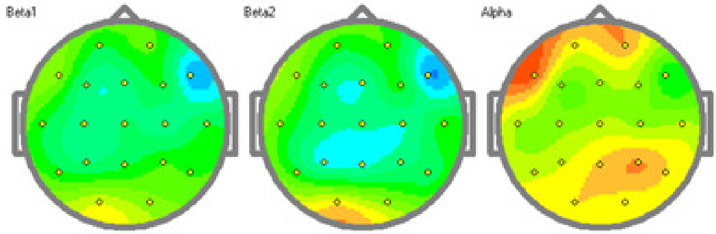


Figure 76: *Alpha, beta 1 and beta 2 brain waves signal during relaxation time after Task 1.*

The EEG reading shows significant changes visible both in alpha and beta wave amplitudes. The student was very focused. He was visibly awaiting the next task. It was difficult for him to relax. This is visible in the lack of both significant beta and alpha wave activity, the presence of which could indicate a state of relaxation or fatigue.

Work on Task 2

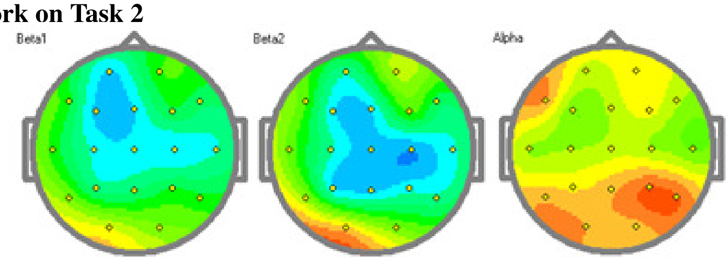


Figure 77: *Alpha, beta 1 and beta 2 brain waves signal while solving Task 2.*

An increase in beta wave amplitude values was observed during solving task no. 2, especially beta2 in the occipital region. The student solved the task in 2 minutes and 20 seconds.He answered A. A significant increase of alpha wave amplitudes was also observed, which could indicate a temporary lack of focus or slight fatigue.

Relaxation after Task 2

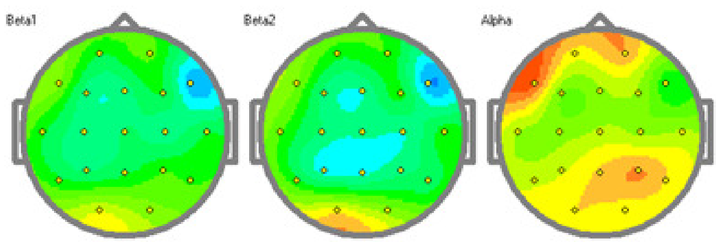


Figure 78: *Alpha, beta 1 and beta 2 brain waves signal during relaxation time after Task 2.*

While listening to music after task no. 2 there is a decrease in beta wave amplitudes in the occipital region as well as a significant decrease of alpha wave amplitudes there. The student was trying to relax and listen to music. There was an increase in alpha wave amplitudes in the frontal region.

Work on Task 3

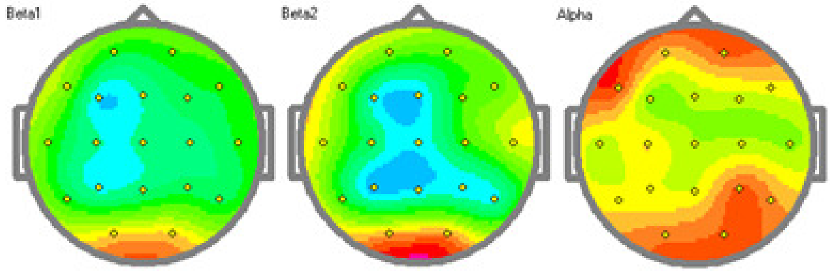


Figure 79: *Alpha, beta 1 and beta 2 brain waves signal while solving Task 3.*

The student then solved task no. 3. It took him 3 minutes and 40 seconds. He chose option A. There was a significant beta wave amplitude increase in the occipital region. It was accompanied by an alpha wave amplitude increase in both the frontal and occipital regions. The increase in alpha wave amplitudes in the frontal region could have been caused by squinting during intensive thinking before giving an answer.

Relaxation after Task 3

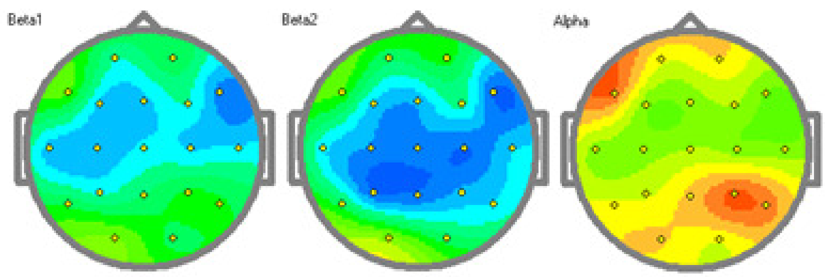


Figure 80: *Alpha, beta 1 and beta 2 brain waves signal during relaxation time after Task 3.*

During listening to music after giving an answer to task no. 3, the EEG reading showed a significant decrease of beta wave amplitudes in the occipital region. There was also a decrease in alpha wave amplitudes. The student tried to relax. He indicated that the stress present from before the study begun is starting to fade away.

Work on Task 4

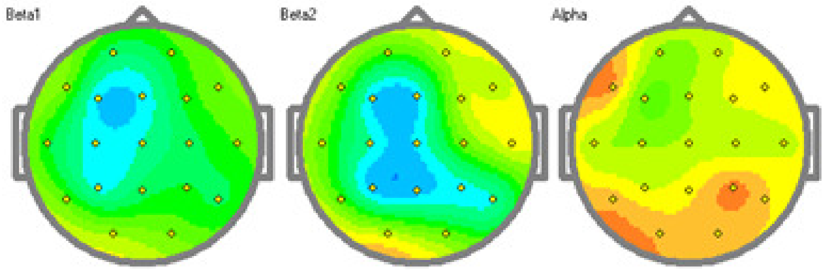


Figure 81: *Alpha, beta 1 and beta 2 brain waves signal while solving Task 4.*

The student solved task no. 4 in 1 minute and 50 seconds, choosing option D. There was no significant increase in beta wave amplitudes while solving this task. There was a minor increase in beta2 wave amplitudes in the occipital region. A minor increase of beta wave amplitudes when compared to the state of relaxation after solving task no. 3 shows a readiness to focus as well as alpha wave suppression. The student described this task as easy in the interview.

Relaxation after Task 4

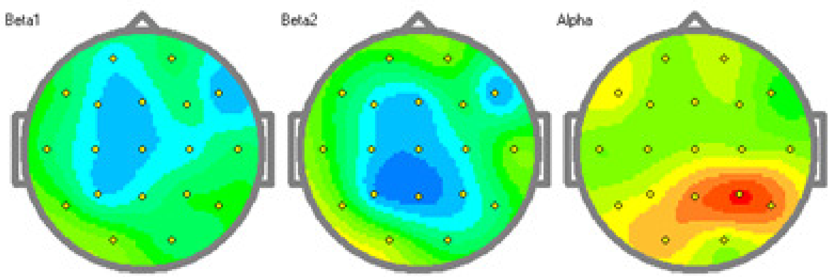


Figure 82: *Alpha, beta 1 and beta 2 brain waves signal during relaxation time after Task 4.*

During relaxation time after task no. 4 there was a minor decrease of beta wave amplitudes in the occipital region. A significant increase in alpha wave amplitudes occurred as well,in a specific location, which could indicate lack of focus and a state of relaxation. The student did not seem anxious, looked calm as he tried to relax.

Work on Task 5

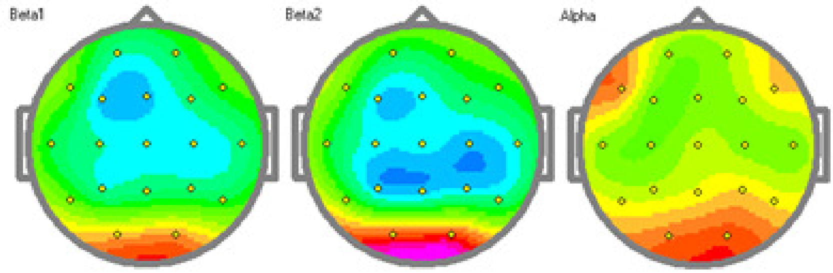


Figure 83: *Alpha, beta 1 and beta 2 brain waves signal while solving Task 5.*

The time spent on solving task no. 5 was 7 minutes and 10 seconds. Option C was chosen. The EEG measurement showed a significant increase in beta wave amplitudes in the occipital region. A visible increase in alpha wave amplitudes in the occipital region occurring in tandem with very strong beta wave amplitudes can indicate fatigue. The student described this task as very hard during the interview. The prolonged amount of time spent on this task can attest to that. The very intensive occipital beta waves visible in the EEG reading could signify very high amounts of cognitive strain.

Relaxation after Task 5

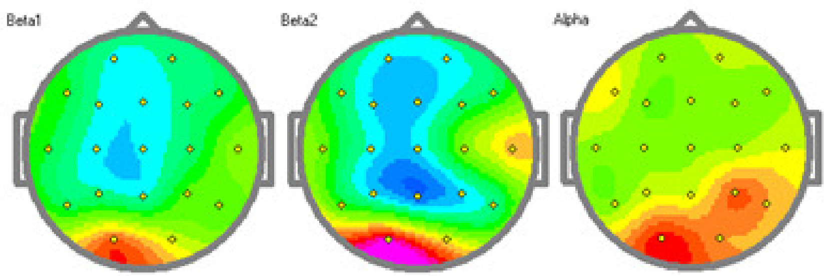


Figure 84: *Alpha, beta 1 and beta 2 brain waves signal during relaxation time after Task 5.*

There was no significant decrease in beta wave amplitudes in the EEG reading during listening to music after solving task no. 5. There were alpha waves visible, which could indicate fatigue. When the student was asked to describe what he had felt while listening to music, he admitted to intensely thinking about the task, trying to verify whether he answered correctly.

Work on Task 6

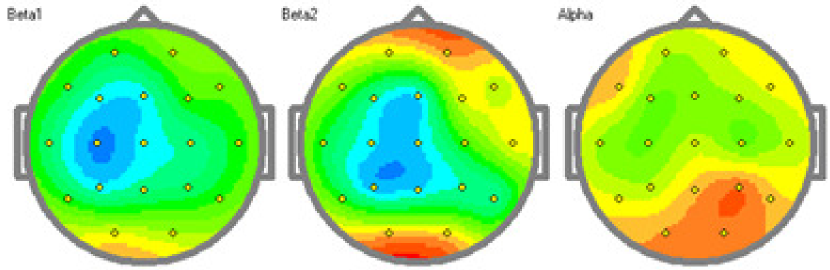


Figure 85: *Alpha, beta 1 and beta 2 brain waves signal while solving Task 6.*

The time spent on solving task no. 6 was 2 minutes and 20 seconds. Option D was chosen.The student described this task as easy. The EEG reading confirmed the student's assessment. The beta wave amplitudes in the occipital region were significantly smaller than during the previous task. The presence of alpha waves could indicate fatigue.

Relaxation after Task 6

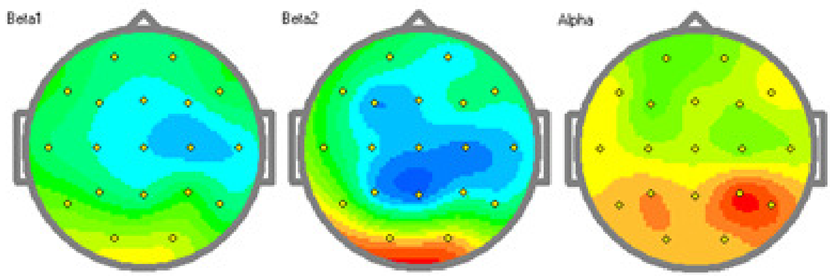


Figure 86: *Alpha, beta 1 and beta 2 brain waves signal during relaxation time after Task 6.*

The presence of beta waves in the occipital region could indicate the mental effort of the student and thinking about the answers. Alpha waves visible alongside beta waves could indicate fatigue.

Work on Task 7

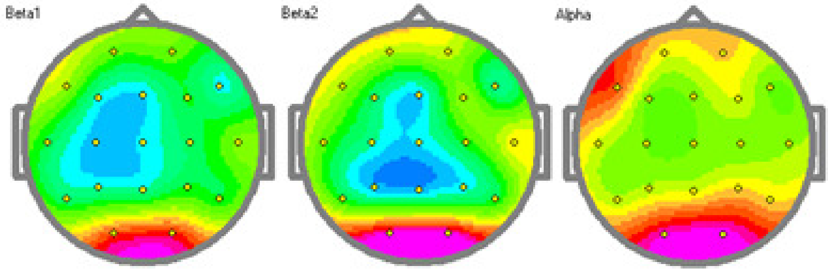


Figure 87: *Alpha, beta 1 and beta 2 brain waves signal while solving Task 7.*

The time spent on solving task no. 7 was 4 minutes and 10 seconds. Option C was chosen.The EEG reading of the occipital region showed very high amplitudes of both beta waves, which could indicate high mental effort, as well as alpha waves, which could indicate fatigue. The student described this task as hard during the interview.

Relaxation after Task 7

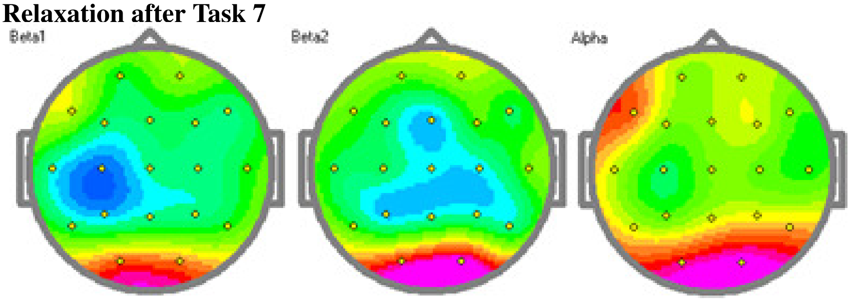


Figure 88: *Alpha, beta 1 and beta 2 brain waves signal during relaxation time after Task 7.*

Even after solving task no. 7 and listening to music, the occipital region still showed very high amounts of beta and alpha waves. Such increased activity of brainwaves is most probablyan electroencephalographic image of very intensive thinking. Following the study, the student confirmed intensely thinking about the previous task.

7.7. Summary

The subject confirmed in an interview conducted after the study that, during listening to music, he twice thought of whether he properly solved the tasks, which he described as hard. Tasks 5 and 7 were identified as such. An analysis of the EEG reading of the relaxation period occurring after tasks 5 and 7 shows the presence of beta waves. It is possible that the subject was tired while thinking of how he solved the tasks, which could be indicated by the presence of high-amplitude alpha waves. A very high-value signal of both alpha and beta waves occurring while solving the first task is related to high amounts of motivation and stress indicated by the subject. Solving the first task directly followed by listening to music caused the subject to calm down, which can be observed on the figure depicting his condition during relaxation time after solving task no. 1. A lack of high amplitudes of both beta and alpha waves in the EEG reading indicates that the subject was in control of his stress and motivation levels. Very intense suppression of alpha waves could indicate that the subject was in a wakeful state, not yet fatigued, but also not relaxed.

The student described tasks 4 and 6 as the easiest in the interview. The EEG readings show the lowest intensity of beta wave activity precisely during these tasks. By analysing the time spent on solving the tasks, it can be observed that the student spent the least amount of time on solving physics-related tasks.

Tasks 5 and 7 were identified as the most difficult by the subject. The EEG reading of the brainwaves of the subject show the highest amplitudes of both beta and alpha waves during these tasks. Lack of alpha wave suppression alongside the presence of high-intensity beta waves could indicate fatigue.

7.8. Conclusions

Due to a significant difference in both alpha and beta wave amplitudes in the EEG reading, drawing conclusions regarding the fatigue of the students requires in-depth research.

Due to lack of experience, low amount of performed electroencephalographic readings, small number of EEG measurements taken for the same person in different situations coupled witha very in-depth interview, no detailed conclusions regarding the optimal time spent on solving tasks in a given study group can be drawn yet.

Without any additional interviews, it is difficult to differentiate between states of fatigue and muscle activity of the subject in the EEG reading. This is why the usefulness scopeof the method as well as the restrictions stemming from its implementation are presented below.

An analysis of the available literature coupled with the results of the study allow for the conclusion that EEG is one of the best ways of recognising the cognitive activity of students. It is worth noting that the study should not consist of only one EEG reading. The most beneficial in terms of acquired information regarding the cognitive activity of students would be multiple EEG readings per person.

An additional aim was to assess whether it would be possible to use the heavily-advertised mobile EEG devices at school, in lesson or lecture conditions. A number of manufacturers advertise their products as testing systems, also for scientific research. An example of thisis Mindwave Mobile (source: www.neurosky.com).

> *As the world's first brainwave-reading device for iOS and Android platforms, the new MindWave Mobile headset is evolved for today's mobile user and communicates via Bluetooth.*
>
> *MindWave Mobile uses ThinkGear technology to read the intensity of the wearer's brainwaves via one sensor on the forehead and a ground and reference contact point positioned on the ear. By detecting mental states (such as concentration and relaxation) they allow the wearer to interact with technology in ways that were once thought to be improbable outside of a research environment. This makes it possible for a computer to read your mental states and provides people with a new level of deep insight into themselves. The headset can read NeuroSky's proprietary*

algorithms, Attention (Focus) and Meditation (relaxation), the power spectrum bands (Apha, Beta, Theta, Delta and Gamma) and the raw brainwave commonly used by researchers and universities for in-depth research applications. For more scientific details on brainwaves and EEG technology (Electroencephalography) visit Wikipedia EEG

Retrieved from: http://press.neurosky.com/MindWave.html

Figure 89: *MindWave, (http://store.neurosky.com/products).*

The use of such devices was considered in the planning phase of the development of the methodology and the selection of measurements and devices to be used for this purposein a classroom environment. Their low price, i.e. approximately €150, and ease of use are additional advantages.

However after conducting multiple studies using professional EEG devices, it can be said with certainty that the use of the aforementioned mobile devices in a classroom environment would generate data that would not have much to do with EEG readings. It is obvious that these devices could not be used scientifically. The use of such devices could be compared to an attempt at recording sound with the microphone situated on a busy motorway.

