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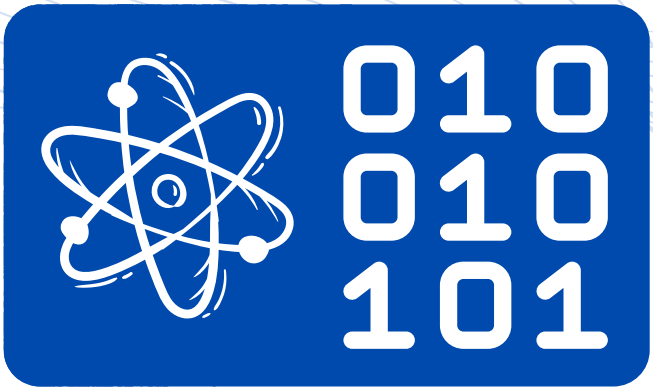

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Spis treści (Contents)

Eye tracking data cleansing for dialogue agent

Czyszczenie danych okulograficznych dla agenta dialogowego

Karolina Gabor-Siatkowska[1], Izabela Stefaniak[2], Artur Janicki[3]

Abstract: Eye trackers are commonly used in many research fields, e.g., education, marketing, psychology, medicine, and human-computer interface. Although eye tracker companies provide software with built-in preprocessing algorithms for handling undesired data issues, e.g. blinks, in eye tracking data, the gathered data often has to be additionally processed to become useful for further analyses. In this article, we present an algorithm for eye-tracking data preprocessing, especially when talking about cleansing pupil diameter data. Due to the insufficient detection algorithm provided by the eye-tracking software, our algorithm considers the maximum velocity of human pupil contraction. Our experiments have been conducted on a Gazepoint GP3 device with a sampling frequency of 60 Hz, which is widely used in various research fields. This proposed approach enables researchers to better preprocess their collected pupil data, referring to the behaviour of the human pupil diameter. It makes pupil data preprocessing quick and applicable for any further analyses in various research fields.

Streszczenie: Urządzenia śledzące ruch gałek ocznych (tzw. okulografy) są powszechnie stosowane w wielu dziedzinach, np. w medycynie, edukacji, marketingu, psychologii oraz w interfejsach człowiek–komputer. Producenci okulografów proponują nie tylko sprzęt, ale również odpowiednie oprogramowanie, które umożliwia wstępną analizę takich parametrów jak punkty fiksacji wzroku czy wielkość średnicy źrenicy użytkownika. Oprogramowania te zazwyczaj posiadają już wbudowany algorytm do wstępnego oznaczenia niepożądanych danych (np. mrugnięć). Mrugnięcia te zazwyczaj nie są pożądanym zjawiskiem i muszą być dodatkowo przetworzone na wczesnym etapie przed przystąpieniem do dalszych analiz. Niestety nie zawsze wbudowany algorytm detekcji mrugnięć jest wystarczający na potrzeby badań. Niniejszy artykuł opisuje algorytm wstępnego przetwarzania danych okulograficznych, a konkretnie danych źrenicznych; uwzględnia on maksymalną prędkość skurczu ludzkich źrenic. Nasze eksperymenty zostały przeprowadzone na urządzeniu Gazepoint GP3 o częstotliwości próbkowania 60 Hz, które jest powszechnie dostępne. Zaproponowane przez

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nas rozwiązanie umożliwia szybsze i dokładniejsze przetwarzanie tych danych, uwzględniając przy tym własności ludzkiej źrenicy, i może być szeroko wykorzystywane przy eksperymentach w różnych badaniach okulograficznych.

Keywords: data cleansing, eye tracking, pupillometric data, human-computer interaction, dialogue agent, psychiatry

Słowa kluczowe: czyszczenie danych, okulografia, dane źreniczne, interakcja człowiek–komputer, agent dialogowy, psychiatria

1. Introduction

Eye trackers allow eye movement tracking using the near-infrared light spectrum. The tracking of eye movements and the pupil is used in many fields, such as education, marketing, psychology, and medicine. The most important parameters obtained during an eye tracking session include pupil diameter and eye movement parameters, among many others (e.g. number of blinks, blink duration, time to first fixation, etc.). The choice of a particular parameter for analysis always depends on the purpose of the test performed. For example, the output data can serve as input to algorithms supporting early medical diagnosis or as part of the human-computer interface (HCI).

Today, pupil size is a measure that has become of interest to a broader public, e.g., in psychology, education, marketing, and medicine[4]. For the past dozen years, eye trackers have also been used to study human-computer interaction. An example in this area is Embodied Conversational Agents (ECAs), which have received much attention recently. These works use non-verbal behaviour to establish contact with a human user[5]. For such dialogue to become more reliable, these agents should be equipped with communicative and expressive abilities similar to those we know from human-to-human interaction (speech, gestures, facial expressions, gaze, etc.)[6]. Thanks to eye tracking studies, it is possible to obtain several

[4] M. Wedel, *Attention Research in Marketing: A Review of Eye Tracking Studies*, "SSRN" 2013, pp. 1–28. S. Białowąs, A. Szyszka, *Eye-Tracking in Marketing Research* [in:] *Managing Economic Innovations – Methods and Instruments*, R. Robert (ed.), Poznań 2019, pp. 91–104.
[5] O. Bartošová, C. Bonnet, O. Ulmanová, M. Šíma, F. Perlík, E. Růžička, O. Slanař, *Pupillometry as an Indicator of L-DOPA Dosages in Parkinson's Disease Patient*s, "Journal of Neural Transmission" 2017 (4), pp. 699–703.
[6] N. Bee, E. André, S. Tober, *Breaking the Ice in Human-Agent Communication: Eye-Gaze Based Initiation of Contact with an Embodied Conversational Agent* [in:] *Intelligent Virtual Agents*, Z. Ruttkay, M. Kipp, A. Nijholt, H. Vilhjálmsson (eds.), Berlin–Heidelberg 2009, pp. 229–242.

parameters that characterise, for example, a person's emotional state[7] or concentration[8]. Increasingly, eye trackers are used as an additional source of information during user conversations with a dialogue agent[9]. Thus, the data obtained are used to support or control conversational agents. The human-computer dialogue that is carried out is thus more natural, and as a result, dialogue agents can interact more realistically with people.

It is essential to mention that regardless of the field and application, eye-tracking data, especially when considering pupil diameter, must be appropriately preprocessed to ensure further analysis. Unlike in EEG, there is no official pre-processing path for handling pupil diameter data[10]. These data always depend on the physiological aspects of the participants involved in the study. Due to the variety, many researchers try to find common problems and establish propositions and guidelines, which can be found in the literature[11]. When analysing pupil diameter data, researchers must consider a physiological aspect: eye blinking. For some disciplines, it has even been a research topic, e.g., considering blinking as a measure of fatigue[12]. However, there must be interest or need for the analysis of blinking data; otherwise, it plays a minor role when the research topic is not connected to or associated with blinks. When analysing complex experiments dependent on the focus, the blinks of participants are treated as undesired or missing data. In these situations, there is no information on the actual size of the pupil, which can often be a problem for further data analysis. Eye tracker companies generally provide some labelling of the blink data in the exported dataset within their eye tracking software (e.g., Gazepoint, Pupil). But, very often, their approach may not be sufficient. When the research areas are not connected to the blink duration or blink number, the blinks do not contribute any informative value to the obtained pupil diameter values (obtained during the individual experiments). There are some ways to deal with the problem of missing/erroneous data from various fields. An example was presented in the article by where different

[7] M. M. Bradley, L. Miccoli, M. A. Escrig, P. J. Lang, *The Pupil as a Measure of Emotional Arousal and Autonomic Activation*, "Psychophysiology" 2008 (4), pp. 602–607.
[8] K.–M. Chang, M.–T. W. Chueh, *Using Eye Tracking to Assess Gaze Concentration in Meditation*, "Sensors" 2019 (7), pp. 1–14.
[9] N. Bee, E. André, S. Tober, *op. cit.* G. Bailly, F. Elisei, S. Raidt, A. Casari, A. Picot, *op. cit.*
[10] S. Mathôt, J. Fabius, E. Van Heusden, S. Van der Stigchel, *Safe and Sensible Preprocessing and Baseline Correction of Pupil-Size*, "Behavior Research Methods" 2018 (1), pp. 94–106.
[11] S. Mathôt, J. Fabius, E. Van Heusden, S. Van der Stigchel, *op. cit*. M. E. Kret, E. E. Sjak–Shie, *Preprocessing Pupil Size Data: Guidelines and Code*, "Behavior Research Methods" 2018 (3), pp. 1336–1342. S. Mathôt, A. Vilotijević, *Methods in Cognitive Pupillometry: Design, Preprocessing, and Statistical Analysis*, "Behavior Research Methods" 2023 (6), pp. 3055–3077.
[12] J. A. Stern, D. Boyer, D. Schroeder, *Blink Rate: A Possible Measure of Fatigue*, "Human Factors: The Journal of the Human Factors and Ergonomics Society" (2), pp. 285–297.

perspectives and approaches to handling missing data are described[13]. The idea is that incomplete data may be grouped into imputation procedures and procedures based on models. In imputation procedures, the aim is to complete the missing data, whereas in the second approach, probability models are suggested (e.g., Bayesian inference models). In practice, there are various ways to deal with such cases, which include the following:

- Inserting extrapolated pupil diameter values from the last few moments before the blink into those time moments where a blink occurred:
- Replacement of all those data points that have been affected, with data from before the disturbance (here: blink);
- An average calculated using several data points before the disturbance is used and inserted in place of the erroneous data;
- A data forecast used in place of the disturbance (e.g. linear interpolation), from the last point before the disturbance to the first point correct after the disturbance,
- Removal of data containing information on the blink itself from the entire experiment,
- Inserting the mean/median of the entire data set in place of the data during the blink.

Approach 1) does not force a reduction in the number of data because it assumes a "swap" of data during blink. This might be beneficial in some cases from the point of view of further data processing. However, this approach has the disadvantage that the resulting prediction may be wrong for the total data. In practice, linear/non-linear prediction is a good data-handling method for similar issues. Processing data using approach 2) may not be applicable when considering particular conditions of some experiments. Approach 3) is unsuitable for the blink problem presented because the mean/median of the data of the entire experiment, depending on the stimuli type, may not add any informative value to the pupil's behaviour at specific moments in time. This approach could significantly negatively affect the result of further analysis. There might also be other possibilities listed here, but since it is not the main agenda of the paper, only the most common ones were mentioned. However, treating blinks as missing data is one of many problems researchers may have when considering eye tracking experiments.

[13] L. O. Silva, L. E. Zárate, *A Brief Review of the Main Approaches for Treatment of Missing Data*, "Intelligent Data Analysis" 2014 (6), pp. 1177–1198.

Sometimes, even correct blink detection is not provided, so the mentioned “blinks as missing data” handling propositions may also not be sufficient.

2. Automatic blink recognition provided by software

After exporting data from a performed study, the initial step is to look at the raw data. When dealing with the Gazepoint GP3 eye tracker, the exported data contains the following types of data gathered during the experiments (regarding the behaviour of pupils):

- pupil size [pixel];
- pupil size [mm];
- a valid flag: if pupil diameter data has been recorded (0: no, 1: yes);
- blink id;
- blink duration [ms].

Depending on which mode was activated during an experiment (monocular or binocular), these types are recorded separately for one or both eyes. Fig. 1 shows an example of raw data of recorded pupil size of one eye when a participant looked at a colorfoul picture (static stimuli) for 10s.

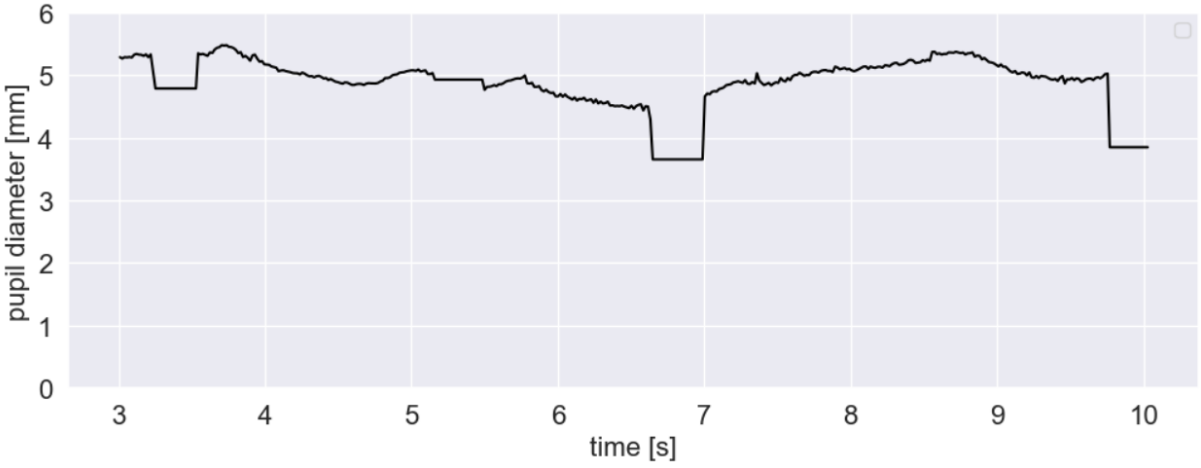

Fig. 1. Example graph of pupil diameter from an experiment with a participant and static stimuli

When looking deeper into the data, one can recognise that there is a built-in blink detection algorithm for pupil size data, which consists of the following steps:

- Check if there are every three consecutive pupil data records whose difference in pupil size is equal to 0 [mm];

- If so, then label the next (so forth) record of pupil size as a “blink” – increase the ‘blink id’ column’;
- Continue labelling the consecutive pupil data records as “blink” as long as the difference between each two new records remains 0;
- If there is any difference > 0 mm in the upcoming pupil data record, stop labelling this record as “blink”.

Require: t_i - timestamp in $i-th$ time;
d_{t_i} - measured pupil diameter [mm] in timestamp t_i
bk_{t_i} - column with labels (0 - no blink, 1 - blink) in timestamp t_i
if $d_{t_{i+3}} - d_{t_{i+2}} = 0$ and $d_{t_{i+2}} - d_{t_{i+1}} = 0$ and $d_{t_{i+1}} - d_{t_i} = 0$ **then**
  record $d_{t_{i+4}}$ label with $bk_{t_{i+4}} = 1$
else
  record $d_{t_{i+4}}$ label with $bk_{t_{i+4}} = 0$
end if

Alg. 1. Provided built-in blink detection algorithm

As shown in Fig. 1, even with regard to such a short experiment, this blink labelling is insufficient. Horizontal lines can be observed because the participant closed the eye (blinked). In the exported data, there are additional columns, e.g., the blink ID, which may indicate in which timestamps blinks occurred. When we leave out that data (with a marked blink ID out of the graph or just filling it with *NaN*-values, the graph will look like shown in Fig. 2.

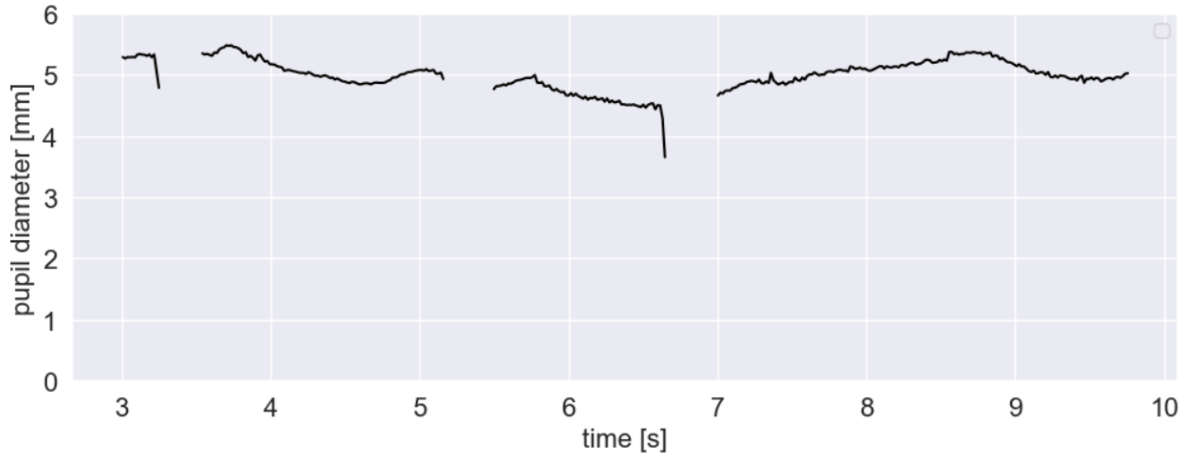

Fig. 2. Example graph of pupil diameter with particular “blink data” left out

The valid-flag column is another column which may also be considered necessary when analysing blinks. When we try to visualise the data regarding this parameter additionally (we visualise only that data, which has a valid-flag marked as valid, so "1 == yes"), the result is the same as presented before, no differences occurred. What is undesirable are the vertical lines, which are associated with the beginning/ending of the blink, that is, when the participant was rapidly closing/opening the eye. Even if the labelled blink data records and valid-flag are considered, this idea of the suggested preprocessing path by the software remains inefficient. It will generate ongoing problems with pupil data analyses. The reason for these problematic data is the first three data records, which are precisely the same size (see step 1 in the blink detection algorithm provided by the GP company). First, after recognising these three, the software recognises only the fourth record as the beginning of a blink. When researchers or data analysts handle blinks in pupil data, only using these software-provided indications, these three records remain falsely classified as real pupil diameter (as it is not recognised as a blink yet) and may lead to undesired problems in further analyses.

The number of such inconvenient vertical lines (as the rest of blinks) in pupillometric data depends mainly on two main parameters: of the blinking rate of the individual (taking part in the experiment) and on the duration of each eye tracking session itself. There are also other circumstances, which can have an impact on the blinks, e.g. the participant's concentration state of the experiment or the involvement of drugs. Regardless of the number of blinks in the data, this is a major issue that will definitely occur and therefore should be handled whenever dealing with eye tracking data.

3. Proposed algorithm

As a result of this problem, we present a novel filtering method for pupil diameter data, which considers the velocity of human pupil constriction. This data preprocessing idea makes it highly applicable to various research fields. Fig. 3 shows our suggested pre-processing steps for the pupil data. First, we propose an extended blink detection (in the first two steps marked in yellow rectangles). The last but one block shows that data filtering should be done with a threshold, whose calculations we report below.

