Chapter 13
Task-Evoked Pupillary Responses in Context of Exact Science Education

Roman Rosiek and Miroslawa Sajka

Introduction

Short Characteristics of Eye Movements

N. Wade and B. W. Tatler (2005), who conducted historical research on the first mentions of eye movement studies in the literature available to them, proved that eye movements have interested researchers since the dawn of time. According to their information, the first mention of eye movements appeared in the work of Du Laurens in 1596. According to the authors, the monograph of Johannes Müller, published in 1826, was the first to describe an eye movement study. The second precursor of eye movement research, according to Wade and Tatler (2005), is believed to be Charles Bell, who, in his work from 1823, presented the results of research on active and passive eye movements in response to visual stimuli, and drew attention to proprioception (referred to as muscle sense in the work) (for: Wade & Tatler, 2005). One should not forget about the work of Czech scientist Jan Evangelist Purkinje, despite the fact that his work concerned a broader subject, mainly physiology. Nowadays, the eye movements of a healthy person are divided into convergent movements, a tremor, gentle eye tremor, drift, microsaccades, optokinetic reflex, tracking, and jumping movements or saccadic eye movements (Soluch & Tarnowski, 2013). We also distinguish fixations, often considered a separate physiological mechanism, composed of minor movements called interfixations, i.e., tremor, microsaccades, and

R. Rosiek
Institute of Physics, Pedagogical University of Krakow, Kraków, Poland

M. Sajka (✉)
Institute of Mathematics, Pedagogical University of Krakow, Kraków, Poland
e-mail: miroslawa.sajka@up.krakow.pl

I. Devetak and S. A. Glažar (eds.), *Applying Bio-Measurements Methodologies in Science Education Research*,
https://doi.org/10.1007/978-3-030-71535-9_13

drift. Although fixations are, in fact, also movements, they are interpreted as focusing on a particular fragment of the image (a static process lasting several hundred ms), which is justified, because small movements are used to broaden the field of precise view—it is a compensation mechanism (Soluch & Tarnowski, 2013). Tracking movements involve following the sight of the observed object changing its position while maintaining a relatively stable position of the head. Ross et al. (1999) proved that the brain centers responsible for undertaking and maintaining tracking movements block the operation of saccadic movements. Under natural conditions, object tracking is also associated with head movement, and sometimes also with corrective saccades. These movements interact with each other, so their mechanisms are quite complex (Srihasam et al., 2009). Although the processes of visual attention were associated mainly with the mechanisms of eye movement, the role of attention mechanisms in tracking movements was increasingly being underlined (Khurana & Kowler, 1987). Hutton and Tegally (2005) showed a decrease in the speed and spatial precision of tracking movements, caused by performing additional tasks which required attention. According to the authors, this type of movement does not depend only on simple nervous mechanisms, but, as in the case of jumping movements, they result from complex processes of the cognitive system. As described by Soluch and Tarnowski (2013), apart from mechanical eye movements, brain mechanisms responsible for perception stability also play an important role in perception processes. Without them, conscious perception of continuous body movement relative to the perceived objects would most likely be impossible due to the need of recognizing the image again after each movement. One of the more important mechanisms is the optokinetic reflex. This mechanism compensates for head movements in order to maintain fixation on a particular object. Saccadic suppression is another important mechanism.

This phenomenon involves blocking certain batches of neurons within certain areas of the brain that are responsible for seeing through other batches that are responsible for saccadic eye movements (Lee et al., 2007). The purpose of this mechanism is to counteract the disturbance in perception that could be caused by rapid image movement (several times per second). This means that saccadic suppression is associated with the lack of vision of the part of the image which is on the path of the saccades. Typical presaccadic suppression causes blindness within 30–40 ms preceding the start of the saccade, and post-saccadic suppression causes a lack of vision lasting 100–120 ms of image perception. It can be concluded that it is not possible to see for all the time during which the fixation occurs, which should be taken into account in precisely determining the duration of the fixation, and more precisely, active focusing (Holmqvist et al., 2011). It is worth noting, after Soluch and Tarnowski (2013), that transsaccadic integration is currently the least known process enabling the stability of perception. The visual cortex is responsible for integration at cerebral level (Findlay & Gilchrist, 2003). This mechanism is of great importance due to the fact that each eye movement fundamentally changes the image of the external world projected onto the retina, and thus the visual system must somehow re-analyze the individual objects and their features (Soluch & Tarnowski, 2013). The integration mechanism guarantees that performing eye movements does not disturb the perception of particular elements, which is currently being explored in search of the bounds of this compensation process (Prime et al., 2004, 2007). An important component of the transsaccadic integration mechanism is not only image analysis after saccadic movement, but mainly analysis of the previous image (Gajewski & Henderson, 2005). Although it has been proven that transsaccadic integration is not associated with iconic memory, many new data (Findlay & Gilchrist, 2003; Melcher, 2009) indicate the involvement of attention processes and active image processing. Studies by Melcher (2005) have shown that transsaccadic integration results from the cortical representation of space, not the retinal image itself.

A precise explanation of this mechanism requires an approach to visual perception as an active way of seeking information, and not just as a passive reflection of the surrounding world. Research on transsaccadic integration is currently one of the most-explored problems in perception psychology, as the latest technological achievements, e.g., neuroimaging, are being used for the purposes of such research.

