Russian Psychological Journal, 2022, Vol. 19, No. 4, 173–185. **doi**: 10.21702/rpj.2022.4.12

Research article

UDC 159.9.072.42

https://doi.org/10.21702/rpj.2022.4.12

Software Possibilities of Using the Eye-tracking Method in Visual Perception Research

Kseniya A. Skuratova[1]✉, Evgeny Yu. Shelepin[2], Konstantin Yu. Shelepin[3]
[1, 2, 3] Pavlov Institute of Physiology, Saint Petersburg, Russian Federation
[2, 3] Neuroiconica Assistive LLC, Saint Petersburg, Russian Federation

✉ kseskuratova@gmail.com

Annotation: Introduction. Eye movements objectively reflect perceptual, cognitive and emotional processes during visual perception. Studies aimed at analyzing human oculomotor activity require the use of special equipment (an infrared video oculograph or eye tracker), as well as software for creating, conducting and analyzing experiments. **Methods**. A qualitative analysis of the results of eye-tracking studies makes it possible to visualize the order of attention (using gaze movement maps), as well as the proportion of attention (using heat maps) to stimulus elements. With the help of quantitative analysis, it is possible to statistically test hypotheses about the distribution of attention, as well as to assess the cognitive load both over the entire stimulus and by highlighting individual areas of interest (the so-called Areas of Interest mechanism, which allows calculating statistics in individual parts of the stimulus). Quantitative parameters are used to classify errors and as a predictive metric for target recognition. Quantitative parameters of fixations and saccades are used to assess professional experience, as well as to diagnose disorders of mental development and emotional disorders. **Results and discussion**. Software with advanced capabilities for qualitative and quantitative analysis allows for a comprehensive assessment of both the mental processes of a person and the visual features of the presented stimulus. An in-depth analysis of oculomotor activity metrics is primarily relevant for research in the field of cognitive psychology, but can also be useful in other scientific and applied areas: psychopathology, pedagogy, ergonomics, medicine, and neuromarketing. The mechanisms of processing «raw data» and algorithms for determining the types of eye movements, identifying saccades and fixations are shown using the IVT algorithm as an example. Examples of research in applied fields are given. The novelty of the article lies in the fact that eye tracking is considered as a tool for studying cognitive processes and analyzing a person's gaze on a spatio-temporal basis. It is an integration of qualitative and quantitative analysis using specialized software.

Keywords: visual perception, research methods, video oculography, eye tracking, oculomotor activity, eye movements, psychophysiology, fixations, saccades, areas of interest

Highlights:

- Eye-tracking is used in the social and humanitarian sciences to objectify the processes of visual perception.
- Algorithms based on the speed of eye movements and algorithms based on the spatial position of eye movements are used to separate fixations from saccades.
- When analyzing eye movements, both qualitative and quantitative results can be obtained.
- Qualitative results of eye-tracking studies include: eye movement maps, heat maps, fog maps, bee swarms.
- The quantitative results of eye-tracking studies include parameters related to the number and duration of fixations, as well as the amplitude of saccades.

Funding: The work was supported by State Program 47 of the State Enterprise «Scientific and Technological Development of the Russian Federation» (2019–2030), topic 63.3. 0134-2019-0006.

For citation: Skuratova, K.A., Shelepin, E. Yu., Shelepin, K. Yu. (2022). Software possibilities of using the eye-tracking method in visual perception research. *Russian Psychological Journal, 19*(4), 173–185. https://doi.org/10.21702/rpj.2022.4.12

Introduction

The processes of visual perception are largely unconscious and inaccessible to introspection. For example, subjects report only some of their eye movements or even eye movements they did not make. For this reason, their study requires special research methods. Eye tracking provides an opportunity to explore mental processes in settings where verbal reports or introspective judgments cannot be obtained (e.g., studies on infants and toddlers) or their validity is questioned.

Eye movements are closely related to perceptual, cognitive and even emotional processes, so eye tracking can be used as an effective, objective and relatively simple method of learning when perceiving complex visual scenes, performing cognitive tasks, interacting with interfaces, perceiving social scenes and much more.

Some of the main scientific and applied areas of application of eye tracking:

1. *Cognitive psychology.* Eye tracking is a highly sensitive method of probing attention by reducing interference from motor or verbal responses, and is therefore often used in visual search paradigms (Blakley et al., 2022). Analysis of oculomotor activity patterns provides evidence that Raven's matrix solving strategies are directly related to individual differences in intelligence (Vigneau et al., 2006). Since eye movements precede and facilitate conscious retrieval of information from memory, eye tracking is also popular in memory research (Hannula et al., 2010).
2. *Psychopathology.* Since eye movements are quite stereotyped and reproducible, even relatively minor deviations in oculomotor patterns can be informative markers for identifying the risk of many mental disorders, such as attention deficit hyperactivity disorder (Maron et al., 2021), schizophrenia (Hashimoto, 2021), obsessive- compulsive disorder (Kim et al., 2021).
3. *Pedagogy.* The subject of eye-tracking research in education is related to various aspects of human cognitive development. For example, eye movements are objective indicators of impaired development of reading skills in children, so they can play a significant role in

their diagnosis (Zashchirinskaya et al., 2019). The close relationship between the study of geometry and spatial reasoning makes eye-tracking a suitable method for investigating the perceptual processing of geometric shapes (Strohmaier et al., 2020). Eye tracking is also used to track student engagement (Kaakinen, 2021).