We wondered if there is a maximum value that the human pupil can reach in every timestamp. We investigated some facts about the nature of the human eye. Because the main task of the pupil is to protect the inner eye from too much light coming in, the pupil constriction velocity is always greater than the pupil dilation velocity. In healthy people, this constriction velocity was reported to be in the range of 3.83–9.27mm/s (in subjects aged 20 to 75 years

old)[14]. Because, unfortunately, there is no value of pupil constriction velocity calculated on a much larger population, we decided to set the maximum possible velocity for healthy humans hypothetically at 11mm/s. Our idea of pupil diameter data preprocessing is that the pupil diameter will never naturally achieve greater values than calculated for a timestamp considering the pupil constriction velocity. Then, using an eye tracker with a measuring frequency of 60 Hz, we calculated the maximum constriction of a pupil in one timestamp. When taking into account not only the reported 9.27mm/s but actually a higher value like 11mm/s, the maximal pupil constriction, which can occur in 0.016667s (for 60 Hz), is calculated to be 0.18337mm for pupil diameter. This is the threshold that we used in our approach.

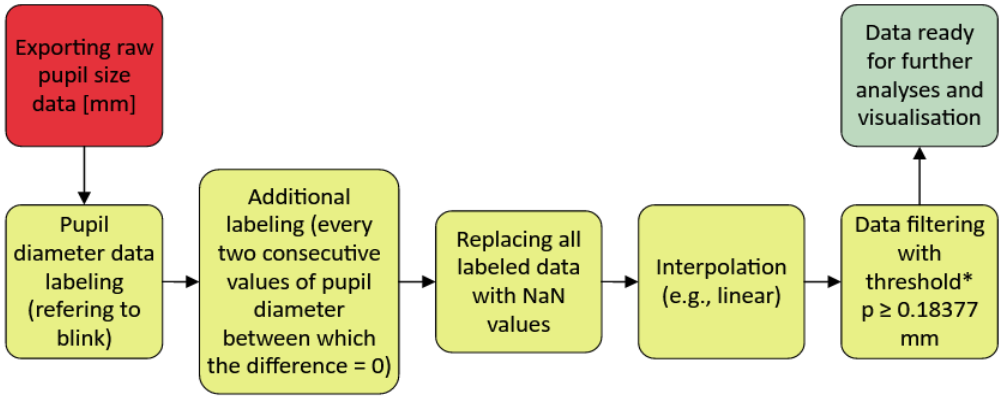

Fig. 3. Block diagram of the proposed steps for pupil data filtration, with the indicated threshold (*).

4. Experiments and results

4.1. Application example 1: healthy participants

First, we tested our algorithm when dealing with the real-life application of our eye tracker. It accompanies the Terabot dialogue system during conversations in Polish language[15]. Firstly,

[14] F. D. Bremner, 2012. *Pupillometric Evaluation of the Dynamics of the Pupillary Response to a Brief Light Stimulus in Healthy* Subjects, "Investigative Ophthalmology and Visual Science" 2012 (11), pp. 7343–7347.
[15] M. Kozłowski, K. Gabor-Siatkowska, I. Stefaniak, M. Sowański, A. Janicki, *Enhanced Emotion and Sentiment Recognition for Empathetic Dialogue System Using Big Data and Deep Learning Methods* [in:] *Computational Science – ICCS 2023. 23rd International Conference, Proceedings, Part I, Lecture Notes In Computer Science*, J. Mikyška, C. de Mulatier, M. Paszyński, V. Krzhizhanovskaya, J. Dongarra, P. M. A. Sloot (eds.), Berlin 2023, pp. 465–480. K. Gabor-Siatkowska, M. Sowański, R. Rzatkiewicz, I. Stefaniak, M. Kozłowski, A. Janicki, *AI to Train AI: Using ChatGPT to Improve the Accuracy of a Therapeutic Dialogue System*, "Electronics" (22), pp. 1–14.

while using this speech-to-speech system, we acquired pupil diameter data when the testers talked with this system. Here, we used the Gazepoint GP3 eye tracker with a measuring frequency of 60 Hz. This eye tracker is widely used in research in different areas[16, 17, 18], and its sampling frequency was sufficient for our purposes. We did not want to use any mobile eye trackers (with cables), because of the patient's comfort, as this would disturb relaxation exercises.

We present visualisations of a participant's pupil raw data (see upper graph in Fig. 4). As can be observed, there are some unrealistic amounts of reported pupil size presented in this gathered data (e.g., about timestamps 100, 310, etc.). We observed the reported blink column and also the valid-flag provided by the software. Unfortunately, this approach did not make any difference to that data. With the application of our algorithm, such problematic data can be easily handled (see lower graph in Fig. 4).

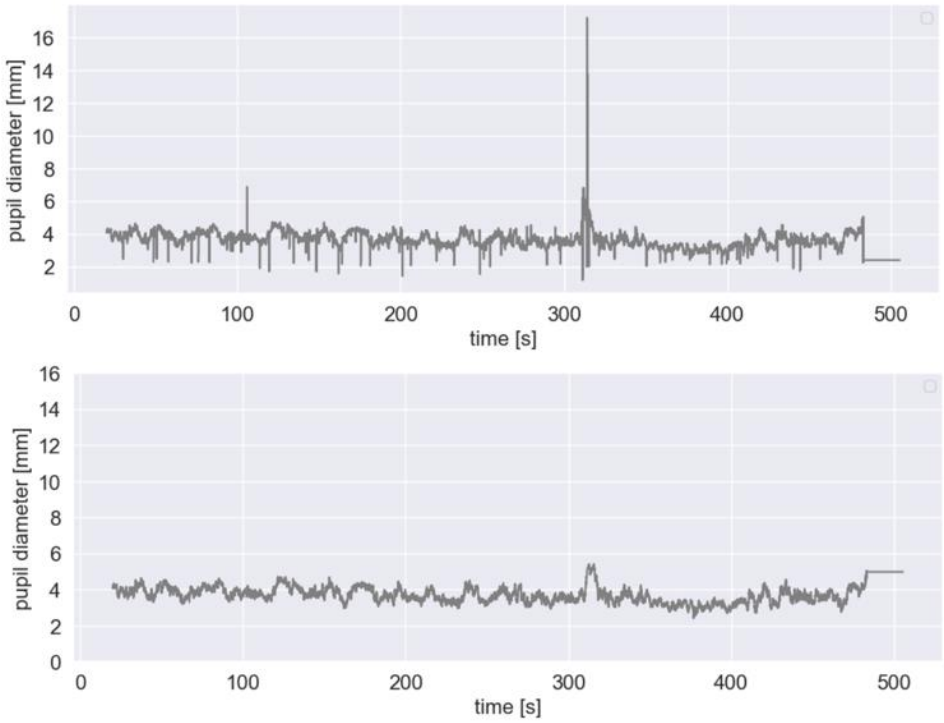

Fig. 4. Pupil diameter data from an experiment with a healthy participant before (upper graph) and after (lower graph) application of our filtering method

[16] P. Sulikowski, T. Zdziebko, *Deep learning-enhanced framework for performance evaluation of a recommending interface with varied recommendation position and intensity based on eye-tracking equipment data processing*, „Electronics" 2020 (9), pp. 1–15.
[17] J. Xu, K. Guo, P. Z. H. Sun, *Driving Performance Under Violations of Traffic Rules: Novice vs. Experienced Driver*s, "IEEE Transactions on Intelligent Vehicles" 2022 (7), pp. 908–917.
[18] J. Xu *et al.*, *Left Gaze Bias Between LHT and RHT: A Recommendation Strategy to Mitigate Human Errors in Left- and Right-Hand Driving*, "IEEE Transactions on Intelligent Vehicles" 2023 (8), pp. 4406–4417.

4.2. Application example 2: psychiatric patients

Nowadays, dialogue systems are increasingly used to improve existing therapies and provide additional help to patients in different areas, e.g. psychiatry. An example is hallucination therapy for psychiatric patients[19]. Our dialogue system has been used at the Institute of Psychiatry and Neurology in Warsaw, Poland. Due to the diagnoses of the patients, they take neuroleptics (antipsychotics) and a combination of drugs from different groups, including antidepressants and mood stabilisers. We used the proposed algorithm to data gained during conversations of our dialogue system with psychiatric patients (more specified information is provided, e.g., in our publication[20]. Again, we used the measuring frequency of the eye tracker of 60 Hz. The upper graph in Figure 5 shows the raw output pupil data of a patient during a dialogue with our dialogue system. Analogously, when considering only the blink data labelled by the software, also regarding the valid-flag labelling, these steps are insufficient. When our algorithm is applied to these data, the output values look much better and are, therefore, ready for further analysing steps (Fig. 5).

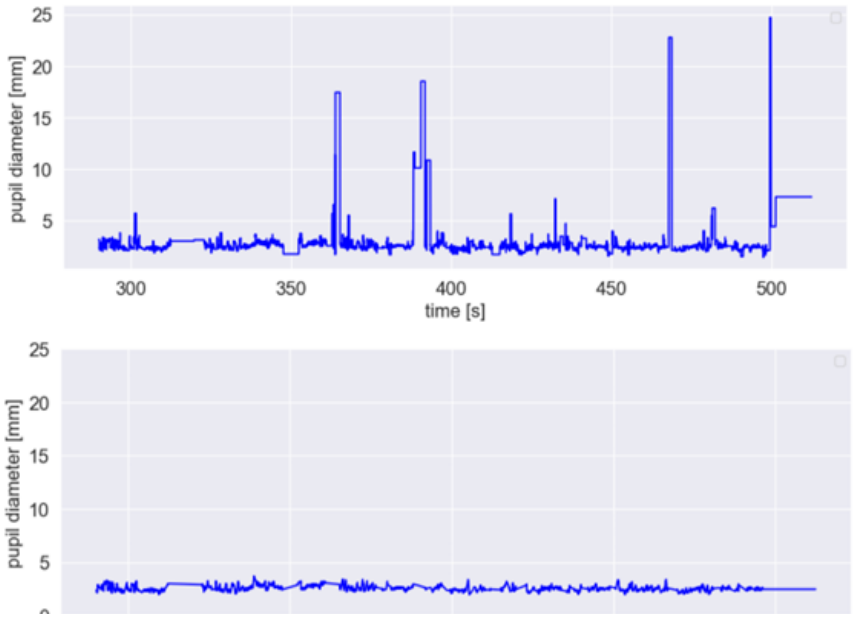

Fig. 5. Pupil size data from a psychiatric patient before (upper graph) and after (lower graph) applying our algorithm

[19] I. Stefaniak, K. Sorokosz, A. Janicki, J. Wciórka, *Therapy Based on Avatar-Therapist Synergy for Patients with Chronic Auditory Hallucinations: A Pilot Study*, "Schizophrenia Research" 2019, pp. A1–A3.
[20] Gabor-Siatkowska, *op. cit*.

Analysing the eye tracking data of one week, four patients had dialogues with Terabot every day, with the time of one dialogue about 7–15min (depending on the progress of the conversation with the patient). It is assumed that in healthy people there are about 15–20 blinks during one minute (each of them lasts about 0.3s), so it can be said that the average number of blinks during such a dialog is about 150–200 (for healthy people). In a group of one-week patients, about 150–360 blinks/patient/dialog were registered during our research, but there were also cases of patients with 84 blinks or 423 or 490 blinks during a dialog. It is important to remember that the number of blinks can vary from person to person, and factors such as fatigue, concentration, or the presence of eye diseases or medication can have a significant impact on it. As it turned out, with such a total number of blinks during about a 10-minute dialog, the algorithm we proposed proved to be very useful.

5. Discussion and further work

As the graphs present, our proposed method has great value in pupil diameter data preprocessing regardless of the state of health of the participants. It reduces undesired noise in the data, and it gives certainty that any data out of range of pupil size will be considered as not realistic and can, therefore, be appropriately processed. Although we are aware that certain medications used in psychiatry may influence pupils' behaviour in psychiatric patients[21], we opted that it could also be helpful in this particular case. In our opinion, there is a lack of any recommended preprocessing path for pupil diameter data from psychiatric patients, although many pupillometric studies are made in general. As a result, our algorithm gives engineers and researchers from many areas the possibility of fast and accurate preprocessing of their pupil diameter data. We have already used the proposed algorithm to focus on areas related to eye movements during specific intervals in the dialogue with our conversational agent. We are specifically interested in the relaxation exercises and want to find out if the patients' pupil's behaviour can give us information about the quality of their relaxation state. We also see that further work on our algorithm, e.g., adjusting this algorithm with particular criteria only for psychiatric patients with specified conditions, e.g., anxiety disorders.

[21] O. Bartošová,, C. Bonnet, O. Ulmanová, M. Šíma, F. Perlík, E. Růžička, O. Slanař, *op. cit.* K. N. Thakkar, J. W. Brascamp, L. Ghermezi, K. Fifer, Je. D. Schall, S. Park, *Reduced Pupil Dilation during Action Preparation in Schizophrenia*, "International Journal of Psychophysiology" 2018 (128), pp. 111–118.

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The Use of Virtual Reality and 3D Models in Medicine and in the Training of Medical Students and Physicians

Wykorzystanie wirtualnej rzeczywistości i modeli 3D w kształceniu studentów medycyny i lekarzy

Krzysztof Kolebski[1]

Abstract: This article aims to show the role and potential of virtual reality (VR) technology and 3D models in medicine, with a special focus on their application in medical education and patient rehabilitation. Research is based on a review of the scientific literature and an analysis of a series of case studies, which encompasses the application of VR in various aspects of healthcare, from geriatric and oncological rehabilitation to surgical training for medical students and practising physicians. The findings indicate significant benefits of VR in medicine, such as improved coordination in the elderly, reduced pain and anxiety in paediatric and oncological patients, and improved efficiency and safety in surgical training. These effects are amplified by the ability to personalise exercises and the increased accessibility and affordability of these technologies. Furthermore, virtual reality offers a unique environment for simulating complex medical and surgical procedures, contributing to better preparation of medical students and young doctors for future clinical practice. In light of these findings, VR emerges as an innovative educational and therapeutic tool, with the potential to significantly improve medical practices and quality of healthcare.

Streszczenie: Artykuł ma na celu przedstawienie roli i potencjału technologii wirtualnej rzeczywistości (VR) oraz modeli 3D w medycynie, ze szczególnym uwzględnieniem ich zastosowania w edukacji medycznej i rehabilitacji pacjentów. Badanie opiera się na przeglądzie literatury naukowej oraz analizie serii studiów przypadków, które obejmują zastosowanie VR w różnych aspektach opieki zdrowotnej – od rehabilitacji geriatrycznej i onkologicznej po szkolenia chirurgiczne dla studentów medycyny i praktykujących lekarzy. Wyniki wskazują na znaczące korzyści płynące z zastosowania VR w medycynie, takie jak poprawa koordynacji u osób starszych, redukcja bólu i lęku u pacjentów pediatrycznych i onkologicznych, a także

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wzrost efektywności i bezpieczeństwa w szkoleniach chirurgicznych. Efekty te są potęgowane przez możliwość personalizacji ćwiczeń oraz zwiększenie dostępności i przystępności tych technologii. Dodatkowo, wirtualna rzeczywistość oferuje unikalne środowisko do symulacji skomplikowanych procedur medycznych i chirurgicznych, co przyczynia się do lepszego przygotowania studentów medycyny i młodych lekarzy do przyszłej praktyki klinicznej. W świetle tych wyników, VR ujawnia się jako innowacyjne narzędzie edukacyjne i terapeutyczne, które ma potencjał do znacznego ulepszenia praktyk medycznych i jakości opieki zdrowotnej.

Keywords: virtual reality, 3D models, medical education, patient rehabilitation, surgical simulation, healthcare technology, medical training, interactive learning, digital innovation, clinical practice

Słowa kluczowe: wirtualna rzeczywistość, modele 3D, edukacja medyczna, rehabilitacja pacjentów, symulacja chirurgiczna, technologia w ochronie zdrowia, szkolenie medyczne, interaktywne uczenie się, innowacje cyfrowe, praktyka kliniczna

1. Introduction

The last decade has witnessed relentless progress in technology, with the advancement of Industry 4.0 and investments in new technologies significantly contributing to the revolutionization of social, economic and scientific spheres. The application of new technological advances in medicine was an obvious step, enabling the improvement of numerous medical procedures and paving the way for new methods of diagnosis, treatment, and patient care. It should be noted especially the use of virtual reality (VR) and 3D models for their potential benefits in the diagnosis, therapy, and more realistic training of medical personnel. Virtual reality allows the creation of immersive environments where patients and medical staff can participate in ways that transcend traditional methods. This article aims to outline the history of virtual reality and provide examples of its application in various branches of medicine and in the training of medical students and doctors, proving its immense usefulness in these areas.

2. Definitions

Virtual reality (VR) technology is an interactive, computer-generated environment that simulates the real world or creates entirely new realms. Users use specialised devices such as VR goggles, gloves, or controllers to immerse themselves in a three-dimensional environment. The primary objective of this technology is to provide the participant with a realistic feeling of presence in a virtual world, allowing interaction with the environment using various senses, such as sight, hearing, and touch. Through the use of virtual reality, medical students have the opportunity to practice and refine their skills in a realistic virtual environment, which can contribute to better preparation for clinical work. In addition, VR allows for the simulation of complex medical procedures, potentially increasing the confidence and competence of future medical professionals.

3D models represent three-dimensional objects or scenes generated computationally. They consist of three-dimensional coordinates (x, y, z) that define points in space. These models are created using various techniques, such as manual modelling, 3D scanning, mathematical methods (e.g., Bézier curves), or through 3D modelling software. Once created, they can be rendered (generating 2D images) for use in animations, video games, simulations, or other fields where three-dimensional representation is beneficial. In medicine, these models enable physicians, students, and researchers to gain a better understanding of anatomical structures, diseases, pathological processes, and interactions within biological systems. Generated 3D models can be viewed on traditional monitors, but their integration with virtual reality technology can offer students and doctors the most extensive opportunities to familiarise themselves with research material.