Pupillometry

The pupil is a movable diaphragm located between the cornea and the lens of the eye. The primary function of the pupil is to regulate the amount of light that falls on the retina of our eye. The pupil of a healthy person is approximately circular, so we can use its diameter to describe changes in pupil size. Winn et al. (1994), Beatty and Lucero-Wagoner (2000), The diameter of the pupil in young, healthy people ranges from 3 to 8 mm (Sosnowski et al., 1993). Studies on pupil diameter changes, often referred to as pupillometry, Andreassi (2000), are widely used in medicine. Examination of pupil diameter changes is used, among others, to diagnose neurological syndromes such as Addison's disease and Horner's syndrome, to monitor the effects of some medications, e.g., psychotropic, or to check for anesthesia (Wilhelm, 2011). Assessment of the rate of change in the diameter of the pupil as its response to light is used in clinical settings to detect optic nerve dysfunction, diagnose the effects of certain medications and substances, drugs, and assess the functioning of the brainstem (Lowenfeld, 1999). It can be said that it is a fast, painless, and non-invasive and relatively convenient diagnostic process. Currently, pupillometry is also used in psychology, Harrison et al. (2006), psychiatry, and in the field of educational research. We can find the first application attempts described in the literature in the 1960s as a measure of cognitive load affect (Hess & Polt, 1964; Hess, 1972), and, in particular, the observation that pupil width increases due to cognitive load (Kahneman & Beatty, 1966), Libby et al. (1973), Matthews et al. (1991). In the 1980s, the use of scientific research on pupil diameter changes was extended (Beatty, 1982). Increasingly, individual differences in the area of learning and processing information were also reflected in the differences in pupil diameter changes, providing potential for the identification and diagnosis of mental disorders.

Pupillometric Hypotheses

The neural efficiency hypothesis assumes that more intelligent people, when processing information and solving problems, are more efficient, without incurring as much mental effort as less intelligent people (Davidson & Downing, 2000; Haier et al., 1992, 415–426; Hendrickson, 1982). This hypothesis is reinforced by research in the field of psychophysiology on eye pupil reactions. The dilation of the eye pupil of the person undergoing research while solving a cognitive task is a psychophysiological measure of the burden of the process of analyzing and processing data. The greater the pupil dilation, the greater the burden of information processing or mental effort (Beatty, 1982). Ahern and Beatty (1979) also showed that there is a relationship between pupil responses and the cognitive abilities of the subjects. They showed that the changes recorded in students during multiplication were negatively correlated with their cognitive abilities. This meant that students with lower scores in the Scholastic Aptitude Test (SAT) had greater pupil dilatation during multiplication. This result is consistent with the neural efficiency hypotheses. Potential in the area of application of pupillometric tests in education and pedagogical sciences can be noted in the areas of anxiety disorder diagnosis. According to Ober et al. (2009) abnormalities in pupillometric reactions can be seen in people suffering from anxiety disorders. In people who showed a high tendency for anxiety, worrying, and rumination, smaller ranges of pupil diameter changes were observed when solving problems requiring a significant cognitive load. Such people, despite deviations in their reaction in terms of pupil diameter changes, performed the tasks in an effective manner, which means that the level of requirements did not exceed their cognitive abilities.

Methodology

The aim of the study is to identify whether monitoring the changes in pupil diameter when solving graph-related tasks concerning physics and mathematics will allow for obtaining information on the cognitive load of the subjects Paas et al. (2003), during the task-solving process and on the subjective assessment of the difficulty of the tasks. Gopher. (1994), Backs and Walrath (1992), Granholm, (2004), Partala et al. (2000), The experiment was carried out in a group of 103 people. The diameter of the examined pupils was measured using a Hi-Speed SMI eyetracker and iViewX ™ software with an assumed sampling frequency of 500 Hz. Data analysis was based on proprietary data analysis procedures which were performed on data series exported to CSV files. Błasiak et al. (2013), The analysis of data regarding the analysis of pupil diameter changes and the examination itself can be carried out assuming that the lighting conditions in the room do not change during the examination for each task and for each person. Therefore, in order to ensure the invariability of the light stream falling on the retina of the subjects' eye, the measurement was carried out when looking at a static image and, what is important, in the absence of changes in the distance between the screen and the eye retina of the subjects, with unchanging lighting conditions of the room in which the research was carried out. During the research, it was ensured that the lighting intensity in the room in which the test was conducted did not change. Therefore, the entire study was conducted with fixed, artificial interior lighting, which did not change for each of the subjects. Prior to the calibration, the subjects additionally spent several minutes in the room in which the examination was carried out, so that their eyes could adapt to the lighting conditions. This procedure was intended to ensure even greater reliability in measuring pupil diameter throughout the study. A 9-point device calibration procedure was performed prior to testing. Due to individual differences in terms of pupil diameter and their response, absolute values were not compared during data analysis. For the purpose of analyses and comparisons, only the percentage values of relative changes in pupil diameter were used. The entire procedure of comparing relative values consisted of the following activities: device calibration, registration of the task-solving process performed by the subjects, including registration of absolute pupil diameter values during the entire process with a sampling rate of 500 Hz, export of the recorded data to CSV files, identification and selection of appropriate data areas illustrating the eye fixations of the examined persons in terms of the visual representations of individual tasks, and all other important elements of the study for which the analysis of pupil width changes was made. The process of calculating the values of relative pupil diameter changes consisted of calculating the average pupil diameter value for each of the subjects individually in terms of task completion time, then calculating the instantaneous values of the percentage differences from the average for individual fixations for each of the solved tasks and for each subject. Subsequently, further assumptions were made. Due to the fact that the subjects did not have a time limit to solve the tasks, they could solve them at their own pace. This was associated with a very large dispersion of the recorded response times, and thus the total inability to impose and directly compare the records of this process for individual subjects. Therefore, for the purpose of analyzing and comparing the registered data, it was assumed that the individual response of the subjects, manifested in changes in the diameter of the pupil (Beatty, 1982) as a subjective assessment of the degree of difficulty, occurs during the first seconds of learning the content of the task, immediately after displaying the task, most often while reading the content of the task. The legitimacy of this assumption is confirmed by the analysis of the first fixations of the subjects during the analysis of the visual representations. Therefore, an analysis of the changes in the diameter of the pupil during the first ten fixations of the subjects in the observed image was made, assuming that it was when the subjects made the first subjective assessment of the category of the task and the degree of its difficulty (Ahern & Beatty, 1979). Therefore, in the first research approach described in this chapter, the relative percentage values of pupil diameter changes in selected groups of people for the first ten fixations were taken into account. This is a conscious simplification in which we assume averaging, i.e., analysis of all changes in the pupil diameter of the participants for the entire group, knowing that the reactions of individual people may occur at different times, the directions of the pupil diameter