Conducting studies with the use of such devices creates multiple technical and organisational difficulties. To properly conduct this type of study, a muted room is necessary, as well as ensuring that the proper conditions for the subjects are met, which would allow for refraining from muscle activity, movement, speaking, blinking, or swallowing. Due to the very high sensitivity of the device, as well as very low amplitude and signal strength, the procedures have to be followed rigorously during the study.

This method has other disadvantages, which are presented on graphs. Picking such a short fragment of time spent on solving a task can be related to an accidental loss of focus or the subject taking a break while solving the task. While listening to music, the subject can, instead of relaxing and refraining from thinking about the tasks, intensely think about potential mistakes made, and the way the previous task was solved. An analysis of the signal requires a very precise description of the course of the study, preferably in the form of camera recordings of the face and body posture of the subject. An in-depth analysis of the recording can allow for precise artefact and result correction.

8. CHAPTER – EXPERIMENT 3. EYE-TRACKING RESEARCH

8.1. General information on Experiment 3

8.1.1 Location and participants of the research

The research was carried out in the Neuroscience Laboratory at the Institute of Physicsat Pedagogical University of Cracow.

The room has air conditioning and temperature stabilising systems. In order to ensure identical conditions for all subjects, the light levels and artificial lighting intensity were fully controlled during the study. Due to the eye tracker infrared illuminators, a modified heating system was used in the room, allowing for omitting radiator use. Light sources emitting marginal amount of infrared radiation were also used.

8.1.2 Hardware

An SMI ultra-high speed 1250 Hz eye tracker was used in the study. Due to the large amount of data and the fact that the study did not need such a recording speed, the frequency of recording the position of the pupil was reduced from 1250 Hz to 500 Hz. This means that the position of the eye of the subject (X and Y coordinates on the screen), as well as the width of the pupil and specific fixation and saccade parameters were recorded 500 times a second.

Figure 90: *Eye-tracker SMI Hi-Speed 1250^{TM} in laboratory IF UP in Krakow.*

ViewX^{TM} software was used for hardware control, and Experiment Center^{TM} was used for the recording process and for carrying out the study. Before starting the calibration process,the subjects spent a few minutes in the room for their vision to adapt to the lighting conditions. This was done in order to ensure the reliability of the measurement of the width of the pupil during the study. Before every measurement, a 13-point calibration and validation of the device was performed. The established calibration error margin was set to half a degree or less.

During the measurement, the head of the subject was still, which, on the one hand, is a slight impediment, but, on the other hand, allows for very precise measurement of the position of the eye. There were difficulties related to the radius of the curvature of the cornea significantly deviating from the norm in the subjects. There was also interference related to mascara use,as well as the subjects wearing glasses and contact lenses. In the case of calibration difficulties and lack of possible correction of the difficulties, such subjects were eliminated from the study.

8.1.3 Software

SMI Experiment Suite™ 360 software (presented above) was used, though with a differences due to using the newest available version of the suite, in which specific parts of the study were carried out by the following applications:

Design - SMI Experiment Center™ 3.4,
Recording - SMI iView X™,
Analysis - SMI BeGaze™.

8.1.4 Participants of the research

103 people were invited to take part in the study. This includes: 24 second year students from one of the high schools in Cracow, 66 students from the Pedagogical University of Cracow, who were the novice group, and 13 experts (9 doctoral students of physics, 3 PhD graduates, and one person with a Habilitation degree in physics).

8.1.5 Research problems

The set of physics tasks were preceded by three questions regarding, on a scale of 0 to 10,the subjects' interest in physics, the desire to pursue a career in physics, and the usefulnessof physics in society. After answering these questions, the subjects were to properly solve eight physics tasks, one maths task, and one algorithmic problem. The last two tasks are the Ridley Stroop test, which is used e.g. to measure cognitive functions, as well as focus and divisibility of attention. It is also used in brain disorder and psychological deficiency diagnostics, e.g. depression. The chart below shows the sequence of tasks.

The difficulty level was adapted to the study group. The tasks were designed for all of the subjects (students of different school types, as well as university students and doctoral students) to have the knowledge necessary to complete the tasks.

During the study, the tasks were presented in the same conditions (temperature, lighting), without a time limit. The study also contained an additional survey conducted before and after the eye tracking measurement. Before the study, the subjects were asked about their interest in physics, mathematics, and IT. After the study, they were asked about their subjective feelings regarding e.g. their stress levels and how difficult the tasks were.

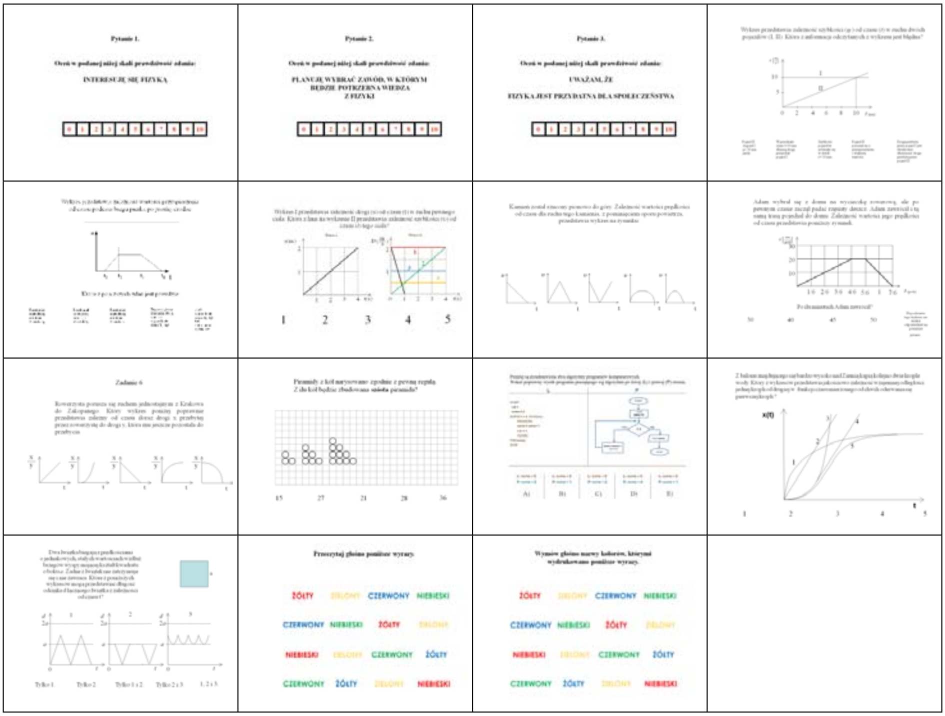


Figure 91: *The sequence of tasks in Experiment 3.*

8.1.6 General methodology of research results analysis

The following chapter contains examples of study results and a qualitative and quantitative analysis thereof from the point of view of the aims of the dissertation.

Based on task no. 4, a multi-faceted qualitative analysis and a selective quantitative analysisof the study results related to this task show a wide scope of possibilities for using eye tracking techniques to aid in physics education research.

8.1.7 Theoretical analysis of the task

The task chosen for the analysis is a high school curriculum-level physics task for 15-18 year old students. In regards to the substantial content of the task used in the experiment, it is related in the Polish education system to the overall goals and physics education in middle school and high school on basic and advanced levels (Podstawa programowa 2009, pp. 195, 201, 203). This task also fulfils the overall goals and mathematics education related to functions at a middle school and high school level.

Figure 92 shows the content of the analysed task.

It is a multiple choice problem with one correct answer.

The text underlines the necessity of choosing the chart depicting the relation between speed and time, omitting air resistance, for the movement of a rock thrown upwards.

Kamień został rzucony pionowo do góry. Zależność wartości prędkości
od czasu dla ruchu tego kamienia, z pominięciem oporu powietrza,
przedstawia wykres na rysunku:

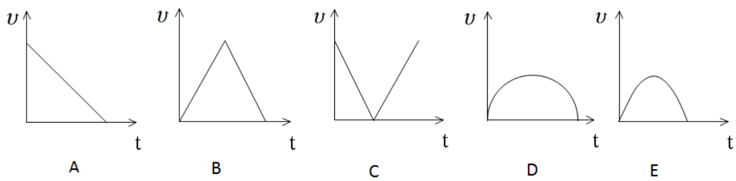


Figure 92: *The content of the analysed task.*

Hypothetical thought process regarding solving the task

The task can be solved by using various strategies. There are two main groups of strategies.

Strategy I based on knowledge gained at school

In order to properly solve this task, the subject should have knowledge of the changesof velocity in a vertical projection. The first phase of the movement, the climb phase, involves uniform decelerated motion, and the second phase involves uniform accelerated motion in free-fall, while remembering to skip air resistance in all of the phases. Both cases involve, though simplified, a linear change of velocity as a function of time: $V(t)=V_o\text{-}gt$, $V(t)=gt$, where$g$ – gravitational acceleration, t – time, V – velocity.

Strategy II based on common knowledge

An important aspect of this task is that a skilled use of common knowledge allows the task to be properly solved. Just visualising the fact that the velocity of a rock thrown vertically upward decreases at first, until it stops, and then rises, is enough. Only one of the available charts shows such changes in velocity.

In both of the aforementioned groups, the task can be solved in two ways – either by choosing a chart in line with one's visualisation, or by elimination.

The elimination of incorrect charts can also be done in different ways – by choosing several features of the movement – e.g. having two phases (rising and falling) (elimination A) and another selected characteristic, e.g. the initial velocity, the monotonicity of the function,the zero point of the function, etc.

The aim behind the choice of including this task in the study was getting to know different solving strategies by analysing scan paths, comparing the pace and the sequence of the analysis of specific objects, as well as measuring the average time required to solve the task.An additional interesting aim is an attempt at ascertaining how common knowledge impedesor helps solve a relatively easy kinematics problem. These specific objectives fit into the main objectives **P1, P4, P5,** and **P6.**

8.2. Pupillary response as an indicator of the self-assessment of the difficultyof a task and cognitive load while solving a problem

Due to the structure of the work, i.e. beginning with the analysis of possible applicability of the simplest possible psychophysiological indicators, pupillometry will be described first,as it relates to the psychophysiological applicability of eye tracking. More complex issues regarding eye-tracking applicability are described further.

8.2.1 Aims of the research

Referring to the aims of the dissertation, an attempt was made at assessing whether traditional test methods used in physics education, e.g. observations and surveys, could be enhancedby the use of non-invasive methods of monitoring the psychophysiological parametersof the subjects (research question Q6).

Referring to research question Q2, two additional aims are presented:

Q2.A.

The aim of the study is an attempt at ascertaining whether monitoring the changes in the width of the pupil during solving physics tasks could allow for gathering information regardinga subjective assessment of the difficulty level of the tasks at hand.

Q2.B.

The aim of the study is an attempt at ascertaining whether monitoring the changes in the width of the pupil during solving physics tasks could allow for gathering information regarding cognitive load

8.2.2 Original methodology of pupillometric result analysis

Measurements of the width of the pupil were made for all of the subjects, while looking at a board containing the text of the task, in identical lighting conditions. During the study,the beam of light illuminating the pupil was identical for all of the subjects.

Due to individual differences among the subjects regarding the size of the pupil and the changes in its diameter, an analysis and comparison of the relative values of the changesin pupil width.

In order to verify these assumptions, the following methodology was used in the study:

1. The average values of pupil width for every fixation of every subject were measured during task solving.
2. The average value of all fixations was calculated (pt. 1) for every subject while task solving.
3. Next, the relative percentage changes in pupil width were calculated based on the aforementioned average value for specific fixations.
4. The relative percentage changes were averaged for groups of subjects (for selected consecutive first and last fixations).
5. A linear function was made by use of the least squares method (for selected consecutive first and last fixations).

For the purpose of the analysis, it was assumed that an individual, subjective assessment of the difficulty level of a task can happen during familiarising oneself with the text. It was therefore assumed that the reaction of the pupils of the subjects to the subjective assessment of the difficulty level happens in the first few seconds of reading the text.

This is why, in order to answer the research questions, the first 10 fixations were chosen as an indicator of the subjective assessment of the difficulty level of a task (aim A), and, due to the fact that there was no time limit to solve the task, for reasons of simplification it was assumed that the decision regarding the answer happened during the last 25 fixations. The last 25 fixations were assumed as the time in which decision making took place, which is the timeof the highest cognitive load (aim B). A linear function was created by use of the least squares method for these results.

8.2.3 Results – self-assessment of the difficulty of a task

This paragraph contains a description of the search for additional tools of assessing the motivation of students, as well as the research for the possibility of using psychophysiological parameters as indicators of a subjective assessment of the difficulty of the tasks being solved by students (Rosiek 2014), (Sajka2015).

The following chart depicts the relative percentage changes of the average values of the width of the pupil in selected groups of subjects for the first 10 fixations related to the analysis of the text of the task.

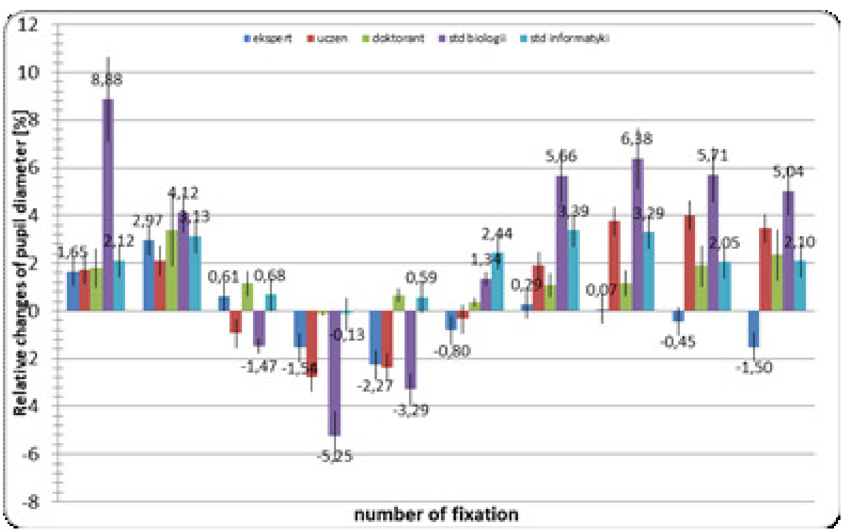


Figure 93: *Relative percentage changes of the average pupil width values in selected groups of subjects for the first 10 fixations.*

8.2.4 Results – cognitive load while solving a problem

Due to the fact that the study was carried out on a considerable number of subjects and due to how difficult ascertaining the precise moment of decision making by the subjects, for simplicity it was assumed that the choice of answer happens during the last 25 fixations of the eye. The following charts depict percentage changes of the average relative valuesof pupil width changes in selected groups of subjects. The changes in pupil width are assumed to be an indicator of cognitive load. The aim of using this manner of presentation of datais an attempt at assessing whether groups with subjects who have more experience and knowledge will exhibit different relative values of the changes of pupil width during decision making than those among the subjects who do not have as much experience and knowledge.

8.2.5 Analysis of the results

By analysing the relative changes in the pupil width of the subjects during the first fixationson the text of the task, a substantial variation can be observed in the average values of the relative reactions for selected groups of subjects due to their adequate qualifications.

Although the group of biology majors is not representative, the scope of the pupillometric reactions measured in this group is the highest. Substantial values of the relative changes in the pupil width of the subjects indicates substantial cognitive load.

The average values of the relative reactions of the subjects in a group of IT majors changeto a lesser degree than in a group of high school students, and to a higher degree than in a group of doctoral students. Due to the fact that the scan paths indicate a number of subjects in the group of IT university students who chose answers without an in-depth analysis of the tasks, and sometimes at random (see: sub-chapter 8.4), discarding the subjects who have not put any intellectual effort into choosing an answer would allow for an even more precise analysis of the pupillometric reactions of this group of subjects.

The linear function made by use of the least squares method is increasing for all groupsof subjects. The parameters describing the equation for the straight line can be a quantitative description of the subjective assessment of the difficulty level of the task at hand in selected groups.

8.2.6 Conclusions

An analysis of the obtained data shows that eye tracking methods of measurement could be helpful in studies regarding the methodology of physics education. Due to substantial individual differences and quite high difficulty of performing the study, formulating didactic conclusion based exclusively on such studies should be done extremely carefully. Although it is worth noting that, especially when performing repeated measurements for the same subjects and getting to know the reactions of the subjects, such methods can be a significant addition to the knowledge of the following subjects:

1. students' subjective assessment of the difficulty level of a task,
2. cognitive load,
3. stress levels related to the task solving process,

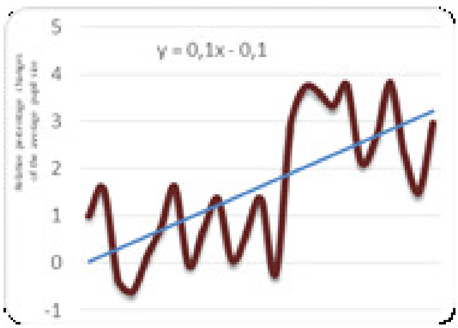


Figure 94: *Relative percentage changes of the average pupil size in a group of experts for the last 25 fixations.*

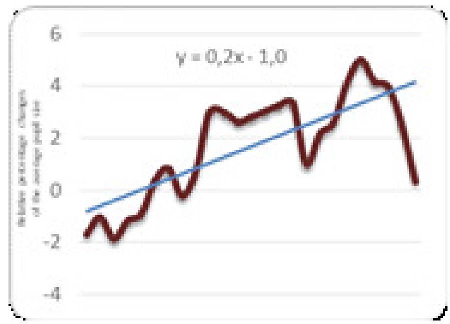


Figure 95: *Relative percentage changes of the average pupil size in a group of PhD students for the last 25 fixations.*

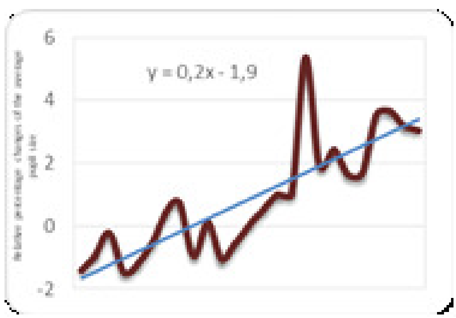


Figure 96: *Relative percentage changes of the average pupil size in a group of high school students for the last 25 fixations.*

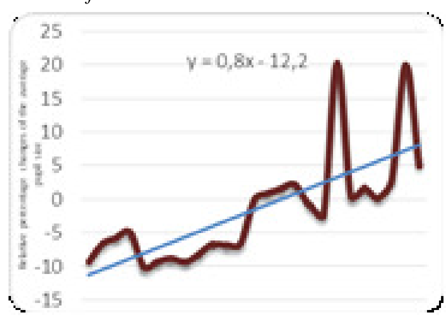


Figure 97: *Relative percentage changes of the average pupil size in a group of biology university students for the last 25 fixations.*

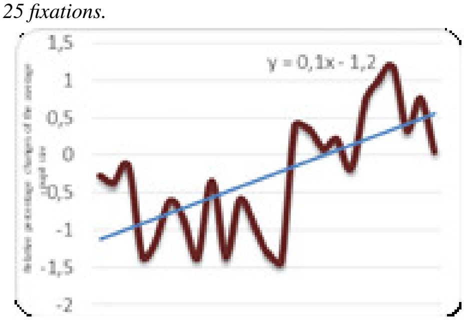


Figure 98: *Relative percentage changes of the average pupil size in a group of IT university students for the last 25 fixations.*

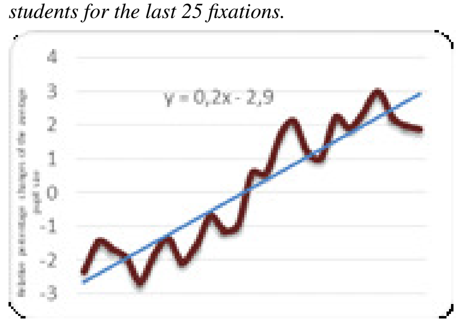


Figure 99: *Relative percentage changes of the average pupil size in a group of all participants for the last 25 fixations.*

As in those cases there can be observed changes in pupil width during physics task analysis.