3. History

Although the term “virtual reality” was coined only in 1987, the concept of virtual reality traces its roots back to the early decades of the 20th century. During this time, the American mathematician and inventor, Edwin Albert Link, created flight simulators known as the *Blue Box* and *Link Trainer*[2]. Although not directly related to today's understanding of virtual reality, Link managed to create an environment that simulated the appropriate conditions and isolated the participant from their surroundings, thereby providing a safe training environment for future pilots. This example illustrates that the desire to immerse people in different environments was

[2] *The National Centre of Simulation*, https://www.simulationinformation.com/hall-of-fame/members/edwin-albert-link/ (on-line 23.11.2023)

not exclusive to artists and the entertainment industry, who sought to elevate the experience of their audience to a new level.

The post-war years brought further development to virtual reality. In 1968, Ivan Sutherland and his team created a device named the *Sword of Damocles*. It was an early virtual reality project using head-mounted displays (HMD)[3]. These were attached to an apparatus mounted on the ceiling and displayed simple images. Although this design did not allow movement within the virtual environment, it was a pioneering step in the development of virtual reality technology and inspired further research in the field.

The development of virtual reality technology was also linked in its later stages to the defence and aviation industries. In the 1960s, General Electric created the first flight simulator with a built-in generator of real-time virtual images, initially for the Apollo program, and later in 1972 for the United States Navy[4]. Subsequently, other companies, such as McDonnell Douglas Corporation, developed helmets and other tools to train pilots.

The advancement of virtual reality technology in these sectors also led to its implementation in other fields, including medicine. Thanks to researchers who sought innovative solutions and technological progress, virtual reality became more widely accessible, enabling its application in medicine.

4. The use of virtual reality technology in medicine

Initially, researchers endeavoured to implement new technologies that were not directly related to the medical industry, but rather to the entertainment sector. In response to the ageing population in many countries, researchers are looking for new solutions to improve the lives of the elderly. They investigated whether the use of virtual reality and console games could improve the coordination of older people. For this study, the Nintendo Wii® console and the Wii Balance BoardTM were used[5]. Although the console and module do not provide full immersion using goggles, the combination of the images displayed on the screen, sound effects, and complex gameplay mechanics makes the experience of the game world more engaging. The

[3] I. Shuterland, *A head-mounted three dimensional display*, "Proceedings of the AFIPS Fall Joint Computer Conference", Washington 1968, pp. 757–759.
[4] *Brittanica.com, Virtual Reality – Education and training*,
https://www.britannica.com/technology/virtual-reality/Education-and-training (on-line 23.11.2023)
[5] M. Żak *et al.*, *Wykorzystanie wirtualnej rzeczywistości i gier konsolowych w profilaktyce upadków osób starszych,* "Gerontologia Polska" 2014 (1), pp. 9–10.

study involved seniors over the age of 65 practising balance using the devices mentioned above. Research confirmed that the use of such solutions should be part of programmes aimed at improving the condition of older patients. Furthermore, it appears that the use of console games and devices that train balance is a good strategy to prevent falls, to which this age group is particularly susceptible. The results of the study also indicate that the combination of conventional kinesiotherapy and virtual reality should be used jointly to achieve the best effects in patient treatment[6]. The above example excellently demonstrates how virtual reality can be used in patient rehabilitation. An additional advantage of incorporating console games into patient rehabilitation is the relatively low cost of such devices compared to specialised equipment. This also allows patients to continue their prescribed exercises at home, due to the popularity of consoles for personal use.

Thanks to immersion in a virtual environment, patients can also perform exercises in a more engaging manner, increasing their motivation to participate in the rehabilitation process. In studies aimed at evaluating the effectiveness of vestibular rehabilitation in patients with vestibular dysfunction, it was shown that „patients reported greater improvement after training with VR"[7]. This indicates that competition-based exercises, tracking progress, and thus more actively engaging the patient, are perceived by them as more effective. The use of virtual reality in the rehabilitation sector can lead to greater patient participation and willingness to cooperate in the pursuit of regaining or improving their physical abilities, especially thanks to the simulation of everyday situations, which supports the training of life functions for those in need.

Rehabilitation of patients using virtual reality also offers the possibility of customising exercises to the needs of the individual patient, by adjusting the level of difficulty, the number of repetitions, or the pace of rehabilitation. Furthermore, it is worth mentioning again that as virtual reality technology develops, its cost will decrease, allowing an increasing number of patients to afford such a set-up and continue exercises at home. Patients could receive personalised exercise programmes and perform them at home, bringing benefits not only in terms of time savings, but also in increasing the regularity of exercise execution.

Virtual reality can help physicians treat pain and anxiety in patients. Cases are known where psychiatrists work with patients struggling with anxiety disorders or posttraumatic stress disorder (PTSD). The use of controlled simulations allows gradual adaptation to stress-inducing

[6] *Ibidem*, p. 12.
[7] O. Rosiak *et al*., *Ocena skuteczności rehabilitacji przedsionkowej u pacjentów z dysfunkcją błędnika,* "Medycyna Pracy" 2019 (5), p. 550.

situations. Another example showing that the virtual reality environment can be used to treat anxiety and pain involves studies with paediatric patients on pain reduction. These patients are particularly sensitive to this discomfort, which during painful medical procedures can discourage the continuation due to negative associations. Furthermore, fear of medical visits and procedures negatively affects patient convalescence[8]. Scientific research on pain reduction in children has confirmed its alleviation through the use of distractions such as television, music, interactive toys, or electronic games; however, the possibilities offered by virtual reality are much greater[9]. The use of virtual reality does not interrupt pain signals but, directly and indirectly, through its impact on emotions, senses, concentration, and attention, affects the perception of pain and its signaling due to immersion. Immersion, which means deep involvement and engagement of the user in a virtual environment, combines both visualisation and sound, as well as the possibility of interaction within virtual reality. This tool in working with children can also be a form of play, positively influencing their development and association with medical procedures. Studies also show that the use of VR to reduce preoperative anxiety is an effective method. Virtual reality technology offers various possibilities for its use and adaptation to the age of the patient. Among the tested methods, it can include familiarising the child with the operating room before a planned procedure. Thanks to this, both the child and the accompanying parent can watch a film displayed in VR that presents the operating room, and then discuss their reflections. Another method involves watching your favourite animated film in VR glasses and repeating this on the day of the procedure while waiting for anaesthesia[10]. Among the medical procedures and treatments that cause stress and anxiety, needle procedures should be mentioned, with particular emphasis on vaccinations. These procedures are necessary for the protection of children's health, but negative stimuli can cause avoidance of vaccinations due to them. The use of VR technology can reduce experienced fear and pain by focussing attention on another activity and isolating the child's mind from the unpleasant environment[11]. The examples shown above demonstrate how virtual reality technology can be an effective tool in reducing stress, anxiety, and pain, especially among paediatric patients. These patients are particularly sensitive to these factors,

[8] U. Fussek-Styga *et al.*, *Wykorzystanie wirtualnej rzeczywistości jako metody redukcji bólu i lęku u pacjentów pediatrycznych – praca przeglądowa*, "Journal of Education, Health and Sport" 2023 (1), p. 83.
[9] *Ibidem*, p. 84.
[10] *Ibidem*, pp. 84–85.
[11] *Ibidem*, p. 86.

which can have a negative impact that can influence their future relationships with the medical sector. They are also more open to testing such devices because of their innate curiosity about the world.

Another group studied for pain reduction is cancer patients. According to the American Cancer Society, cancer-related disorders include mood decline, irritability, and side effects of treatment methods such as nausea[12]. These difficulties do not support treatment, during which patient attitude is extremely important. The prolonged experience of the negative effects of the disease, as well as its treatment, can significantly reduce the quality of life of patients. To counteract side effects and improve the overall well-being of patients, researchers from the University of Wrocław and Wrocław University of Technology conducted studies to verify whether virtual reality can reduce stress and increase patient comfort during treatment. The study involved patients who destroyed cancer cells in a virtual environment using VR weaponry[13]. As mentioned above, virtual reality technology is an engaging medium that affects multiple senses. Individuals who have a lower ability to create vivid mental images, and hence for whom visualisation techniques are not effective, can benefit from virtual reality technology, achieving better results and progress, including an increased subjective sense of control over pain. The cancer patients studied indicated that the VR game arranged had a significant impact on their experiences during chemotherapy sessions, greatly contributing to an increased subjective sense of control over the treatment process. It should be noted that the patients' reactions to the VR game experience were positive and rated the game as fascinating and generally conducive to relaxation[14]. The virtual experience of destroying cancer cells with drug particles shows that potentially modern therapeutic methods can revolutionise cancer treatment, minimising side effects and increasing the effectiveness of therapy. These studies also indicate that, in addition to fighting/treating the disease, an important aspect is the patient's well-being and the regaining of control.

5. Using virtual reality with 3D models for training students and physicians

One of the key areas of virtual reality application is surgical simulation, where physicians can perfect their skills in a realistic virtual environment, minimising risk to patients. A prime example of this type of VR implementation in medical staff training is Eyesi, a German VR

[12] J. Piskorz *et al*., *Virtual Reality Use for Stress Reduction and Patient Comfort During Chemotherapy*, "Polish Psychological Bulletin" 2023 (2), p. 136.
[13] *Ibidem*, p. 144.
[14] *Ibidem*, p. 136.

simulator that allows virtual cataract surgery simulation. This equipment enables training at four levels (A–D) and, by accumulating points from previous simulations, allows one to compare the results[15]. With these characteristics, it is a tool that allows the training of a physician from the beginning of their education to achieving masterful precision, but it also offers the possibility of use by more experienced physicians who feel the need for further education. The ability to track one's results is a valuable source of information on personal progress. The Eyesi simulator has been used among residents of the Royal College of Ophthalmologists, Botucatu Medical School, Miller School of Medicine, as well as among surgeons in Denmark. Studies in these centres confirm that training in the virtual reality environment improved the work of residents and practising surgeons. Training with the Eyesi simulator contributes to a reduction in complications, especially among young physicians, who are at the highest risk of making errors[16]. In addition to improving patient safety, this also leads to reduced costs of treating complications, allowing the saved funds to be invested, for example, in further training for physicians.

Another example of training future physicians using virtual reality technology is a study conducted with students from Jinan University (China). The students participated in a one-year internship during which they used virtual reality technology (apart from the control group) as part of their learning. The study showed that medical students who had access to virtual reality teaching methods exhibited greater perseverance in their careers. In addition, they showed a tendency to active learning and achieved higher instructional grades during the clinical practice stage of surgery. Furthermore, it was noted that the VR teaching mode could contribute to improving the performance of medical students on physical examinations as part of the Final Practice Examination (OBWE). The study also demonstrated that by shaping a learning model based on non-linear dynamics, the VR teaching mode has the potential to become an effective and stable initial element for medical students[17].

Compared to conventional teaching methods or a hybrid approach using 3D technology, the immersive learning method provided by VR technology can effectively engage students,

[15] P. Łajczak *et al.*, *Zastosowanie symulatora VR Eyesi w szkoleniach operacji zaćmy* [in:] *Innowacje w medycynie przegląd wybranych technologii XXI w*., J. Kufel, P. Lewandowski (eds.), v. 10, Łódź 2023, pp. 274–275.
[16] *Ibidem*, p. 283.
[17] W. Gan *et al.*, *Researching the application of virtual reality in medical education: one-year follow-up of a randomized trial,* "BMC Medical Education" 2023 (3), pp. 9–10.

stimulate their motivation for active learning, and create a personalised system of accumulated medical knowledge. From a didactic objectives perspective, it can be stated that virtual reality simulation improves the quality and efficiency of the educational process, serving as a complement to traditional forms of teaching rather than replacing it. According to the data, when asked about strengthening the determination to become a doctor after the internship, 28 students (52.8%) from the VR group gave a positive response, compared to 17 students (30.9%) from the control group[18]. The role of medical education, in which VR enables realistic simulations of clinical cases, integrating theoretical knowledge with practice, should also be emphasised. Medical students have access to interactive scenarios, increasing their readiness to work under real clinical conditions.

In the context of the recent pandemic, teaching with the use of virtual reality seems extremely useful. As indicated by a meta-analysis conducted by Hyeon-Young Kim and Eun-Young Kim, access to medical education programmes using VR through immersive experiences can be particularly valuable in circumstances where the safety of students and educators cannot be guaranteed due to the spread of infectious diseases or in the event of other natural disasters[19]. The authors also note that students can improve clinical skills in a safe environment through repeated learning, appropriately modifying interventions that ended in failure. This is an effective way to improve skills, which can also reduce student stress. This method is not only effective but also positive for the general well-being and motivation of students. Systematic practice of skills can build confidence and increase competence, positively impacting the management of stress associated with educational demands. Additionally, creating a friendly environment for learning and skill development can result in a better understanding of the material and promote a positive attitude towards education. The research confirms that medical education based on virtual reality technology effectively improves students' skills and satisfaction levels[20]. These indicators are also significant due to demographic changes and other requirements for today's students and future medical doctors.

Furthermore, virtual reality technology not only allows entry into a created world, but also facilitates connection with others, even if they are in different parts of the world. A study conducted in the USA using such an environment involved testing a virtual anatomy

[18] *Ibidem*, p. 7.
[19] H. Kim, E. Kim, *Effects of Medical Education Program Using Virtual Reality: A Systematic Review and Meta-Analysis*, "International Journal of Environmental Research and Public Health" 2023 (5), p. 12.
[20] *Ibidem*, p. 12–13.

laboratory[21]. Using images from medical databases, 3D anatomical models were developed and then evaluated by neurosurgeons and neurosurgery residents in virtual space. The study created 10 immersive anatomical environments in which physicians and residents viewed, evaluated and discussed 3D models. Each researcher who participated in the session had their own virtual avatar and controllers, which allowed them to rotate, move, zoom in and out of the designed models. The camera and microphone setup allowed for free exchange of opinions among the participants[22]. Study participants unanimously stated that incorporating such virtual educational experiences into the traditional programme could improve the learning of anatomy by surgical interns. In addition, virtual reality technology would be useful during surgical simulations and in gaining knowledge about surgical approaches. Furthermore, the students also noted that the immersive environment creates a more engaging setting, which improves learning, and that this technology could have a significant impact on international neurosurgeon training.

Anatomical 3D models can also be used on a smaller scale in specific specialisations. An example is the application of a photorealistic virtual ear in otological education, particularly in surgical procedures. The greater realism of the external and middle ear model enabled a more immersive interaction among the training participants. In addition to improving the understanding of human ear anatomy, this technology may change the way otology is taught, confirming the universality of virtual reality technology in medical training and the possibility of its personalization to individual fields through appropriate development of anatomical 3D models.

6. Conclusions

As the examples above illustrate, the use of virtual reality in medicine is becoming increasingly popular. The advancement of digitisation in the healthcare sector serves as an impetus for the implementation of innovative solutions, including virtual reality technology. As a result, patients can benefit from more advanced forms of therapy, and medical personnel can refine their skills under simulated conditions, improving the effectiveness of training. This positive impact accelerates the adoption of modern technologies and raises healthcare standards. This technology not only allows, as repeatedly emphasised in this article, training in a safe

[21] N. Gonzalez-Romo *et al.*, *Virtual neurosurgery anatomy laboratory: A collaborative and remote education experience in the metaverse*, "Surgical Neurology International" 2023 (14), pp. 2–3.
[22] *Ibidem*, p. 6–8.

environment, but also has a range of other advantages. Firstly, it enables multiple people to connect in one session, allowing a group of students to be trained simultaneously, and medical databases provide materials that make it possible to create highly detailed anatomical 3D models. Increasingly extensive medical databases will contribute to the creation of even more detailed and refined 3D anatomical images, which, when implemented in virtual reality, will become excellent training material. Such models vividly illustrate anatomy, allowing students to delve deeper into it, and once prepared, a model can be used for many years. Another positive aspect of using virtual reality technology in student training is its positive reception among the target group. Students are eager to use such tools, they are well acquainted with technology, have a positive attitude towards it, and learn to operate it easily. The ability to practice difficult procedures in a safe environment improves learning comfort, and training software that continuously tracks student progress provides the opportunity to monitor one's own development, which can be associated with greater willingness to continue learning. Virtual reality represents a promising training tool in the field of medicine, offering innovative and effective methods of education.

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Dwa nowe algorytmy klasyfikacji farmakokinetycznych szeregów czasowych

Two novel classification algorithms of the pharmacokinetic time series

Piotr Wilczek[1]

Streszczenie: Przedkładana praca zawiera propozycję dwóch nowych miar odległości pomiędzy szeregami czasowymi. Mianowicie, wprowadzamy tzw. rekurencyjno-kanoniczną miarę odległości oraz jej krzyżową formę. Nasze podejście opieramy na bezprogowych (krzyżowych) macierzach rekurencyjnych, których koncepcje zostały rozwinięte w ramach (krzyżowej) analizy rekurencyjnej szeregów czasowych oraz na kanonicznej mierze odległości pomiędzy dwoma wielowymiarowymi zbiorami danych, której koncepcja została rozwinięta w obrębie chemometrii. Wyczerpujące symulacje komputerowe przeprowadzone na 27 farmakokinetycznych szeregach czasowych pokazały, iż algorytmy bazujące na nowo opracowanych funkcjach odległości są bardziej efektywne niż algorytmy bazujące na klasycznych miarach $L2$ i DTW oraz na ich modyfikacjach.

Abstract: In the present contribution, we proposed two novel distance measures between time series. Namely, we introduced the so-called recurrence-canonical measure of distance as well as its cross form. Our approach is based on the notion of the unthresholded (cross-)recurrence matrices developed in the field of the (Cross-)Recurrence Quantification Analysis and the notion of the canonical measure of distance between multidimensional datasets developed in the field of chemometrics. The extensive computer simulations carried out on 27 pharmacokinetic time series showcased that the algorithms based on the newly designed distance functions outperform the protocols based on the classical $L2$ and DTW functions and on their modifications.

Słowa kluczowe: szereg czasowy, (krzyżowa) analiza rekurencyjna, kanoniczna miara odległości, farmakokinetyka

Keywords: time series, (cross-)recurrence quantification analysis, canonical measure of distance, farmacokinetics

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1. Wprowadzenie

W ostatnich latach można zaobserwować wzrost popularności analiz opartych na tzw. „danych temporalnych". Mianowicie, biorąc pod uwagę powszechne wykorzystanie nowoczesnych technologii cyfrowych, możliwa jest rejestracja dużej liczby pomiarów czasowych w obrębie nauk podstawowych (np. w fizyce, chemii, biologii czy też geologii), jak również nauk stosowanych (np. w farmakologii, medycynie, robotyce czy też automatyce). W związku z tym nastąpił dramatyczny wzrost zainteresowania gromadzeniem oraz eksploracją danych temporalnych, co z kolei zaowocowało dużą liczbą artykułów naukowych proponujących nowatorskie techniki indeksacji, klasyfikacji, grupowania, aproksymacji oraz prognozowania szeregów czasowych. W szczególności zaproponowano wiele nowych miar odległości pomiędzy danymi temporalnymi. Przedkładana praca ma na celu wprowadzenie dwóch nowych funkcji odległości pomiędzy szeregami czasowymi. Efektywność nowo zaproponowanych miar temporalnych zostanie przetestowana na 27 farmakokinetycznych przykładowych zbiorach danych.