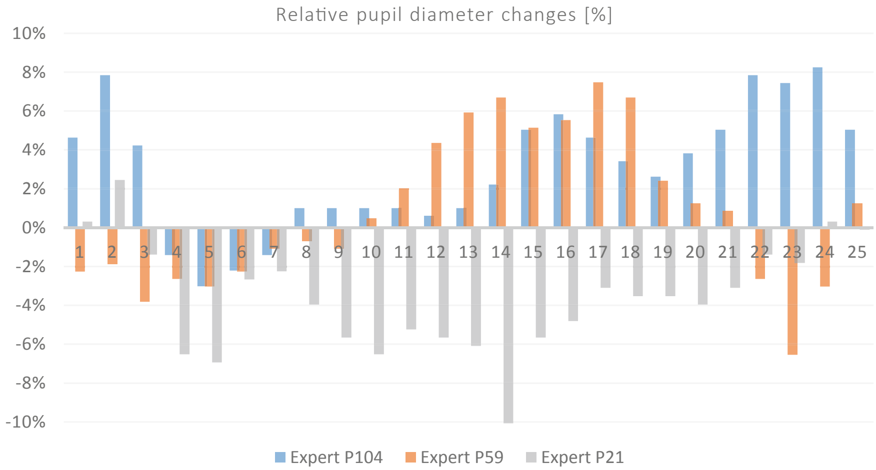

Fig. 13.1 Percentage pupil size changes of P104, P59, P21, during first 25 fixations

changes may not be consistent, and that some people can carry out tasks with very different levels of motivation (including a total lack of motivation). Assuming this method of analysis, we are aware that the calculation and visualization of average changes for selected groups of study participants is associated with the "blurring" of individual changes. We assume, however, that if it is possible to demonstrate the existence of certain tendencies for the whole group with such large simplifications, despite the process of averaging, it will mean that individual reactions combined with a precise description of their actions obtained through the interview process will provide even less ambiguous results, where the changes in relative values may be even bigger. As an example of the discrepancy of individual responses, we present the following drawings. Figs. 13.1 and 13.2 present selected examples of the pupil's reaction to the content of the task during the first fixations, including a person whose motivation, based on their interview, was very low.

Results

The following groups were distinguished from all the examined persons: experts, i.e., persons with at least a Ph.D. in physics or mathematics, Ph.D. students in physics, computer science students, biology students, high school students specializing in mathematics and physics. The mean values of relative pupil diameter changes during the first ten fixations were calculated for individual groups. The chart below presents the percentage average values of changes in relative pupil diameter, calculated for all groups of examined people (Fig. 13.3).

The second important element of the implemented tasks that affects the changes in the pupil diameter is the moment when the subject makes a decision regarding the