It could be worth making use of this methodology for longitudinal studies in selected groups. It could be useful for e.g. supplementing a description of the subjective reactions regarding the assessment of the difficulty level of a task, as well as the motivation and stress levels related to solving the task. It is worth remembering that the highest values of relative changes in pupil width are caused by negative emotions, stress, subjective assessment of tasks as difficult,or significant intellectual effort (Madsen, 2012, Sosnowski, 2002).

Multiple studies of the same subjects in the same lighting conditions could be an indicator of their negative emotions, as well as allowing for assessing which events cause stressin students.

Studies confirm the hypothesis of neural effectiveness in the scope of solving physics tasks.It can be assumed that subjects with a higher intelligence quotient, or having more experience and knowledge related to the tasks at hand can put in less effort, as well as exhibit calmer psychophysiological reactions. This could be an indicator of lower cognitive load or intellectual effort while solving physics tasks. It is however important to note that an analysis of exclusively the relative changes of pupil width can only be used as an indicator, and a full interpretationof the changes has to be supported by an in-depth interview conducted with the subject coupled with an analysis of other psychophysiological parameters such as heart rate, respiration, or EEG.

8.3. Using scan paths for individual task solving strategies analysis

8.3.1 Aim of the research and methodology of analysis of the results

The aim of the study is to demonstrate the possibility of using eye tracking technology to diagnose individual task solving strategies and reasons for the subjects choosing the wrong answers. In particular, recognising the differences in task solving strategies used by the experts of a scientific field and subjects with less experience, including the students and future teachers of mathematics, physics, biology, and computer science. This specific objective fits in with overall research questions Q4, Q1, and Q6.

This chapter shows analysis examples of individual study results recorded in video form,i.e. *scan paths*. An analysis is made of consecutive saccades and fixations of the subjects while working on a task.

An analysis of individual *scan paths* yields information on which elements of the task the subject spent the most amount of time observing, meaning that they were important to the subject in regards to solving the task (Błasiak 2013)

8.3.2 Individual task solving strategies – the experts

Following is a *scan path* analysis of three experts solving a task, showing different strategies of solving a given task.

8.3.2.1 Strategy of analysis of the correct graph The following figure depicts the strategy used by the expert with a designated number of P52.

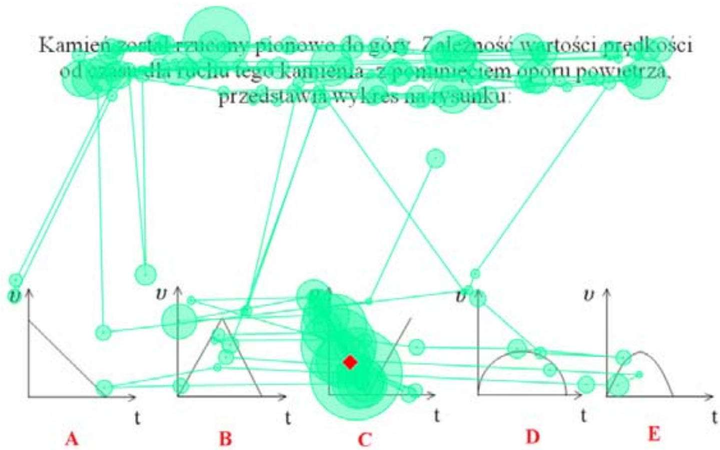


Figure 100: *Scan path of expert P52.*

The subject analyses the task very thoroughly. The only word without a fixation is the word *rock*, presumably deemed unimportant by the expert, who analyses the remainder of the task very intently. Multiple fixations are noted on nearly every word of the task, the biggest concentration happening on the words most relevant to the task, i.e. the description of the relation: “*speed versus time*”. Multiple repeating fixations as well as revisits are noted on these words, which might indicate mental processes related to the analysis of this relation. Reading the text is followed by a brief analysis of chart shapes, as well as an analysis of the description of the axis of the chart containing the speed symbol, followed by a return to the words describing the relation: “*speed versus time*”. Further analysis is related to multiple, relatively lengthy fixations almost exclusively in area C of the chart. A high amount of fixations in this area and a lack of fixations in areas A, B, D, and E can indicate the amount of knowledgeof the subject regarding the shape of the chart. Limiting the analysis only to the aforementioned area most definitely indicates the beginning of solving a task by imagining the expected shape of the chart, followed by searching for the shape based on theoretical knowledge and the thought-up image of the chart. The next phase would be the search for the proper chart shape describing the relation. This process is distinctive, which means it must be a consciously used task solving strategy. After an in-depth analysis, chart C is chosen as the answer.

8.3.2.2 The wrong answers elimination strategy Figure 101 depicts the scan path of expert.

An analysis of the scan path shows multiple revisits on elements significant for the proper solving of the task. There are multiple, lengthy fixations, with a significant number of them on the description of the axes of the coordinate system. Based on the following record it canbe ascertained that the expert employed a strategy of in-depth analysis and elimination of particular distractions. A large amount of lengthy fixations as well as

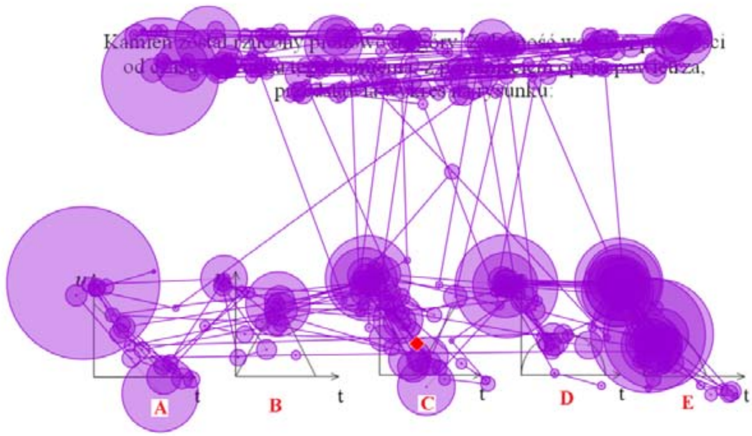


Figure 101: *Scan path for expert - duration of 120 seconds.*

revisits are observed in chart area E. An analysis of the video footage confirms that the subject employed a strategy of in-depth elimination of particular answer choices, resulting in choosing chart C as the final answer.

8.3.2.3 Linear function analysis strategy The following figure 102 depicts the scan path record presenting the task solving strategyof the second expert, who has a PhD in mathematics. The record shows the subject analysing charts B and C exclusively after intently reading the text. Only charts with linear changesof speed (increase and decrease) were considered by the subject. It can be ascertained that the subject assumed the changes in the velocity of the rock are described by the linear function$v(t) = gt$, which is a piecewise linear function. The subject later confirmed using this strategy.

8.3.3 Individual task solving strategies – the students

8.3.3.1 Analysis of only one graph The record clearly shows the student not trying to analyse the graphs. After reading the text, the student's fixations concentrate on the first object on the left. Single fixations or complete lack thereof in graph areas B, C, D, and E indicate the usage of different criteria to give the wrong answer. An analysis of only the scan paths allows for ascertaining two possible reasons for choosing option A.

During the in-depth analysis of the text, the student could have been imagining the graph of speed versus time relations of the vertical movement of the rock, and then choosing it. The student could have also been imagining the upward movement of the rock exclusively. Interviews conducted with the students confirm that some of the students, encountering the following sentence: "a rock was thrown vertically upwards," imagine that the rock moves upwards exclusively, as they are only taking into account what is written in the text, and not realising that the rock has to fall.

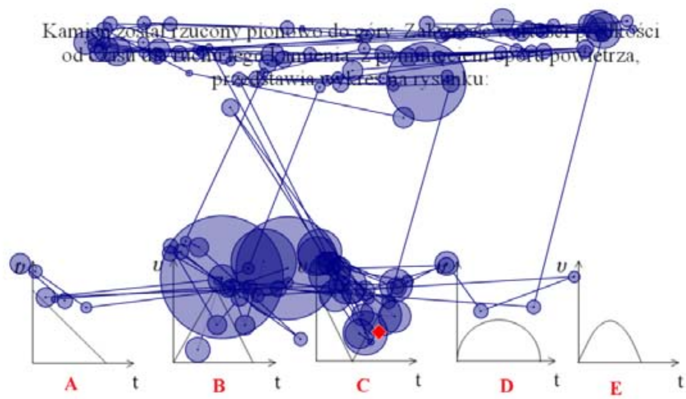


Figure 102: *Scan path for expert P62.*

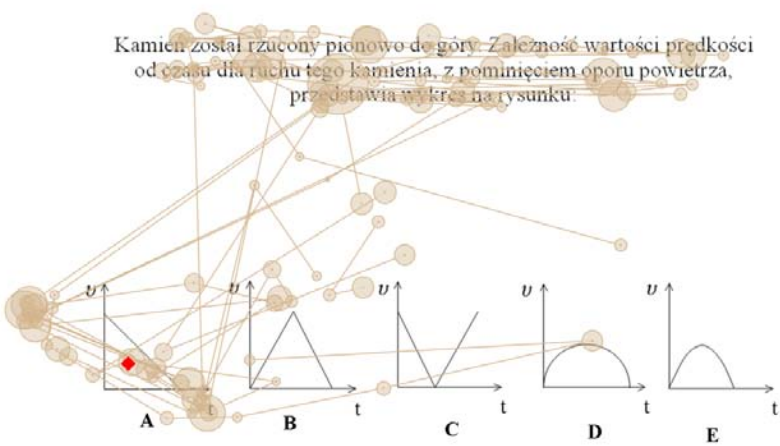


Figure 103: *Scan path for computer science student - duration of 34 seconds.*

There are, however, multiple indications of the fact that the second reason is more likely to have been the cause of incorrectly choosing option A. The student, after an in-depth analysis of the text, could have considered the task to be too difficult. The very short period of time between reading the text and choosing an answer, at 34 seconds, as well as the lack of analysis of the remaining graphs coupled with choosing the first option on the left suggests that the choice was random. In the case of lack of knowledge regarding the proper answer, the first answer on the left is usually chosen (Madsen 2012).

8.3.3.2 Interference of common knowledge during in-depth task analysis Below are three more scan path analysis examples of students, recorded during task analysis.

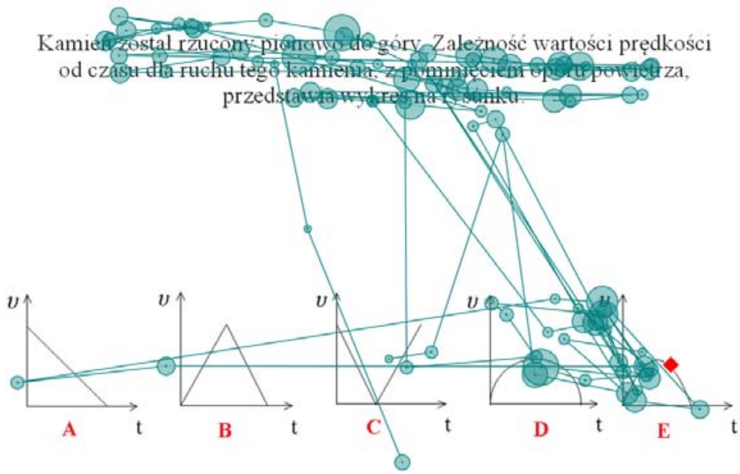


Figure 104: *Scan path for student 1- common knowledge, duration of 30 seconds.*

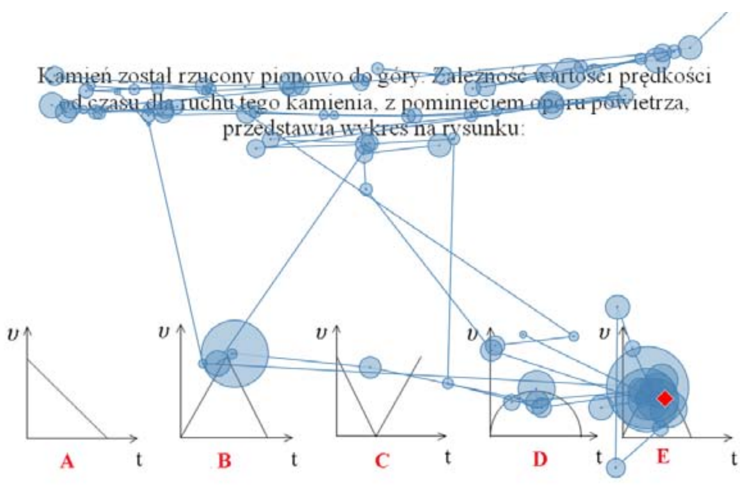


Figure 105: *Scan path for student 2 - common knowledge, duration of 25 seconds.*

The duration of solving the task was relatively short for the aforementioned students, at 25, 28, and 30 seconds. The *scan paths* presented above show that the subjects studied the text carefully and concentrated on analysing the two last graphs, D and E. The shape

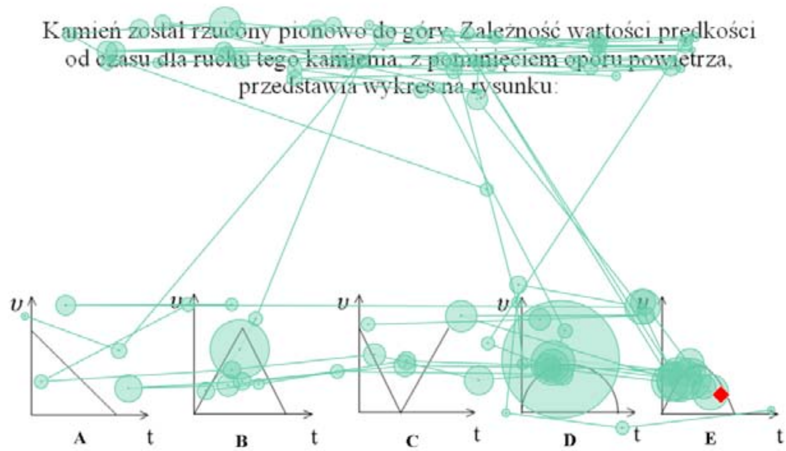


Figure 106: *Scan path for student 3 - common knowledge, duration of 28 seconds.*

of these graphs resembles a graph analysed at school of the height changes in time of a vertically thrown rock or the trajectory of a rock in projectile motion. Graph E was chosen as the answer in all cases.

An assumption can be made that in the case of these students, their common knowledgeof an incorrect image of movement influenced them choosing graph E. This assumption also works for the multiple occurrences in which the subjects do not read the text correctly, which is described below.

8.3.3.3 Interference of common knowledge with lack of in-depth analysis of the task The records of students presented so far show that the task was not intently analysed by them which resulted in choosing options D or E.

The following record shows a student's way of solving the task.

The text is read very quickly. When analysing the graph, the descriptions of the horizontal axis were omitted. The longest fixation was registered on the word "vertically." One revisit is noted in the text area "the rock was thrown vertically," alongside the analysis of the shapes of graphs D and E. The area of graph D has the most amount of fixations, followed by choosing option D as the answer. The time spent by the subject from the analysis of the task to giving the answer was only 16 seconds.

The longest, double fixation was registered on the word "vertically." There is a lack of in-depth analysis of the task, particularly omitting the last two words of the first line while reading the text: "*value of speed*," describing the type of movement and graphs contained in the task. This information is crucial to properly solving this task. Graph E is taken into consideration, shaped similarly to a parabola, with 9 fixations in the area. The analysis of the whole task took only 13 seconds.