1. Podstawy teoretyczne i terminologia

Z matematycznego punktu widzenia sygnałem nazywamy zmianę jednej (lub kilku) wielkości fizycznie mierzalnych w zależności od zmian innej wielkości. W powszechnym użyciu pojęcie sygnału stosuje się do zmian pewnych fizycznie mierzalnych wielkości (np. chemicznych, biologicznych czy też biochemicznych) w funkcji czasu. Taki sygnał nazywamy szeregiem czasowym. Przypomnijmy, iż szereg czasowy to ciąg pomiarów (obserwacji) uporządkowany w czasie. W prezentowanej pracy przyjmujemy, iż zmienna niezależna (tj. zmienna czasowa) jest dyskretna. A więc, z formalnego punktu widzenia, szereg czasowy T to ciąg par uporządkowanych o postaci: $T = [(t_1, x_1), (t_2, x_2), \dots, (t_i, x_i), \dots, (t_n, x_n)]$ dla $t_1 < t_2 < \cdots < t_i < \cdots < t_n$ oraz dla zbioru indeksów $I = \{1,\ 2, \dots, i, \dots, n\}$, gdzie każdy wyraz x_i to wynik pomiaru (obserwacji) zmiennej zależnej w d-wymiarowej przestrzeni cech (ang. *feature space*) oraz każdy element t_i to punkt (krok) czasowy (ang. *timestamp*), w którym dany pomiar (dana obserwacja) został zarejestrowany. W prezentowanej pracy zakładamy, iż wszystkie analizowane dane temporalne są jednowymiarowe (ang. *univariate*), a więc $d = 1$ dla każdego z rozpatrywanych szeregów czasowych. Ponadto przyjmujemy, iż każdy badany ciąg temporalny jest regularny, a więc punkty czasowe t_i wszystkich rozpatrywanych szeregów czasowych są równomiernie rozmieszczone. Liczba zarejestrowanych pomiarów (obserwacji), (n), to długość szeregu czasowego T. Z kolei, i-ty wyraz szeregu czasowego T oznaczamy

przez $T(i)$. Etykietowany temporalny zbiór danych $\boldsymbol{TD}$ to kolekcja $\boldsymbol{T} = \{T_g\}_{g=1}^{m}$ szeregów czasowych z których każdy ma długość n razem z określonym (ang. *predefined*) dyskretnym wektorem[2] etykiet $\boldsymbol{C}$ o długości m. Konkludując, etykietowany temporalny zbiór danych to struktura o postaci $\boldsymbol{TD} = (\boldsymbol{T}, \boldsymbol{C}) = (T_g, C^{T_g})$, gdzie $T_g \in \boldsymbol{T}$ to g-ty szereg czasowy, natomiast $C^{T_g} \in \boldsymbol{C}$ to jego etykieta. W przedkładanej pracy przyjmujemy, iż dwie etykiety $C^{T_g}, C^{T_h} \in \boldsymbol{C}$ są równoważne ($\cong$) wtedy i tylko wtedy gdy są identyczne, tj. $C^{T_g} \cong C^{T_h} \leftrightarrow C^{T_g} = C^{T_h}$, gdzie $\leftrightarrow$ to logiczny spójnik równoważności międzyzdaniowej. Dla szeregu czasowego T o długości n, jego pierwsza dyskretna pochodna T' to nowy szereg czasowy o długości $n-1$, którego wyrazy dane są zależnością[3]: $T'(i) \coloneqq T(i+1) - T(i)$, gdzie $i = 1, 2, \ldots, n-1$.

3. Nowe algorytmy obliczania odległości pomiędzy szeregami czasowymi

Proponowane w tej części pracy nowe techniki obliczania odległości pomiędzy danymi temporalnymi oparte są na analizie rekurencyjnej (ang. *recurrence quantification analysis*) szeregów czasowych RQA[4], jej *krzyżowej* formie (ang. *cross-recurrence quantification analysis*) $CRQA$ oraz na metodzie obliczania odległości pomiędzy wielowymiarowymi zbiorami danych opracowanej przez Roberta Todeschiniego oraz jego współpracowników[5]. Techniki te składają się z następujących kroków:

1. Dla każdego szeregu czasowego w analizowanej bazie danych, tj. $T_g \in \boldsymbol{T}$ obliczamy jego bezprogową macierz rekurencyjną (ang. *unthresholded recurrence matrix*) UR^g lub jej krzyżową formę (ang. *unthresholded cross-recurrence matrix*) UCR^g zgodnie z następującymi formułami[6]:

$$UR_{ij}^{g} \coloneqq \left\| T_g(i) - T_g(j) \right\|_2$$

oraz

[2] Z matematycznego punktu widzenia wektor $\boldsymbol{C}$ to multizbiór.
[3] T. Górecki, M. Łuczak, *Multivariate time series classification with parametric derivative dynamic time warping*, „Expert Systems with Applications" 2015, nr 42, s. 2307.
[4] J.–P. Eckmann, S. O. Kamphorst, D. Ruelle, *Recurrence plots of dynamical systems*, „Europhysics Letters" 1987, nr 5, s. 973–977; N. Marwan, M. C. Romano, M. Thiel, J. Kurths, *Recurrence plots for the analysis of complex systems*, „Physics Reports" 2007, nr 438, s. 237–329.
[5] R. Todeschini, D. Ballabio, V. Consonni, A. Manganaro, A. Mauri, *Canonical measure of correlation (CMC) and canonical measure of distance (CMD) between sets of data. Part 1. Theory and simple chemometric applications*, „Analytica Chimica Acta" 2009, nr 648, s. 45–51.
[6] N. Marwan *et al.*, *op. cit*.

$$UCR_{ij}^{g} \coloneqq \left\| T_g(i) - T'_g(j) \right\|_2,$$

gdzie $\|\cdot\|_2$ to norma *euklidesowa*, a $T'_g(j)$ to j-ty wyraz pierwszej dyskretnej pochodnej T'_g szeregu temporalnego T_g. Macierz UR^g to symetryczna względem głównej przekątnej macierz kwadratowa o wymiarach $n \times n$, natomiast macierz UCR^g to prostokątna macierz o wymiarach $n \times (n-1)$[7].

2. W drugim kroku wyrazy otrzymanych macierzy, tj. UR_{ij}^{g} oraz UCR_{ij}^{g}, transformujemy według zależności[8]:

$$TUR_{ij}^{g} \coloneqq e^{-UR_{ij}^{g}}$$

oraz

$$TUCR_{ij}^{g} \coloneqq e^{-UCR_{ij}^{g}}$$

otrzymując transformowaną bezprogową macierz rekurencyjną (ang. *transformed unthresholded recurrence matrix*) TUR^g oraz jej krzyżową wersję (ang. *transformed unthresholded cross-recurrence matrix*) $TUCR^g$.

3. W trzecim kroku zapisujemy macierze TUR^g oraz $TUCR^g$ w formie kolumnowej[9]:

$$TUR^{g} = \begin{bmatrix} TUR_{11}^{g} & TUR_{12}^{g} & \dots & TUR_{1n}^{g} \\ TUR_{21}^{g} & TUR_{22}^{g} & \dots & TUR_{2n}^{g} \\ \cdots & \dots & \ddots & \dots \\ \dots & \dots & \ddots & \dots \\ TUR_{n1}^{g} & TUR_{n2}^{g} & \dots & TUR_{nn}^{g} \end{bmatrix} = \left[TUR_{\cdot 1}^{g}, TUR_{\cdot 2}^{g}, \dots, TUR_{\cdot n}^{g} \right]$$

oraz

[7] Przypomnijmy, iż macierze rekurencyjne (progowe lub bezprogowe) zawsze są symetrycznymi macierzami kwadratowymi, mającymi na celu porównywanie odległości pomiędzy wyrazami tego samego szeregu czasowego. Natomiast, krzyżowe macierze rekurencyjne progowe lub bezprogowe zawsze służą do porównywania odległości pomiędzy wyrazami dwóch różnych szeregów czasowych i tylko w wyjątkowych przypadkach, gdy długości obu szeregów są równe, są one kwadratowe. Por. *Ibidem*. Bezprogowe krzyżowe macierze rekurencyjne prównujące odległości pomiędzy wyrazami oryginalnego (wejściowego) szeregu czasowego i jego pierwszej dyskretnej pochodnej rozpatrywane były w: P. Wilczek, *An application of the local binary pattern algorithm and its uniform variant to improve the recurrence and cross-recurrence quantification analyses of the pharmacologically important time series* [w:] *Recent Advances in Computational Oncology and Personalized Medicine*. *Vol. 2. The Challenges of the Future !*, red. K. Krukiewicz, M. Marczyk, M. Bugdol, S. Bajkacz, Z. Ostrowski, Gliwice 2022, s. 128–152.

[8] D. Eroglu, T. K. DM. Peron, N. Marwan, F. A. Rodigues, L. da F. Costa, M. Sebek, I. Z. Kiss, J. Kurths, *Entropy of weighted recurrence plots*, „Physical Review E" 2014, nr 90, s. 042919.

[9] Por. formuły 3 i 4 w R. Todeschini *et al.*, *op. cit*.

$$TUCR^g = \begin{bmatrix} TUCR_{11}^g & TUCR_{12}^g & \dots & TUCR_{1(n-1)}^g \\ TUCR_{21}^g & TUCR_{22}^g & \dots & TUCR_{2(n-1)}^g \\ \dots & \dots & \ddots & \dots \\ \dots & \dots & \ddots & \dots \\ TUCR_{n1}^g & TUCR_{n2}^g & \dots & TUCR_{n(n-1)}^g \end{bmatrix} = \left[TUCR_{\cdot 1}^g, TUCR_{\cdot 2}^g, \dots, TUCR_{\cdot (n-1)}^g \right].$$

W powyższym zapisie symbole $TUR_{\cdot i}^g$ oraz $TUCR_{\cdot i}^g$ oznaczają i-tą kolumnę, odpowiednio macierzy TUR^g oraz macierzy $TUCR^g$.

4. W czwartym kroku obliczamy macierz współczynników korelacji Pearsona r pomiędzy dwiema macierzami TUR^g oraz TUR^h, odpowiadającymi dwóm szeregom czasowym $T_g, T_h \in \boldsymbol{T}$, pomiędzy którymi chcemy obliczyć odległość rekurencyjno-kanoniczną, lub pomiędzy dwiema macierzami $TUCR^g$ oraz $TUCR^h$, odpowiadającymi dwóm szeregom czasowym $T_g, T_h \in \boldsymbol{T}$, pomiędzy którymi chcemy obliczyć krzyżową odległość rekurencyjno-kanoniczną. W pierwszym przypadku macierz korelacji oznaczona jest przez r_{TUR^g,TUR^h}, a w drugim przez $r_{TUCR^g,TUCR^h}$. Mają one postać:

$$r_{TUR^g,TUR^h} = \begin{bmatrix} r\left(TUR_{\cdot 1}^g, TUR_{\cdot 1}^h\right) & r\left(TUR_{\cdot 1}^g, TUR_{\cdot 2}^h\right) & \dots & r\left(TUR_{\cdot 1}^g, TUR_{\cdot n}^h\right) \\ r\left(TUR_{\cdot 2}^g, TUR_{\cdot 1}^h\right) & r\left(TUR_{\cdot 2}^g, TUR_{\cdot 2}^h\right) & \dots & r\left(TUR_{\cdot 2}^g, TUR_{\cdot n}^h\right) \\ \dots & \dots & \ddots & \dots \\ \dots & \dots & \ddots & \dots \\ r\left(TUR_{\cdot n}^g, TUR_{\cdot 1}^h\right) & r\left(TUR_{\cdot n}^g, TUR_{\cdot 2}^h\right) & \dots & r\left(TUR_{\cdot n}^g, TUR_{\cdot n}^h\right) \end{bmatrix}$$

oraz

$$r_{TUCR^g,TUCR^h} = \begin{bmatrix} r\left(TUCR_{\cdot 1}^g, TUCR_{\cdot 1}^h\right) & r\left(TUCR_{\cdot 1}^g, TUCR_{\cdot 2}^h\right) & \dots & r\left(TUCR_{\cdot 1}^g, TUCR_{\cdot (n-1)}^h\right) \\ r\left(TUCR_{\cdot 2}^g, TUCR_{\cdot 1}^h\right) & r\left(TUCR_{\cdot 2}^g, TUCR_{\cdot 2}^h\right) & \dots & r\left(TUCR_{\cdot 2}^g, TUCR_{\cdot (n-1)}^h\right) \\ \dots & \dots & \ddots & \dots \\ \dots & \dots & \ddots & \dots \\ r\left(TUCR_{\cdot (n-1)}^g, TUCR_{\cdot 1}^h\right) & r\left(TUCR_{\cdot (n-1)}^g, TUCR_{\cdot 2}^h\right) & \dots & r\left(TUCR_{\cdot (n-1)}^g, TUCR_{\cdot (n-1)}^h\right) \end{bmatrix}.$$

Wyraz na pozycji (i, j) macierzy r_{TUR^g,TUR^h} to współczynnik korelacji liniowej Pearsona pomiędzy i-tą kolumną macierzy TUR^g a j-tą kolumną macierzy TUR^h. A więc w ogólnym przypadku ma on postać $r\left(TUR_{\cdot i}^g, TUR_{\cdot j}^h\right)$[10]. Ponieważ obie macierze mają n kolumn, macierz r_{TUR^g,TUR^h} ma wymiary $n \times n$. Podobnie, wyraz na pozycji (i, j) macierzy $r_{TUCR^g,TUCR^h}$

[10] Por. formuła 5 w *Ibidem*.

to współczynnik korelacji liniowej Pearsona pomiędzy i-tą kolumną macierzy $TUCR^g$ a j-tą kolumną macierzy $TUCR^h$. Wtedy ma on postać $r\left(TUCR^g_{\cdot i}, TUCR^h_{\cdot j}\right)$. Ponieważ obie macierze mają $n-1$ kolumn, macierz ich współczynników korelacji $r_{TUCR^g,TUCR^h}$ ma wymiary $(n-1)\times(n-1)$. Zauważmy, iż w ogólnym przypadku $r_{A,B} \neq r_{B,A}$, gdzie A oraz B to dowolne macierze mające równą ilość rzędów.

5. W piątym kroku obie macierze współczynników korelacji liniowych są symetryzowane względem głównej przekątnej za pomocą mnożenia macierzowego[11]:

$$Q_{RCMD} = r_{TUR^g,TUR^h} \times r_{TUR^h,TUR^g}$$

lub

$$Q^*_{RCMD} = r_{TUR^h,TUR^g} \times r_{TUR^g,TUR^h},$$

gdzie $\left(r_{TUR^g,TUR^h}\right)^T = r_{TUR^h,TUR^g}$

oraz

$$Q_{CRCMD} = r_{TUCR^g,TUCR^h} \times r_{TUCR^h,TUCR^g}$$

lub

$$Q^*_{CRCMD} = r_{TUCR^h,TUCR^g} \times r_{TUCR^g,TUCR^h},$$

gdzie $\left(r_{TUCR^g,TUCR^h}\right)^T = r_{TUCR^h,TUCR^g}$. Działanie $(\cdot)^T$ to transpozycja macierzowa. Macierze produktowe Q_{RCMD} oraz Q^*_{RCMD} mają wymiary $n \times n$, natomiast macierze Q_{CRCMD} oraz Q^*_{CRCMD} mają wymiary $(n-1)\times(n-1)$.

6. W szóstym kroku obliczmy wartości własne macierzy produktowych Q_{RCMD} (lub Q^*_{RCMD}) oraz Q_{CRCMD} (lub Q^*_{CRCMD}). Macierz produktowa Q_{RCMD} ma takie same niezerowe wartości własne jak macierz Q^*_{RCMD}. Podobnie, macierz produktowa Q_{CRCMD} ma takie same niezerowe wartości własne jak macierz Q^*_{CRCMD}.

7. W siódmym kroku obliczamy wartości odległości rekurencyjno-kanonicznej pomiędzy szeregami czasowymi $T_g, T_h \in \boldsymbol{T}$ według wzoru[12]:

[11] Por. Formuła 6 w *Ibidem*.

[12] W oryginalnej pracy Todeschiniego i współautorów kanoniczna miara odległości $CMD(A,B)$ pomiędzy dwoma wielowymiarowymi zbiorami danych A i B wyrażona jest formułą: $CMD(A,B) \coloneqq p_A + p_B - 2\sum_j^k \sqrt{\lambda_j}$, gdzie p_A oraz p_B to, odpowiednio liczba zmiennych (kolumn) w zbiorze A i w zbiorze B, λ_i to wartości własne

$$RCMD(T_g, T_h) \coloneqq 2n - 2\sum_{j=1}^{k}\sqrt{\lambda_j^{RCMD}},$$

gdzie n to długość obu szeregów, λ_j^{RCMD} to wartości własne macierzy Q_{RCMD} (lub Q_{RCMD}^*), a indeks k równy jest ilości niezerowych wartości własnych λ_j^{RCMD}. Przy tych założeniach zachodzi, iż dla dowolnych $T_g, T_h \in \boldsymbol{T}$, $0 \leq RCMD(T_g, T_h) \leq 2n$. Z kolei krzyżowa odległość rekurencyjno-kanoniczna pomiędzy szeregami $T_g, T_h \in \boldsymbol{T}$ dana jest zależnością:

$$CRCMD(T_g, T_h) \coloneqq 2(n-1) - 2\sum_{j=1}^{k}\sqrt{\lambda_j^{CRCMD}},$$

gdzie n to długość obu szeregów, λ_j^{CRCMD} to wartości własne macierzy Q_{CRCMD} (lub Q_{CRCMD}^*), a indeks k równy jest ilości niezerowych wartości własnych λ_j^{CRCMD}. W tym przypadku zachodzi, iż dla dowolnych $T_g, T_h \in \boldsymbol{T}$, $0 \leq CRCMD(T_g, T_h) \leq 2(n-1)$.