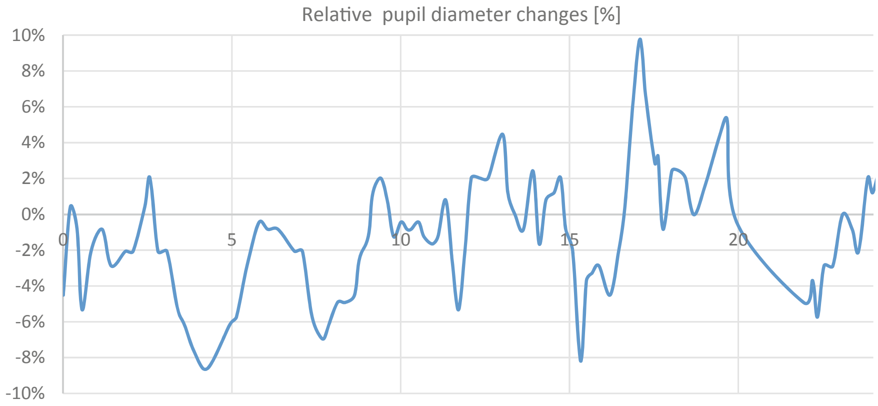

Fig. 13.2 Percentage pupil size changes of P22 during first 25 fixations

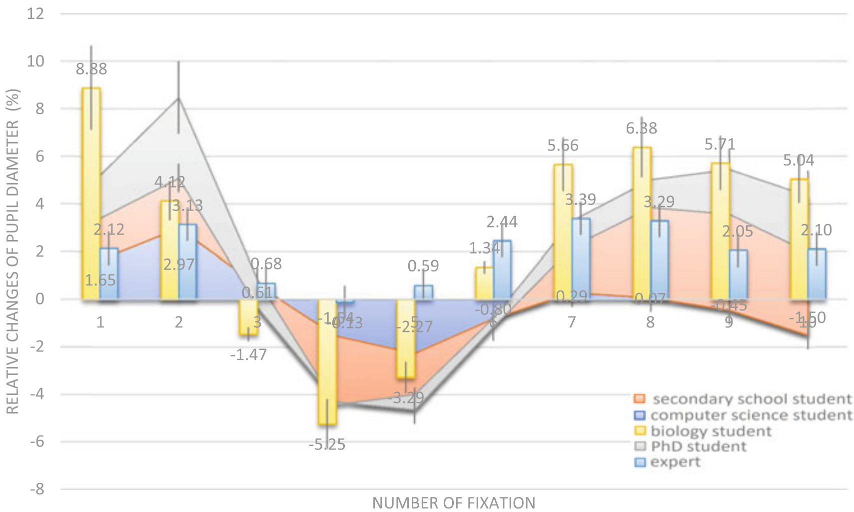

Fig. 13.3 Relative percentage changes in pupil diameter in selected groups, during first ten fixations

choice of the distractor. Due to the fact that the respondents’ time was not limited for solving the tasks, they adopted various strategies for choosing the correct answer. This happened at different times during the task-solving process. In this case, a thorough analysis of the cognitive load and the degree of concentration, aside from a very detailed interview with the examined, requires the use of other measurement methods, such as EEG, including a thorough analysis of the changes in brainwave amplitudes over the course of solving a physics task. However, it is an invasive and very time-consuming method, requiring long-term preparation of the examined person, and the research method itself generates additional stress that significantly affects the size of the lesions, mainly dilation and pupil diameter. For this reason, the use of electroencephalography was abandoned in the described experiment. Such an extension will be the subject of more detailed case studies, which are being planned. Some simplification was used in this experiment. Because each of the respondents carried out the process of solving the task at a different pace, the time for solving tasks differed significantly between subjects. Due to the fact that it was not possible to directly compare these times, based on the analysis of all records of the task-solving process, it was assumed that the decision regarding the choice of answers as well as the greatest cognitive load should occur during the last 25 fixations preceding the selection of answers. For the analysis of the results, 25 fixations preceding the answer were selected for each of the subjects. For this time interval, pupil diameter values for each fixation were identified and their relative changes were calculated for each person. Then, the average values of the relative changes were calculated for each of the examined groups and all examined persons. The graphs below show the average values of the relative changes for individual groups of respondents. As for the results obtained for individual study groups, a straight equation was fitted using a linear regression method. It is represented by a dashed line in the figures. It was assumed that the directional coefficients of a straight line, including its slope, should describe the size and direction of the changes in pupil diameter. It was assumed that if the cognitive load differs in individual groups of examined people, we should obtain different amounts of relative pupil diameter changes, and hence the directional coefficients of the straight lines that illustrate this process should differ. The charts below present the results obtained, taking into account the division resulting from experience in solving problems in the field of physics and mathematics (Figs. 13.4, 13.5, and 13.6).

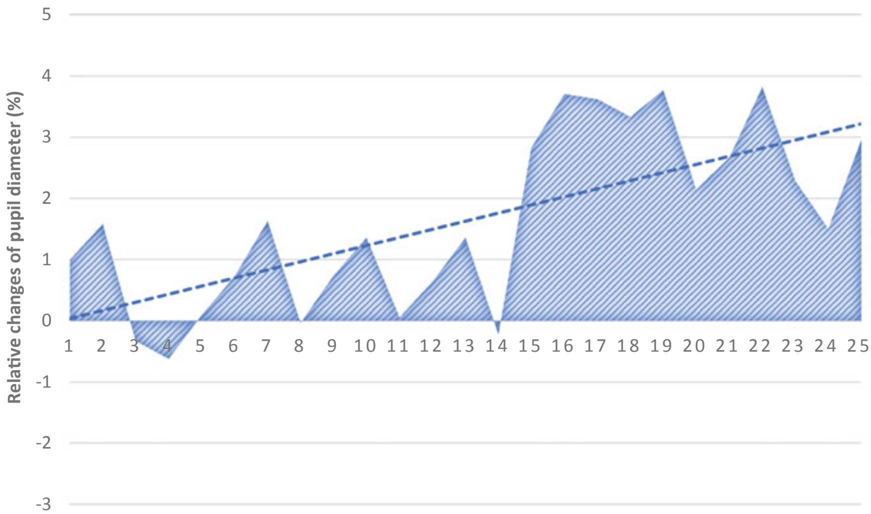

Fig. 13.4 Relative percentage changes in average pupil diameter values in expert group for last 25 fixations

