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Educational Computer Programs as a Mechanism and Means of Mathematical Literacy Forming

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Abstract

Educational routes personalization in the direction of cognitive processes correcting for problem solving of student's mathematical literacy forming, development of complex student's mathematical knowledge through the digital technologies and computer learning systems are an important concept in mathematics education. The aim of research – to optimize and evaluate the effectiveness of student's mathematical literacy process forming by using a computer training program with animation elements. Complex knowledge forms the ability to maintain the dynamic stability of mental activity, motivation, self-organization, and creativity. Materials and methods: methodology of student's personaluzation by digital environment using with complex knowledge learning on the base of visual modeling, technology of parameterization as a resource of mathematical objects optimization, computer design of stages growth dynamics of student's mathematical literacy. Results: basis of criteria characterizing of student's mathematical literacy testing in educational process; parameters of mastering degree of educational materials by students and quality of educational materials assimilation in mathematics learning. The test establishes the statistically significant dynamics for all the studied indicators (coefficient of concepts volume assimilation and the coefficient of completeness of an ability to operate with concepts in solving problems with the depth of connections assimilation.

Keywords: computer training program, mathematics learning, complex knowledge, limit of sequence and function.

1. Introduction

UNESCO coordinates the implementation of "Education 2030" agenda to reimagine education for a sustainable future and to educate every learner, provide the quality learning opportunities for all, and empower them to be a creative and responsible global citizen.

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The problem of mathematical literacy forming in pedagogical science is not new, but extremely important and widely has reflected in scientific research on philosophy, economics, psychology and pedagogy (Yaroshenko, 2021; Konoplyansky, 2017). Scientific and methodological experience demonstrate that education today is no longer feasible without the incorporation of digitalization. At the same time, an integration of modern achievements adaptation in science with digital technologies using creates the basic aspect of student's personal development in teaching mathematics. So, formation of student's mathematical literacy should include the elements of fractal geometry, theory of encoding and encrypting information, fuzzy sets and fuzzy logic and other complex mathematical knowledge. It is realized in school mathematics course by practice-oriented subtasks, concerning with generelized constucts solving.

The decline of student's motivation, an avoiding complexity in learning mathematics and gap between the classical content of teaching mathematics and modern science leads to an increase in crisis phenomena in mathematical education, both at school and at the university. Therefore, the task is to create a rich information and educational environment for teaching mathematics by changing the content of education in the direction of mastering complex knowledge through the support of distance learning and digital technologies.

At the present stage of development of education systems in various countries, including Russia, the mainstream is the creation of an integrated textbook on mathematics and computer science for secondary school. This idea is closely related to the concept of smart-education. The prerequisites for the development of the concept of smart-education were: 1) technological factors providing new means and technologies for learning in the modern information and telecommunication environment; 2) social factors including society's need for a new quality of educational services; 3) economic factors conclude that education has always made a significant contribution to the development of macroeconomics (Dneprovskaya et al., 2015). Mathematics teaching based on the development of complex knowledge generalized constructs (for example, modern achievements in science) becomes an effective direction for the formation of school student's mathematical literacy with a significant applied and mathematical-informational potential of personal development (Smirnov et al., 2021). Today, various innovative tools, including computer tools and programs, are used to solve this problem of mastering complex knowledge. Computer software for training first appeared in the USA in the 40s of the last centuries (flight simulators). The high price of computers at the time, their massiveness, imperfect monitors, input of programs using first-generation programming languages from punch cards, and access only in computer centers were all obstacles to the mass application of computers in science, technology, and education.