Aby zilustrować powyższy algorytm, rozpatrzmy dwa czteroelementowe szeregi czasowe T_1 oraz T_2, tj. $T_1 = \langle 1, 3, 8, 5\rangle$ oraz $T_2 = \langle 2, 0, 9, 7\rangle$. Ich bezprogowe macierze rekurencyjne oraz ich transponowane formy mają postać:

$$UR^1 = \begin{bmatrix} 0 & 2 & 7 & 4 \\ 2 & 0 & 5 & 2 \\ 7 & 5 & 0 & 3 \\ 4 & 2 & 3 & 0 \end{bmatrix}, UR^2 = \begin{bmatrix} 0 & 2 & 7 & 5 \\ 2 & 0 & 9 & 7 \\ 7 & 9 & 0 & 2 \\ 5 & 7 & 2 & 0 \end{bmatrix}$$

oraz

$$TUR^1 = \begin{bmatrix} 1 & 0{,}1353 & 0{,}0009 & 0{,}0183 \\ 0{,}1353 & 1 & 0{,}0067 & 0{,}1353 \\ 0{,}0009 & 0{,}0067 & 1 & 0{,}0498 \\ 0{,}0183 & 0{,}1353 & 0{,}0498 & 1 \end{bmatrix},$$

$$TUR^2 = \begin{bmatrix} 1 & 0{,}1353 & 0{,}0009 & 0{,}0067 \\ 0{,}1353 & 1 & 0{,}0001 & 0{,}0009 \\ 0{,}0009 & 0{,}0001 & 1 & 0{,}1353 \\ 0{,}0067 & 0{,}0009 & 0{,}1353 & 1 \end{bmatrix}.$$

Z kolei macierze korelacji liniowych Pearsona mają postać:

odpowiednich macierzy produktowych, a indeks k równy jest ilości niezerowych wartości własnych λ_i. Por. formuła 7 w *Ibidem*.

$$r_{TUR^1,TUR^2} = \begin{bmatrix} 0{,}9999 & -0{,}083 & -0{,}4688 & -0{,}4424 \\ -0{,}1417 & 0{,}9913 & -0{,}5105 & -0{,}3441 \\ -0{,}4229 & -0{,}4137 & 0{,}9961 & -0{,}1655 \\ -0{,}445 & -0{,}3001 & -0{,}2315 & 0{,}9821 \end{bmatrix}$$

oraz

$$\left(r_{TUR^1,TUR^2}\right)^T = r_{TUR^2,TUR^1} = \begin{bmatrix} 0{,}9999 & -0{,}1417 & -0{,}4229 & -0{,}445 \\ -0{,}083 & 0{,}9913 & -0{,}4137 & -0{,}3001 \\ -0{,}4688 & -0{,}5105 & 0{,}9961 & -0{,}2315 \\ -0{,}4424 & -0{,}3441 & -0{,}1655 & 0{,}9821 \end{bmatrix}$$

Obie macierze produktowe dane są poniżej:

$$Q_{RCMD} = r_{TUR^1,TUR^2} \times r_{TUR^2,TUR^1} = \begin{bmatrix} 1{,}4223 & 0{,}1676 & -0{,}7823 & -0{,}746 \\ 0{,}1676 & 1{,}3819 & -0{,}8018 & -0{,}4542 \\ -0{,}7823 & -0{,}8018 & 1{,}3696 & -0{,}0808 \\ -0{,}746 & -0{,}4542 & -0{,}0808 & 1{,}3061 \end{bmatrix}$$

oraz

$$Q^*_{RCMD} = r_{TUR^2,TUR^1} \times r_{TUR^1,TUR^2} = \begin{bmatrix} 1{,}3968 & 0{,}0851 & -0{,}7147 & -0{,}7606 \\ 0{,}0851 & 1{,}2509 & -0{,}8099 & -0{,}5306 \\ -0{,}7147 & -0{,}8099 & 1{,}5262 & -0{,}0091 \\ -0{,}7606 & -0{,}5306 & -0{,}0091 & 1{,}306 \end{bmatrix}$$

Wartości własne obu macierzy produktowych Q_{RCMD} oraz Q^*_{RCMD} są równe 2,838209; 1,513631; 1,128044; 0. Trzy pierwsze z nich służą do obliczenia wartości odległości $RCMD(T_1, T_2)$. Wynosi ona 0,04582047. Odległość $CRCMD(T_1, T_2)$ obliczana jest w sposób podobny. Wynosi ona 2,256611.

Nowo zaproponowane protokoły obliczania odległości pomiędzy danymi temporalnymi będą testowane w przykładowych zadaniach klasyfikacyjnych w części czwartej poniższej pracy. Przypomnijmy, iż dla kolekcji $\boldsymbol{T} = \{T_g\}_{g=1}^{m}$ szeregów czasowych i dyskretnego wektora ich etykiet $\boldsymbol{C}$ (w naszym przypadku jest to wektor binarny) zagadnienie klasyfikacji polega na aproksymacji funkcji o postaci: $c: \boldsymbol{T} \rightarrow \boldsymbol{C}$ (gdzie $c(T_g) = C^{T_g}$ dla $\forall T_g \in \boldsymbol{T}$) funkcją $\hat{c}: \boldsymbol{T} \rightarrow \boldsymbol{C}$, tak aby spełniony był warunek: $\hat{c}(T_g) = C^{T_g}$ dla $\forall T_g \in \boldsymbol{T}$. Funkcja c to klasyfikator aprioryczny (ang. *predefined*), natomiast funkcja $\hat{c}$ to klasyfikator aposterioryczny[13]. A więc, jeżeli:

[13] Oczywiście pojęcia klasyfikatora apriorycznego oraz aposteriorycznego mają sens tylko w odniesieniu do klasyfikacji formalnej (matematycznej). Oznacza to, iż chociaż elementy dyskretnego wektora etykiet C mogły zostać przyporządkowane poszczególnym danym temporalnym na podstawie procedur empirycznych, to podczas

$c(T_g) = \hat{c}(T_g)$ dla $\forall T_g \in \boldsymbol{T}$, to mówimy, że klasyfikator aposterioryczny w pełni (perfekcyjnie, doskonale) aproksymuje klasyfikator aposterioryczny. Natomiast jeżeli tylko dla większości $T_g \in \boldsymbol{T}$ zachodzi warunek $c(T_g) = \hat{c}(T_g)$, to mówimy, iż klasyfikator aposterioryczny tylko częściowo przybliża klasyfikator aprioryczny. Problem klasyfikacji polega na znalezieniu jak najdokładniejszego klasyfikatora aposteriorycznego. Tym samym wydajność klasyfikatora aposteriorycznego może być mierzona w procentach poprawnie sklasyfikowanych szeregów czasowych w analizowanym temporalnym zbiorze danych. Postępując zgodnie z sugestią Eamonna Keogha oraz ShrutiKasetty[14], w części czwartej poniższej pracy nowo zaproponowane funkcje odległości pomiędzy danymi temporalnymi będą testowane przez pryzmat klasycznego klasyfikatora jednego najbliższego sąsiada (ang. *1-nearest neighbor classifier* (1NN)) na 27 przykładowych farmakokinetycznych zbiorach danych.

4. Porównawcze algorytmy obliczania odległości pomiędzy szeregami czasowymi

Zgodnie z ogólnie przyjętą metodologią walidacji nowo zaproponowanych miar odległości pomiędzy danymi temporalnymi[15] w części czwartej prezentowanej pracy porównamy efektywność nowych technik klasyfikacji szeregów czasowych z efektywnością technik bazujących na klasycznych miarach odległości oraz na niedawno wprowadzonych funkcjach odległości. Mianowicie, wydajność w przykładowych zadaniach klasyfikacyjnych nowych algorytmów będzie porównana z wydajnością algorytmu euklidesowego ($L2$), jego trzech modyfikacji ($DL2$, $PDL2$ oraz $CIL2$), algorytmu DTW oraz jego trzech ulepszeń ($DDTW$, $PDDTW$ oraz $CIDTW$). Przypomnijmy, iż dla dwóch szeregów czasowych T_g oraz T_h, których wyrazy indeksowane są tym samym zbiorem I, algorytm euklidesowy ma postać $L2(T_g, T_h) \coloneqq \sqrt{\sum_{i=1}^{n}\left[T_g(i) - T_h(i)\right]^2}$. Z kolei miara DTW obliczana jest według procedury zaimplementowanej w pakietach obliczeniowych języka *R*, tj. w pakietach *dtw*[16] oraz *TSdist*[17]. Dla dwóch szeregów czasowych T_g oraz T_h, których wyrazy indeksowane są tym samym zbiorem I, niech $M(T_g, T_h)$ będzie kwadratową $n \times n$ dodatnią macierzą odległości (tzw.

matematycznego procesu klasyfikacji owo przyporządkowanie jest czymś z góry ustalonym (ang. *predefined*), a więc z wewnętrznego punktu widzenia klasyfikacji formalnej jest to przyporządkowanie aprioryczne.

[14] E. Keogh, S. Kasetty, *On the need for time series data mining benchmarks: a survey and empirical demonstration* [w:] *Proceedings of the eight ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, New York 2002, s. 102–111.

[15] *Ibidem*, a także P. Wilczek, *op. cit.*

[16] T. Giorgino, *Computing and visualizing dynamic time warping alignments in R: The dtw package*, „Journal of Statistical Software" 2009, nr (7), s. 1–24.

[17] U. Mori, A. Mendiburu, J. A. Lozano, *Distance measures for time series in R: The TSdist Package*, „The R Journal" 2016, nr 2, s. 451–459.

macierzą kosztów lokalnych), której wyraz M_{ij} dany jest zależnością: $M_{ij} \coloneqq \left|T_g(i) - T_g(j)\right|$. Wtedy tak zwana krzywa (ang. *warping path*) P o postaci: $P \coloneqq [(e_1, f_1), (e_2, f_2), \dots, (e_i, f_i), \dots, (e_s, f_s)]$ to ciąg punktów (tj. par indeksów) definiujących trawersalę macierzy $M(T_g, T_h)$. W definicji odległości DTW zakładamy, iż krzywa P musi spełniać następujące warunki: $(e_1, f_1) = M_{11}$ oraz $(e_s, f_s) = M_{nn}$, jak również $0 \leq e_{i+1} - e_i \leq 1$ oraz $0 \leq f_{i+1} - f_i \leq 1$ dla $\forall i < n$. A więc krzywa P to ścieżka biegnąca od elementu M_{11} macierzy $M(T_g, T_h)$ do elementu M_{nn} tejże macierzy, przy czym przy przejściu od wyrazu M_{11} do wyrazu M_{nn} dozwolone są tylko kroki: (0,1), (1,0) oraz (1,1). Niech $p_i = \gamma M_{e_i f_i}$ będzie odległością globalną (tj. kumulacyjną) pomiędzy elementem w pozycji e_i szeregu T_g a elementem w pozycji f_i szeregu T_h dla i-tej pary punktów (tj. indeksów) na krzywej P. Wtedy odległość pomiędzy szeregami czasowymi T_g i T_h wzdłuż krzywej P, D_P, dana jest zależnością $D_P(T_g, T_h) \coloneqq \sum_{i=1}^{s} p_i$. Niech $\mathcal{P}$ będzie przestrzenią wszystkich możliwych krzywych P. Wtedy ścieżka DTW, P^*, to krzywa minimalizująca odległość D_P, tj. $P^* \coloneqq \min_{P \in \mathcal{P}} D_P(T_g, T_h)$. Odległość DTW pomiędzy dwoma ciągami temporalnymi T_g oraz T_h to odległość wzdłuż ścieżki P^*[18]. Można ją znaleźć za pomocą procedur programowania dynamicznego[19] na podstawie następującego warunku rekurencyjnego, umożliwiającego obliczenie globalnej odległości $\gamma M_{e_i f_i}$ pomiędzy elementami szeregów T_g oraz T_h na podstawie znajomości wartości kosztów lokalnych: $\gamma M_{e_1 f_1} = M_{11}$ oraz dla $i, j \neq 1$ $\gamma M_{e_i f_i} = M_{ij} + \min\{\gamma M_{e_{i-1} f_{i-1}}, \gamma M_{e_{i-1} f_i}, \gamma M_{e_i f_{i-1}}\}$. A więc obliczenie kumulacyjne odległości $\gamma M_{e_i f_i}$ pomiędzy elementem w pozycji e_i szeregu T_g a elementem w pozycji f_i szeregu T_h dla i-tej pary indeksów na krzywej P redukuje się do znajomości odległości lokalnej bieżącego elementu M_{ij} oraz kumulacyjnych odległości elementów przyległych (ang. *adjacent*), tj. odległości $\gamma M_{e_{i-1} f_{i-1}}$, $\gamma M_{e_{i-1} f_i}$ oraz $\gamma M_{e_i f_{i-1}}$. Dla dwóch szeregów czasowych T_g oraz T_h, których wyrazy indeksowane są tym samym zbiorem I, oraz funkcji $DF \in \{L2, DTW\}$, tzw. algorytm odległości pochodnej DDF ma postać $DDF(T_g, T_h) \coloneqq DF(T_g', T_h')$, gdzie T_g' oraz T_h'

[18] D. J. Berndt, J. Clifford, *Using dynamic time warping to find patterns in time series* [w:] *Proceedings of the 3rd International Conference on Knowledge Discovery and Data Mining*, 1994, s. 359–370.

[19] Wyczerpujące informacje na temat procedur programowania dynamicznego czytelnik znajdzie w następujących pozycjach: T. Giorgino, *op. cit*., E. Keogh, C. A. Ratanamahatana, *Exact indexing of dynamic time warping*, „Knowledge and Information Systems" 2005, nr 7, s. 358–386, L. Rabiner, B.–H. Juang, *Fundamentals of Speech Recognition*, New Jersey 1993, D. Sankoff, J. Kruskal, *Time Warps, String Edits, and Macromolecules. The Theory and Practice of Sequence Comparison*, Stanford 1999.

to pierwsze dyskretne pochodne szeregów T_g i T_h[20]. Z kolei dla dwóch szeregów czasowych T_g oraz T_h, których wyrazy indeksowane są tym samym zbiorem I, oraz funkcji $DF \in \{L2, DTW\}$, tzw. algorytm pochodnej odległości parametrycznej $PDDF$ to ważona wypukła kombinacja o postaci $PDDF(T_g, T_h) \coloneqq aDF(T_g, T_h) + bDDF(T_g, T_h)$, gdzie DDF to algorytm odległości pochodnej oraz $b = 1 - a$, gdzie $a \in [0,1]$ to parametry rzeczywiste[21]. W części czwartej poniższej pracy algorytm $PDDF$ obliczany jest względem parametrów równych: $a = b = cos\alpha = sin\alpha = 0{,}7071068$, gdzie $\alpha = \frac{\frac{\pi}{2}}{2}$. Natomiast dla dwóch szeregów czasowych T_g oraz T_h, których wyrazy indeksowane są tym samym zbiorem I, oraz funkcji $DF \in \{L2, DTW\}$, tzw. algorytm niezmienniczy ze względu na złożoność szeregów czasowych (ang. *complexity-invariant*) ma postać $CIDF(T_g, T_h) \coloneqq DF(T_g, T_h) \times CF(T_g, T_h)$, gdzie $CF(T_g, T_h)$ to tzw. czynnik korygujący złożoność (ang. *complexity correction factor*), obliczany dla T_g oraz T_h według zależności: $CF(T_g, T_h) \coloneqq \frac{max\{CE(T_g), CE(T_h)\}}{min\{CE(T_g), CE(T_h)\}}$. W powyższej zależności $CE(T)$ (dla $T \in \{T_g, T_h\}$) to tzw. wyznacznik złożoności (ang. *complexity estimate*) szeregu T. Ma on postać: $CE(T) \coloneqq \sqrt{\sum_{i=1}^{n-1}[T(i) - T(i-1)]^2}$ dla $i = 1, 2, \dots, n - 1$[22].

5. Materiały i metody

Nowo zaproponowane algorytmy obliczania funkcji odległości pomiędzy szeregami czasowymi zostaną przetestowane na części publicznie dostępnego zbioru danych HTS007[23]. Zbiór ten został wygenerowany w laboratorium *High Throughput Screening* Uniwersytetu Vanderbilta[24]. Obejmuje on pięciodniowe pomiary proliferacji komórek przeprowadzone na 8 liniach komórkowych (BT20, HCC1143, MCF10A-HMS, MCF10A-VU, MDAMB231, MDAMB453, MDAMB468 oraz SUM149) traktowanych 27 lekami przeciwnowotworowymi o różnym stężeniu (próba testowa) oraz nietraktowanych żadnym lekiem (próba kontrolna). Do naszych symulacji komputerowych użyliśmy tylko szeregów czasowych, będących wynikami

[20] E. J. Keogh, M. J. Pazzani, *Dynamic time warping with higher order features* [w:] *Proceedings of the 2001 SIAM International Conference on Data Mining*, red. V. Kumar, R. Grossman, 2001, s. 1–11.
[21] T. Górecki, M. Łuczak, *Using derivatives in time series classification*, „Data Mining and Knowledge Discovery" 2013, nr 2, s. 310–331.
[22] G. E. A. P. A. Batista, X. Wang, E. J. Keogh, *A complexity-invariant distance measure for time series* [w:] *Proceedings of the 2011 SIAM International Conference on Data Mining*, red. B. Liu, H. Liu, C. Clifton, T. Washio, C. Kamath, 2011, s. 699–710.
[23] Thunor, https://www.thunor.net, (on-line 16.02.2024).
[24] A. L. R. Lubbock, L. A. Harris, V. Quaranta, D. R. Tyson, C. F. Lopez, *Thunor: visualization and analysis of high-throughput dose-response datasets*, „Nucleic Acids Research" 2021, nr 46, s. w633–w640.

pomiarów przeprowadzonych na linii BT20. Nazwy poszczególnych zbiorów danych pomiarowych odpowiadają nazwą leków testowanych na komórkach, których te pomiary dotyczą. Są one wyszczególnione w Tabeli 1. Kolumny Test oraz Kontrola odpowiadają kolejno liczbie testowych oraz kontrolnych szeregów czasowych w każdym ze zbiorów danych.