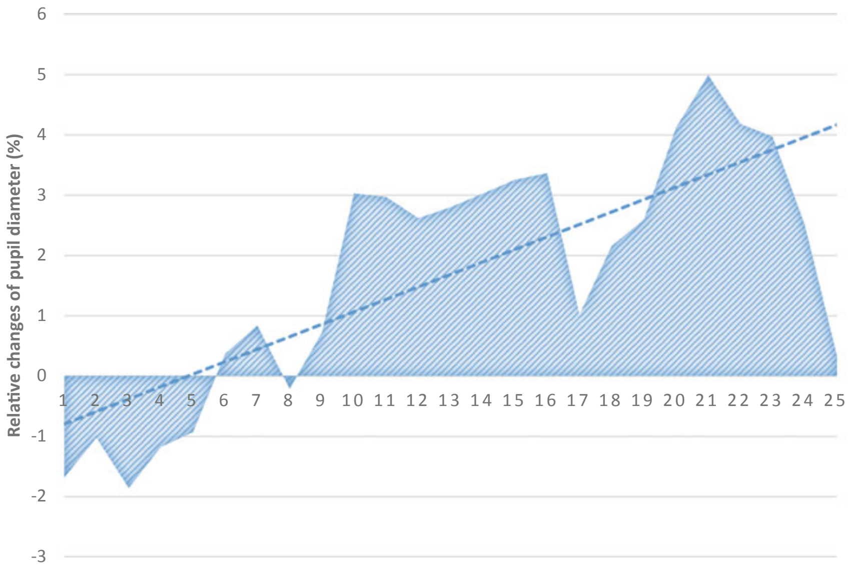

Fig. 13.5 Relative percentage changes in average pupil diameter values in Ph.D. student group for last 25 fixations

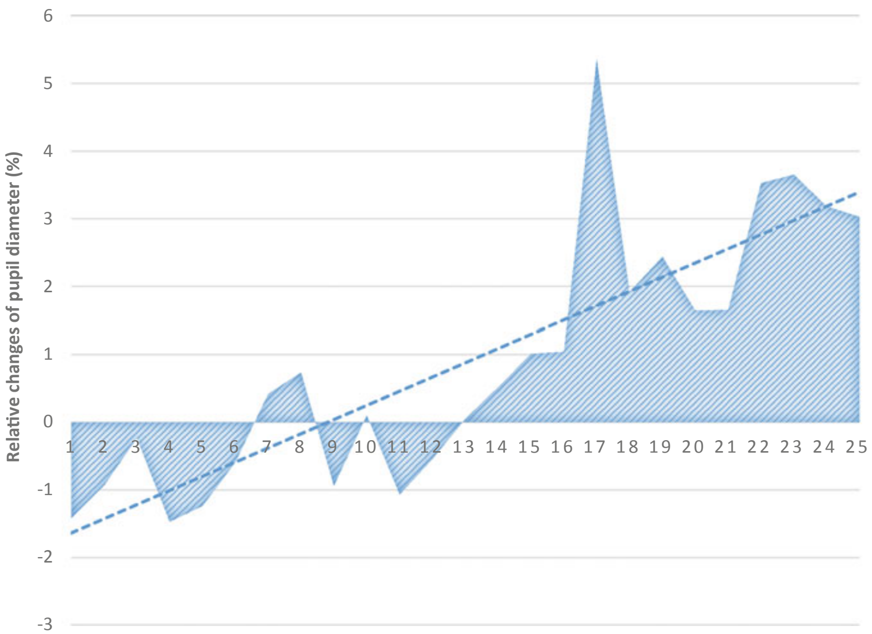

Fig. 13.6 Relative percentage changes in average pupil diameter values in secondary school student group for last 25 fixations

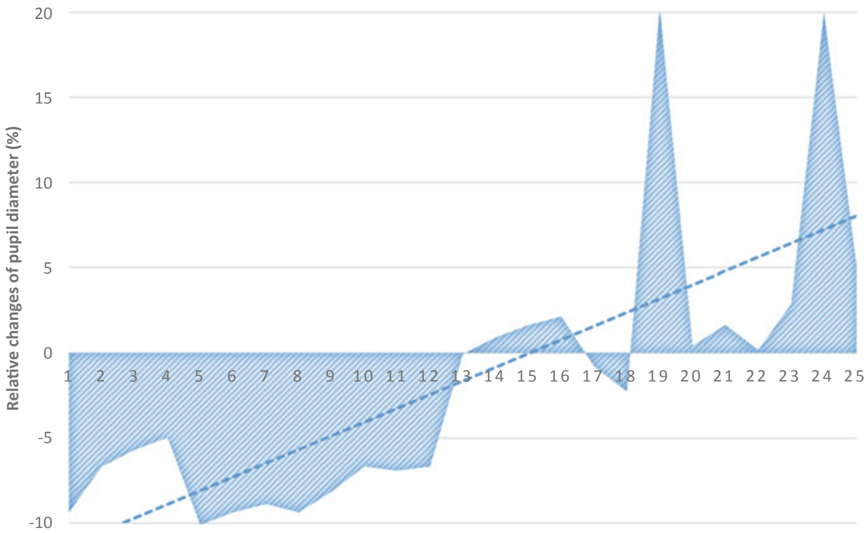

Fig. 13.7 Relative percentage changes in average pupil diameter values in biology student group for last 25 fixations