4. *Neuromarketing*. One of the main application areas using the eyetracking method. The registration of eye movements allows us to explore the visual attention of consumers and provides information about the level of visibility and attractiveness of advertising or product packaging elements (Motoki et al., 2021).
5. *Ergonomics*. Increased cognitive load can negatively affect the performance of professionals in high-risk industries (such as aviation) and increase the likelihood of dangerous situations. A potential benefit of using eye-tracking to measure cognitive load is that it can capture fluctuations in cognitive load that occur over short time intervals (Ahlstrom & Friedman-Berg, 2006).
6. *Medicine*. Tracking eye movements can help not only to objectively consider the features of the cognitive processes that underlie the interpretation of diagnostic images, but also make a significant contribution to the process of medical education. Allowing students to observe the scanning paths performed by experts is more effective than verbal description of the visual diagnostic method (Fox & Faulkner-Jones, 2017).

For a long time, only foreign solutions were presented on the Russian market of software for recording and analyzing eye movements. After analyzing their functionality, as well as the needs of researchers, we developed the Neuroburo software, which provides synchronous recording of eye movements, ECG (electrocardiograms), EMG (electromyograms), EDA (electrodermal activity), EEG (electroencephalography) and responses of the subjects, as well as a wide range of qualitative and quantitative methods of analysis.

Methods

Algorithms for detecting commits

Specialized software designed for research with eye movement registration uses various algorithms for detecting fixations and separating them from saccades.

The input data for the algorithm is a sequence of the form [time stamp, coordinate along the horizontal axis, coordinate along the vertical axis], where the spatial coordinates of the gaze positions correspond to each time stamp. Timestamps follow with a frequency based on the sampling rate and for the Gazepoint series eyetrackers are 60 and 150 Hz and correspond to the resulting CNT / TIME / TIME_TICK value. Spatial coordinates correspond to the gaze direction point (POG, point-of-gaze), calculated on the eye tracker using the LPOGX, LPOGY/RPOGX, RPOGY/BPOGX, BPOGY values, on the monitor screen, and are given as coordinates, where (0,0) – top left, (0.5,0.5) the center of the screen, and (1.0,1.0) the bottom right.

There are two groups of algorithms: algorithms based on the speed of eye movements and algorithms based on the spatial position of eye movements (Komogortsev et al., 2010).

Rate-based commit detection algorithms include:

– I-VT (classification based on saccade velocity threshold);
– I-HMM (classification based on the hidden Markov model);
– I-KF (classification based on the Kalman filter).

Spatial data-based fixation detection algorithms include:

– I-MST (minimum spanning tree classification);
– I-DT (classification based on the spatial dispersion of gaze points).
–

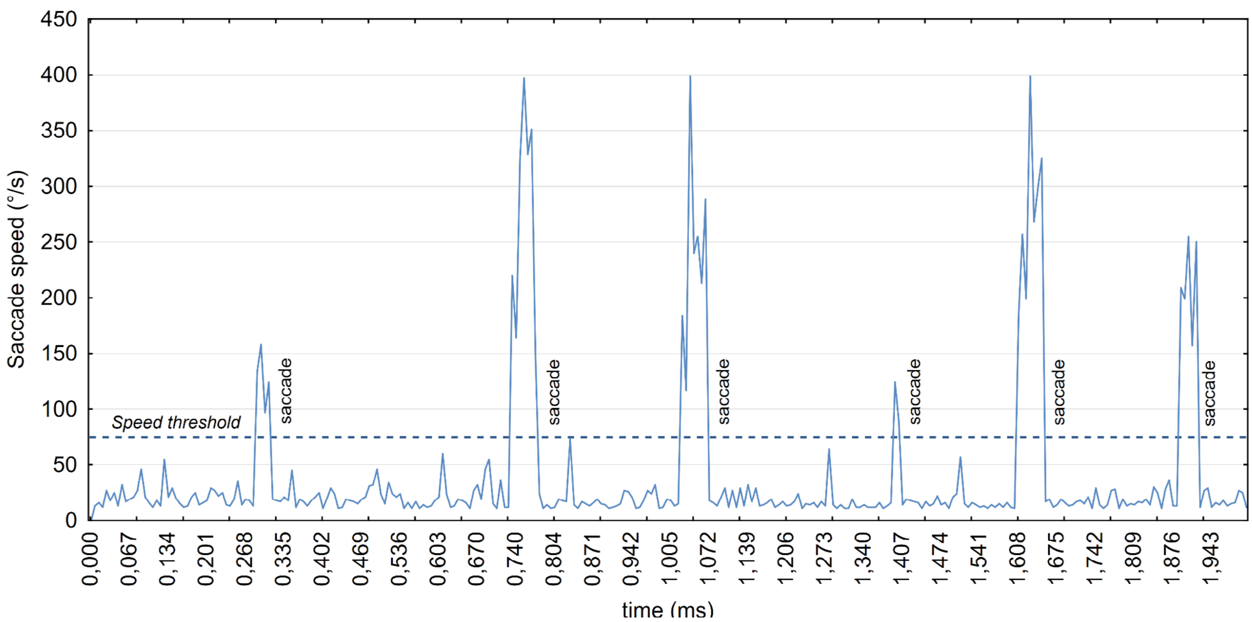
Fixation detection based on the determination of the saccade speed threshold