Lp.	***TD***	Test	Kontrola	Lp.	***TD***	Test	Kontrola
1	Abemaciclib	20	31	15	Neratinib	15	31
2	Alpelisib	15	31	16	Osimertinib	20	31
3	Azd7762	20	31	17	Paclitaxel	20	31
4	Bleomycin	20	31	18	Palbociclib	17	31
5	Buparlisib	19	31	19	Panobinostat	19	31
6	Cediranib	17	31	20	Pictilisib	17	31
7	Certitinib	19	31	21	Saracatinib	17	31
8	Dasatinib	17	31	22	Taselisib	20	31
9	Doxorubicin	20	31	23	Tivantinib	19	31
10	Etoposide	19	31	24	Torin2	20	31
11	Everolimus	19	31	25	Trametinib	16	31
12	Ink128	15	31	26	Volasertib	20	31
13	Ipatasertib	18	31	27	Vorinostat	19	31
14	Luminespib	20	31				

Tab. 1 Przykładowe farmakokinetyczne zbiory danych ze zbioru HTS007

Każdy z 27 pojedynczych zbiorów danych składa się z 31 dwudziestoczteroelementowych kontrolnych szeregów czasowych oraz z od 15 do 20 (por. Tabela 1) dwudziestoczteroelementowych testowych szeregów czasowych. Tym samym każdy zbiór danych ma dwie etykiety: 1/ kontrola oraz 2/ test. Wszystkie obliczenia zostały wykonane w języku programowania R oraz w jego pakietach[25].

[25] T. Giorgino *op. cit*., U. Mori *et al.*, *op. cit*., R Core Team, *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna 2022, https://www.R-project.org/ (on-line 16.02.2024), W. N. Venables, B. D. Ripley, *Modern Applied Statistics with S*, New York 2002.

6. Wyniki

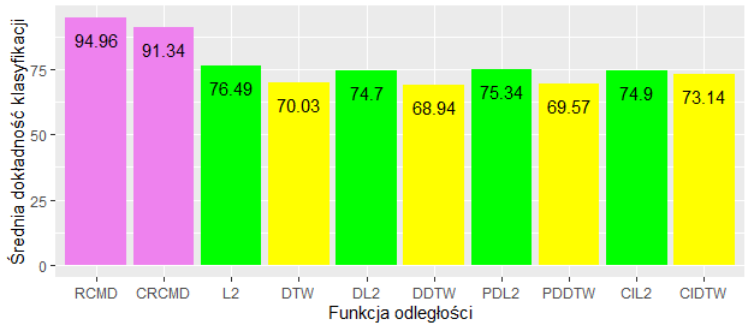
Tabela 2 zawiera wyniki analizy porównawczej wydajności algorytmów klasyfikacyjnych opartych na nowo zaproponowanych funkcjach odległości, tj. na funkcjach $RCMD$ oraz $CRCMD$, jak również na referencyjnych miarach typu $L2$ (tj. miarach $L2$, $DL2$, $PDL2$ oraz $CIL2$) oraz typu DTW (tj. miarach DTW, $DDTW$, $PDDTW$ oraz $CIDTW$). Wykres na Rycinie 1 podsumowuje wyniki z Tabeli 2. Dane te jednoznacznie wskazują, iż w 96,3% pomiarów efektywność techniki $RCMD$ jest równa lub wyższa niż 90% poprawnie sklasyfikowanych szeregów czasowych w każdym zbiorze danych. Natomiast, skuteczność techniki $CRCMD$ jest równa lub wyższa niż 90% poprawnie sklasyfikowanych szeregów w 66,67% testowanych przypadków. Z drugiej strony, na podstawie danych z Tabeli 2 można wywnioskować, iż efektywność technik typu $L2$ jest równa lub wyższa niż 90% tylko w 13,89% dokonanych pomiarów. Z kolei wydajność technik typu DTW jest równa lub wyższa niż 90% poprawnie sklasyfikowanych szeregów tylko w 5,56 % przeprowadzonych symulacji.

TD	*RCMD*	*CRCMD*	*L2*	*DTW*	*DL2*	*DDTW*	*PDL2*	*PDDTW*	*CIL2*	*CIDTW*
1	**90,2**	**92,16**	68,63	64,71	70,59	58,82	74,51	62,75	68,63	74,51
2	**97,83**	**91,3**	69,57	58,7	63,04	58,7	63,04	56,52	69,57	58,7
3	**100**	**96,08**	68,63	62,75	66,67	50,98	68,63	64,71	58,82	64,71
4	**96,08**	**96,08**	72,55	56,86	49,02	60,78	60,78	52,94	68,63	66,67
5	**92**	88	68	58	80	56	64	50	62	74
6	**91,67**	87,5	83,33	70,83	66,67	70,83	75	68,75	70,83	66,67
7	**98**	**96**	66	58	66	64	62	64	64	70
8	**100**	85,42	85,42	81,25	83,33	62,5	85,42	79,17	83,33	87,5
9	**92,16**	88,24	72,55	78,43	72,55	68,63	72,55	74,51	68,63	76,47
10	**96**	**92**	68	68	64	62	68	62	72	54
11	**98**	**100**	**100**	**100**	**98**	**100**	**100**	**100**	**100**	**100**

12	**91,3**	**93,48**	**91,3**	89,13	**91,3**	89,13	**93,48**	89,13	89,13	93,48
13	**95,92**	**93,88**	79,59	63,27	75,51	53,06	69,39	63,27	73,47	63,27
14	**92,16**	84,31	68,63	74,51	84,31	76,47	72,55	72,55	70,59	62,75
15	**100**	**93,48**	73,91	50	80,43	65,22	76,09	60,87	71,74	56,52
16	**96,08**	**92,16**	72,55	68,63	64,71	66,67	74,51	74,51	78,43	74,51
17	80,39	**96,08**	**90,2**	84,31	82,35	86,27	**92,16**	80,39	**90,2**	82,35
18	**100**	**95,83**	83,33	68,75	66,67	56,25	77,08	70,83	77,08	72,92
19	**90**	78	72	68	82	72	74	66	70	74
20	**97,92**	**95,83**	68,75	62,5	68,75	60,42	66,67	66,67	66,67	72,92
21	**95,83**	89,58	66,67	58,33	75	68,75	68,75	60,42	66,67	58,33
22	**94,12**	88,24	72,55	52,94	68,63	70,59	70,59	50,98	66,67	50,98
23	**96**	**92**	72	74	70	78	74	72	80	88
24	**90,2**	78,43	80,39	78,43	80,39	68,63	80,39	68,63	78,43	74,51
25	**100**	**97,87**	76,6	72,34	80,85	74,47	74,47	76,6	76,6	80,85
26	**92,16**	**94,12**	**92,16**	88,24	**92,16**	**96,08**	**90,2**	88,24	**90,2**	**96,08**
27	**100**	**90**	82	80	74	66	86	82	**90**	80

Tab. 2 Procentowe wyniki klasyfikacji 27 farmakokinetycznych zbiorów danych

Ponadto dane zawarte w Tabeli 2 wskazują, iż algorytmy $RCMD$, $CRCMD$, typu $L2$ oraz typu DTW osiągają najlepsze wyniki spośród wszystkich analizowanych przypadków, odpowiednio w 81,48%, 18,52%, 3,7% oraz w 5,56% wykonanych pomiarów. Tak więc można stwierdzić, iż skuteczność nowo wprowadzonych algorytmów $RCMD$ oraz $CRCMD$ jest znacznie wyższa niż skuteczność metod bazujących na klasycznych miarach odległości $L2$, DTW oraz ich udoskonaleniach.



Ryc. 1. Wykres ilustrujący średnią procentową efektywność porównywanych funkcji odległości

Ściśle rzecz biorąc, zestawiając średnie wartości efektywności porównywanych protokołów klasyfikacyjnych, można stwierdzić, iż schemat $RCMD$ średnio przewyższa najlepszy schemat typu $L2$ (tj. algorytm $L2$) oraz typu DTW (tj. algorytm $CIDTW$) o odpowiednio, 19,45% oraz o 22,98% poprawnie sklasyfikowanych szeregów temporalnych (por. Ryc. 1). Natomiast drugi z nowo zaproponowanych protokołów, tj. protokół $CRCMD$, przewyższa średnio schematy $L2$ oraz $CIDTW$ o odpowiednio, 16,26% oraz o 19,93% poprawnie sklasyfikowanych ciągów czasowych (por. Ryc. 1).

7. Dyskusja

W swojej obszernej i ważnej pracy *The Elements of Statistical Learning. Data Mining, Inference, and Prediction*, Trevor Hastie, Robert Tibshirani oraz Jerome Friedman zauważają, iż „wyszczególnienie adekwatnej miary niepodobieństwa [pomiędzy analizowanymi obiektami – przyp. mój – P. W.] jest o wiele bardziej istotne w osiągnięciu sukcesu w procesie klasteryzacji niż wybór samego algorytmu analizy skupień. Ten aspekt problemu jest mniej podkreślany w literaturze poświęconej klasteryzacji, ponieważ aspekt ten zależy od specyficzności dziedziny przedmiotowej [poddawanej analizie skupień – przyp. mój – P.W.]

oraz jest mniej podatny na ogólne analizy”[26]. W naszej opinii te deklaracje, choć odnoszą się do zagadnienia „klasyfikacji bez nadzoru” (ang. *unsupervised learning*), mogą być uogólnione względem każdego rodzaju klasyfikacji, z włączeniem zagadnienia klasyfikacji szeregów czasowych. Dlatego też, aby poprawić efektywność znanych algorytmów klasyfikacji szeregów czasowych (np. algorytmu $L2$ lub DTW połączonych z klasyfikatorem $1NN$), zaproponowaliśmy nowe miary odległości pomiędzy danymi temporalnymi. Z przeprowadzonych symulacji komputerowych wynika, iż wydajność algorytmów klasyfikacji opartych na nowych bezparametrycznych funkcjach odległości jest znacznie wyższa niż wydajność protokołów opartych na funkcjach referencyjnych (np. na klasycznych miarach $L2$, DTW oraz na ich parametrycznych modyfikacjach). Rezultat ten wydaje się być bardzo istotny, ponieważ jak zauważają Tomasz Górecki oraz Maciej Łuczak „[…] prosta metoda łącząca klasyfikator jednego najbliższego sąsiada (1NN) oraz pewną formę miary odległości DTW okazała się być jedną z najwydajniejszych technik klasyfikacji szeregów czasowych. […]. Euklidesowa miara odległości ma kilka zalet. Mianowicie, złożoność wyznaczania tej metryki jest liniowa, jest ona łatwa do zaimplementowania, może być łączona z dowolnymi innymi metodami oraz jest bezparametryczna. […]. Zostało empirycznie dowiedzione, iż prosta Euklidesowa metryka odległości jest konkurencyjna lub lepsza względem wielu złożonych miar odległości oraz spełnia ważną nierówność trójkąta”[27]. Ci sami autorzy w dalszych częściach swojego tekstu twierdzą, iż „metryka odległości Euklidesowej jest najbardziej oczywistą miarą podobieństwa dla szeregów czasowych, natomiast miara DTW jest jedną z najbardziej wydajnych funkcji odległości dla danych temporalnych”[28]. Powyższe fragmenty zaczerpnięte z bieżącej literatury dotyczącej analizy i klasyfikacji szeregów czasowych mogą być bezpośrednio skonfrontowane z wynikami zamieszczonymi w Tabeli 2 oraz na Rycinie 1. Z postulowanego zestawienia można jednoznacznie wywnioskować, iż rezultaty uzyskane przez proponowany w naszej pracy rekurencyjno-kanoniczny schemat klasyfikacji oraz jego krzyżowa forma są kontrprzykładami względem stwierdzenia Góreckiego i Łuczaka, a także trudno jest znaleźć metodologię klasyfikacji danych temporalnych przewyższającą swoją skutecznością metodologię opartą na mierze DTW. Można zaznaczyć, że proponowany w tej pracy algorytm jest na tyle elastyczny, iż dzięki jego modyfikacjom można określić nowe rodziny miar odległości opartych na dyskretnych

[26] T. Hastie, R. Tibshirani, J. Friedman, *The Elements of Statistical Learning. Data Mining, Inference, and Prediction*, New York 2009, s. 506.
[27] T. Górecki, M. Łuczak, *Using*…, *op. cit.*, s. 311.
[28] *Ibidem*., s. 320.

pochodnych analizowanych szeregów czasowych. Np. dla szeregu czasowego T_g o długości n z rozpatrywanej kolekcji szeregów $\boldsymbol{T}$ można zdefiniować następujące oparte na pochodnych macierze rekurencyjne: $UR_{ij}^{(1)g} \coloneqq \left\|T_g'(i) - T_g'(j)\right\|_2$, $UR_{ij}^{(2)g} \coloneqq \left\|T_g''(i) - T_g''(j)\right\|_2$, gdzie T_g'' to druga dyskretna pochodna szeregu czasowego T_g[29] oraz następujące oparte na pochodnych krzyżowe macierze rekurencyjne: $UCR_{ij}^{(0,2)g} \coloneqq \left\|T_g(i) - T_g''(j)\right\|_2$ oraz $UCR_{ij}^{(1,2)g} \coloneqq \left\|T_g'(i) - T_g''(j)\right\|_2$[30]. Analizie tego typu 2D struktur poświęcona będzie oddzielna praca.

7. Uwagi końcowe

Podsumowując, można stwierdzić, iż cel przedkładanej pracy został osiągnięty, a nowe rekurencyjno-kanoniczne funkcje obliczania odległości pomiędzy danymi temporalnymi znajdą praktyczne zastosowanie w analizie i klasyfikacji danych farmakokinetycznych i tym samym przyczynią się do zwiększenia stopnia automatyzacji w badaniach podstawowych stosowanych.

Podziękowania: Autor powyższej pracy pragnie wyrazić podziękowania anonimowej recenzentce tekstu, której uwagi przyczyniły się do znacznego ulepszenia przedkładanej pracy.

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[29] Druga dyskretna pochodna T'' szeregu czasowego T o długości n to nowy szereg czasowy o długości $n-2$, będący pierwszą dyskretną pochodną pierwszej dyskretnej pochodnej T' wejściowego (oryginalnego) szeregu T.

[30] W powyższej notacji macierze z kroku pierwszego prezentowanego algorytmu to odpowiednio macierze $UR_{ij}^{(0)g}$ oraz $UCR_{ij}^{(0,1)g}$, gdyż wejściowy (oryginalny) szereg czasowy T_g może być traktowany jako swoja dyskretna zero-rzędowa pochodna.

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Will Chat GPT take our jobs? Discourse analysis on generative AI from the moral panic perspective

Czy Chat GPT zabierze nam pracę? Analiza dyskursu o generatywnych SI w perspektywie paniki moralnej

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Abstract: This article presents the results of discourse analysis conducted on three language corpora, *Polish Trends*, corpus of press texts, and corpus of tweets, exploring the topic of generative artificial intelligence, particularly ChatGPT. The aim of the investigation was to verify whether the Polish online discourse on AI could be characterised as a moral panic and whether the premises present in the discourse indicate active societal reflection on issues of trust in the technology itself and the content it generates. The analysis revealed that the discourse on AI involves moderate anxiety, which is reasonable – authors of the analysed articles and statements reflect on the real consequences of the popularisation of generative AI, including the issue of lack of adequate digital competencies to have a sense of control over it. This article emphasises the need to extend expert and academic reflections to a societal perspective, including awareness of the main threads and societal concerns raised at the level of discourse. This analysis gives a voice to society, underscoring the role of ordinary users in the assumptions of Trustworthy AI and building trust in new technologies, referring to Michael Foucault's concept of knowledge-power and Shoshana Zuboff's surveillance.

Streszczenie: Niniejszy artykuł prezentuje wyniki analizy dyskursu przeprowadzonej na trzech korpusach językowych – *Polish Trends*, korpusie tekstów prasowych i korpusie tweetów – eksplorując temat generatywnej sztucznej inteligencji, w szczególności Chatu GPT. Celem badania była weryfikacja, czy polski dyskurs internetowy na temat SI może być określany jako panika moralna, a także czy obecne w nim przesłanki wskazują na aktywną refleksję społeczną nad kwestiami zaufania wobec samej technologii, jak i wytwarzanych przez nią treści. Analiza wykazała, że w dyskursie o SI mamy do czynienia z umiarkowanym niepokojem, któremu nie brakuje podstaw – autorzy analizowanych artykułów oraz wypowiedzi zastanawiają się nad realnymi konsekwencjami popularyzacji generatywnych SI, w tym kwestią braku odpowiednich kompetencji cyfrowych, aby mieć nad nią poczucie kontroli. Artykuł ten akcentuje potrzebę rozszerzenia refleksji eksperckich i akademickich o perspektywę społeczną,

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w tym świadomość głównych wątków i obaw społecznych podnoszonych na poziomie dyskursu. Niniejsza analiza oddaje głos społeczeństwu, podkreślając rolę zwykłych użytkowników przy założeniach idei Trustworthy AI oraz w budowaniu zaufania do nowych technologii, odnosząc się do koncepcji wiedzy–władzy Michaela Foucault oraz kapitalizmu nadzoru Shoshany Zuboff.

Keywords: artificial intelligence, trust, moral panic, discourse analysis, corpus analysis

Słowa kluczowe: sztuczna inteligencja, zaufanie, panika moralna, analiza dyskursu, analiza korpusowa

1. Introduction

It is not difficult to notice that Artificial Intelligence (AI) is becoming increasingly popular and of interest both in the scientific and business communities, as well as in the perception of society at large. Conceptions of its operation, purpose, and potential are often the result of individual observations during interactions with AI-based software, deep reflection on technological transformations, or prevailing societal beliefs based on myths about AI constructed over several decades. It is easy to see that AI is spoken about differently and according to different criteria in universities, corporate environments, or everyday situations – differently expressed by technologists, programmers, sociologists, doctors, and even representatives of various age groups or generations, although these discourses may have their common narratives and repeatedly reproduced imaginings. Therefore, reflection on the discourse orientated around Artificial Intelligence cannot be limited solely to the scientific community, where within various disciplines issues of potential and risk associated with AI development are raised, neglecting how society or popular media construct the narrative about said technology – and whether they perceive it through a similar lens.