It should be noted that the following graph, due to the size of the relative changes, uses a different scale. In an interview after the study, biology students emphasized that they had already completed their education in physics, described the tasks they were solving as difficult, and that they were invited to a study which they had not been sufficiently informed about beforehand. Many of them described this situation as stressful. The highest values of relative pupil diameter changes were observed for this group of subjects (Figs. 13.7 and 13.8) (Table 13.1).

Discussion

By analyzing the relative changes in the pupil diameter during the first fixations on the task content made by the subjects, we can easily see a significant variation in the values of average relative reactions for individual groups of subjects, resulting from substantive preparation. Although the group of biology students is not fully representative, the size of the recorded reactions of pupil diameter changes in this group is the largest. High values of changes in the relative diameter of the pupils of the subjects testify to their significant cognitive effort and possible stress. The average values of relative pupil diameter changes in the group of computer science students vary to a lesser extent than in the group of high school students and to a larger extent than in the group of doctoral students. A detailed analysis of the scan path records shows that multiple subjects from IT student group chose the answer without

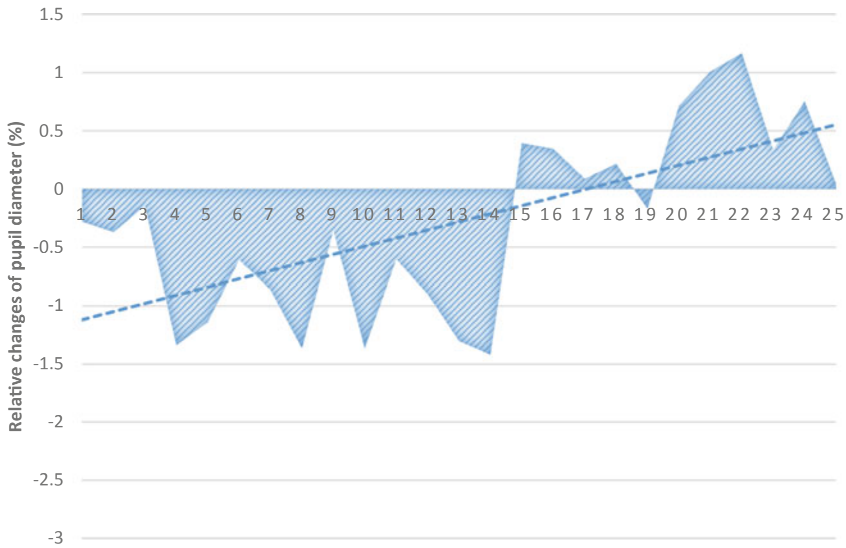

Fig. 13.8 Relative percentage changes in average pupil diameter values in computer science student group for last 25 fixations

Table 13.1 List of equations of fitted straight lines

	Formulas of linear function matched to data series
High school students	Y = 0.2 x – 1.9
Computer science students	Y = 0.1 x – 1.2
Biology students	Y = 0.8 x – 12.2
Ph.D. students	Y = 0.2 x – 1.0
Experts	Y = 0.1 x – 0.1
All	Y = 0.2 x − 2.91

a thorough analysis of the task content, sometimes randomly. This is evidenced by significantly smaller amounts of fixations in the area of the problems being solved.

Rejection of such people, based on interviews and scan path records, which did not have adequate motivation, i.e., did not read the content of the tasks, blindly guessed the solutions, did not carry out research in a reliable way, i.e., who did not make an intellectual effort when choosing answers, would allow to describe even more precise reactions of pupil diameter changes in each examined group in further studies. The linear function adjusted by the linear regression method is a function increasing for all groups of the examined persons. The value of the parameters describing the straight equation can be a quantitative description of the subjective assessment of the degree of difficulty of the problem for individuals and groups.