At present, Neurobureau software uses an algorithm of the I-VT (the Velocity-Threshold Identification) family, which consists in classifying eye movements based on the determination of the saccade velocity threshold:

1. For each distance between the current point and the next point, a speed is calculated.
2. Each point is then classified as either a fixation point or a saccade point based on the velocity threshold: if the point's velocity is below the threshold, it becomes a fixation point, otherwise it becomes a saccade point.
3. The process then aggregates successive commit points into a commit group.
4. Finally, I-VT translates each fixation group into an <x, y, t, d> representation using the centroid of the points as x and y, the time of the first point as t, and the duration of the points as d (Salvucci & Goldberg, 2000).

Figure 1

Classification based on saccade velocity threshold



Thus, for the I-VT algorithm to work, it is necessary to set the saccade velocity threshold (Fig. 1). The recommended value for this parameter is 70 °/s (Komogortsev et al., 2010).

To improve the accuracy of fixation detection in the «Neurobureau» software, the I-VT algorithm was supplemented with the following functions: gap filling, data source selection, noise suppression, merging of adjacent fixations, removal of short fixations. These functions will be discussed in more detail below.

The gap filling feature helps fill in data where it is missing: for example, if the subject blinked or looked at an area off the monitor. «Neurobureau» allows you to select the maximum duration of the gap that must be filled. The recommended value for this parameter is 75 ms (Komogortsev et al., 2010).

For detection of fixations, it is possible to select the source of data obtained both from one individual eye (for example, right or left), and averaged data. When choosing the left eye, the source of coordinate data is LPOGX, LPOGY. When choosing the right eye, the data source for coordinates is RPOGX, RPOGY. When averaging is selected, the coordinate data source is BPOGX, BPOGY / (LPOGX+RPOGX) : 2, (LPOGY + RPOGY) : 2.

The I-VT algorithm implemented in the «Neurobureau» software includes the possibility of using the noise reduction function based on the mean or median. This function is a special case of a low pass filter, better known in signal processing terms as an unweighted moving average filter (Oppenheim, 1997). To use the noise reduction function, you must set the "window size" parameter: the higher it is, the smoother the output data will be. It should be taken into account that an increase in the numerical values of the "window size" parameter leads to an increase in the duration of saccades and a decrease in the duration of fixations. The advantage of using median-based denoising, compared to moving average, is that fewer «false» gaze coordinates are created.

If the fixations are close together both in time and space, there is a high chance that they are actually parts of the same long fix. To correct such errors, you can use the function of merging adjacent commits (Komogortsev et al., 2010). «Neuroburo» allows you to set the maximum time and maximum angle between two fixation parts, after which they will be considered as separate fixations. The value of the parameter «maximum time between fixations» should not exceed the blink duration (Ingre et al., 2006). The recommended value is 75 ms (Komogortsev et al., 2010). For the "maximum angle between fixations" parameter, the recommended value is 0.5° (Kliegl et al., 2004; Komogortsev et al., 2010; Over et al., 2007).

Even after using the function of combining adjacent fixations, fixations of very short duration can still remain, the analysis of which is not meaningful in the study of oculomotor behavior, since the eye and brain take some time to process information about what it sees (Munn et al., 2008). The solution to this situation is to use the *function to remove short fixations*, for which you need to set the minimum duration of fixation. The recommended value for this parameter is 60 ms (Komogortsev et al., 2010), which corresponds to the shortest fixations during reading (Over et al., 2007).

Results and its discussion

This section will describe the functionality implemented by us in the Neuroburo software.

Mode «Creating an experiment»

This mode is designed to create an experiment design and includes the functions of selecting, adding and editing the name of the experiment, description of the experiment, necessary information about the subject, psychophysiological sensors that will be used in the experiment, as well as stimulus material.