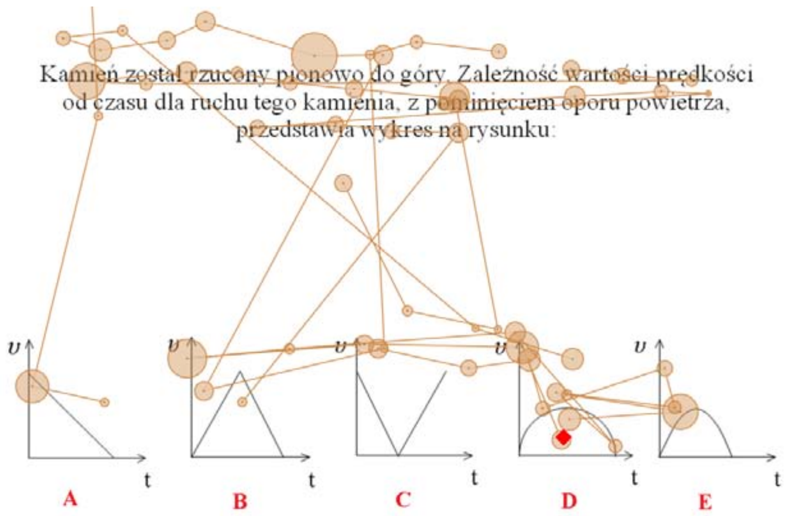


Figure 107: *Scan path for student 4 - common knowledge, duration of 16 seconds.*

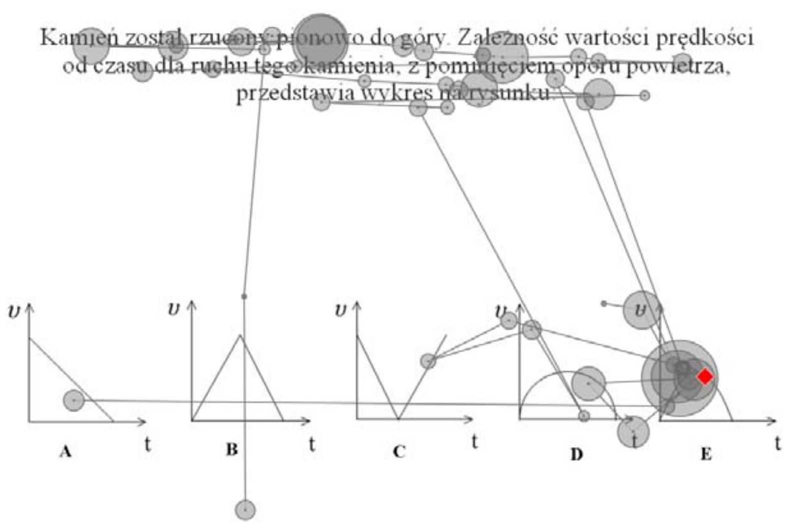


Figure 108: *Scan path for student 5 – common knowledge, duration of 13 seconds.*

It can be assumed with a high degree of certainty that the subjects chose the answer to the task purely on the basis of their first thought related to the movement described in the task - the graph of the trajectory of a rock in projectile motion.

8.3.4 Conclusions based on individual scan path analysis

The analysis of all of the results allowed to formulate conclusions.

Most importantly, eye tracking technology, particularly scan path analysis, allows for distinction between the group of people that analysed the task thoroughly, and the group of people who chose the answers at random.

An in-depth analysis of scan path records of the subjects allows for the distinction of several task solving and answer choosing strategies:

1. The strategy of imagining the correct shape of the graph of the relation described in the task based on text analysis, followed by choosing that graph (sometimes coupled with checking whether it is correct). This strategy can be separated in two - one of them correct, and the second one related to choosing graph A - related exclusively to the upward motion.

2. The strategy of analysing all graphs and eliminating incorrect ones.

3. This strategy combines knowledge related to the relation of the speed of the rock to time during its movement, as well as knowledge of piecewise linear functions - an analysis exclusively of piecewise linear functions.

4. The pseudo-strategy of choosing a graph based on its shape - relating it to the trajectory of a rock in projectile motion or changes in height in the function of time in a vertical throw.

5. The pseudo-strategy of choosing the first answer on the left.

6. Random answer combined with lack of in-depth task analysis. This is a case of either inadequate task solving motivation of the subject or the difficulty level of the task being too high, making it impossible to solve.

The following sub-chapters make use of a different methodology to analyse these results particularly in the context of conclusion 4 - the existence of a pseudo-strategy based on the interference of common knowledge related to an incorrect association of the answer to the shape of the trajectory of the rock.

The analysis of individual scan path video recordings allowed for distinguishing individual differences in solving physics tasks by both novices and experts. The differences can be observed in the scope of the strategies used. Another important differential parameter is the total time spent on solving the task.

The analysis of individual scan paths also allowed for preliminary explanations for the reasons of picking incorrect answers (conclusions 4 – 6).

8.4. Use of the gridded AOI methodology in groups of participants for analysis of differences in task solving between novices and experts

8.4.1 Methodology of results analysis

The aim of this part of study result analysis was assessing which areas of the screen containing tasks with answers in the form of charts were particularly analysed by the subjects.

The screen was divided into a 16x16 grid, a so-called *gridded AOI*. For each region, the average dwell time, as well as the average revisit and fixation numbers were calculated.

This helps ascertain in what way specific subjects or groups of subjects analysed the taskas well as the charts which were answer distractors.

8.4.2 Results – dwell time in groups

The following figures depict study results developed in such a way. First, the average *dwell time* analysis is presented. Colours depict the time the subjects spent looking at specific areas. Red shows areas at which the subjects looked the longest. The areas with the least amountof time spent looking at are in blue. Numerical values represent the average time spentin a specific region - the *dwell time*.

The first chart shows the average values of dwell time for all subjects taking part in the experiment.

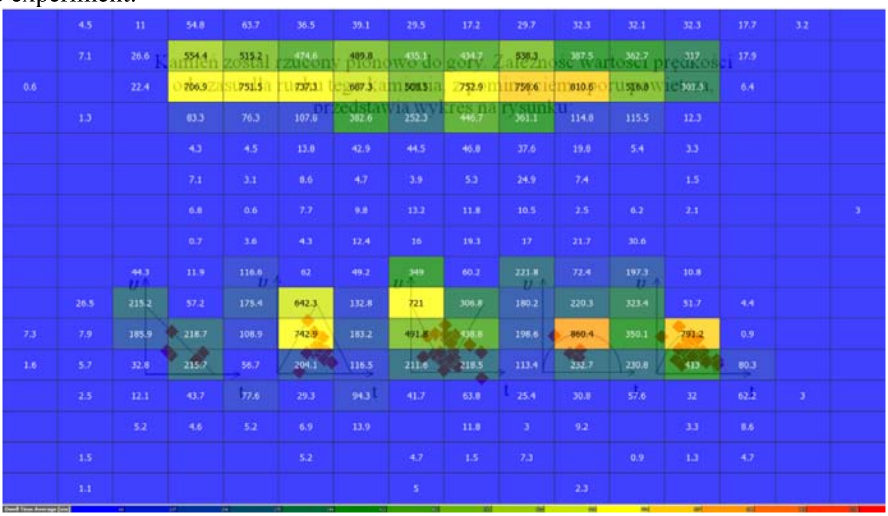


Figure 109: *Gridded AOI showing average dwell time for all 103 participants.*

An analysis of the average dwell time values for all subjects shows that when it comes to the text area, the second line of the task was analysed the longest, particularly the phrases “speed versus time” and “omitting air resistance.” The average dwell time values in these areas are from approx. 707 ms to approx. 810 ms. When it comes to the chart area, most time was spent analysing the shape of charts B, C, D, and E, particularly charts D and E, for which the average dwell time was from approx. 790 ms to approx. 860 ms.

The analysis of average dwell time values for all subjects was followed by ascertaining what method was used for analysis and whether there are any significant differences in the waysof analysing the text and the distractors in the task between different groups of subjects, specifically between pupils, students, and experts. The following figures depict dwell time values for a defined 16x16 gridded AOI for particular groups of subjects.

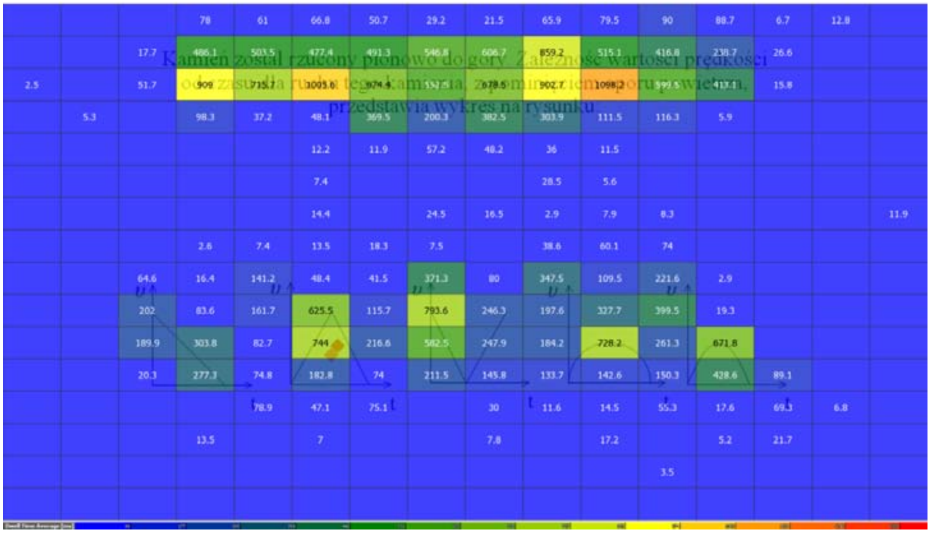


Figure 110: *Gridded AOI showing average dwell time for high school students.*

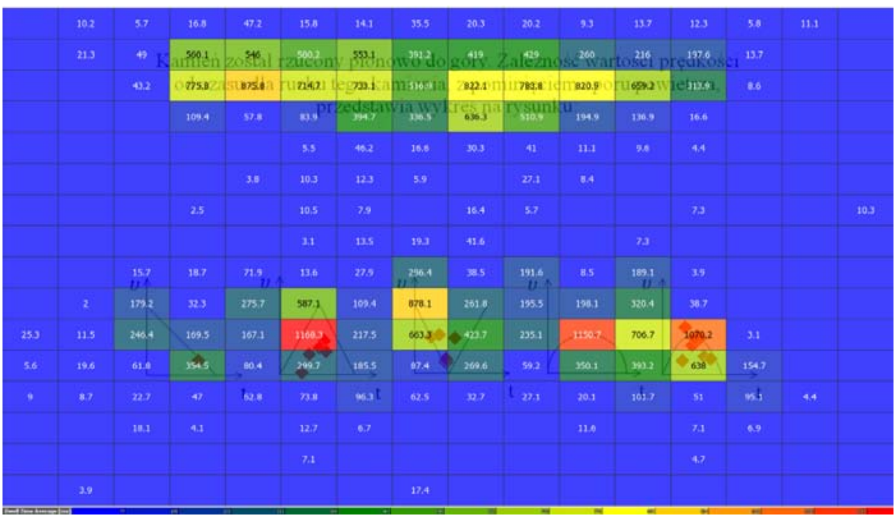


Figure 111: *Gridded AOI showing average dwell time for university students.*

A comparison the charts presented above shows significant differences in the scopeof the average time spent looking at specific areas of the screen. In all groups, the most time was spent on the second line of the text during task analysis. The dwell times in pupil and student groups do not differ significantly when it comes to words crucial to properly solving the task, e.g. the dwell times for the phrase “the value of speed” are approx. 200 ms for students up to 500 ms for pupils. The group of experts paid significantly more attention to the text.The text area containing the phrase “speed versus time” was looked at for a significantly longer time by the experts, the word “speed” alone clocking in at approx. 1800 ms. The amount of time by the group of experts on the word “speed”

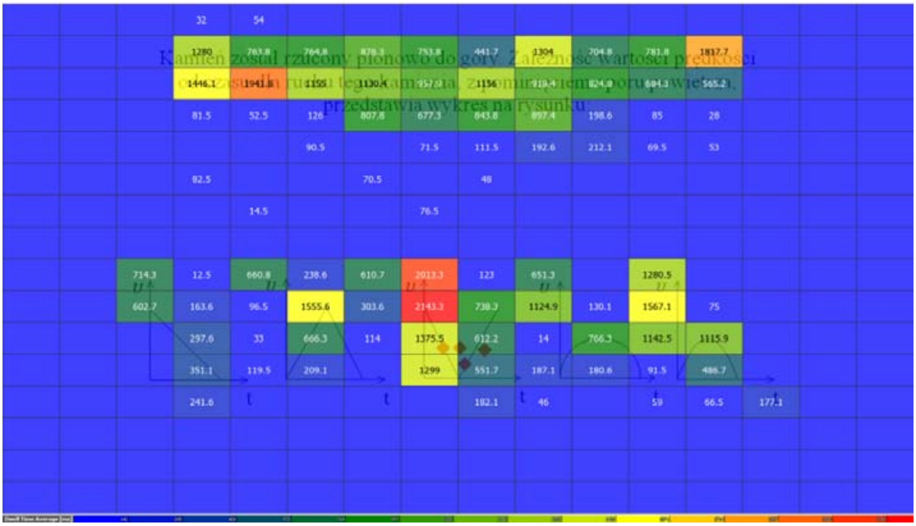


Figure 112: *Gridded AOI showing average dwell time for experts.*

was multiple times the amount of time spent by the groups of pupils and students. This demonstrates the experts' ability of choosing and analysing the most important elements of the task at hand. This word defined the type of relation and its perception was crucial to properly solving the task. A long analysis time of that area shows an ability of in-depth analysis of tasks by the experts. Similarly, in the area of the distractor containing the proper answer, the experts spent the most amount of time analysing the area related to the unit of the vertical axis, the initial speed value. The time spent in that area was, on average, over 20 seconds. For the remaining subjects, the average dwell time in that area was less than a second.

An interesting aspect related to the area of distractors is a very in-depth analysis of the second, fourth, and fifth charts by the pupils and students. Not only students and pupils, but also experts spent the most time analysing these areas. This could demonstrate that common knowledge could have been an obstacle in solving this task.

8.4.3 Results – number of fixations in groups

The following four figures contain defined 16x16 gridded AOIs. The grid elements contain the average number of the subjects' fixations on specific areas of the screen.

Due to the fact that the task analysis method of the group of experts significantly differed from the methods employed by the other subjects, the analysis of the average fixation countin defined gridded AOI elements begins with the aforementioned group.

Similarly to the case of the *dwell time* parameter, the largest number of fixations was observed in areas related to the most important words needed for understanding the type and description of the motion. The average number of fixations of the experts on the word "*velocity*" was 6.5, while the average for the phrase "*versus time*" was 9.3. The experts analysed the axis units and area related to chart C, which is related to the initial value of the velocity of the rock being thrown. The maximum average number of fixations in this area for the group of experts is was 7.8.

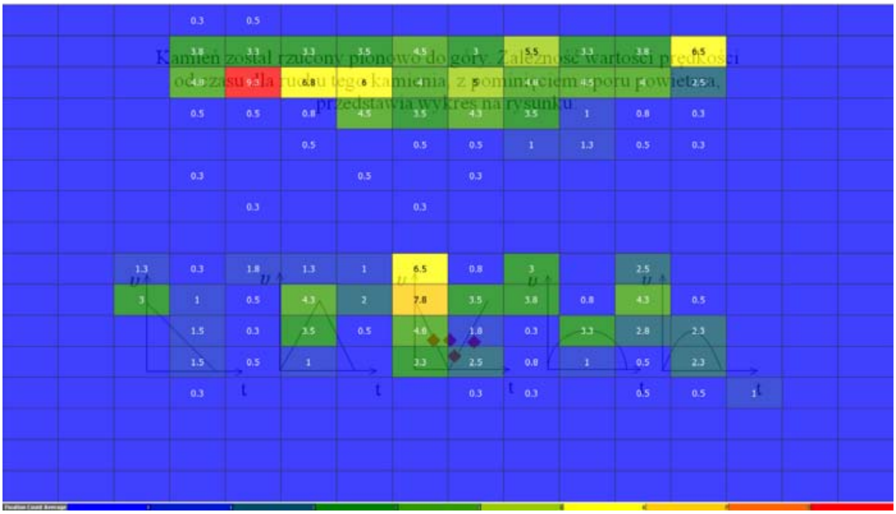


Figure 113: *Gridded AOI showing the average number of fixations for experts.*

The following figures depict the average values of fixation time for groups of students and high school pupils. There is a significantly lower number of fixations on the area of the text of the task, even though it is crucial for the understanding of the type of movement described in the task. The maximum average number of fixations in this area for the group of students was 4.1, while for the group of pupils it was 4.7. In both the group of students and the pupils, a relatively large number of fixations can be observed in the area related to the analysis of the shape of charts B and D. The high school pupils, similarly to the experts, gazed at the area of the vertical axis of the C chart, related to the initial velocity of the upward thrown rock. The pupils, however, did not consider the vertical axis of the C chart as important as the experts did, which is evidenced by a significantly lower average number of fixations on this area equalling 1.3.

The following figure depicts a summary of the average number of fixations of all the subjects. This method of analysis allows to pinpoint the area at which the subjects fixated the most. This leads to the conclusion that these were the areas the subjects paid the most attention to. Sucha low average number of fixations in the area of the text of the task is puzzling. In order to properly solve the task, the last few words of the first line of the text need to be noticed. It points out that a chart portraying the changes of the "*value of velocity...*" is to be selected. This area experienced, on average, less than two fixations. A large quantity of wrong answers coupled with a low number of fixations in this area can suggest that the subjects did not pay enough attention to the task, omitting vital information required to pick the correct answer.

An analysis of the average number of fixations in the distractor area shows that the largest average number of fixations occurs in the areas of charts B, C, and D (3.3, 3.5, and 3.6 fixations respectively).