Conclusions

The obtained results indicate this methodology is worth using to conduct longitudinal studies in selected groups. It can be helpful, for example, for the purpose of supplementing descriptive, subjective responses regarding the assessment of the difficulty of tasks, as well as the motivation and stress levels associated with solving physics-related problems. However, it is important to remember that the largest values of relative changes in the diameter of the pupil are caused by negative emotions, e.g., stress. This should be taken into account when examining the subjective assessment of the difficulty of tasks and the intellectual effort (Madsen et al., 2012; Sosnowski et al., 1993). The results obtained during the experiment, mainly for biology students, confirm this rule. It is worth noting, however, that the study can be used as a method of determining the level of stress. The results obtained through repeated examinations of the same people, under the same lighting conditions, can be an indicator of their emotions, mainly negative, and also allow to indicate events that cause stress in students. The research results we obtained in the field of physics tasks confirm the hypothesis of neuronal efficiency. We can assume that people with a higher intelligence quotient, more experience, and broader substantive knowledge in the field of the related tasks use less resources and their psychophysiological response is smaller. This may indicate less cognitive burden, less intellectual effort when solving physics tasks. The obtained results confirm this hypothesis. However, it should be clearly emphasized that the analysis of solely the relative changes in the diameter of the pupil can only serve as an indicator, while a full interpretation of the changes must be supported by a thorough interview conducted with the examined person coupled with the analysis of other psychophysiological parameters such as heart rate, breathing, and electroencephalographic examination. By analyzing the relative changes in the diameter of the pupil during the first fixations of the subjects on the content of the task, we can easily see a significant variation in the values of average responses for individual test groups, resulting from substantive preparation. It is worth noting the need for a more detailed and thorough analysis of the results obtained for individual groups, especially the group of IT students. Further detailed analysis which involves taking note of those subjects who chose their answers without a thorough analysis of the task content among the surveyed IT students will allow to further describe the strategies and motivations when solving this task. We assume that this will become the subject of subsequent publications. In further research, it would be worthwhile to include, apart from the interview, the possibility of obtaining information on cognitive load using EEG methods.

Analysis of recorded data indicates that eyetracking methods can be very helpful in research on the didactics of STEM, e.g., in teaching subjects such as physics, IT, or mathematics. These are excellent methods supplementing our knowledge in the field and research regarding new technologies which are applicable for didactic research. It is worth using this methodology to conduct longitudinal studies in selected groups. It could be used, for example, for the purpose of supplementing the description of subjective reactions regarding the assessment of the difficulty of tasks, as well as the motivation and stress levels associated with the solving process.

References

Ahern, S., & Beatty, J. (1979). Pupillary responses during information processing vary with Scholastic Aptitude Test scores. *Science, 205,* 1289–1292.

Andreassi, J. L. (2000). Pupillary response and behavior. In N. J. Mahwah (Ed.), *Psychophysiology: Human behavior and physiological response* (pp. 218–233). Lawrence Erlbaum Association

Backs, R. W., & Walrath, L. C. (1992). Eye movement and pupillary response indices of mental workload during visual search of symbolic displays. *Applied Ergonomics, 23,* 243–254.

Beatty, J. (1982). Task-evoked pupillary responses, processing load, and the structure of processing resources. *Psychological Bulletin, 91*(2), 276–292.

Beatty, J., & Lucero-Wagoner, B. (2000). The pupillary system. In J. T. Cacioppo, L. G. Tassinary, & G. G. Berntson (Eds.), *Handbook of psychophysiology* (pp. 14–162). Cambridge, UK: Cambridge University Press.

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

Davidson, J. E., & Downing, C. L. (2000). Contemporary models of intelligence. In R. J. Sternberg (Ed.), *Handbook of intelligence*. Cambridge, UK: Cambridge University Press.

Findlay, J. & Gilchrist, I. (2003). Active vision: The psychology of looking and seeing. *Journal of Neuro-Ophthalmology,* 26. 10.1093/acprof:oso/9780198524793.001.0001

Gajewski, D. A., & Henderson, J. M. (2005). The role of saccade targeting in the transsaccadic integration of object types and tokens. *Journal of Experimental Psychology: Human Perception and Performance, 31*(4), 820–830.

Gopher, D. (1994). Analysis and measurement of mental load. In d'Y. Gery, P. Eelen, & P. Bertelson (Eds.), *International perspectives on psychological science: Vol. 2. The state of the art*. Hillsdale, NJ, England: Lawrence Erlbaum Associates.

Granholm, E. (2004). Introduction: Pupillometric measures of cognitive and emotional processes. *International Journal of Psychophysiology, 52*(1), 1–6.

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.

Harrison, N. A., Singer, T., Rotshtein, P., Dolan, R Ji, & Critchley, H. D. (2006). Pupillary contaginion: Central mechanisms engaged in sadness processing. *Social Cognitive and Affective Neuroscience, 1*(1), 5–17.

Hendrickson, A. E. (1982). The biological basis of intelligence, Part I: Theory. In H. J. Eysenck (Ed.), *A model for intelligence*. New York: Springer.

Hess, E. H. (1972). Pupillometrics: A method of studying mental, emotional, and sensory processes. In N. S. Greenfield & R. A. Sternbach (Eds.), *Handbook of psychophysiology* (pp. 491–531). New York: Holt. Rinehart & Winston.

Hess, E. H., & Polt, J. H. (1964). Pupil size in relation to mental activity during simple problem solving. *Science, 143,* 1190–1192.

Holmqvist, K., Nyström, N., Andersson, R., Dewhurst, R., Jarodzka, H., & Van de Weijer, J. (Eds.). (2011). *Eye tracking: A comprehensive guide to methods and measures*. Oxford, UK: Oxford University Press.

Hutton, S., & Tegally, D. (2005). The effects of dividing attention on smooth pursuit eye tracking: Experimental brain research. *Experimentelle Hirnforschung. Expérimentation cérébrale, 163,* 306–313. https://doi.org/10.1007/s00221-004-2171-z.

Kahneman, D., & Beatty, J. (1966). Pupil diameter and load on memory. *Science, 154*(3756), 1583–1885.