In the 1960s and 1970s the main paradigms of programming languages were developed, which are still used today, and in the 1980s there was a consolidation: some languages adopted features of object-oriented and system programming, others concentrated more possibilities in the application of modules, etc. After 1980, personal computers became available and the leading companies (usually from the USA) began to specialize in educational software, the main purpose of which was to improve the efficiency of the educational process. In 2020, at the third international conference eSTARS 2020, dedicated to the study of the role of digitalization in higher education, Rector of the National Research University Higher School of Economics Ya. Kuzminov noted that many higher education institutions in the country have insufficient implementation of digital technologies due to poor professional training of teachers and the established opinion that digital education (in particular, online) is of poor quality. It is obvious that the introduction of digital components into the educational process of higher education should be based on various types of high-quality content. Today in many countries of the world there is an active search for new pedagogical methods and techniques, which together with digital technologies could ensure the universality of learning, including the activation of the learning process, individualize it, provide access to modern sources of knowledge from leading experts in their fields of activity (Romanova, 2020). The authors of a joint study by Jisc, British organization for the development of digital technologies in higher education, and Emerge Education believe that it is time to move to a complete transformation of teaching in higher education. In their research "Roadmap to 2030" (Barosevcic et al., 2021), the authors identify of three areas where digital technologies are most useful – educational content (growth in the quality of digital learning programs), its delivery through learning and assessment infrastructure, and support in the learning process.

Purpose of the study: optimization of the learning process through the use of computer learning program with animation elements in mathematical literacy formation. Development of student's mathematical activity in the context of complex stochastic processes managing will be based on the coordination of different factors and principles in three contexts: meaningful (semiotic), procedural (imitation) and social (Smirnov et al., 2021).

2. Methods and materials

One of the methods of student's mathematical literacy formation through complex knowledge mastering is the introduction of computer technologies into the educational process of mathematics teaching on the base of student's self-organization in research activity (Zayats, 2020; Kozel, 2021; Makarova, 2023; Chernyakova, 2023). We define *of student's mathematical literacy* as a socially approved of properties severity measure of individual's functional systems, manifested in the success of student's mathematical and digital activity in the development of sciences and real life. The *main characteristics* determine the essence of monitoring the formation of student's mathematical literacy:

– Understanding the plot situation and translating it into the language of mathematics with computer support, the procedure for finding a solution;
– Transitions of sign systems in the dynamics of animation;
– Visual modeling of data, quantities and units of measurement;
– Interpretation of the result based on variability and distant associations;
– Independence in the selection of mathematical and digital resources.

In our article we will use the computer training program with elements of animation, which has already been implemented in the educational. The program is focused on the propaedeutics of mathematical knowledge in the elements of higher mathematics. Cognitive mechanisms in the form of bright dynamic images, attract attention, stimulate thinking activate the cognitive abilities of students and help to better remember the material. At such moments, the emotional state is "...a multidimensional and complex process that includes a number of components, which include cognitive, motivational, motor ..." (Dvoryatkina, 2015). The training program is a set of program modules that focus the students' attention on such complex concepts of mathematics as modulus of number, limit of sequence, limit and continuity of function, points of functions discontinuity, construction of functions graphs. As an example, let us consider the module of "Limit".

3. Results

3.1. Visual modeling of pattern procedures

Example 1. The motivation for addressing this topic was the analysis of test results. It turned out that there is a global misunderstanding of an expression «$|x - 2| < 3$» meaning. Obviously, this misunderstanding is a direct consequence of competence work with absolute value. The program module "Limit" is presented in the form of 3 blocks: Module, Associations and Limit. Selecting the "Module" button, the program demonstrates to students the formula for determining the numerical module, shows and explains the conceptual error that, as evidence by extensive teaching experience, "imposes" this formula on students (Figure 1), suggests an applying another, more "universal" formula (Figure 2).