The «Experiment» mode

The «Experiment» mode is intended for conducting an experiment, as well as for setting up and testing equipment.

Mode «Experiment Analysis»

This mode is designed to analyze the results of the experiment, as well as export the obtained data for further statistical processing.

The «Experiment Analysis» mode provides such types of visualization and analysis of eye movements as: eye movement, heat map, areas of interest, bee swarm, combined analytics.

In the «Experiment Analysis» mode, it is possible to change the following parameters for eye movement registration data: *speed scale; speed threshold; minimum duration of fixation; association of fixations (by time; by time and angle); maximum time between fixations; maximum angle between fixations; noise reduction (average; median); filling gaps.*

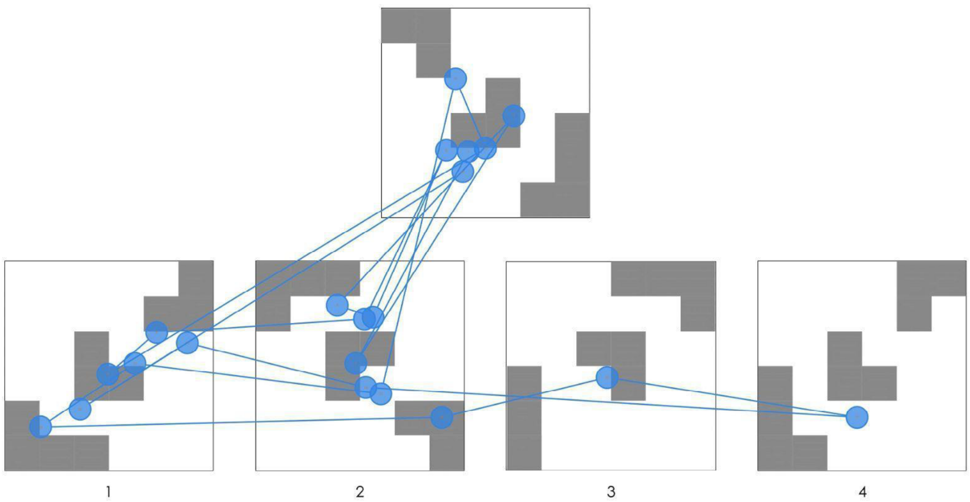
Next, consider the visualization and analysis methods available in the «Experiment Analysis» mode.

Analytics «Movement of the eye». The commit sequence map is based on spatial data (where the commit occurred) and temporal data (when the commit occurred and how long it lasted). The sequence of fixations and its schematic representation depends on where the subjects look and how much time they spend on it, and gives a deeper understanding of the mechanism of attention. The order of attention is a commonly used parameter in oculomotor activity studies because it reflects a person's interest and allows you to highlight the most significant objects on the screen or in the environment that stand out visually (for example, by color or brightness) or are emotionally or socially significant. Also, this type of analytics helps to evaluate the pattern of image analysis or problem solving.

Figure 2 shows an example of a visualization obtained using the Eye Movement analytics.

Figure 2

Visualization obtained using the Eye Movement analytics



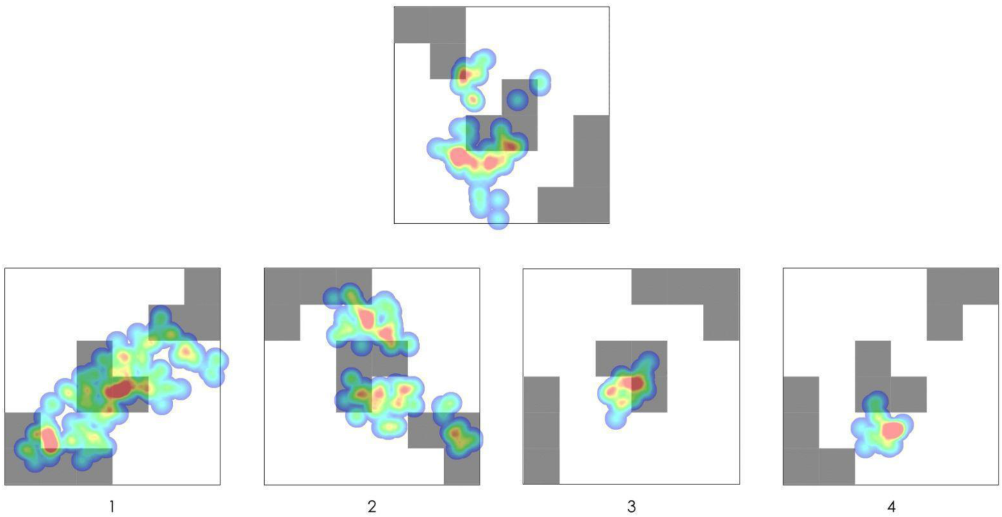
Analytics «Heat map». A heat map is a static or dynamic union of all points of view of the subject, showing the distribution of visual attention and displayed by overlaying a color gradient on the presented image. Using an easy-to-understand color scheme, heat maps are an excellent way to visualize which stimulus items received the most attention: warmer red areas correspond to more gaze points (and thus the most interest), cooler yellows and then, green areas correspond to fewer viewpoints (and thus a lower proportion of attention). The colorless areas correspond to elements that did not receive the attention of the subjects.