Khurana, B., & Kowler, E. (1987). Shared attentional control of smooth eye movement and perception. *Vision Research, 27*(9), 1603–1618. https://doi.org/10.1016/0042-6989(87)90168-4.

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

Libby, W. L., Lacey, B. C., & Lacey, J. I. (1973). Pupillary and cardiac activity during visual attention. *Psychophysiology, 10,* 270–294.

Lowenfeld, I. E. (1999). *The pupil: Anatomy, physiology, and clinical applications.* Boston: Butterworth Heinemann.

Madsen A., Larson A., Loschky L., & Rebello N. (2012). Using scan match scores to understand differences in eye movements between correct and incorrect solvers on physics problems. In *Proceedings of the Symposium on Eye Tracking Research and Applications, EXTRA 2012*, Santa Barbara, CA, USA.

Matthews, G., Middleton, W., Gilmartin, B., & Bullimore, M. A. (1991). Pupillary diameter and cognitive load. *Journal of Psychophysiology, 5,* 265–271.

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.

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

Paas, F., Tuovinen, J. E., Tabbers, H. K., & Van Gerven, P. W. M. (2003). Cognitive load measurement as a means to advance cognitive load theory. *Educational Psychologist, 38,* 63–71.

Partala, T., Jokiniemi, M., & Surakka. (2000). Pupillary responses to emotionally provocative stimuli. In *V. Eye Tracking Research & Application: Proceedings of the 2000symposium on Eye Tracking Research and Applications* (123–129). New York: ACM Press.

Prime, S., Niemeier, M., & Crawford, J. D. (2004). Trans-saccadic integration of the orientation and location features of linear objects. *Journal of Vision, 8*, 742.

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

Ross, R. G., Olincy, A., & Radant, A. (1999). Amplitude criteria and anticipatory saccades during smooth pursuit eye movements in schizophrenia. *Psychophysiology, 36,* 464–468.

Srihasam, K., Bullock, D., & Grossberg, S. (2009). Target selection by the frontal cortex during coordinated saccadic and smooth pursuit eye movements. *Journal of Cognitive Neuroscience, 21,* 1611–1627.

Soluch, P., & Tarnowski, A. (2013). O metodologii badań eyetrackingowych. *Lingwistyka Stosowana, 7,* 115–134.

Sosnowski, T., Zimmer, K., Zaborowski, P., & Krzymowska, A. (1993). *Metody psychofizjologiczne w badaniach psychologicznych: praca zbiorowa.* Warszawa: Wydawnictwo Naukowe PWN.

Wade, N., & Tatler, B. W. (2005). *The moving tablet of the eye: The orings of modern eye movement research.* Oxford: Oxford University Press.

Wilhelm, H. (2011). Disorders of the pupil. *Handbook of Clinical Neurology, 102,* 427–466.

Winn, B., Whitaker, D., Elliott, D. B., & Phillips, N. J. (1994). Factors affecting light-adapted pupil size in normal human subjects. *Investigative Ophthalmology & Visual Science, 35,* 1132–1137.

Roman Rosiek, Ph.D. is an Associate Professor of Physics Education at the Pedagogical University, Division of Theoretical Physics and Didactics of Physics, Faculty of Exact and Natural Sciences, Krakow, Poland. His research and development focuses on issues related to the didactics of physics, in particular the education of physics and computer science teachers, understanding of concepts by students and teachers, and the use of new research and teaching methods. Since January 2014, he has been a member of the Interdisciplinary Cognitive Didactic Research Group, currently under his leadership. As part of this activity, he conducts research on the applications

of eyetracking methodology, EEG and psychophysiological methods e.g.: HRV, EDA, Respiration for research in the field of cognitive science and didactics of physics. Habilitation subject: Psychophysiological Methods in Research on Didactics of Physics. The results of his scientific and research work have been published in over 50 publications. Among them there are publications indexed in the Web of Science and SCOPUS databases, chapters in monographs, a book. His works are quoted by many scientists. He delivered national and international guest lectures, plenary lectures at international conferences e.g. GIREP.

Miroslawa Sajka, Ph.D. is an Assistant Professor and the head of Chair of Mathematics Education at the Institute of Mathematics, Faculty of Exact and Natural Sciences, Pedagogical University of Krakow, Poland. She is a contributing member of the Interdisciplinary Research Group of Cognitive Didactics at Pedagogical University of Krakow from 2014, runs research on using eye-tracking in mathematics education also from physics education point of view. Her research areas: in general mathematical reasoning, specifically understanding the notion of function; teacher cognition, education and knowledge in/for teaching; comparative studies; eyetracking and other psychophysiological methods in research on mathematics and science education. Dr. Sajka authored a scientific book (monograph), over 50 scientific papers on thinking, learning and teaching mathematics and several school resources and textbooks in mathematics for secondary school students. Dr. Sajka is Vice Editor-In-Chief of a scientific journal "Annales Universitatis Paedagogicae Cracoviensis. Studia ad Didacticam Mathematicae Pertinentia" in the field of mathematics education. She undertakes co-leaderships of working groups at international conferences on mathematics education (e.g. "Comparative Studies in Mathematics Education" at CERME, "Knowledge in/for teaching at secondary level" at ICME) and she delivered national and international guest and plenary lectures at conferences.