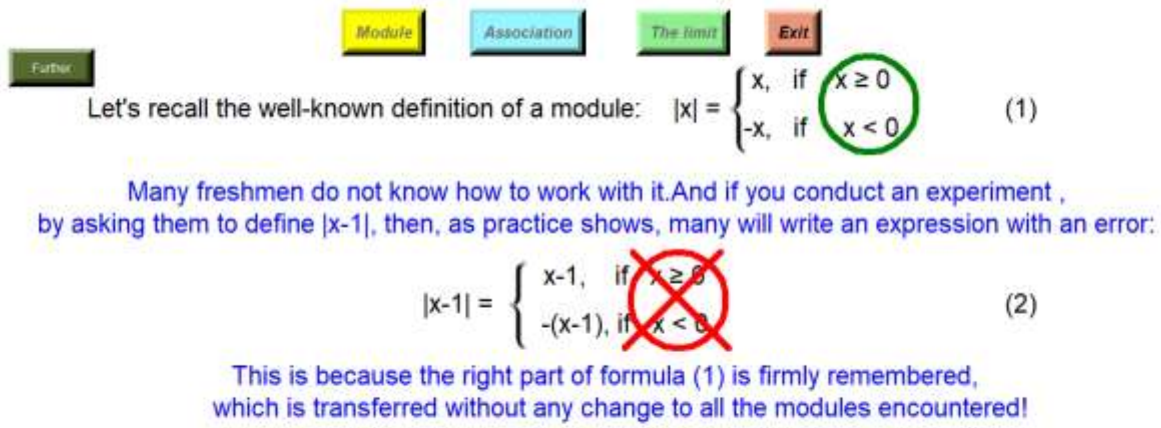

Fig. 1. A typical mistake of first-year students when working with the module

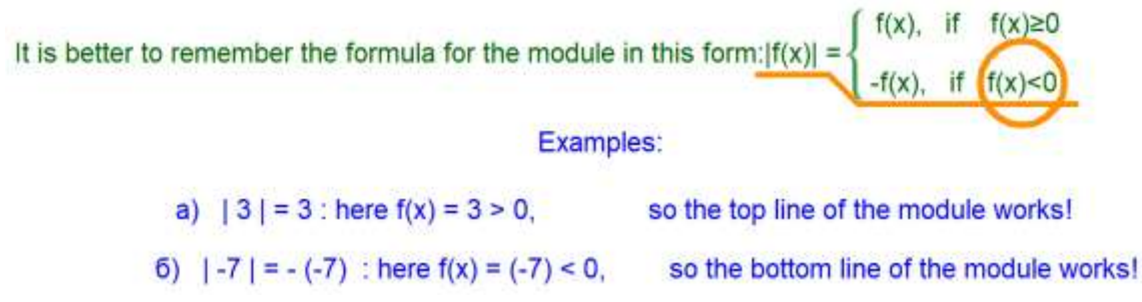

Fig. 2. The universal formula for the module

Then, various examples of modules with difference of two numbers with reference to the numerical axis, will encourage students to draw the correct conclusion (Figure 3).

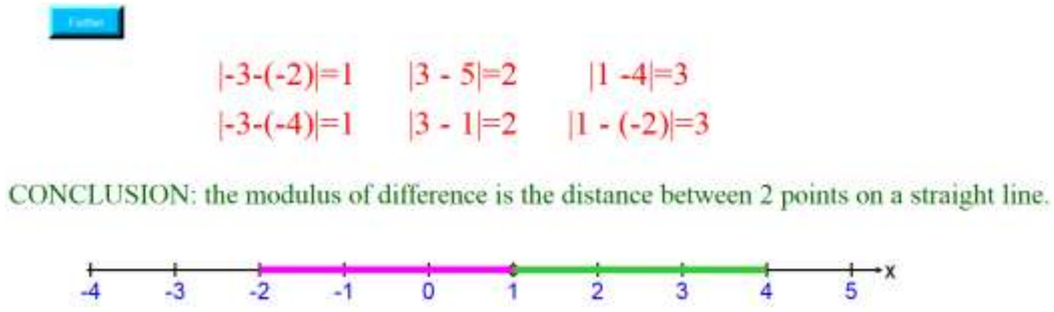

Fig. 3. Formation of modulus concept for difference between two numbers

After discussing the inequality |x - 3| < 2 on the number line (Figure 4), the geometric interpretation of the definition $|x - a| < \varepsilon$ becomes clear (Figure 5).