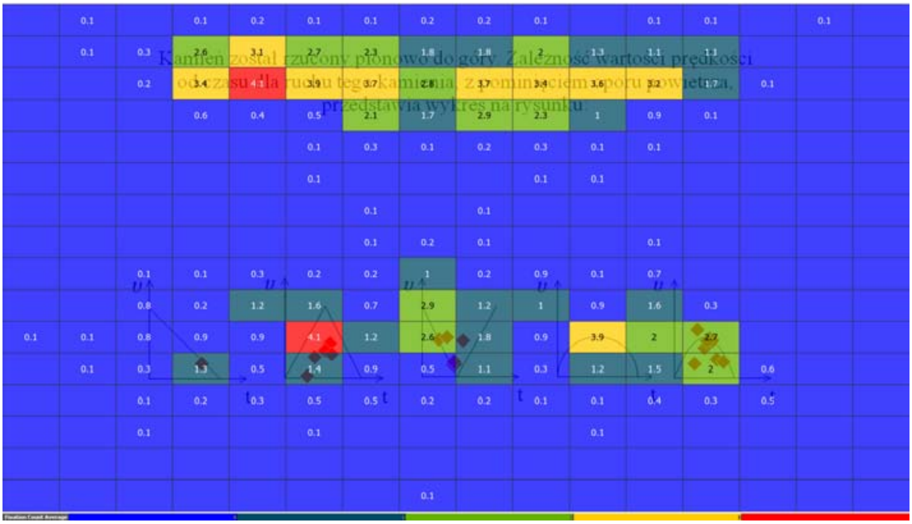


Figure 114: *Gridded AOI showing the average number of fixations for university students.*

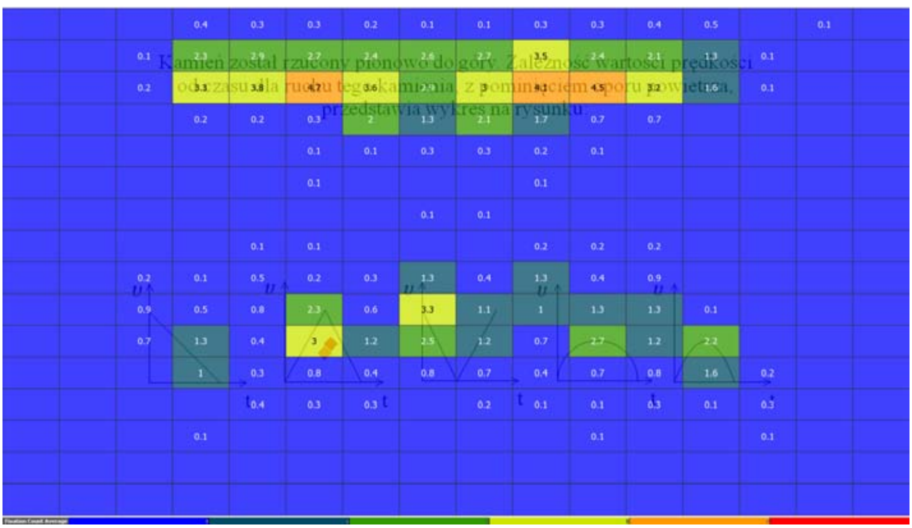


Figure 115: *Gridded AOI showing the average number of fixations for high school students.*

8.4.4 Results analysis and conclusions

Eye-tracking, particularly gridded AOI analysis, allows to divide the subjects into those who spent a significant amount of time analysing the task, and those who analysed it insufficiently or skipped the text altogether, making their decisions random. This also allows for identification of subjects with varying degrees of motivation related to solving this task.

In regards to the text of the task, a list of words which were analysed the most can be compiled.

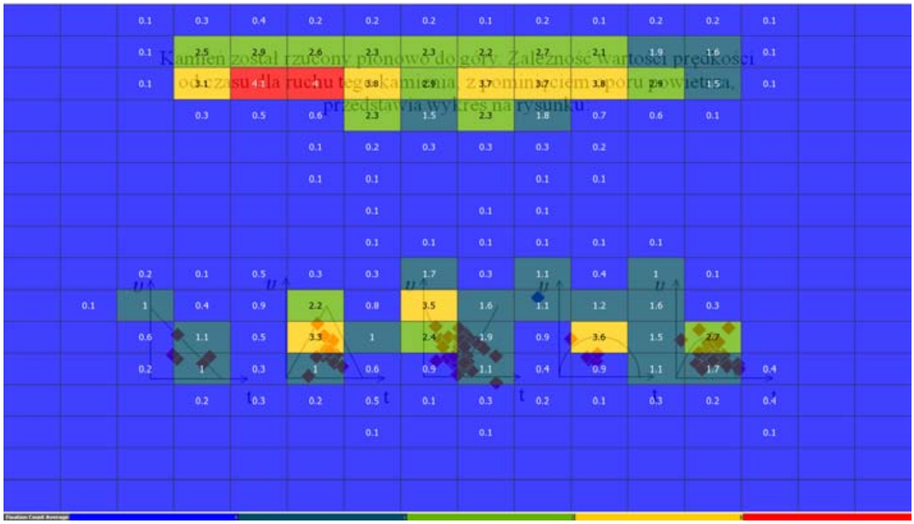


Figure 116: *Gridded AOI showing the average number of fixations for all 103 participants.*

In regards to the charts, either chart areas or entire charts which were analysed the most canbe acknowledged. This leads to the conclusion that these objects were regarded by the subjects as necessary to correctly solve the task.

Use of the gridded AOI methodology allowed for distinguishing individual differencesin solving physics tasks between novices and experts.

There are differences in dwell time parameter (the time spent analysing particular elementsof a sentence) values between the experts and the remaining subjects. One could assume that due to superior knowledge and experience of the experts, the amount of time spent on task analysis would be significantly lower than the other subjects. The gridded AOI data shows however that significantly higher dwell time values were noted for the experts, which is a sign of more in-depth analysis. For instance, in regards to the area of the text of the task,the maximum average dwell time values for the group of students is approximately 800 ms, whereas for the experts this value is almost doubled at approximately 2 seconds. A similar conclusion can be drawn from analysing the number of fixations in the area of the text of the task. Similarly, in the area of particular charts, which are treated as graphical objects,a difference in the scope of the dwell time parameter as well as the number of fixations of the experts when compared to the other subjects can be seen. For instance, while the experts carefully assessed the description of the axes of the coordinate system, the average numberof fixations for chart C being 7.8, the students did not pay as much attention, their average number of fixations in the same area being 2.9.

The study thus confirms an important differential parameter being the total time spenton analysis and task solving, as well as the number of fixations in important areas both in the case of the text and the distractors of the task.

An in-depth analysis of parameters such as dwell time and the average fixation count within the bounds of a gridded AOI for particular groups of subjects allowed to distinguish multiple strategies for solving the task and picking an answer, and to confirm the conclusions provided earlier.

Particularly notable is the strategy of preferring charts B, D, and E during analysis solely due to the expected chart shape of the function containing a maximum.

The following subchapter contains, based on a different method, an analysis of the resultsin order to note the occurrences of this pseudo-strategy, which is based on common knowledge in the form of an incorrect association of the answer with the shape of the trajectory of a rock in projectile motion or the differences in height in an upward throw motion. An analysis of the gridded AOI containing the average fixation count and dwell time resulted in additional explanations of the reasons for making the wrong choices.

8.5. Use of defined AOI for a collective analysis of results. Common knowledge – aid, or obstacle?

8.5.1 Aims and method of result summary (AOI)

This part of the paper contains different, complementary methods of result analysis. For the purpose of this analysis, an area was defined containing the text of the task as well as areas representing whole charts treated as separate graphic objects. Additional AOI for the description of the axes of the coordinate system were also defined. These AOI (areas of interest) were then analysed in detail. The analysis is simplified: Only the subjects' way of lookingat chart shapes and the chosen answer is being analysed. The research question is: Is common knowledge an aid, or an obstacle in solving a task? Is the task solving strategy based on chart shape analysis as well as attempts at pairing the answer and associating it with a shape similar to charts known from school an important element of the adopted strategies?

If the charts are treated as graphic objects in which areas of interest are defined, a statistical analysis of the basic parameters which describe the methods of analysis and the dwell timeof the subjects in those areas can be made.

Due to the fact that fixations and revisits are significantly connected to the analysisand perception of visual stimuli, specific parameters have to be taken into account, such as the total percentage of dwell time on specific AOI grid elements, the number of revisitson an element, and the number of fixations on an element.

8.5.2 Overall research results for the chosen task

An analysis of the gridded AOI of the correctness of the answers of all the subjects as wellas information received from the subjects during an interview conducted after the study both suggest that multiple subjects, when choosing their answer, mainly considered the similarityof the shape of the trajectory of a rock in projectile motion with the curve shapes depictedin the charts. The following diagram shows that 40% of subjects answered by choosing a curve with a parabolic shape (D, E), while 60% of subjects chose answers B, D, or E.

8.5.3 Research results based on defined AOI in groups

This subchapter begins with a presentation of figures with the cumulative results for all subjects as well as in groups: experts, students, and pupils. This shows the applicability of this method for group analysis. In order to limit the excessive amount of presented

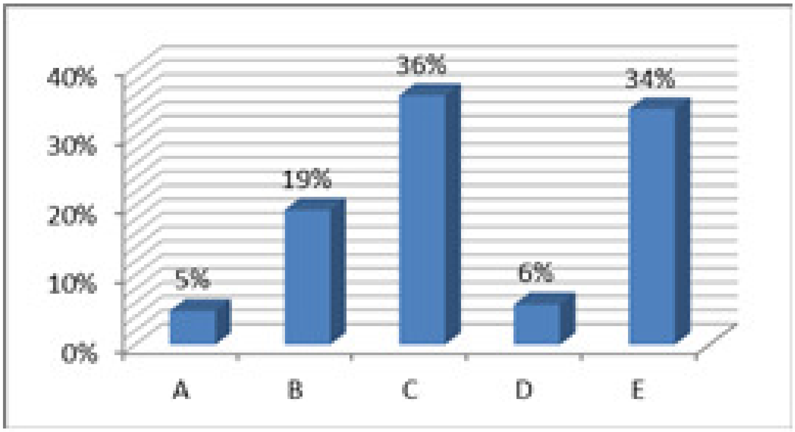


Figure 117: *Distribution of answers given by all 103 participants.*

results and analyses, the presentation and analysis of individual results will not be present, even thoughit is possible, and it very precisely shows significant eye tracking data.

Figure 118 shows the average values of chosen eye tracking parameters for all subjectsin defined AOI.

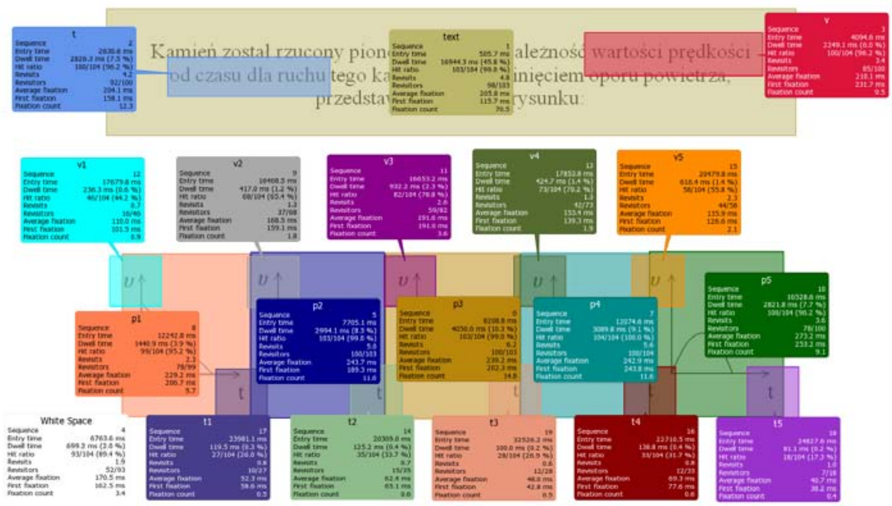


Figure 118: *Average results for defined AOI of all 103 participants.*

Figure 119 shows the average results of the experts.

In the expert group, only one person (a doctoral candidate) answered incorrectly.

To help compare results in chosen groups, a summary of the most important eye tracking parameters in the AOI of the given distractors derived from all the parameters presented above is necessary. Table 2 shows the average results for selected AOIs recorded for the student, pupil, and expert groups.

Table 6 contains average dwell time parameter values for the defined areas containing descriptions of the axes compared to the total time spent solving the task.

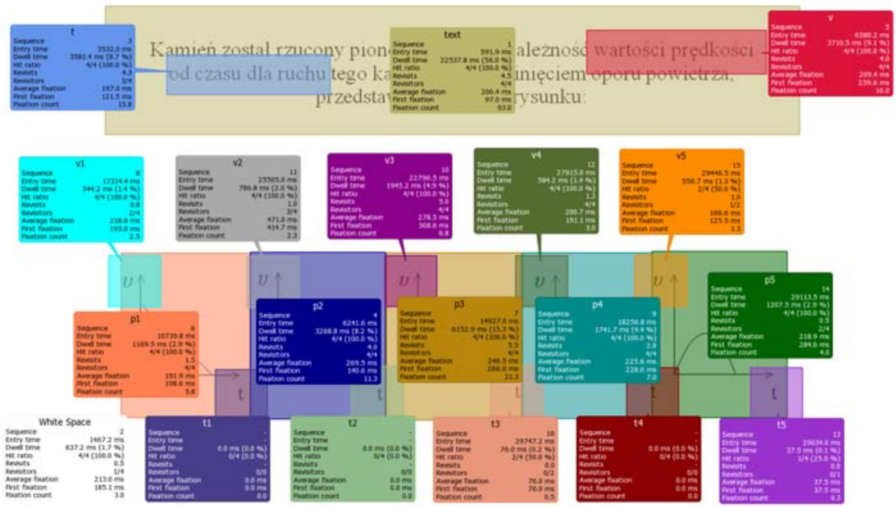


Figure 119: *Average results for defined AOI of the experts.*

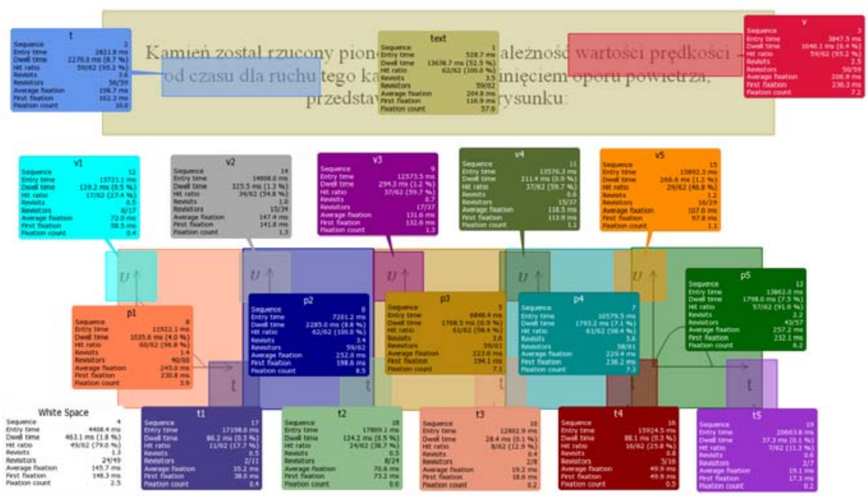


Figure 120: *Average results for defined AOI of university students.*

Table 7 shows the average task analysis time which includes both the analysis of the task as well of as the available answers of each of the three groups: experts, students, and pupils.It is worth noting that this is not the total time spent on solving the task.

8.5.4 Analysis of the results and conclusions

It is worth noting that, in order to pick the correct chart, common knowledge and life experience need be the only prerequisites. The sole awareness of the fact that when a rock is thrown upwards, its velocity decreases at first (to zero, as the rock has to stop), and then rises (due to gravity) allows to choose the correct answer. Among the available

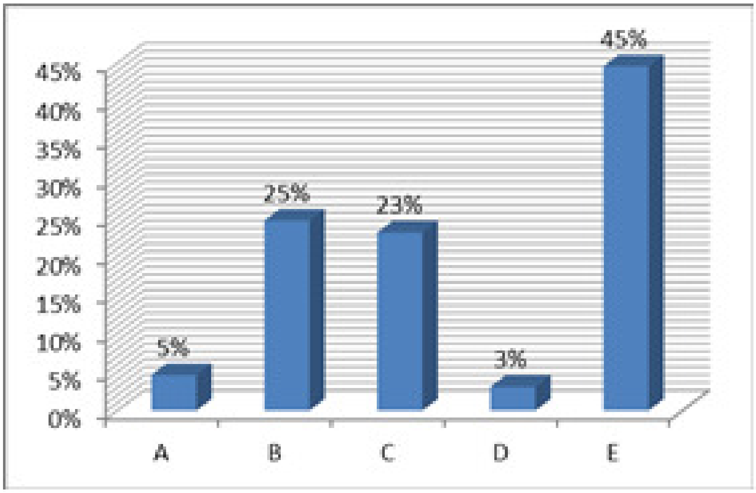


Figure 121: *Distribution of answers given by university students.*

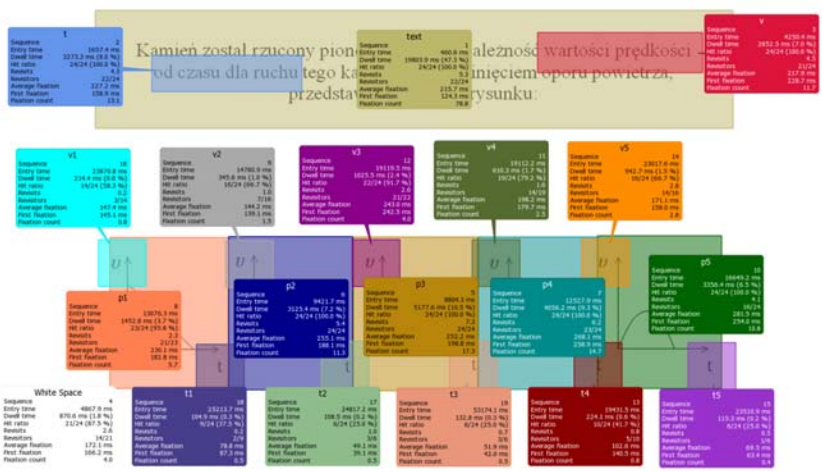


Figure 122: *Average results for defined AOI of high school students.*

charts, only chart C depicts a function with such properties. This means that in the case of this task, the strategy of searching for the correct chart as well as eliminating incorrect charts can lead to success at this level of common knowledge. From this point of view, common knowledge is an aid in task solving. There is no need for knowledge of physics in the scope of uniformly varying motion. The difficulty level of this task is therefore appropriate for middle school pupils (recognition of a monotonically decreasing function achieving the minimum value, and then increasing). In this study it was being solved by subjects with significantly higher levels of knowledge:

– Second year high school pupils with an extended physics curriculum, who, four months before the study, discussed kinematics in class, including the upward throw, and despite this, over 50% of this group chose the wrong answer.