The «Experiment Analysis» mode allows you to select an algorithm for constructing a heat map (you can select such functions as: constant, linear, exponential).

An example of a visualization obtained using the Heat Map analytics is shown in Figure 3.

Figure 3

Visualization obtained using the Heatmap analytics



Analytics «Areas of interest». An area of interest (AOI, short for Area of Interest) is a tool for selecting areas of a presented image or video and extracting metrics specific to those areas.

The Areas of Interest analytics allows you to select any shape to highlight (rectangle, circle, ellipse, freeform, polygon).

Using the Regions of Interest analytics, the following eye movement parameters can be calculated and optionally exported in CSV (Comma-Separated Values) or XLS (Excel) format:

1. *Time to first fixation on the region of interest*. Bright (Bojko, 2006), large (Schreij et al., 2008) or out-of-context elements (de Graef et al., 1990) attract attention faster. Based on this, location, color, contrast, brightness and size are called *ascending* factors, as they cause involuntary switching of attention to oneself (Orquin et al., 2020). This type of attention is

called *exogenous*, or *ascending*. *Endogenous*, or *downward* attention, provides an arbitrary switching of attention to a certain element of the stimulus. For example, the time to the first fixation on a target trait is related to the specialist's professional experience (Kundel et al., 2008). In addition to the time to the first fixation, «Neurobureau» also calculates the number of fixations before the first fixation on the area of interest.

2. *The total fixation time on the region of interest*. This parameter can be used to compare the amount of attention given to different areas of interest (Poole & Ball, 2005).
3. *Duration of the first fixation*. One of the most popular parameters in psycholinguistics, it reflects the process of lexical activation and depends on the grammatical characteristics of the word (Clifton et al., 2007).
4. *The number of returns to the region of interest*. Re-fixations on a previously scanned area are necessary to remove information ambiguity and other processing difficulties (Spivey & Tanenhaus, 1998).
5. *Average fixation time*. Longer fixations indicate that subjects spend more cognitive resources on analyzing and interpreting the content of the area of interest (Sharafi et al., 2015). For visual search tasks, fixation duration can be used to classify errors and as a predictive metric for target recognition (Williams & Drew, 2019). Fixation duration indicates the time needed to plan the next saccade (Liversedge et al., 2012). Anxiety has also been found to reduce the duration of fixations (Wilson, 2012).
6. *The ratio of the number of subjects who looked at the area of interest to the total number of subjects*. This parameter is used as an indicator of the visibility of an interface element, advertising or product packaging (Jacob & Karn, 2003). In reading studies, this parameter can be used to calculate the «percentage of gaps», i.e. the percentage of words on which the reader did not fixate (Inhoff & Radach, 1998).
7. *The total number of commits*. The number of fixations per area of interest is related to the information value and complexity of information processing (Henderson et al., 2009). A higher number of fixations for the entire stimulus indicates a less efficient search for relevant information (Goldberg & Kotval, 1999).
8. *Average amplitude of saccades*. The smaller the saccade amplitude, the higher the cognitive load (Poole & Ball, 2005). When reading, the amplitude of saccades is limited to 7–9 letters (approximately 2°), while it depends on the reading skill: it is much smaller in children and dyslexics (Rayner, 1998). When reading aloud, the amplitude of saccades decreases to 1.5 angular degrees (Rayner & Pollatsek, 1989). Problems with understanding the text also lead to a decrease in the amplitude of saccades. For visual search tasks, the amplitude of saccades averages 3 angular degrees, and when perceiving visual scenes, it increases to 4–5 angular degrees (Rayner, 2009).
9. *The number of saccades*. This parameter reflects the process of comparing or integrating several elements of the stimulus (Eckstein et al., 2017). In addition, the number of saccades increases with increasing cognitive load (Hébraud et al., 2004). Work experience also affects the number of saccades: experts perform fewer saccades than beginners (Dong et al., 2018).
10. *The total length of the scan path*. The longer scanning path suggests that the subject paid more attention to switching between different areas of interest and explored the stimulus more in general, which indicates a less effective visual search (Goldberg et al., 2002). The length of the scanning path decreases as the professional skill improves (Skuratova et al., 2021).