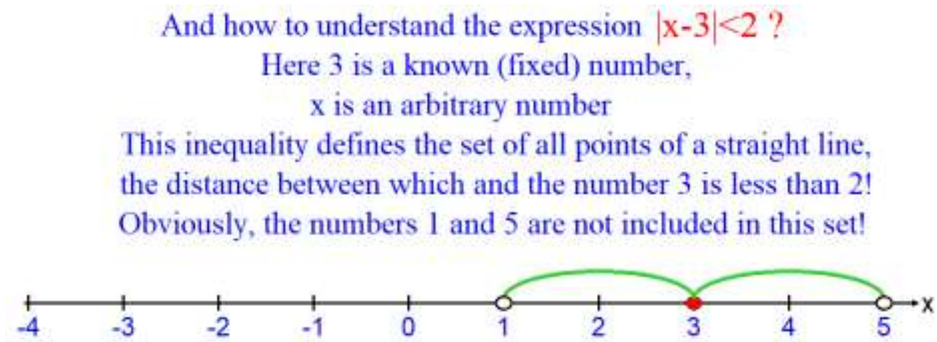

Fig. 4. Discussion of inequality $|x - 3| < 2$

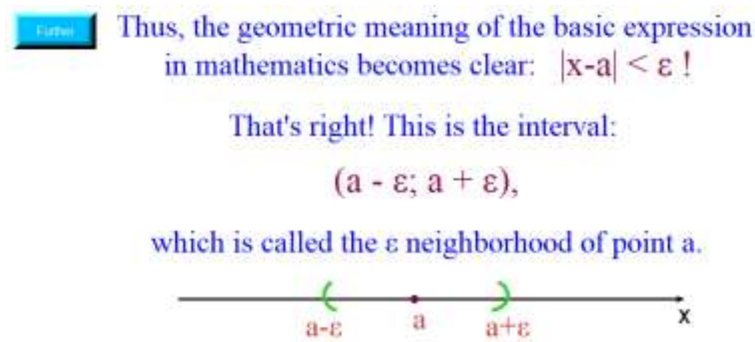

Fig. 5. The key inequality of mathematical analysis

Example 2. Next, a transition is made to the "Association" section (menu button), where Zenon's famous paradox "Achilles and the Tortoise" is presented in animated form, which "demonstrates" that Achilles will never overtake the tortoise (Figures 6 and 7).

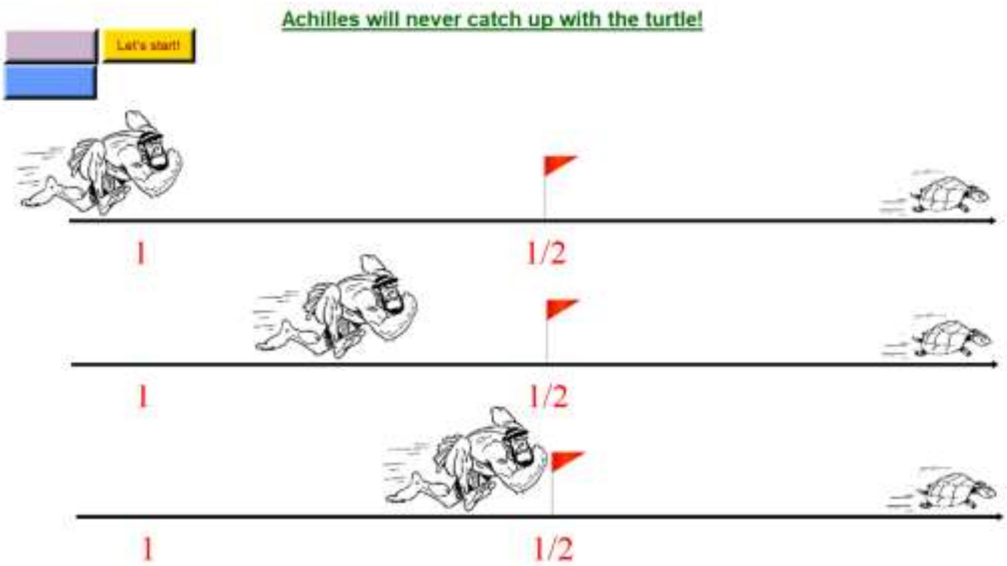

Fig. 6. The animation of Achilles

Part of the program code is presented below:

```
def clicked1():
global k, k1, q4
ac_kn(0, knop1)
ac_kn(0, knop4)
for i in range(1,250):
cnv.move(id_img1, 2, 0)
cnv.update()
sleep(0.01)
knop1.configure(text="CONTINUE!")
if q4 < 4:
t_ext(-20,-270+40*q4, spisok[q4], zw="DarkGreen", grup="group5", ti=mF2)
q4 = q4 + 1
ac_kn(1, knop2)
def clicked2():
global k, k1, tex_1, tex_2
ac_kn(0, knop2)
ac_kn(0, knop4)
cnv.delete(tex_1)
cnv.delete(tex_2)
for i in range(1,250):
cnv.move(id_img1, -2, 0)
cnv.update()
tex_1 = cnv.create_text(-540, 254, text=Fraction(k1/2), fill="red",
font=('Times', 35))   # The beginning of the path
tex_2 = cnv.create_text(22, 254, text=Fraction(k1/4), fill="red",
font=('Times', 35))   # The middle of the road
k1=k1/2
k=k+1
ac_kn(1, knop1)
if k >= 5:
ac_kn(1, knop4)
```