Although artificial intelligence might seem like a fresh topic, not broadly discussed until recently, the discourse regarding its usefulness and implementation dates back decades. In particular, in 1956, during the Dartmouth conference, McCarthy first coined the term artificial intelligence, aiming to define and establish a conceptual framework for discussing the implications and applications of this technology. At this conference, the LT programme, developed by Allen Newell, John Clifford Shaw, and Herbert Simon, was presented. This

programme had the capability to formulate proofs for logical theorems, indicating the potential integration of computer machinery with human-like intelligence[2]. According to McCarthy, AI involves the creation of intelligent computer programmes and machines designed to fulfil objectives in the real world[3]. However, it raises the question of whether the goals achieved or envisioned through AI are beneficial for society, in terms of both the end results and the methods employed. Research findings, particularly those concerning the widely-discussed ChatGPT, suggest that while AI has the potential to contribute to numerous commendable initiatives, it falls short in several fundamental aspects. A report by Polish researchers titled *ChatGPT: Jack of all trades, master of* none highlights how Chat GPT struggles with false information provided by users, often presuming its accuracy. The authors even tested the model's ability to detect irony and humour, finding instances where Chat GPT generated politically incorrect responses[4]. Other scholarly articles have criticised Chat GPT for making errors, fabricating bibliographies[5], or disseminating incorrect information about reality through various hallucinations[6], which are somewhat emblematic of large language models, based on unfounded responses[7].

Researchers Sonia Sousa, Jose Carvino and Paulo Martins highlight that recent waves of technological innovation, along with the dispersion of data and the appeal of behaviour prediction, have led to the rapid spread of AI-based software, generating outcomes in an automated and unpredictable manner, including not guaranteeing the truthfulness of the content, forecasts, or recommendations provided[8]. Furthermore, the researchers suggest that such models might prompt humanity to make incorrect decisions and to use them for malicious surveillance practices or disinformation. According to the researchers, the abundance of freely available generative AIs contributes particularly to initiating discussions among experts and

[2] B. G Buchanan, *A (Very) Brief History of Artificial Intelligence*, "AI Magazine" 2005 (4), p. 57.
[3] J. McCarthy, *What is Artificial Intelligence?*, Stanford 2007, https://www-formal.stanford.edu/jmc/whatisai.pdf (on-line 31.01.2024)
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legal professionals about trust in AI, raising the issue of regulations aimed at reducing user concerns and ensuring trust in the development of these technologies. One example of such software, also widely popular in Poland, is Chat GPT. Sousa, Carvino, and Martins emphasise the need to cultivate societal trust in artificial intelligence by promoting the concept of 'trustworthy AI'. Nevertheless, they also observe that European Union initiatives and legal debates primarily focus on countering excessive corporate surveillance and the emerging datafication. Thus, they aim to address issues related to AI itself, but not necessarily focusing adequately on understanding the impact of user trust on the use of these technologies and the consequent implications. It seems necessary, therefore, to pay attention to the users themselves, their attitudes and opinions on the use of open-source AI tools, including the issue of trust in the knowledge generated and the technology itself.

2. Ideas and definitions

Michel Foucault, a French philosopher and sociologist, developed a concept linking knowledge with power, arguing that they do not exist separately but together form a unity reflected in various social processes[9]. Knowledge-power is exercised within different institutions, being legitimised and reproduced through discourses that determine what is accepted as truth and what is rejected as false. Simultaneously, to wield power, one must understand the knowledge and control its truthfulness. This becomes particularly problematic in the context of the rapid development of surveillance capitalism, which Shoshana Zuboff describes as unprecedented[10]. This means that humanity, in response to such swift technological advancement, is unable to proactively prepare for its consequences, as it lacks experience with similar transformations and cannot refer to existing precedents – it lacks the knowledge that would enable control.

The discourse, as defined by Teun van Dijk, among others, is nothing but text in context, a certain form of language use behind which lie specific intentions and goals, the presentation of certain ideas[11]. Just as important as what is said (or written) is who speaks or writes down the content[12]. Paweł Śpiewak, in his ironic dictionary of trendy and untrendy

[9] M. Foucault, *Porządek dyskursu*, transl. M. Kozłowski, Gdańsk 2002.
[10] S. Zuboff, *Wiek kapitalizmu inwigilacji. Walka o przyszłość ludzkości na nowej granicy władzy*, trans. A. Unterschuetz, Poznań 2020.
[11] *Dyskurs jako struktura i proces*, T. van Dijk (ed.), Warszawa 2001, pp. 9–28.
[12] *Ibidem*.

words, describes discourse as "perhaps the most important word in common humanities"[13] noting that everyone is somehow participating in some discourse. The presence of new actors in the form of generative AIs in open access, responsive to posed questions and generating content, as well as the multitude of discussions about data flow, knowledge production, and trust, indicates the formation of new, complex digital dependencies and new challenges related to control, production, and interpretation of information. These dilemmas are faced not only by software creators and the academic community but also by ordinary people, users who talk with AI and also discuss AI. However, does the discourse generated by society consider the issue of knowledge and its veracity? Do technological innovations currently provoke a social stir?

The concept of moral panic was described in 1972 by Stanley Cohen in the book *Folk Devils and Moral Panics: The Creation of the Mods and Rockers*[14]. Cohen focuses on the mutual influence of the media and the public in response to previously unknown events or behaviours. Although the term moral panic refers to a sudden outbreak of discrimination and attributing all the worst to representatives of certain subcultures, this concept can be applied in the analysis of discourse on any new phenomenon that provokes social unrest and implies reactions. Cohen states that the cause of a moral panic can be conditions, episodes, individuals, or groups identified as a threat to societal values and interests. Furthermore, the components of a moral panic include: (1) simplification and stereotyping of individuals or the issue by the mass media, (2) the involvement of 'right-thinking' individuals (e.g., politicians, clergy, editors) in the defence of moral values, (3) the issuance of expertise and solutions by socially recognised experts, and (4) the development of solutions and ways to deal with the problem by society. A panic can pass and be forgotten or lead to serious and lasting consequences, including "changes in law and social policy or even in the way society perceives itself", which is definitely the case when addressing the issue of artificial intelligence[15].

The purpose of this article is to present the results of a study on the discourse of internet users and the press discourse centred around the topic of artificial intelligence, particularly ChatGPT itself, using corpus analysis. In the context of the reflections presented here, the research objective is to verify whether the Polish Internet discourse on AI can be described as

[13] P. Śpiewak, *Słowniczek słów modnych i niemodnych (w humanistyce)*, "ResPublica Nowa" 2002 (10), http://niniwa22.cba.pl/spiewak_slowniczek_slow_modnych_i_niemodnych.html (on-line 31.01.2024)
[14] S. Cohen, *Folk Devils and Moral Panics: The Creation of the Mods and Rockers*, London 1972.
[15] *Ibidem*.

moral panic and whether the premises present indicate an active reflection by users on issues of trust in AI itself, as well as the content it generates, verification of data truthfulness, and reflections related to the use of this technology – the risks and threats stemming from its open-source dimension. For these purposes, three language corpora were analysed, which are described in more detail in the methodological section. The results were then interpreted using Stanley Cohen's theory of moral panic, Michael Foucault's power-knowledge, and Shoshana Zuboff's surveillance capitalism, which enabled contextualisation and deepening of the answers to the research questions asked.

3. Research questions and adopted research methods

To adequately address the discussed issues, the following research questions were adopted:

1. Can the Polish Internet discourse on AI be characterised as a moral panic in the sense of Stanley Cohen?
2. Do Polish Internet users actively engage in the topic of AI trust, both in terms of the credibility of the data it presents and the safety of its use?

To answer these research questions, a corpus analysis of online texts was employed. The choice of this research method allows consideration of both quantitative and qualitative aspects of the analysis. Through quantitative analysis, statistical relationships between individual words are observed, while qualitative analysis focuses on the observation of discourse elements in their context. In this study, the Sketch Engine tool was used, enabling a clear analysis of language corpora[16]. This platform also provides access to the Polish Trends language corpus, characterised by a significant word resource, which was originally planned to be analysed as the most representative of the Internet discourse. However, due to the size of the corpus, it would not allow a comprehensive and detailed answer to the research questions, which is why two additional corpora were created to enable comparative analysis. The final list of corpora analysed in this study is as follows:

1. The *Polish Trends* corpus (available through Sketch Engine) – a daily updated monitoring corpus containing press articles or other sources that are regularly updated from their RSS feeds (*newsfeeds*). Systematic updates allow for the use of diachronic

[16] *What is Sketch Engine?,* Sketch Engine, https://www.sketchengine.eu (on-line 31.01.2024)

analysis tools and the study of changes in word usage[17]. At the time of analysis, the Polish Trends Corpus consisted of 263,811,493 unique words.

2. The press texts corpus – created for the study, containing press articles published on the websites of online magazines such as Gazeta Wyborcza, Dziennik Gazeta Prawna, Newsweek, Onet, Wirtualna Polska, tagged with the phrase "Chat GPT" or "artificial intelligence", published from 1 January 2023 to 24 October 2023. The Press Texts Corpus consists of 30,895 unique words.
3. The tweet corpus – created for the study, consisting of Polish tweets containing the phrase "Chat GPT", published on the platform X (formerly Twitter) from 8 May 2023 to 24 October 2023. The Tweets corpus consists of 3,664 unique words. Corpus analysis proceeded in 4 stages, which were: (1) building auxiliary corpora for comparative analysis, (2) identification of topoi and adjectives related to AI in the individual language corpora, (3) observation of topoi and adjectives in the context of their occurrence, (4) determination of concordances with selected words, (5) determination of 2 and 3-grams, if there are justified reasons for this, (6) comparative analysis of corpora.

4. Analysis results

After preparing the data for analysis, a specific number of topics, verbs, and adjectives that occur the most frequently were identified, from which those that appeared to be most significant from the perspective of the research questions were selected. For the Polish Trends corpus, this was a list of 1,000 words, for the Press Texts corpus 500, and for the tweets corpus 100. Words that could indicate an interest in artificial intelligence were sought.

4.1. The *Polish Trends* corpus

Regarding the Polish Trends corpus, among the 1,000 most popular nouns (keywords) related to the research questions, topics such as "inteligencja" ("intelligence", 514th place in the ranking, 37,241 occurrences) and "AI" (753rd place in the ranking, 25,592 occurrences) were observed. Interestingly, the word "Putin" occupied the 513th position in the ranking, which constitutes an interesting reference point for the analysis, considering that the Russian

[17] *Polish Trends: a daily-updated monitor corpus of news articles*, Sketch Engine, https://www.sketchengine.eu/polish-trends-corpus/ (on-line 31.01.2024)

aggression in Ukraine is one of the most mediatically resonant topics in Poland.

Among the adjectives that occur most frequently in the *Polish Trends* corpus, the word "sztuczny" ("artificial", 111th place in the ranking, 43,957 occurrences) appeared. Given that "sztuczna inteligencja" ("artificial intelligence") naturally occurs as a two-word chain, and one of the identified topics turned out to be the term "inteligencja" itself, an analysis of 2-grams related to the concept of intelligence was also carried out to examine whether the high positioning of this topic and adjective results mainly from numerous mentions of artificial intelligence or from other, related terms, such as "inteligencja emocjonalna", "iloraz inteligencji" or "poziom inteligencji" ("emotional intelligence", "intelligence quotient", "intelligence level"). The analysis showed that the 2-gram "sztuczna inteligencja" occurs in the *Polish Trends* corpus 34,055 times, while other double sequences related to intelligence appeared significantly less frequently – "inteligencja emocjonalna" only 200 times, "iloraz inteligencji" 100 times, "poziom inteligencji" 96 times. Thus, there is a clear predominance of interest in topics related to artificial intelligence over those dedicated to other aspects of intelligence. Furthermore, if the sequence "sztuczna inteligencja" and the acronym "AI" were treated as identical and their frequency of occurrence in the Polish Trends corpus were summed up, we would obtain a number of 59,647 occurrences in the corpus, which compared to the occurrence of the word "Putin" (37,115) also prompts reflection.

4.2. The press text corpus

In analysing the Press Texts Corpus, which consisted of texts tagged with "Chat GPT" or "artificial intelligence", the primary focus was on identifying the adjectives that occur the most frequently in the corpus to observe the reactions provoked by this type of open-source software in social discourse. An analysis of topoi from the perspective of texts deliberately chosen for the sample would have been less effective here. Therefore, particular attention was focused on adjectives describing Chat GPT.

The adjectives in the *wordlist* "nowy" ("new", 103), "inny" ("different", 74), "ludzki" ("human", 42), "prawny" ("legal", 39), "polski" ("Polish", 34), "ogromny" ("enormous", 30), "ważny" ("important", 24), "dobry" ("good", 24), "amerykański" ("American", 23), and "osobowy" ("personal", 20) stand out for their frequent use. To more accurately answer the research questions after observing the most frequently occurring adjectives in the corpus, it was decided to examine their concordances, which allowed for understanding the context of

each word's occurrence. The adjective “nowy” typically refers to the ongoing technological revolution, updates to the Chat GPT version, but also to the new market for digital services and jobs. However, there were also mentions of “nowy autorytaryzm” (“new authoritarianism”) which can be enforced through artificial intelligence, or “nowe bańki technologiczne” (“new technology bubbles") leading to social polarisation, as well as “nowe regulacje” (“new regulations”) and necessary laws. Regarding the adjective “different”, it usually refers to comparing Chat GPT with other generative AIs. The discourse here revolves around the possible applications of this type of technology. “Ogromny” generally concerns how Chat GPT operates, the data on which it was tested, but also its application in the business sector (“ogromna szansa dla firm”, “huge opportunity for companies”), or “ogromna władza” (“huge power”). The adjective “ważny” usually refers to AI decision-making, the credibility of its proposed solutions. With the adjective “dobry”, issues such as comparing human abilities and artificial intelligence or discussions about who ‘better’ managed specific tasks are discussed. The adjective “polski” refers to the use of Chat GPT in Polish universities, with references to the government, Polish companies, startups, platforms, and foundations. There is also talk of Polish awareness, Polish analytical circles, and Polish IT specialists. “Amerykański” usually appears in reference to the media, or the situation of American companies, job markets. Essentially, these adjectives relate to the job market situation related to Chat GPT, or possibly to the governmental and media situation in given countries. The adjective “ludzki” garners interest as it relates to comparing AI with humans, but also touches on issues such as human morality, human competencies, human nature, human effort, imagination, or knowledge. It addresses the human mind, consciousness, and also biological matters such as the human brain. This adjective also appears when discussing everyday life, interpersonal contacts, and even a longing for them (for example, reminiscing about the times when medical receptionists were not replaced by chatbots). “Osobowy” is used exclusively in the context of personal data processing. Meanwhile, “prawny” accompanies the debate on whether Chat GPT can be treated as a legal entity, also raising issues of legal risk associated with using such technology, as well as matters of its regulation.

To further deepen the collected conclusions, it was decided to also identify the verbs most commonly associated with the sequence "Chat GPT". A frequent personification of Chat GPT was observed, described as one that “przejrzał”, “pomylił”, “zastępuje”, „pracuje” (“reviewed”, “mistook”, “replaces”, “works”).

4.3. The tweet corpus

Tweets corpus containing the sequence “Chat GPT” proved to be highly diverse in terms of the occurrence of unique words. It is also a relatively small corpus in terms of its number, but it is important to remember that tweets are generally a short form of text. In this context, the significantly greater range of topics compared to other corpora is particularly interesting. Among the 100 most common themes, words such as “człowiek” (“human” 15), “praca” (“work”, 10), “programista” (“programmer”, 9), “osoba” (“person”, 9) appeared. There were also individual words related to the work environment such as “branża” (“industry”), „zwolnienie” (“layoff”), “money” (“pieniądz”), “biznes” (“business) and mentions of the future (3 instances), as well as negatively charged vocabulary such as solitary swear words, and “głupota” (“stupidity”), “idiota” (“idiot”), “idiotyzm” (“idiocy”), “kretynizm” (“cretinism”), “afera” (“scandal”).

Regarding the context of the occurrence of the most frequent themes, the concordances of the word “człowiek” indicate its use in both singular and plural (“ludzie, “people”) in contexts of replacing humanity in various work settings. Here, the issue of replacing humans in creative work appears, comparing the abilities of a chatbot with human capabilities (“a real human cannot draw conclusions from something in 3 seconds”). In the context of the ‘person’ topos, there was an aspect of using Chat GPT to manipulate less intelligent individuals who might not be able to distinguish Chat GPT utterances from human ones. Among the 3-grams in this corpus, it is worth noting “Chat GPT can”, “Chat GPT writes”, “Chat GPT will change transport”, “Chat GPT said”. Observing these 3-grams in context leads to the conclusion that users of the X platform feel satisfied when AI appears incapable of something or makes a mistake.

5. Corpus comparison and conclusions

Analysing three such varied corpora seemed essential from the perspective of the research questions and their specificity. The Polish Trends corpus is the largest of the examined corpora, which, due to its size, best meets the criteria of representativeness, although it does not contain texts other than those found in RSS feeds. In such a large corpus, it should be noted that the topic of AI appears more frequently than the surname Vladimir Putin, and the sequence

"artificial intelligence" turns out to be significantly more popular than other 2-grams related to intelligence, such as emotional intelligence. This indicates that this topic is frequently discussed within RSS feeds. Compared to the corpus of purpose-built press texts, which contains only articles tagged with the phrases "Chat GPT" and "artificial intelligence", the *Polish Trends* corpus provides only partial knowledge of AI placement in discourse.

In the press texts corpus, several particularly significant threads were observed from the perspective of research questions, such as reflections on the place of AI in society and its legal subjectivity, as well as the issue of similarity to humans or the encroachment of AI in areas identified as human, e.g. with respect to creativity or interpersonal relationships. Here, a certain type of social unease can be discerned, related to the discomfort that technology imitates human behaviours, yet does not understand things like morality or human effort. AI is identified within the press discourse as both an opportunity and a threat to the job market. The theme of new positions intertwines with those suggesting greater efficiency of AI, and at the same time, a danger for less specialised and less efficient people. Very often in this discourse, business area issues are raised: perspectives of using AI and its possibilities. The discourse on AI in press texts also includes the theme raised by Sousa, Carvino, and Martins[18], which is the concern about the reliability of the information provided and the validity of decisions made by artificial intelligences. There is also the question of knowledge and its construction, and even the impossibility of verifying its truthfulness by average users, which can be attempted to be linked with Michael Foucault's theory[19]. This discourse also includes themes related to the governing potential of using AI, isolated suggestions of the danger of the so-called new authoritarianism based on strict control and predictions, fitting into Shoshana Zuboff's theory of surveillance capitalism[20], and even Stanley Cohen's idea of moral panic[21].