11. *Average and peak speed of saccades*. The peak saccade velocity, in contrast to the average velocity, does not depend on the saccade duration, because it is not associated with it a priori by a mathematical function (Di Stasi et al., 2011). According to the cognitive-energy performance model of Sanders (Sanders, 1983), peak saccade velocity varies with changes in the resources required to complete a task (App & Debus, 1998), decreasing as task complexity increases, as well as cognitive fatigue (Di Stasi et al., 2011).

A display of the ratio of the area of interest to the total area of the stimulus is also available.

Analytics «Bee Swarm». Analytics is designed to display the movement of the gaze of the subject without pre-processing.

Combined analytics. This mode is designed to combine several methods of visualization and analysis of results. You can combine any type of analytics.

Data export. The «Data Export» function is designed to save the original signal received from the eye tracker, EDA sensor, ECG sensor, EMG sensor and electroencephalograph, as well as data on mouse clicks and keyboard buttons for further processing in third-party software. Export is possible in the following formats: for electroencephalography, edf+ format, for other devices, csv and xlsx formats. It is possible to export data containing synchronization marks, which indicate the time of entry and exit from the region of interest. A multi-export function is available, which allows you to save all the results obtained in one experiment with the click of a button.

Conclusion

The software presented in the article allows you to conduct experiments to study the processes of visual perception. It is also possible to combine various sensors of the psychophysiological state. In the future, the expansion of the functionality of creating an experiment to support behavioral and cognitive experiments, by creating a functionality for logical control of the presentation of stimuli (selection of answers, repetition of tasks, etc.).

References

Ahlstrom, U., & Friedman-Berg, F. J. (2006). Using eye movement activity as a correlate of cognitive workload. *International Journal of Industrial Ergonomics*, *36*(7), 623–636. https://doi.org/10.1016/j.ergon.2006.04.002

App, E., & Debus, G. (1998). Saccadic velocity and activation: Development of a diagnostic tool for assessing energy regulation. *Ergonomics*, *41*(5), 689–697. https://doi.org/10.1080/001401398186856

Blakley, E. C., Gaspelin, N., & Gerhardstein, P. (2022). The development of oculomotor suppression of salient distractors in children. *Journal of Experimental Child Psychology*, *214*. https://doi.org/10.1016/j.jecp.2021.105291

Bojko, A. (2006). Using eye tracking to compare web page designs: A case study. *Journal of Usability Studies*, *1*(3), 112–120.

Clifton, C., Staub, A., & Rayner, K. (2007). Eye movements in reading words and sentences. In R. Van Gompel, M. Fischer, W. S. Murray, & R. L. Hill (Eds.), *Eye movements: A window on mind and brain* (pp. 341–372). Elsevier.

de Graef, P., Christiaens, D., & D'Ydewalle, G. (1990). Perceptual effects of scene context on object identification. Psychological Research, 52(4), 317-329

Di Stasi, L. L., Antolí, A., & Cañas, J. J. (2011). Main sequence: An index for detecting mental workload variation in complex tasks. *Applied Ergonomics*, *42*(6), 807–813. https://doi.org/10.1016/j.apergo.2011.01.003

Dong, W., Zheng, L., Liu, B., & Meng, L. (2018). Using eye tracking to explore differences in map-based spatial ability between geographers and non-geographers. *ISPRS International Journal of Geo-Information*, *7*(9). https://doi.org/10.3390/ijgi7090337

Eckstein, M. K., Guerra-Carrillo, B., Singley, A. T. M., & Bunge, S. A. (2017). Beyond eye gaze: What else can eyetracking reveal about cognition and cognitive development? *Developmental Cognitive Neuroscience*, *25*, 69–91. https://doi.org/10.1016/j.dcn.2016.11.001

Fox, S. E., & Faulkner-Jones, B. E. (2017). Eye-tracking in the study of visual expertise: Methodology and approaches in medicine. *Frontline Learning Research*, *5*(3), 43–54. https://doi.org/10.14786/flr.v5i3.258

Goldberg, J. H., & Kotval, X. P. (1999). Computer interface evaluation using eye movements: Methods and constructs. *International Journal of Industrial Ergonomics*, *24*(6), 631–645. https://doi.org/10.1016/S0169-8141(98)00068-7

Goldberg, J. H., Stimson, M. J., Lewenstein, M., Scott, N., & Wichansky, A. M. (2002). Eye tracking in web search tasks: Design implications. *Paper presented at the Eye Tracking Research and Applications Symposium (ETRA)* (pp. 51–58). https://doi.org/10.1145/507072.507082

Hannula, D. E., Althoff, R. R., Warren, D. E., Riggs, L., Cohen, N. J., & Ryan, J. D. (2010). Worth a glance: Using eye movements to investigate the cognitive neuroscience of memory. *Frontiers in Human Neuroscience*, *4*. https://doi.org/10.3389/fnhum.2010.00166

Hashimoto, R. (2021). Do eye movement abnormalities in schizophrenia cause Praecox Gefühl? *Psychiatry and Clinical Neurosciences*, *75*(3), 79–80. https://doi.org/10.1111/pcn.13197