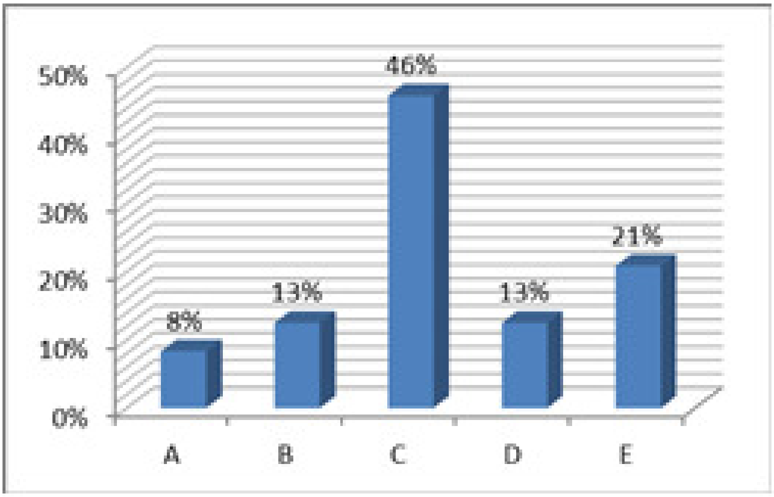


Figure 123: *Distribution of answers given by high school students.*

Table 4. *Chosen average eye-tracking values for the analysis of specific AOIs defined for the following graphs (distractors) for pupils, students, and experts.*

		A	**B**	**C**	**D**	**E**
Average percentage dwell time in AOI of distractors	*pupils*	3.7%	7.2%	10.5%	9.3%	6.5%
	students	4%	8.8%	6.9%	7.1%	7.5%
	experts	2.9%	8.2%	15.3%	4.4%	2.9%
multirow 3* *Average number of revisits in AOI of distractors*	*pupils*	2.3	5.4	7.3	6.2	4.1
	students	1.4	3.4	3.6	3.6	2.2
	experts	1.5	4	5.5	2.8	0.5
multirow 3* *Average number of fixations in AOI of distractors*	*pupils*	5.7	11.3	17.3	14.7	10.8
	students	3.9	8.5	7.1	7.3	6.2
	experts	5.8	11.3	21.3	7	4

– Students (physics, IT, mathematics, and biology majors) who finished a physics course (including kinematics) in high school.

– Experts, among which are physics doctoral candidates and scientists with at least a doctorate-level degree in fields such as physics, mathematics, or IT.

Table 5. *Average percentage of total dwell time spent on reading the text of the task.*

Average percentage of total dwell time spent on reading the text of the task		
Experts [%]	Students [%]	Pupils [%]
56	52.5	47.3

Table 6. *Average percentage of total dwell time spent on axis descriptions for the selected groups.*

Average percentage of total dwell time spent on axis descriptions for the selected groups		
Experts [%]	Students [%]	Pupils [%]
11,3	8,8	6,4

In this study, answer C was selected by 92% of experts, 46% of pupils, and 19% of students. The amount of incorrect answers is puzzling. Why was the incorrect answer E chosenby so many subjects?

The first attempt at an explanation focused on the relationship between the amount of time spent reading the text of the task and the correctness of the answer. Table 7 shows however that the percentage difference in task analysis time compared to total solving time between experts, pupils, and students is marginal. It is approximately 50% of the total time spent on solving the task.

The chart shown in answer E could have been correct if the vertical axis contained a coordinate of the differences in distance between the rock and the ground taking place during the movement, and not the velocity value. It can be assumed that the wrong answers could stem from neglecting the analysis of the description of the axes. The study shows that for the experts, the analysis of the description of the axes is a crucial element allowing for correctly answering the question contained in the task. An analysis of the dwell time of the areas containingthe descriptions of the axes shows that the experts spent, on average, 11.3% of their total time identifying the chart axes. An analysis of the dwell time shows that the groups of students and pupils spent, respectively, 8.8% and 6.4% of their total time on chart axis description analysis. In the case of answer E, this significantly influenced choosing this distractor. In interviews conducted after the study, the subjects recounted that in their mind, chart E was recognisable and they associated with a shape discussed in class. A lack of precision during axis description analysis could have also contributed to choosing the wrong answers. This was the distinguishing factor between the group of experts and the groups of students and pupils.

The eye tracking results provide further interesting remarks. The percentage of time spent on analysing the incorrect charts B, D, and E by the students and pupils is almost double the time spent on analysing answer A. Similar tendencies are observed during the analysis of the number of revisits in a given chart area as well as the number of fixations, which signifies the subjects overcoming difficulties. What is more, the students spent the largest percentage of time on chart analysis. In interviews conducted after the study, they

Table 7. *Average time spent on reading text of task together with graphs analysis.*

Average time spent on reading text of task together with graphs analysis		
Experts [%]	Students [%]	Pupils [%]
57 40 (including PhD students)	30	38

described shaped D, E, and even B as similar to the shape of the trajectory of a rock in projectile motion. The answers of biology majors were incorrect after this association had occurred. 85% of mathematics majors selected answers B, D, or E, whereas in the case of IT majors, 75% of them chose wrong. An important fact is that this group of subjects spent the least amount of time solving this task as wellas having the least amount of revisits and fixations, which could be interpreted as an indicator of how accidental is option A as an answer. The answers of physics majors were in this case correct, and they can be considered a part of the group of experts. A significantly interesting fact is that half of the pupils answered correctly, whereas the second half had incorrect associations. This group contained subjects who picked answer E (approx. 20%). The pupils gave more correct answers than the students due to the fact that, before the study, they discussed kinematics in class. No one in this group selected answer A, which is an answer that does not elicit any associations with the trajectory of the rock.

Based on the results of the study, a further assumption can be made that choosing answers B, D, and E could have been conditioned by common knowledge, which mostly consisted of associating the chart with a commonly observed trajectory of a rock in projectile motion. The subjects recounted that they expected the shape of the chart to resemble a parabola, a function chart with a maximum value. This type of common knowledge is an obstaclein solving this task. This is a very strong association, which, in order for the task to be solved correctly, needs to be broken by discipline and analytical thinking, which will allow for the identification of the type and substantial experience in the field of mathematics and physics. This is why such a large number of subjects fell into this trap. Among them was even a doctoral candidate in physics.

An analysis of the reasons for such a large number of incorrect answers for this task is foodfor thought. The reason for this occurrence might not solely be factors such as incorrect useof common knowledge as well as school and substantial knowledge. From a psychological point of view, this could also be explained by Kehneman's concept of fast and slow thinking.The problem stated in the task could involuntarily trigger System I related to a lack of attempts of decision-making verification based on the activation of System II (Kahneman, 2011).

9. FINAL DISCUSSION AND CONCLUSIONS

Six big experiments were carried out so far with 301 subjects, using 69 slides with tasksor questions. In the last two years, the author (and the Cognitive Didactics Research Group) has published 18 works regarding eye tracking and psychophysiological methods usedin science education with more on the way, e.g.: (Andrzejwska 2015a, 2015b), (Pęczkowski 2014), (Błasiak 2013a, 2013b), (Błasiak 2014), (Rosiek 2014a, 2014b, 2014c), (Rożek 2015), (Sajka 2014), (Sajka 2015a, 2015b), (Stolińska 2014), (Wcisło 2014).

Due to the restrictions stemming from the volume of the paper, only a fragment of the results and analyses can be presented. The study results presented in the work were chosen solelyto illustrate the possibility of using modern psychophysiological methods and eye trackingin physics education.

The results confirm the usefulness of the inclusion of psychophysiological parameter analysis methods to research in the scope of physics education. What is particularly of note is the ease of photoplethysmographic HRV measurement application and the usefulnessand informativeness of these parameters for assessing stress levels and stimulation duringthe process of physics task analysis and solving.

The presented indicative analyses of the eye tracking studies show a need of expanding traditional research methods in physics education to use modern technology such as eye tracking.

The conducted research shows, that:

T1. Psychophysiological methods such as HRV, IBI, BVP, S.C., RESP, EEG, or remote eye tracking readings are usable in physics education.

T2. Psychophysiological parameters such as IBI and BVP measured by useof a photoplethysmogram and RESP are relatively easy to measure, but also accurately describe the cognitive activity of a student while solving physics tasks.

T3. Changes in eye tracking and psychophysiological parameters such as e.g. pupil width changes, number and scope of changes in the duration and location of fixations, respiration, IBI, and BVP could be indicators of motivation, changes in cognitive strain, or stress of students or pupils while solving physics tasks.

T4. Eye tracking parameters allow for precise documentation and detailed descriptions of physics problem solving strategies. They also allow for finding what causes the mistakes made while solving physics tasks. In particular, eye tracking allows to:

- distinguish those who read the text of the task attentively and those whose answersare random,
- objectively and precisely document all stages of task analysis, beginning with the text of the task up to choosing the answer,
- distinguish the words, sequences of words, sentences, and symbols that were the subject of in-depth analysis,
- study individual differences in methods of physics problem solving,
- distinguish unique strategies of solving tasks and choosing answers,

- learn the differences in the strategies of solving tasks and choosing answers between beginners and experts,
- indicate hypothetical causes for choosing incorrect answers.

T5. The studies allow to distinguish the advantages, disadvantages, and technical restrictions of particular test methods.

The following summary shows a shortened list of the application, advantages, disadvantages, and technical restrictions of particular test methods described in this work.

This summary contains conclusions drawn from all the conducted experiments.

T6. It is possible to draw practical conclusions from the research concerning the adaptation of the research methods described in this work in physics education.

In learning, it is vital for a teacher to be aware of the reasons behind the mistakes made by their students. Having this knowledge allows to steer the student so that their education processis more effective (Błasiak 2011). One of the methods of obtaining knowledge of the reasonsof mistakes made by students is analysis by comparison of the way a problem is being solved by people who have extensive knowledge on a subject, i.e. are regarded as experts (Madsen 2012) and by students without such knowledge. This is made possible by eye tracking.

The author of this work has been conducting research for many years on the application,in a natural experiment environment, of custom-made Personal Response Systems used for wireless measurement and analysis of the level of content comprehension declared by pupils and students. These measurements allow to quickly distinguish those who need additional help, as well as elements of lesson plans which are difficult to them. The results of such studies were published by the author e.g. in an article called *Spectrum of physics comprehension,* included in an issue of the European Journal of Physics. Assessing the level of motivation was always an obstacle in these types of studies. Assessing whether a student or pupil is actively participating by listening and trying to comprehend what is e.g. being presented at a lecture.A frequent observation was that students who were not interested by the lecture communicated that they perfectly understood what was being presented using wireless transmitters. Tests conducted immediately after the lecture confirmed a complete lack of understanding of the presented information. Another group was of students and pupils who exhibited inadequately high levels of motivation and stress which greatly impeded prolonged periods of concentration and active participation of the subjects in the lecture. This was one of the reasons for attempting to improve the PRS systems created by the author (Rosiek 2014) by including methodsof measuring psychophysiological parameters allowing for obtaining additional information related to subjective assessment of difficulty, cognitive strain, and stress. It was attemptedto assess whether monitoring parameters such as perspiration, HRV, S.C., as well as eye tracking parameters will allow to obtain additional information regarding the state of the pupils and students in class or during a lecture. The conclusions above give a positive answer to those questions as well as to the usefulness of the described methods.

The conducted studies and results contained in this work allow establishment of two possible paths of further research in the scope of physics education:

1. Application of mobile devices monitoring the psychophysiological parameters, including mobile eye trackers and simultaneous monitoring of multiple subjects

RESE-ARCH TECH-NIQUE	APPLICATION	ADVANTAGES	DISADVANTAGES
EEG	- study of cognitive strain and fatigue during the process of task solving - study of relative changes of brainwave amplitudes	- very sensitive and precise measurement method, provides insight into brainwave amplitudes related to a specific activity	- preparation for the study is very time consuming - high levels of discomfort of subjects - necessity of restraining the subject - very difficult data processing - high number of artefacts - solely laboratory condition uses - some EEG equipment requires use of Faraday cages
EDA	- stress detection - detection of changes in motivation and stimulation	- ease of measurement - high speed and scope of changes in the measured conductivity - ease of use - possibility of using inexpensive and easily accessible equipment - the anticipatory character of EDA changes	- necessity of including individual specificities of the reactions of subjects - problems with generalisation and in-depth change interpretation - necessity of longitudinal studies
HRV, BVP	- monitoring of the cognitive activity of the subjects - subjective assessment of task difficulty - assessment of stress levels	- high ease of use compared to EEG which requires restraining the subjects - high speed and scope of changes	- necessity of including individual specificities of the reactions of subjects - BVP measurements do not provide precise phase change data - difficult analysis
Respiration	- monitoring of the cognitive activity of the subjects - assessment of stress levels	- high ease of measurement - possibility of using inexpensive and easily accessible equipment	- necessity of including individual specificities of the reactions of subjects - problems with generalisation and in-depth change interpretation
Pupillometry	- cognitive strain measurements - stress level measurement	- ease and swiftness of measurement - non-invasiveness of method - higher values of pupillometric reactions in case of negative emotions	- result analysis is time-consuming - mostly qualitative studies are possible - necessity of identical lighting conditions during the course of the study - calibration difficulties in the case of eye trackers, especially for subjects with visual impairment

[130]

RESE-ARCH TECH-NIQUE		APPLICATION	ADVANTAGES	DISADVANTAGES
EYE TRACKING	Scan paths	- analysis of quality and method of reading - distinguishing task solving strategies - comparing task solving strategies - distinguishing words and symbols responsible for information processing (number and duration of fixations, revisits, and dwell time) - distinguishing the sequence of analysis of particular areas of the screen	- accuracy of method - accuracy of measurement - precision of video capture in time - possibility of doing an in-depth analysis of the strategy of reading the text of a task - individual and comparative analysis available	- study and analysis are time consuming - calibration difficulties, especially for subjects with visual impairment
	Gridded AOI	- provides numeric data, e.g. number and duration of fixations, number of revisits, and dwell time used to distinguish areas which trigger the process of processing information or interest - comparison of results can be individual, collective, or in groups	- possible analysis of areas causing interest or cognitive strain - easy to compare work of different people - analysis can be individual or in groups	
	Definied AOI	- provides numeric data, e.g. number and duration of fixations, number of revisits, and dwell time in a given research context, used to distinguish areas related to the process of processing information or interest - comparison of results can be individual, collective, or in groups	- possible analysis of areas causing interest or cognitive strain - easy to compare work of different people - analysis can be individual or in groups	
	Sequence charts	- provides numeric data, e.g. number and duration of fixations, number of revisits, and dwell time used to distinguish areas related to the process of processing information or interest - comparison of results can be individual, collective, or in groups	- possible analysis of areas causing interest or cognitive strain - easy to compare work of different people - analysis can be individual or in groups	

taking part in the teaching process in a natural environment, i.e. in class or during lectures.

2. Conducting further laboratory tests with use of precise and quick eye-tracking devices combined with EEG and laboratory devices which monitor psychophysiological parameters.

There are two simultaneous research-and-development activities being planned by the author, particularly in the scope of the author's upcoming thesis:

The first is further development of the ZDF UP neurodidactics laboratory as well as conducting detailed laboratory tests combining very precise and quick eye-tracking methods with monitoring psychophysiological parameters such as EEG, HRV, RESP, S.C. to assessthe reactions of students in a typical teaching environment as well as to develop schemesof individual reactions and general conclusions.

The second type of activity regards further development of custom-made PRS systems created for the Android platform. The reason for choosing this platform are: the large availabilityof high-performance mobile devices using this system, their low costs, high data processing capabilities, and built-in wireless communication modules. Based on such devices, attempts are made at creating psychophysiological parameter acquisition software among multiple subjects, combined with recording the declared values of understanding presented content. The authoris also working on editing and testing server platform software used for the acquisition and processing of data originating from such devices, i.e. processing both objective psychophysiological parameters measured by mobile devices as well as subjectively declared assessments of the level of comprehension of presented content.

The author has also attempted making use of *The Eye Tribe Tracker* mobile eye-trackers alongside using *Software Development Kit (SDK)* libraries for open source software adaptation and for creating original data analysis solutions. The aim of the work is to facilitatethe implementation of methods of simultaneous eye tracking monitoring of multiple subjectsin a natural experiment environment, e.g. in class or during lectures. The author is currently testing the use of multiple mobile eye-trackers in a classroom environment.

Bibliography

Acharya, U. R., Joseph, K. P., Kannathal, N., Lim, C. M., Suri, J. S., (2006), Heart rate variability: A review. Medical & Biological Engineering & Computing, 44, 1031–1051.

Abrams, S., Zubel, S., (1972), Some temporal characteristics of information processing during reading, (in:) Reading Research Quarterly 12, 41–51.

Abrams, R., Meyer, D. E., Kornblum, S., (1989), Speed and accuracy of saccadic eye movements: Characteristics of impluse variability in the oculomotor system, (in:) Journal of Experimental Psychology: Human Perception and Performance 15, 529–543.

Ahern, S., Beatty, J., (1979), Pupillary responses during information processing vary with scholastic aptitude test scores, Science 205.

Aleksandrow, D., Wysznacka-Aleksandrow, W., Czaplicki, S., (1983), Diagnostyka elektrokardiograficzna, Warszawa, PZWL.

Allen, M., Obrist, P. A., Sherwood, A., Crowell, M. D., (1987), Evaluation of myocardialand peripherial vascular responces during reaction time, mental arithmetic, and cold pressor task, Psychophysiology, 24, 648-656.

Anderson, J. R., Bothell, D., Douglass, S., (2004), Eye Movements Do Not Reflect Retrieval Processes. Limits of the Eye–Mind Hypothesis, (in:) Psychological Science, 15(4), 225–231.

Andrzejewska, M., Stolińska, A., (2015), Zastosowanie okulografii do identyfikacji metod analizy problemu algorytmicznego, Edukacja, Technika, Informatyka 3(13), 209-215.

Andrzejewska, M., Stolińska, A., Błasiak, W., Rosiek, R., Rożek, B., Sajka, M.,Wcisło D., (2015), Eye- tracking verification of the strategy used to analyse algorithms expressed in a flowchart and pseudocode, Interactive Learning Environments, 1-15.

Allen, M. T., Obrist, P. A., Sherwood, A., Crowell, M. D., (1987), Evaluation of myocardial and peripheral vascular responses during reaction time, mental arithmetic, and cold pressor tasks, Psychopysiology, 24, 700-713.

Alshehri, M., Alghowinem, S., (2013), An exploratory study of detecting emotion states using eye-tracking technology, Science and Information Conference 2013, October 7-9, 2013 London, UK.

Augustyniak, P., (2001), Przetwarzanie sygnałów elektrodiagnostycznych, Uczelniane Wydawnictwo Naukowo-Dydaktyczne, AGH.

Beatty, J., (1982), Task-evoked pupillary responses, processing load, and the structure of processing resources. Psychol. Bull., 91, 276–292.

Biecek, P., (2014), Odkrywać! Ujawniać! Objaśniać! Zbiór esejów o sztuce prezentowania danych, Fundacja Naukowa SmarterPoland.pl, Warszawa.

Blix, A., Stromme, S., Ursin, H., (1974), Additional heart rate – an indicator of psychological activation, Aerospace Medicine, 45, 1219-1222.