The tweet corpus, being a complement in this analysis but also the closest to authenticity, carries similar conclusions. Tweets containing the sequence "Chat GPT", as press texts, consisted of numerous references related to the job market and the consequences of technological changes. This corpus proved to be the most emotionally charged due to the content of vocabulary suggesting annoyance and irritation. Similarly to the corpus of press texts, the issue of the similarity of AI with humans was raised, even to the extent of AI traits

[18] S. Sousa, J. Cravino, P. Martins, *op. cit*., pp. 2–4.
[19] M. Foucault, *op. cit.*
[20] S. Zuboff, *op. cit.*
[21] S. Cohen, *op. cit*., p. 46.

that deviate from known human norms. Thus, a disruption of certain kinds of habit and the existing balance is visible, which would also fit Stanley Cohen's assumptions of moral panic.

After analysing the research material, it can be observed that the issues presented in the Polish press discourse and in user discussions themselves fit into the concept of moral panic and the issue of knowledge-power in Foucault's terms, sometimes also highlighting problems similar to those in Shoshana Zuboff's theory of surveillance capitalism. However, the frequency of the mentioned themes turned out to be relatively low and interspersed rather with a rational, albeit exciting, discussion about the observed technological changes. AI is often presented as a possible reason for job loss, technology provoking reflection on what falls within the sphere of human competencies or typically human attributes, but these issues did not appear in the analysed discourses in an evident and obvious way, nor were they unequivocally dominating. Responding to the first of the adopted research questions, it should be stated that the Polish discourse about AI consists of threads causing unease, but it is not so focused on them as to fully define it as moral panic. To consider that a given topic causes moral panic, there must be a high level of threat perception and disturbance of existing norms along with exaggeration and attribution of responsibility for caused or possible harms to someone or something. In the analysis material, possible consequences of the proliferation of AI were discussed, especially in the context of the job market, but there was no reference to large corporations or specific persons who wanted to use AI to take over the world. AI itself, although often personified, was not habitually demonised. Although the issue of new authoritarianism appeared, it was a niche topic in the context of the entire corpus. Moral issues were raised in the context of comparing AI's capabilities with humans, from which concerns about potential consequences could be distinguished, but this still occurred in the dimension of discussion rather than panic. It is also worth noting that, according to Cohen's claims, moral panic is the result of an exaggerated interpretation of threat and an outbreak of emotion. In the discourse about AI, we deal with moderate unease, which is not without basis: the authors of the analysed articles and statements ponder the real consequences, also raised by experts, including the topic of the reliability of content generated by generative AIs, legal issues, and pondering the implications of this technology. Thus, this is an answer to the second research question.

The conducted analysis identified key elements of the discourse on artificial intelligence, manifesting itself in both press texts and internet users' statements. Corpus data suggest that society engages in an active discussion about the role of AI and its place in social

reality. On the other hand, corpus data do not provide sufficient evidence to determine whether AI is spoken predominantly in a positive or negative way. Perhaps constructing a representative corpus dedicated to this issue and using quantitative sentiment analysis and thematic analysis would obtain such an answer. A more in-depth, qualitative discourse analysis on this issue is also recommended, motivated by the belief that combining two types of analysis, quantitative and qualitative, can provide fuller and more precise conclusions.

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Communication Hierarchies and User Engagement in Digital Media Design

Hierarchie komunikacji i zasady interakcji użytkownika w projektowaniu mediów cyfrowych

Maciej Kaźmierczak[1]

Abstract: This article embarks on an exploration of how design principles in the digital domain impact user engagement, aiming to elucidate the correlation between design methods and user interaction. Employing a review of design philosophies such as minimalism and integrating psychological principles such as Daniel Kahneman's "minimising cognitive effort" and Hick's law, the study explores various aspects of digital design, mainly using message hierarchy. The investigation reveals that simplicity and clarity in design, coupled with a user-centric approach, markedly enhance user experience and engagement on digital platforms. The results demonstrate that intuitive navigation, effective use of whitespace, and adherence to foundational design principles substantially elevate the quality of user interaction and content assimilation.

Streszczenie: Artykuł ten podejmuje analizę wpływu zasad projektowania w środowisku cyfrowym na zaangażowanie użytkownika, mając na celu wyjaśnienie związku między metodami projektowania a interakcją użytkownika. Artykuł bada różne aspekty projektowania cyfrowego, zwłaszcza posługiwanie się hierarchią komunikatów, wykorzystując filozofię projektowania opartego na minimalizmie oraz wcielając w życie zasady psychologiczne takie jak „minimalizowanie wysiłku poznawczego" Daniela Kahnemana i Prawo Hicka. Badanie ujawnia, że prostota i jasność w projektowaniu, połączone z podejściem zorientowanym na użytkownika, znacząco poprawiają doświadczenie użytkownika i zaangażowanie na platformach cyfrowych. Wyniki pokazują, że intuicyjna nawigacja, efektywne wykorzystanie białej przestrzeni i przestrzeganie podstawowych zasad projektowania znacznie podnoszą jakość interakcji użytkownika i przyswajania treści.

Keywords: digital design, user engagement, minimalism, cognitive effort, whitespace, intuitive navigation, communication hierarchy

Słowa kluczowe: projektowanie cyfrowe, zaangażowanie użytkowników, minimalizm, wysiłek poznawczy, biała przestrzeń, intuicyjna nawigacja, hierarchia komunikacji

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1. Introduction

In the realm of IT industry humour, an intriguing proposition asserts that the most effective location for concealing information mirrors the notion of hiding a body: it is found on the second page of a Google search result. This humorous observation, originating in the domain of search engine optimisation (SEO), poignantly highlights a prevalent lack of motivation in the average Internet user to actively search for and engage with online content. This phenomenon is characterised by a tendency to favour conciseness over expansiveness in the consumption of digital information. Daniel Kahneman, in his seminal work *Thinking, Fast and Slow*, provides a thorough analysis of this behavioural pattern, identifying it as a principle of minimising cognitive effort[2]. He argues that individuals, naturally inclined towards a state of inertia, demonstrate a preference for cognitive ease. This preference, in turn, has significant implications for the field of graphic design. By applying the principles derived from Kahneman's thesis, content creation can be made more approachable and comprehensible for a wide range of audiences, thus facilitating greater accessibility and assimilation of information.

2. Determinants of audience engagement in contemporary media consumption

Before starting any design endeavour, it is crucial to consider the target audience. The 2020 report by the National Library of Poland sheds light on a surprising reality: 58% of the Polish population did not use books and 23% did not own a single volume[3]. This statistic escalates to approximately 6 million people who are disconnected from the culture of written text and do not participate in the reading of lengthy texts within one year. These findings are instrumental in informing compositional and substantive choices in message design. Similarly, analysis of content consumption patterns reveals that reading modalities have evolved. Contemporary tools for content reception predominantly include tablets and smartphones, and reading frequently transpires within urban spaces, such as public transportation. This shift is highlighted in a study at UX Myths, which indicates that 60–80% of mobile users browse the Internet from home or office settings[4]. The fragmented attention span of the modern reader necessitates a design approach that accommodates frequent interruptions and the need for reengagement with the material.

[2] D. Kahneman, *Thinking Fast and Slow*, New York 2011.
[3] R. Chymkowski, Z. Zasacka, *Stan czytelnictwa w Polsce w 2020 roku*, Warszawa 2021, https://bn.org.pl/download/document/1621420376.pdf (on-line 15.12.2023)
[4] Z. Gócza, *Myth #33: Mobile users are distracted*, https://uxmyths.com/post/99302792550/myth-33-mobile-users-are-distracted (on-line 15.12.2023)

3. The science of message hierarchy in communication design

The establishment of a hierarchy among various text elements constitutes a fundamental task in designing any form of communication. The term "communication" here encompasses all types of content where longer characters appear, regardless of the medium – this includes browser interfaces, phone screens, restaurant menus, advertising posters, or even televised commercials.

The message hierarchy involves assigning a class of importance to different areas of the text. This is particularly evident in newspapers, which typically feature a structure comprising headline, lead, and body text. A recent trend in the condensation of news articles into bullet points illustrates this principle effectively. This approach, as exemplified by the portal onet.pl, allows the reader to swiftly grasp the main themes without delving into the minutiae. As an example, Figure 1 of Onet Sport shows this method in action.

Fig. 1. The message hierarchy in the Onet Sport article[5]

[5] *Srebro uwłacza*, https://www.onet.pl/sport/onetsport/wlochy-anglia-anglicy-nie-chcieli-srebrnych-medali-brak-klasy-final-euro-2020/bzf6fc9,d87b6cc4 (on-line 15.12.2023)

Distinguishing the importance of different text sections enables users to quickly assess whether a particular text fits their needs. This differentiation often occurs through the use of font weight, size, and/or colour: the higher the position in the hierarchy, the more pronounced the appearance of the letters. In the realm of digital content design, the use of HTML tags is advantageous, as their inherent hierarchy aids in visually illustrating the relationships between categories. The hierarchy is typically structured as follows:

1. Title [h1] – Often the briefest text in the media, but one of the most crucial, as it influences the conscious choice of reading material.
2. Lead [h2] – The first visually distinct paragraph following the title or subtitle, providing further clarification of the content and offering greater assurance of its relevance to the reader.
3. Subheading [h3] – Additional internal titles that are applied to sections of the message, commonly marking subchapters.
4. Quote [h4] – Incorporating quotes allows the reader to take a momentary respite from the main text, drawing attention to significant observations. Employing a different colour for this content is advisable.
5. Summary [h5] – Key information in the text pointed by bullets.
6. Body text [p] – The main content of the communication.
7. Emphasis in the text [b] – It is often beneficial to highlight small portions of the text, especially when they are crucial to the reader.

4. The essence of minimalism in digital design and its cognitive impacts

Minimalism, a trend with origins tracing back to the 1920s, marked its entry into the digital realm around the year 2000, but it has only become significantly noticeable in recent years. The emergence of the principle “less is more” has allowed for a sense of relief in the composition of web pages.

In previously cluttered on-line services, a compositional solution known as white space has begun to emerge, offering a reprieve from interfaces densely packed with content. By eliminating non-essential elements from a webpage, it has been observed that users experience reduced stress and increased emotional engagement with the content. Research involving older adults, published in *Computers in Human Behavior*[6], indicates that the use of negative space

[6] D.–Y. M. Lin, *Evaluating older adults' retention in hypertext perusal: impacts of presentation media as a function of text topology,* “Computers in Human Behavior” 2004 (20), pp. 491–503.

between paragraphs and in margins can improve information assimilation by 20%. The full study can be explored in *Human Factors*[7].

The concept of white space, while essential in creating minimalist designs, does not necessitate the colour white. It refers to the intentional leaving of empty space between elements such as graphics, photos, margins, or texts to enhance readability and ease of interpretation. A prime example of effective whitespace use is the Google search engine homepage.

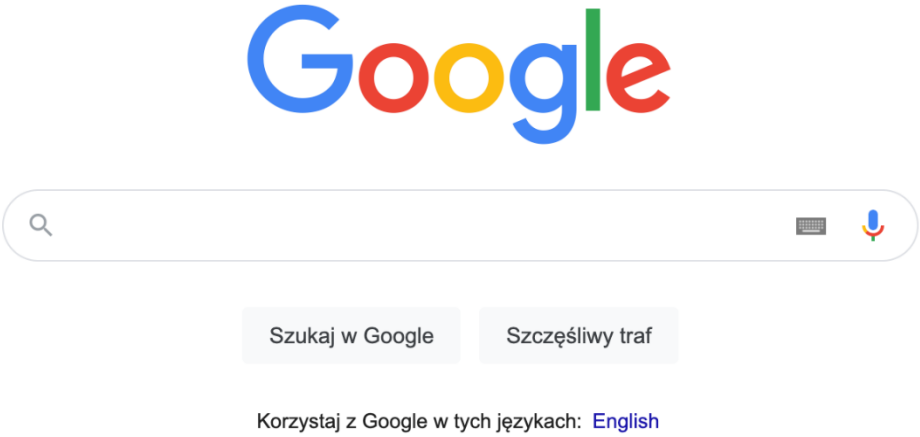

Fig. 2. Google search engine homepage

By including only essential elements, the design focusses user attention solely on the purpose of the site, content search. The absence of distractions and the simplicity of the design significantly improve the user experience (UX), as detailed in *Usability Geek*[8].

Hick's law, which posits that the more choices a user has, the longer it takes to make a decision, further supports minimalist design. This principle is evident in scenarios where the number of available options is minimised, thus focussing the user's attention on specific actions, such as entering a query and proceeding to search results. More information on Hick's

[7] K. Straub, *Yeah, but can you give me a reference?*, https://www.humanfactors.com/newsletters/yeah_but_can_you_give_me_a_reference_2004.asp (on-line 15.12.2023)
[8] A. Smith, *Less Is Still More: The Importance Of The Minimalist Approach To Web Design*, https://usabilitygeek.com/less-is-more-importance-minimalist-web-design/ (on-line 15.12.2023)

law can be found in an article by *Interaction Design Foundation*[9].

Furthermore, the principle of proximity, a concept from Gestalt psychology's visual perception laws, describes how people perceive relationships between elements, particularly graphical ones[10]. Elements placed closely together are perceived to be related, unlike those spaced more liberally.

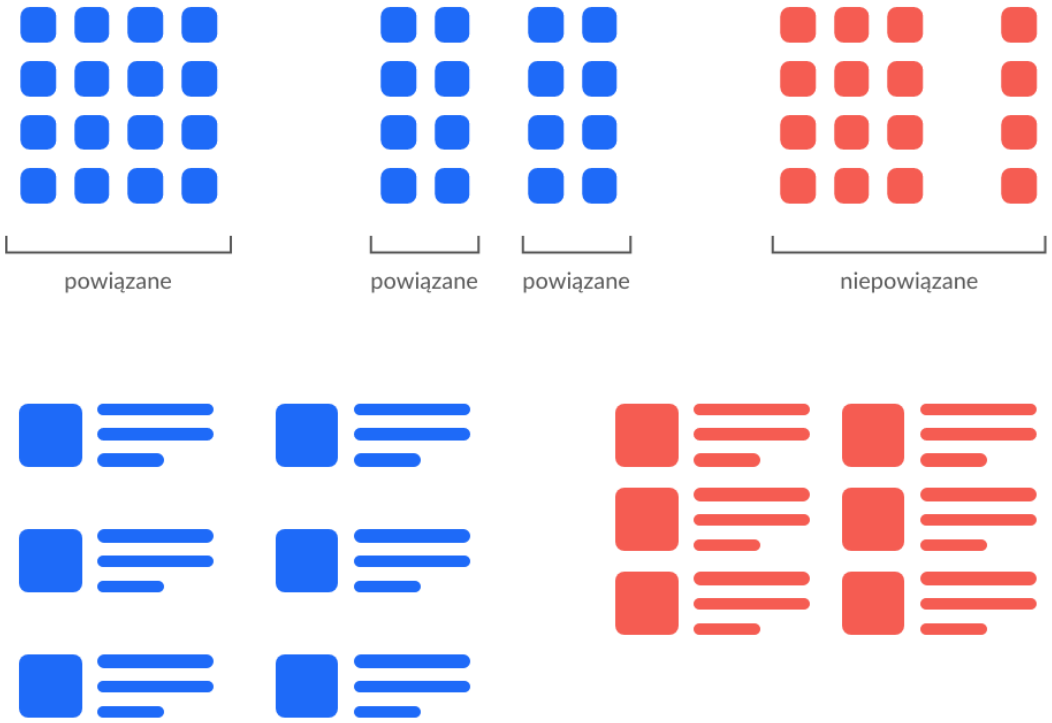

Fig. 3. The principle of proximity

This knowledge allows designers to use white space effectively to create appropriate distances between layout elements, thereby forging connections among various components of a composition. A simple example of this principle can be seen in any book, where the text is

[9] *Hick's Law*, https://www.interaction-design.org/literature/topics/hick-s-law (on-line 15.12.2023)
[10] Interaction Design Foundation, *What are the Gestalt Principles?*, https://www.interaction-design.org/literature/topics/gestalt-principles (on-line 15.12.2023)

segmented into paragraphs that link sentences, thoughts, or arguments to the overarching narrative.

5. The imperative of clarity and simplicity in design

At the heart of my design philosophy lies a maxim that resonates profoundly with both my teaching and professional work: “Go bold or not at all”. This expression, borrowed from the contemporary youth vernacular, encapsulates the principle that I advocate among students and frequently apply in my own projects. When establishing a hierarchy of messages for any medium, it is essential to visually differentiate between content of varying importance, regardless of whether this distinction is made through colour, size, or transparency. The disparity between elements should be conspicuous enough for an uninitiated observer to perceive it instinctively and accept it as self-evident. The more intuitive the design, the easier it is to use. An illustration of this principle can be seen in the KISS approach (“Keep It Simple, Stupid”), as depicted in Figure 4.

Fig. 4. An example of intuitive design. Author: Terretta[11]

[11] Interaction Design Foundation, *KISS (Keep it Simple, Stupid) – A Design Principle*, www.interaction-design.org/literature/article/kiss-keep-it-simple-stupid-a-design-principle (on-line 15.12.2023)

If the content presented to a user is not readily accessible, they are likely to abandon the page in search of a more user-friendly alternative. Research indicates that users rarely give up on a second chance, and 88% are unlikely to return to a site after a negative experience[12]. From this, it can be inferred that users do not prefer to read extensively, wait excessively, or search laboriously. With this in mind, content must be crafted to suit their preferences. To illustrate this point, I often compare designing a website with preparing a sandwich for a child. It should be cut into small, manageable pieces, easily navigable by tiny fingers, and effortlessly consumable.

6. Conclusions

The approach presented in this article underscores the essence of effective communication design: the simplification and accessibility of content are paramount. By adhering to the maxim, "Go bold or not at all", designers can ensure that their creations are not only visually striking, but also intuitively navigable, thus improving the user experience and engagement.

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[12] M. Philips, *Know Your User – UX Statistics and Insights (with Infographic)*, www.toptal.com/designers/ux/ux-statistics-insights-infographic (on-line 15.12.2023)

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