Hébraud, C., Hoffman, E., Pene, N., Rognin, L., & Zeghal, K. (2004). Assessing the impact of a new air traffic control instruction on flight crew activity. Paper presented at the Collection of Technical Papers - AIAA Guidance, Navigation, and Control Conference, , 3 1590-1598

Henderson, J. M., Malcolm, G. L., & Schandl, C. (2009). Searching in the dark: Cognitive relevance drives attention in real-world scenes. *Psychonomic Bulletin & Review*, *16*, 850–856. https://doi.org/10.3758/PBR.16.5.850

Ingre, M., Åkerstedt, T., Peters, B., Anund, A., & Kecklund, G. (2006). Subjective sleepiness, simulated driving performance and blink duration: Examining individual differences. *Journal of Sleep Research*, *15*(1), 47–53. https://doi.org/10.1111/j.1365-2869.2006.00504.x

Inhoff, A. W., & Radach, R. (1998). Definition and computation of oculomotor measures in the study of cognitive processes. In G. M. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 29–53). Elsevier.

Jacob, R. J. K., & Karn, K. S. (2003). Commentary on Section 4. Eye tracking in human-computer interaction and usability research: Ready to deliver the promises. *The Mind's Eye*, 573–605. https://doi.org/10.1016/B978-044451020-4/50031-1

Kaakinen, J. K. (2021). What can eye movements tell us about visual perception processes in classroom contexts? Commentary on a special issue. *Educational Psychology Review*, *33*, 169–179. https://doi.org/10.1007/s10648-020-09573-7

Kim, M., Shin, W., Lee, T. H., Kim, T., Hwang, W. J., & Kwon, J. S. (2021). Eye movement as a biomarker of impaired organizational strategies during visual memory encoding in obsessive–compulsive disorder. *Scientific Reports*, *11*. https://doi.org/10.1038/s41598-021-97885-1

Kliegl, R., Grabner, E., Rolfs, M., & Engbert, R. (2004). Length, frequency, and predictability effects of words on eye movements in reading. *European Journal of Cognitive Psychology*, *16*(1–2), 262–284. https://doi.org/10.1080/09541440340000213

Komogortsev, O. V., Gobert, D. V., Jayarathna, S., Koh, D. H., & Gowda, S. M. (2010). Standardization of automated analyses of oculomotor fixation and saccadic behaviors. In *IEEE Transactions on Biomedical Engineering*, *57*(11), 2635–2645. https://doi.org/10.1109/TBME.2010.2057429

Kundel, H. L., Nodine, C. F., Krupinski, E. A., & Mello-Thoms, C. (2008). Using gaze-tracking data and mixture distribution analysis to support a holistic model for the detection of cancers on mammograms. *Academic Radiology*, *15*(7), 881–886. https://doi.org/10.1016/j.acra.2008.01.023

Liversedge, S. P., Gilchrist, I., & Everling, S. (Eds.). (2012). *The Oxford Handbook of eye movements*. Oxford Library of Psychology. https://doi.org/10.1093/oxfordhb/9780199539789.001.0001

Maron, D. N., Bowe, S. J., Spencer-Smith, M., Mellahn, O. J., Perrykkad, K., Bellgrove, M. A., & Johnson, B. P. (2021). Oculomotor deficits in attention deficit hyperactivity disorder (ADHD): A systematic review and comprehensive meta-analysis. *Neuroscience and Biobehavioral Reviews*, *131*, 1198–1213. https://doi.org/10.1016/j.neubiorev.2021.10.012

Motoki, K., Saito, T., & Onuma, T. (2021). Eye-tracking research on sensory and consumer science: A review, pitfalls and future directions. *Food Research International*, *145*. https://doi.org/10.1016/j.foodres.2021.110389

Munn, S. M., Stefano, L., & Pelz, J. B. (2008). Fixation-identification in dynamic scenes: Comparing an automated algorithm to manual coding. In *Proceedings of the Symposium on applied perception in graphics and visualization* (pp. 33–42). https://doi.org/10.1145/1394281.1394287

Oppenheim, A. (1997). *Signals and systems* (2nd ed.). Prentice-Hall.

Orquin, J. L., Bagger, M. P., Lahm, E. S., Grunert, K. G., & Scholderer, J. (2020). The visual ecology of product packaging and its effects on consumer attention. *Journal of Business Research*, *111*, 187–195. https://doi.org/10.1016/j.jbusres.2019.01.043

Over, E. A. B., Hooge, I. T. C., Vlaskamp, B. N. S., & Erkelens, C. J. (2007). Coarse-to-fine eye movement strategy in visual search. *Vision Research*, *47*(17), 2272–2280. https://doi.org/10.1016/j.visres.2007.05.002

Poole, A., & Ball, L. J. (2005). Eye tracking in human–computer interaction and usability research: Current status and future. In C. Ghaoui (Ed.), *Encyclopedia of human–computer interaction* (pp. 211–219). Idea Group, Inc.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*(3), 372–422. https://doi.org/10.1037/0033-2909.124.3.372

Rayner, K. (2009). Eye movements and attention in reading scene perception, and visual search. *The Quarterly Journal of Experimental Psychology*, *62*(8), 1457–1506.