Błasiak, W., (2011), Rozważania o nauczaniu przyrody, Wydawnictwo Naukowe Uniwersytetu Pedagogicznego, Kraków.

Błasiak, W., Godlewska, M., Rosiek, R., Wcisło, D., (2013), Nowe technologie w badaniach edukacyjnych, (in:) Morbitzer, J., (red.), Człowiek, media, edukacja, Uniwersytet Pedagogiczny, Kraków.

Błasiak, W., Godlewska, M., Rosiek, R., Wcisło, D., (2013), Eye tracking: nowe możliwości eksperymentalne w badaniach edukacyjnych, Edukacja, Technika, Informatyka, 4, 1, 481-488.

Błasiak, W., Godlewska, M., Rosiek, R., Wcisło, D., (2014), Od Daniela Kahnemana do dydaktyki kognitywnej, Zeszyty Naukowe WMSE w Tarnowie, 36, 23 – 34.

Bober, S., Dabrowska, B., Dabrowski, A., (1982), Elektrokardiografia praktyczna, Warszawa, PZWL.

Budohowska, W., Grabowska, A., (1995), Procesy percepcji, (in:) Tomaszewski, T., (red.), Psychologia ogólna, Warszawa, 9–90.

Buswell, G. T., (1935), How People Look at Pictures, Chicago: Univ. Chicago Press, Hillsdale, NJ: Erlbaum.

Burleson, W., (2006), Affective Learning Companions: strategies for empathetic agents with real-time multimodal affective sensing to foster meta-cognitive and meta-affective approaches to learning, motivation, and perseverance, Thesis for the degree of Doctor of Philosophy at the Massachusetts Institute of Technology, p. 11.

Buswell, G. T., (1937), How adults read, Chicago, IL: University of Chicago Press.

Cacioppo, J. T., Petty, R. E., Morris, K. J., (1985), Semantic, evalutive, and somatovisceral activity, Psychophysiology, 4, 371-384.

Campion, M., (2013), LookTracker, Downloaded XI 2014 from: The History of Eye Tracking Studies & Technology: www.looktracker.com

Carrol, D., Turner, J. R., Hellawell, J. C., (1989), Heart rate and oxygen consumption during active psychological challenge: The effects of level of difficulty, Psychophysiology, 23, 174-181.

Carroll, D., Turner, J. R., Prasad, R., (1986), The effects of level of difficulty of mental arithmetic challenge on heart rate and oxygen consumption, International Journal of Psychophysiology, 4, 167-173.

Cavallo, V. E., Cohen, A. S., (2001), Perception, (in:) Baronet, P. E., (red.), Traffic Psychology Today, Dordrecht.

Chaffin, R., Morris, R. K., Porly, R. E., (2001), Learning new word meanings from context: A study of eye movements, (in:) Journal of Experimental Psychology: Learning, Memory and Cognition, 27, 225–235.

Chesney, D. L., McNeil, N. M., Brockmole, J. R., Kelley, K., (2013). An eye for relations: Eye- tracking indicates long-term negative effects of operational thinking on understanding of math equivalence, Memory & Cognition, 41, 1079-1095.

Clifton, Ch., Staub, A., Rayner, K., (2007), Eye Movements In Reading Words And Sentences, (in:) Van Gompel, R. P. G., Fischer, M. H., Murray, W. S., Hill, R. L., (red.), Eye Movements: A Window on Mind and Brain, Elsewier, 341–372.

Cohen, J. T., Thayer, J. F., (1984), Temporal patterns of the integrated EMG as a function of muscle area, Psychophysiology, 21, 572.

Cohen, J. T., Thayer, J. F., (1985), Emotional responses to music as measured by facial electromyography, Psychophysiology, 22, 555.

Coëffe, C., O'Regan, J. K., (1987), Reducing the influence of nontarget stimuli on saccade accuracy: Predictability and latency effects, (in:) Vision Research, 27, 227–240.

Coles, M. G. H., Gale, A., Kline, P., (1971), Personality and habituation of the orienting reaction: Tonic and response measures of electrodermal activity, Psychophysiology, 8, 54-63.

Coles, M. G. H., Duncan-Johnson, C., (1975), Cardiac activity and information processing: The effects of stimulus significance and detection and response requirements, Journal of Experimental Psychology: Human Perception and Performance, 4, 418 - 428.

Crane, H. D., (1994), The Purkinje Image Eyetracker, Image Stabilization, and related Formsof Stimulation Manipulation, (in:) Kelly, D.H., (Ed.), Visual Science and Engineering: Models and Applications New York: Marcel Dekker, 13-89.

Crane, H. D., Steel, C. M., (1985), Generation-V Dual-Purkinje-Image Eyetracker,Applied Optics, 24, 527-537.

Curcio, C. A., Sloan, K. A., Kalina, R. E., Hendrickson, A. E., (1990), Human photo receptor topography, The Journal of Comparative Neurology, 292, 497-523.

Dacey, D., M., (2000), Parallel pathways for spectral coding in primate retina,Annual Review of Neuroscience, 23, 743-775.

Davidson, J. E., Downing, C. L., (2000), Contemporary models of intelligence, In: Sternberg, R. J., (ed.), Handbook of Intelligence, Cambridge University Press, Cambridge, United Kingdom.

Deja, S., (2010), System rozpoznawania i aktywnego śledzenia oczu użytkownika komputera za pośrednictwem kamery w czasie rzeczywistym, Praca magisterska, Wydział Elektrotechniki, Automatyki, Informatyki i Elektroniki, Akademia Górniczo-Hutnicza w Krakowie, software: http://sourceforge.net/projects/gazepointer/ .

Delabarre, E. B., (1898), A method of recording eye-movements, Psychological Review, 8, 572–74.

Deubel, H., (1995), Separate addaptive mechanisms for the control of reactive and volitional saccadic eye movements, (in:) Vision Research, 35, 3529–3540.

Dimberg, U., (1982), Facial reactions and autonomic activity to auditory stimuli with highand low intensity, Psychophysiology, 24, 586.

Dodge, R., (1900), Visual perception during eye movement, Psychological Review,7, 454-465.

Dodge, R., (1904), The participation of the eye movements in the visual perception of motion, Psychological Review, 11, 1-14.

Dodge, R., (1905), The illusion of clear vision during eye movement, Psychological Bulletin, 2, 193-199.

Dodge, R., (1906), Recent studies in the correlation of eye movement and visual perception, Psychological Bulletin, 3, 85-92.

Dodge, R., Cline, T.S., (1901), The angle velocity of eye movements, Psychological Review, 8, 145-157.

Duchowski, A. T., (2002), A Breadth-First Survey of Eye Tracking Applications, Behavior Research Methods, Instruments, & Computers (BRMIC), 34(4), 455–470.

Duchowski, A. T., (2007), Eye Tracking Methodology, Springer Science & Business Media.

Edelberg, R., (1970), The information content of the recovery limb of the electrodermal response, Psychophysiology, 6, 527-539.

Edelberg, R., (1972a), Electrical activity of the skin: Its measurement and uses in psychophysiology, (in:) Greenfield, N.S., Sternbach, R.A., (red.), Handbook of psychophysiology, New York, Holt, Rinehart and Winston, 367-418.

Edelberg, R., (1972b), Electrodermal recovery rate, goal orientation, and aversion, Psychophysiology, 2, 512-520.

Edelberg, R., (1973), Mechanisms of electrodermal adaptations for locomotion, manipulation, or defense, (in:) Stellar, E., (red.), Progress in Physiological Psychology, New York, Academic Press, 5, 155-209.

Ehrlich, S. F., Rayner, K., (1981), Contextual effects on word perception and eye movements during reading, (in:) Journal of Verbal Learning and Verbal Behavior, 20, 641–655.

Erk, S., Kiefer, M., Grothe, J., Wunderlich, A.P., Spitzer, M., Walter, H., (2003), Emotional Context Modulates Subsequent Memory Effect, NeuroImage, 18, 439-447.

Everling, S., Fischer, B., (1998), The antisaccade a review of basic research and clinical studies, (in:) Neuropsychologia, 36(9), 885–899.

Ferstl, R., Rief, W., (1984), Does facial EMG indicate social skills? Psychophysiology,24, 576.

Findlay, J. M., Gilchrist, I. D., (2003), Active Vision: The Psychology of Looking and Poring, Oxford.

Fischer, B., Breitmeyer, B., (1987), Mechanisms of visual attention revealed by saccadiceye movements, (in:) Neuropsychologia, 25, 73–83.

Fischer, B., Gezeck, S., Huber, W., (1995), The three loop model: a neural network for the generation of saccadic reaction times, (in:) Biological Cybernetics, 72, 185–196.

Fischer, B., Weber, H., (1993), Express saccades and visual attention, (in:) Behavioral and Brain Sciences 16. 553–610.

Flash, H., Ducharme, R., (1987), Development of phasic heart rate patterns during recalland arithmetic tasks, Acta Psychologica, 65, 115-132.

Fowles, D. C., (1974), Mechanism of electrodermal activity, (in:) Thompson, R. F., Patterson, M. M., (red.), Methods in physiological psychology, t.l.: Bioelectric recording techiques, New York, Academic Press, 231-271.

Francuz, P., (2013), Imagia. W kierunku neurokognitywnej teorii obrazu, Wydawnictwo KUL, Lublin.

Fredrickson, B. L., (2004), The broaden-and-build theory of positive emotions, Philosophical Transaction of the Royal Society, 359, 1367–1377.

Gajewski, D. A., Henderson, J. M., (2005), The role of saccade targeting and in the transsacadic integration of object types and tokens, (in:) Journal of Experimental Psychology: Human Perception and Performance, 31, 820–830.

Garrity, L. I., (1977), Electromyography: A review of the current status of subvocal speech research, Memory and Cognition, 5, 615-622.

Glassner, A., (1995), Principles of Digital Image Synthesis, Morgan Kaufmann Publ., San Francisco.

Glimcher, P. W., (2003), The neurobiology of visual–saccadic decision making, (in:) Annual Review of Neuroscience, 26, 133–179.

Goldwater, B. C., (1987), Effects of arousal on habituation of electrodermal versus vasomotor responses, Psychophysiology, 24, 142-150.

Grings, W. W., (1973), Cognitive factors in electrodermal conditioning, Psychological Bulletin, 79, 200-210.

Grings, W. W., Dawson, M. E., (1973), Complex variables in conditioning, (in:) Prokasy, W. F., Raskin, D. C., (red.), Electrodermal activity in psychological research, New York, Academic Press, 203-253.

Haier, R. J., Siegel, B., Tang, C., Abel, L., Buchsbaum, M. S., (1992), Intelligence and changes in regional cerebral glucose metabolic rate following learning, Intelligence, 16, 415–426.

Hare, R. D., (1972a), Response requirements and directional fractionation of autonomic responses, Psychophysiology, 9, 419-427.

Hare, R. D, (1972b), Cardiovascular components of orienting and defensive responses, Psychophysiology, 9, 606-614.

Hare, R. D., (1973), Orienting and defensive responses to visual stimuli, Psychophysiology, 10, 453-464.

Hare, R. D., (1978), Electrodermal and cardiovascular correlates of psychopathy, (in:) Hare, R. D., Schalling, D., (red.) Psychopatic behaviour: Approaches to research, Chichester, Wiley,107-143.

Hatamikia, S., Maghooli, K., Nasrabadi, A. M., (2014), The emotion recognition system based on autoregressive model and sequential forward feature selection of electroencephalogram signals, Journal of Medical Signals and Sensors, 4(3), 194–201.

Henderson, J. M., Hollingworth, A., (1998), Eye Movements During Scene Viewing:An Overview, (in:) Underwood, G., (red.), Eye Guidance in Reading and Scene Perception, Elsevier, 269–294.

Hendrickson, A. E., (1982), The biological basis of intelligence, Part I: theory, (in:) Eysenck, H. J., (dd.), A Model for Intelligence, Springer, New York.

Hofer, H., Carrol, J., Williams, D. R., (2009), Photoreceptor mosaic, (in:) Square, L. R., (red.), Encyclopedia of neuroscience, Elsevier Ltd., 7, 661-668.

Holm, L., (2007), Predictive eyes recede retrieval, Visual recognition as hypothesis testing, Doctoral dissertation, Department of Psychology, Umea University Sweden.

Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., Joost van de Weijer, (2011), Eye Tracking. A comprehensive guide to methods and measures, Oxford.

Hulewicz, A., Cysewska-Sobusiak, A., Grzybowski, A. M., (2005), Badania elektrofizjologiczne w okulistyce – pozyskiwanie i analiza sygnałów pomiarowych, Pomiary Automatyka Kontrola, 9, 13-17.

Hutton, S. B., Tegally, D., (2005), The effects of dividing attention on smooth pursuit eye movements, (in:) Experimental Brain Research, 163, 306–313.

Ince, I. F., Yang, T. Ch., (2009), A New Low-Cost Eye Tracking and Blink Detection Approach: Extracting Eye Features with Blob Extraction, Emerging Intelligent Computing Technology and Applications Lecture Notes in Computer Science, Volume 5754, 526-533.

Jaśkowski, P., (2004), Zarys psychofizjologii, Wyższa Szkoła Finansów i Zarządzania, Warszawa.

Jacob, R. J. K., Karn, K. S., (2003), Eye Tracking in Human-Computer Interaction and Usability Research: Ready to Deliver the Promises, (in:) Radach, R., Hyona, J., Deubel, H., (eds.), The mind's eye: cognitive and applied aspects of eye movement research, Boston: North-Holland/Elsevier, 573–605.

Jacobson, E., (1932), Electrophysiology of mental activities, American Journal of Psychology, 44, 667-694.

Jaques, N., Conati, C., Harley, J., Azevedo, R., (2014), Predicting Affect from Gaze Data During Interaction with an Intelligent Tutoring System, Intelligent Tutoring Systems, 12th International Conference, ITS 2014, Honolulu, HI, USA, June 5-9, 2014.

Proceedings, 29-38.

Jennings, J. R., Tahmoush, A. J., Redmond, D. P., (1980), Non-invasive measurementof peripheral vascular activity, (in:) Martin, I., Venables, I., (red.), Techniquesin psychophysiology, Chichester, Wiley, 69-139.

Jennings, J. R., Wood, C., (1980), Cardiac cycle time effects on performance phasic cardiac responses and their intercorrelation in choice reaction time, Psychophysiology, 14, 297-307.

Jennings, J. R., (1986), Memory, thought, and bodily response, (in:), Coles, M. G. H., Donchin, E., Porges, S. W., (red.), Psychophysiology: Systems, processes and application, New York, Guilford Press, 290-309.

Jennings, J. R., Nebes, R., Brock, K., (1988), Memory retrieval in noise and psychophysiological response in the young and old, Psychophysiology, 25, 633-644.

Johnson, H. J., Campos, J., (1967), The effect of cognitive tasks and verbalization instructions on heart rate and skin conductance, Psychophysiology, 4, 143-150.

Jonas, J. B., Schmidt, A. M., Muller-Bergh, J. A., Schlotzer-Schrehardt, U.M., Naumann, G. O. H., (1992), Human optic nerve fiber count and optic disc size. Investigative Ophthlalmology; Visual Science, 33 (6), 2012-2018.

Juhasz, B. J., (2005), Age–of–acquisition effects in word and picture processing,(in:) Psychological Bulletin, 131, 684–712.

Just, M. A., Carpenter P. A., (1980), A theory of reading: from eye fixation to comprehension, (in:) Psychological Review, 87, 329–354.

Kahneman, D., (2011), Thinking Fast and Slow, Farrar, Straus and Giroux.

Khurana, B., Kowler, E., (1987), Shared attentional control of smooth eye movementand perception, (in:) Vision Research, 27, 1603–1618.

Konarska, L., (red), (1995), Molekularne mechanizmy przekazywania sygnałów w komórce,PWN, Warszawa.

Kowler, E., Blaser, E., (1995), The accuracy and precision of saccades to small and larger targets, (in:) Vision Research 35. 1741–1754.

Krauzowicz, J., (2013), Stress - builder or destroyer of cognitive processes? Annales Academiae Medicae Stetinensis, 84–92.

Kingstone, A., Klein, R. M., (1993), Visual offset facilitates saccade latency: Does pre–disengagement of attention mediate the gap effect? (in:) Journal of Experimental Psychology: Human Perception and Performance, 19, 251–265.

Kowler, E., Blaser, E., (1995), The accuracy and precision of saccades to small and larger targets, (in:) Vision Research, 35, 1741–1754.

Kryjak, T., (2009), Wizyjne śledzenie ruchu gałek ocznych, Automatyka, t. 13, 3, 1141-1152.

Kuno, Y. (1956). Human perspiration. Springfield, Charles C. Thomas.

Kurcz, I., Polkowska, A., (1990), Interakcyjne i autonomiczne przetwarzanie informacji językowych na przykładzie procesu rozumienia tekstu czytanego na głos, Wydawnictwo Polskiej Akademii Nauk.

Lai, M.-L., Tsai, M.-J., Yang, F.-Y., Hsu, C.-Y., Liu, T.-C., Lee, S. W.-Y., et al., (2013), A review of using eye-tracking technology in exploring learning from 2000 to 2012, Educational Research Review, 10, 90-115.

Lanzetta, J. T., (1982), Use of facial electromyography in studies of empathy and counterempathy, Psychophysiology, 19, 543.

Lee, P. H., Sooksawate, T., Yanagawa, Y., Isa, K., Isa, T., Hall, W. C., (2007), Idenity of a pathway for saccadic suppression, (in:) Proceedings of National Academy of Science 104, 6824–6827.

Levine, M. W., (2000), Fundamentals of Sensation and Perception, Oxford.

Lewartowski, B., (1990), Fizjologia serca (in:) Traczyk, A., Trzebski (red), Fizjologia człowieka z elementami fizjologii stosowanej i klinicznej, Warszawa, PZWL.

Liversedge, S. P., Findlay, J. M., (2000), Saccadic eye movements and cognition, (in:) Trends In Cognitive Sciences, 1, 6–14.

Liversedge, S. P., Gilchrist, I. D., Everling, S.,(2011), The Oxford handbook of eye movements, Oxford, New York : Oxford University Press, Series: Oxford library of psychology.

Loon, E. M., Hooge, I.T., Van Den BERG, A. V., (2002), The timing of sequences of saccades in visual search, (in:) Proceedings of the Royal Society of London.