Rayner, K., & Pollatsek, A. (1989). *The psychology of reading*. Prentice Hall.

Salvucci, D. D., & Goldberg, J. H. (2000). Identifying fixations and saccades in eye-tracking protocols. In *Proceedings of the Eye Tracking Research and Applications Symposium* (pp. 71–78). https://doi.org/10.1145/355017.355028

Sanders, A. F. (1983). Towards a model of stress and human performance. *Acta Psychologica*, *53*(1), 61–97. https://doi.org/10.1016/0001-6918(83)90016-1

Schreij, D., Owens, C., & Theeuwes, J. (2008). Abrupt onsets capture attention independent of top-down control settings. *Perception and Psychophysics*, *70*, 208–218. https://doi.org/10.3758/PP.70.2.208

Sharafi, Z., Soh, Z., & Guéhéneuc, Y.-G. (2015). A systematic literature review on the usage of eye-tracking in software engineering. *Information and Software Technology*, *67*, 79–107. https://doi.org/10.1016/j.infsof.2015.06.008

Skuratova, K. A., Shelepin, E. Yu., & Yarovaya, N. P. (2021). Optical search and visual expertise. *Journal of Optical Technology*, *88*(12), 700–705. https://doi.org/10.1364/JOT.88.000700

Spivey, M. J., & Tanenhaus, M. K. (1998). Syntactic ambiguity resolution in discourse: Modeling the effects of referential context and lexical frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*(6), 1521–1543. https://doi.org/10.1037/0278-7393.24.6.1521

Strohmaier, A. R., MacKay, K. J., Obersteiner, A., & Reiss, K. M. (2020). Eye-tracking methodology in mathematics education research: A systematic literature review. *Educational Studies in Mathematics*, *104*, 147–200. https://doi.org/10.1007/s10649-020-09948-1

Vigneau, F., Caissie, A. F., & Bors, D. A. (2006). Eye-movement analysis demonstrates strategic influences on intelligence. *Intelligence*, *34*(3), 261–272. https://doi.org/10.1016/j.intell.2005.11.003

Williams, L. H., & Drew, T. (2019). What do we know about volumetric medical image interpretation?: A review of the basic science and medical image perception literatures. *Cognitive Research: Principles and Implications*, *4*, 21. https://doi.org/10.1186/s41235-019-0171-6

Wilson, M. R. (2012). Anxiety: Attention, the brain, the body and performance. In S. Murphy (Ed.), *The Oxford handbook of sport and performance psychology* (pp. 173–190). Oxford University Press.

Zashchirinskaya, O. V., Skuratova, K. A., Shelepin, E. YU. (2019). Specifika glazodvigatel'noj aktivnosti detej pri chtenii tekstov raznyh vizual'nyh formatov. *Sibirskij Psihologicheskij Zhurnal,* 73, 141–158. https://doi.org/10.17223/17267080/73/9 (in Russ).

Received: May 16, 2022
Revision received: August 15, 2022
Accepted: August 08, 2022

Author Contributions

K. A. Skuratova provided the description of fixation detection algorithms and preparation of illustrations.

E. Yu. Shelepin provided the description of the functionality of the software.

K. Yu. Shelepin provided the description of the quantitative parameters of oculomotor activity.

Author Details

Kseniya Andreevna Skuratova – Juniour Researcher, Pavlov Institute of Physiology, Saint Petersburg, Russian Federation; Scopus Author ID: 7216979736, ResearcherID: ABA-2446-2021, SPIN-code: 5940-0930, ORCID: https://orcid.org/0000-0001-8371-4348, e-mail: kseskuratova@gmail.com

Evgeny Yurievich Shelepin – Juniour Researcher, Pavlov Institute of Physiology, «Neuroiconica Assistive» LLC, Saint Petersburg, Russian Federation; Scopus Author ID: 7200940465, ResearcherID: AAA-9227-2021, SPIN-code: 5938-7368, ORCID: https://orcid.org/0000-0002-3124-5540, e-mail: sey2@yandex.ru

Konstantin Yurievich Shelepin – Cand. Sci. (Medicine), researcher, Pavlov Institute of Physiology, «Neuroiconica Assistive» LLC, Saint Petersburg, Russian Federation ORCID: https://orcid.org/0000-0002-1728-3794, e-mail: neiroiconica@ya.ru

Conflict of Interest Information

The authors have no conflicts of interest to declare.