Loftus, G. R., (1981), Tachistoscopic Simulations of Eye Fixations on Pictures, (in:) Journal of Experimental Psychology: Human Learning and Memory, 7(5), 369–376.

Mackworth, N. H., Thomas, E. L., (1958), Head-mounted eye-marker camera, Journal of the Optical Society of America, 52:713-716.

Madsen, A., Larson, A., Loschky, L., Rebello, S., (2012), Differences in visual attention between those who correctly and incorrectly answer physics problems, Physical Review Special Topics, Physics Education Research, 8, 1–13.

Madsen, A., Larson, A., Loschky, L., Rebello, N., (2012), Using ScanMatch scores to understand differences in eye movements between correct and incorrect solvers on physics problems, Proceedins of the Symposium on Eye Tracking Research and Applications, EXTRA 2012, Santa Barbara, CA, USA, 28-30, 193 – 196.

Madsen, A., Rouinfar, A., Larson, A., Lester C. Loschky, Sanjay Rebello, N. (2013), Can short duration visual cues influence students' reasoning and eye movements in physics problems? Phys. Rev. ST Phys. Educ. Res., 9, 020104 .

Marek, T., Fąfrowicz, M., (1995), Neuropsychologiczne mechanizmy procesu przenoszenia uwagi wzrokowej, (in:) Kolokwia Psychologiczne, 3, 69–86.

Martinez-Conde, S., Macknik, S. L, Troncoso, X. G., Hubel, D. H., (2009), Microsaccades:a neurophysiological analysis, (in:) Trends in Neurosciences, 32(9), 463–475.

Marshall, S. P., (2007), Identifying cognitive state from eye metrics, Aviation, Space,and Environmental Medicine, 78, 165–175.

Maspfuhl, B., Metz, A., (1970), Veranderungen im Electromyogram bei der Beurteilung perzeptiver Muster unterschedlicher Schwierigkeit. Zeitschrift fur Psychologie, 177, 286-301.

Mayer, A. R., Dorflinger, J. M., Rao, S., M., Seidenberg, M., (2004), Neural networks underlying endogenous and exogenous visual–spatial orienting, (in:) NeuroImage, 23, 534–541.

McHugo, C. J., (1983), Facial EMG and self-reported emotion, Psychophysiology, 20, 459.

Melcher, D., (2005), Spatiotopic transfer of visual form adaptation across saccadic eye movements, (in:) Current Biology, 15, 1745–1748.

Melcher, D., (2009), Selective attention and the active remapping of object features in trans–saccadic perception, (in:) Vision Research, 49, 1249–1255.

Merkley R., Ansari D., (2010), Using eye tracking to study numerical cognition: the case of the ratio effect, Exp Brain Res., 206(4),455-460, doi: 10.1007/s00221-010-2419-8.

McGuigan, F. J., (1978), Cognitive psychophysiology: principles of covert behavior, New York, Prentice Hall.

Młodkowski, J., (1998), Aktywność wizualna człowieka, PWN, Warszawa.

Moeller, K., Klein, E., Nuerk, H. C., (2011), Three processes underlying the carry effect in addition–Evidence from eye tracking, British Journal of Psychology, 102 (3), 623-645.

Montagu, J. D., Coles, E. M., (1968), Mechanism and measurement of the galvanic skin response: An addendum, Biological Bulletin, 69, 74-76.

Muldner, K., Christopherson, R., Atkinson, R., Burleson, W., (2009), Investigating the utility of eye-tracking information on affect and reasoning for user, Proc. of the 17th Int. Conf. on User Modeling Adaptation, and Personalization. SpringerVerlag, Italy, 138–149.

Nazir, T. A., Jacobs, A. M, (1991), The effects of target discriminability and retinal eccentricity on saccade latencies: An analysis in terms of variable–criterion theory, (in:) Psychological Research, 53, 281–289.

Nicholas, J., Wade, N. J., Brožek, J., (2001). Purkinje's Vision, Lawrence Erlbaum Associates, 13, ISBN 978-0-8058-3642-4.

Niżankowska, M. H., (2000), Podstawy okulistyki, Wolumed, Warszawa.

Ober, J., Dylak J., Gryncewicz, W., Przedpelska-Ober, E., Sakkadometria – nowe możliwości oceny stanu czynnościowego ośrodkowego układu nerwowego, Nauka, 4, 2009,109 – 135.

Prendinger, H., Ishizuka, M., (2005). The empathic companion: A character-based interface that addresses users'affective states, APAI, 19, 3-4, 267–285.

Pearce, J. M., (2001), Emil Heinrich Du Bois-Reymond (1818-96). Journal of Neurology, Neurosurgery, and Psychiatry, 71 (5): 620.

Pernice, K., Nielsen, J., (2009), Eyetracking Methodology. How to Conduct and Evaluate Usability Studies Using Eyetracking, Nielsen Norman Group.

Pęczkowski, P., Błasiak, W., Wcisło D., Rosiek R., Stolińska A., Andrzejewska M., Sajka M., Rożek B., (2014), Research of strategies applied to solve a physic problem by persons with different degree of experience and different attitudes towards physics eye-tracking investigation, (in:) Cieśla, P., Michniewska, A., (ed.), Teaching and learning science at all levels education, Pedagogical University,Kraków, 99-107.

Posner, M. I., Raichle, M., (1994), Images of Mind, New York: Scientific American Library.

Prime, S. L., Tsotsos, L.,. Keith, G. P., Crawford, J. D., (2007), Visual memory capacityin transsacadic integration, (in:) Experimental Brain Research, 180, 609–628.

Pratt, J., Lajonchere, C.M., Abrams R. A., (2006), Attentional modulation of gap effect,(in:) Vision Research, 46, 2602–2607.

Purkinje, J. E., (1825), Neue Beiträge zur Kenntniss des Sehens in Subjectiver Hinsicht. Reimer, Berlin, 109–110.

Rayner, K., (1978), Eye movements in reading and information processing, Psychological Bulletin, 85, 618–660.

Reichle, E. D., Pollatsek, A., Fisher, D. L., Rayner, K., (1998), Toward a Model of Eye Movement Control in Reading, (in:) Psychological Review 105(1). 125–157.

Reichle, E. D., Warren, T., Mcconnell, K., (2009), Using E-Z Reader to model the effects of higher level language processing on eye movements during reading, Psychonomic Bulletin & Review, 16 (1), 1-21.

Rayner, K., (1998), Eye movements in reading and information processing: 20 years of research, Psychological Bulletin, 124, 372–422.

Rayner, K., Pollatsek, A., (1992), Eye Movements and Scene Perception, (in:) Canadian Journal of Psychology, 46(3), 342–376.

Rayner, K., Well, A. D., (1996), Effects of contextual constraint on eye movements in reading: A further examination, (in:) Psychonomic Bulletin & Review, 3, 504–509.

Rimehaugh, T., Svebak, S., (1987), Psychogenic muscle tension: the significance of motivation and negative affect in perceptual-cognitive task performance, International Journalof Psychology, 5, 97-106.

Robinson, D. A., (1968), The oculomotor control system: A review, Proceedings of the IEEE (Volume: 56 , Issue: 6), 1032-1049.

Rosiek, R., Sajka, M., (2014), Reakcja źrenicy, jako wskaźnik przetwarzania informacji podczas rozwiązywania zadań testowych z zakresu nauk ścisłych. (in:) Edukacja – Technika – Informatyka, nr 5/2014/ 2, 368-374.

Rosiek R., Sajka M., (2014), Neurodidactical Approach to Research on Science Education, (in:) New Technologies in Science Education, Nodzyńska M., Cieśla P., Różowicz K., (ed.), Kraków, Pedagogical University, 7-20.

Rosiek R., Sajka M., (2014), Using heart rate monitoring to explore student's motivation to solve a science problem - case study, Zvyšování kompetencí studentů DSP v oblasti didaktiky matematiky, Olomouc: UP, 20-24.

Rosiek, R., (2014), Mobile technologies in science education - the usage of a proprietary voting system, Proceedings of the 23rd International Conference on Chemistry Education, Hradec Králové / ed. Bílek M., Hradec Králové.

Ross, J., Morrone, M. C., Burr, D. C., (1997), Compression of visual space before saccades, (in:) Nature, 386(6625), 598–601.

Rożek, B., Błasiak, W., Andrzejewska, M., Godlewska, M., Kazubowski, P., Rosiek, R., Sajka, M., Stolińska, A., Wcisło, D., (2015), Neurodydaktyczne aspekty procesu rozwiązywania testowego zadania matematycznego w oparciu o badania eyetrackingowe, Edukacja, Technika, Informatyka 3(13), 202-208.

Sabitzer, B., (2011), Neurodidactics - A new stimulus in ICT and Computer Science Education, Conference Paper (Conference: ATEE Winter Conference 2012) http://www.creamos.eu/NeurodidactisSabitzerSIGCSE2011.pdf

Sajka, M., Rosiek, R., (2014), Wiedza potoczna: pomoc czy przeszkoda? Eye-trackingowa analiza rozwiązań zadania z zakresu nauk przyrodniczych, (in:) Edukacja – Technika – Informatyka, nr/5/2014/part 2, 375-383.

Sajka, M., Rosiek, R., Błasiak, W., Andrzejewska, M., Godlewska, M., Kazubowski, P., Rożek, B., Stolińska, A., Wcisło, D., (2015), Analiza reakcji pupilometrycznych uczniów gimnazjum podczas rozwiązywania zadania – badania porównawcze, *Edukacja, Technika, Informatyka 3(13)*, 188-194.

Sajka, M., Rosiek, R., (2015), Analiza porównawcza wybranych parametrów okulograficznych uczniów gimnazjum podczas rozwiązywania zadania, Edukacja, Technika, Informatyka 3(13), 195-201.

Sekuler, R., Blake, R. (1994), Perception, New York.

Selvaraj, J., Murugappan, M., Wan Kh, Yaacob, S., (2013), Classification of emotional states from electrocardiogram signals: a non-linear approach based on hurst, BioMedical Engineering OnLine 2013, 12:44 DOI:10.1186/1475-925X-12-44 http://www.biomedical-engineering-online.com/content/12/1/44

Schafer, E. W. P., (1982), Neural adaptability: a biological determinant of behavioral intelligence, Int. J. Neurosci., 17.

Schneider E., Maruyama, M., Dehaene, S., Sigman, M., (2012), Eye gaze reveals a fast, parallel extraction of the syntax of arithmetic formulas, Cognition, 125 (3), 475-490.

Shapley, R., Kaplan, E., Soodak, R., (1981), Spatian summation and contrast sensitivity os X and Y cells in the lateral geniculate nucleus of the macaque, Nature, 292, 543-545.

Siddle, D. A. T., Turpin, G., (1980), Measurement, quantification, and analysis of cardiac activity, (in:) Martin, I., Venables, P.H., (red.), Techniques in psychophysiology,Chichester, Wiley, 139-247.

Smilek, D., Carriere, J. S., and Cheyne, J. A., (2010), Out of mind, out of sight eye blinking as indicator and embodiment of mind wandering, Psych. Sci., 21, 6, 786–789.

Smith, A. D.; Mestre, J. P.; Ross, B. H., (2010), Eye-gaze patterns as students study worked-out examples in mechanics. Physical Review Special Topics-Physics Education Research 6, (2).

Snellen, Herman Adrianus (1995), Willem Einthoven (1860–1927) Fatherof Electrocardiography, Life and Work, Ancestors and Contemporaries, Dordrecht: Kluwer Academic Publishers, ISBN 0-7923-3274-1.

Soluch, P., Tarnowski, A., (2013), O metodologii badań eyetrackingowych, Lingwistyka Stosowana, Tom 7, 115-135.

Sosnowski., T., (red), (1993), Metody psychofizjologiczne w badaniach psychologicznych, PWN, Warszawa.

Sosnowski, T., (2002), Zadania umysłowe a aktywność sercowo-naczyniowa, Gdańskie Wydawnictwo Psychologiczne.

Spitzer, M., (2006), Brain Research and Learning over the Life Cycle, Personalising Education, OECD, Paris, 55.

Srihasam, K., Bullock, D., Grossberg, S., (2007), Coordinating saccades and smooth pursuit eye movements during VISUAL tracking and perception of objects moving with variable speeds, (in:) Journal of Vision, 6, 908–908.

Steptoe, A., (1980), Blood pressure, (in:) Martin, I., Venables, P.F., (red.), Techniquesin psychophysiology, Chichester, Wiley, 247-275.

Steptoe, A., Melville, D., Ross, A., (1984), Behavioral response demands, cardiovascular reactivity and essential hypertension, Psychosomatic Medicine, 46, 33-48.

Stolińska, A., Andrzejewska, M., Błasiak, W., Godlewska, M., Pęczkowski, P., Rosiek, R., Rożek, B., Sajka, M., Wcisło, D. (2014), Analysis of saccadic eye movements of experts and novices when solving text tasks, New Technologies in Science Education, editors: Nodzyńska, M,Cieśla, P., Różowicz K., Pedagogical University, Kraków, ISBN 978-83-7271-879-2, 7-20.

Strelau, J., (2006), Psychologia różnic indywidualnych, Scholar, 2006, ISBN 8373832092.

Susac, A., Bubic, A., Kaponja, J., Planinic, M., Palmovic, M., (2014), Eye

Movements Reveal Students'strategies In Simple Equation Solving, International Journal of Science and Mathematics Education, 12 (3), 555-577.

Svebak, S., (1986), Cardiac and somatic activation in the continuous perceptual-motor task: the significance of threat and serious-mindness, International Journal of Psychophysiology, 3, 155-162.

Svebak, S., Rimehaugh, T., (1987), Psychogenic muscle tension: The significanceof motivation and negative affect in perceptual-cognitive task performance, International Journal of Psychophysiology, 5, 97-106.

Thiel, Ch. M., Ziles, K., Fink, G.R., (2004), Cerebral correlates of orienting and reorienting visuospatial attention: an event–related fMRI study, (in:) Neuroimage, 21, 318–328.

Thompson, M., Thompson, L., (2012) - Neurofeedback - wprowadzenie do podstawowych koncepcji psychofizjologii stosowanej, Wrocław, Wydawnictwo Biomed Neurotechnologie.

Traczyk, W. Z., Trzebski, A., (1990), Fizjologia człowieka z elementami fizjologii stosowaneji klinicznej (t. 2), Warszawa, PZWL.

Tsai, Meng-Jung, Huei-Tse, Houb, Meng-Lung, Laic, Wan-Yi, Liua, Fang-Ying, Yangd, (2012),Visual attention for solving multiple-choice science problem: An eye-tracking analysis, Computers & Education, 58, 1, 375–385.

Turpin, G., (1986), Effects of stimulus intensity on autonomic responding: The problemof differentiating orienting and defense reflexes, Psychophysiology, 23, 1-4.

Valko, P., Mumenthaler, M., Bassetti, C. L., (2006), History of neurological contribiutiosin the Swiss Archives of Neurology and Psychiatry, Schweizer Archiv Fur Neurologie und Psychiatrie, 15792, 62-76.

Van Gompel, R. P. G., Fischer, M. H., Murray, W.S., Hill, R. L., (2007), Eye Movements:A Window on Mind and Brain. Elsevier.

Venables, P. H, Christie, M. J., (1980), Electrodermal activity, (in:) Martin, I., Venables P., (red.), Techniques in psychophysiology, Chichester, Wiley.

Wade, N., Tatler, B., (2009), Did Javal measure eye movements during reading? Journalof Eye Movement Research, 2(5):5, 1-7.

Wcisło, D., Błasiak, W., Andrzejewska, M., Godlewska, M., Rosiek, R., Rożek, B. Sajka, M., Stolińska, A., (2014), Różnice w rozwiązywaniu problemów fizycznych przez nowicjuszy i ekspertów (in:) Edukacja – Technika – Informatyka, nr/5/2014/part 2, 361-367.

Weimann, J., (1989), Mental effort in problem solving as manifest in the power spectra of heart-interbeat intervals, (in:) Landau, K., Rohmert, W., (red.), Recent Developments in Job analysis. London, Taylor & Francis, 227-236.

Wilcott, R. C., (1967), Arousal sweating and electrodermal phenomena, Psychological Bulletin, 67, 58-72.

Witzner, D. H., Qiang Ji, (2010), In the Eye of the Beholder:A Survey of Models for Eyes and Gaze, IEEE Transactions On Pattern Analysis And Machine Intelligence, vol. 32, no. 3.

Yarbus, A. L., (1967), Eye Movements and Vision, New York: Plenum, Originally published in Russian 1962.

Young, L. R, Sheena, D., (1975), Survey of eye movement recording methods, (in:) Behavior research methods, instruments and computers, 7(5), 397–429.

Zając, M., (2003), Optyka okularowa, Dolnośląskie Wydawnictwo Edukacyjne, Wrocław.

Zee, D. S., Lasker, A. G., (2004), Antisaccades Probing cognitive flexibility with eye movements, (in:) Neurology 63, 1554–1554.

Webpages:

BioGraph Infiniti:http://www.thoughttechnology.com/pdf/manuals/SA7560 %20rev.%204%20FlexComp%20Infiniti%20User%20Manual%20(2).pdf

Edisonda : http://www.edisonda.com/

Experiment Centerhttp://www.smivision.com/en/gaze-and-eye-tracking-systems /products/experiment-center-software.html

Gazepointer : http://sourceforge.net/projects/gazepointer/http://www.umoove.me/ about.html

Facereader:http://www.noldus.com/human-behavior-research/products/facereader

Opengazer: open-source gaze tracker for ordinary webcam: http://www.inference. phy.cam.ac.uk/ opengazer

Oziembowski 2013: Przemysław Oziembowski, Technika świetlna od podstaw www.swiatlo.tak.pl, za zgodą autora.

Smart Scroll, Software by Samsung:http://www.samsung.com/us/support/faq/ FAQ00053081/62452/SCH-R970ZWAUSC

SMI products :http://www.smivision.com/en/gaze-and-eye-tracking-systems/products /redm.html

Tobii products:http://www.tobii.com/en/what-is-eye-tracking/

Nikon D60, CCD

http://www.gizmodo.jp/2013/06/4cmos.html

Distribution of rods and cones along a line passing through the fovea and the blind spot of a human eye: http://en.wikipedia.org/wiki/Blind_spot_%28vision%29

The test proving the lack of receptors in the area of blind spot (macula ceca). http://serendip.brynmawr.edu/bb/blindspot/

ISBN 978-83-8084-611-1
9 788380 846111