Fig. 7. The infinity of the process (the results are shown in a step)

In this context, students learn about the concept of sequence limit. Achilles can get as close to the turtle as he wishes, but he will never be able to touch it (Figure 8).

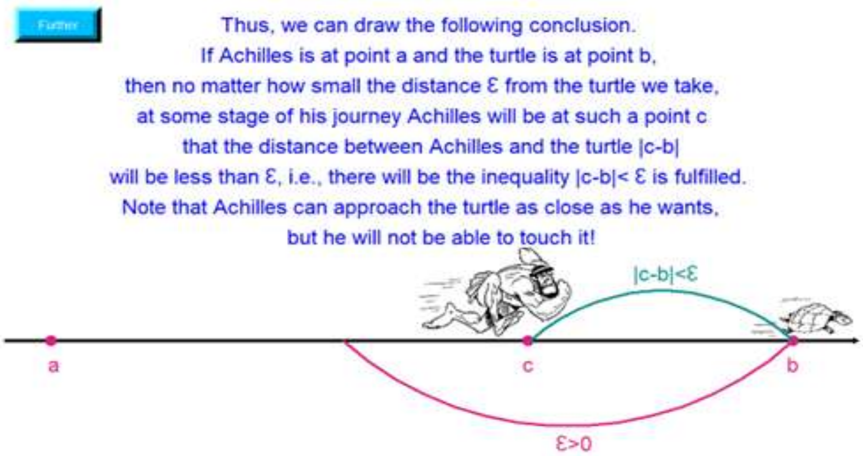

Fig. 8. The essence of the sequence limit

Example 3. In the "Limit" section, after defining the sequence, examples of various types of limits are provided (Figure 9).

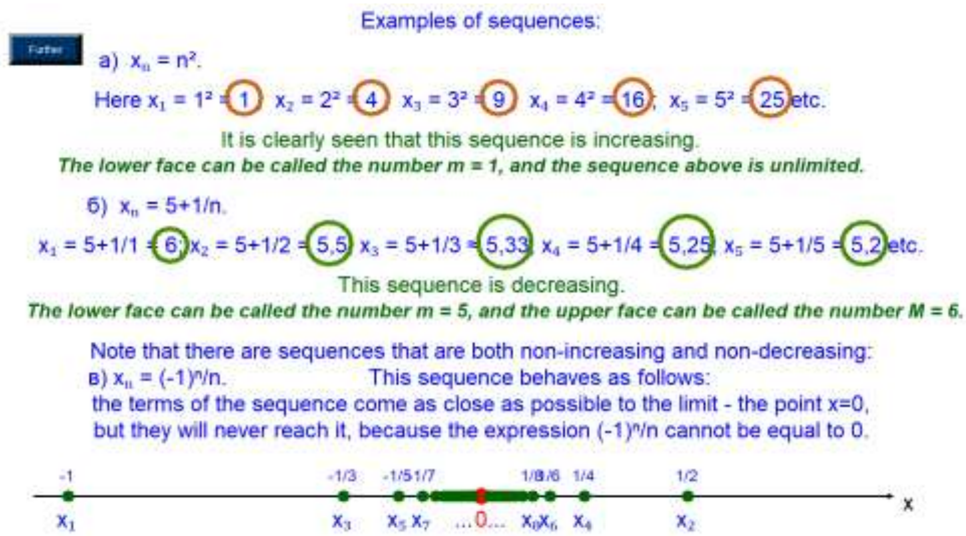

Fig. 9. Different kinds of sequences

Further, considering the increasing sequence on a straight line, the dependence is shown in dynamics N(ε) (Figure 10).

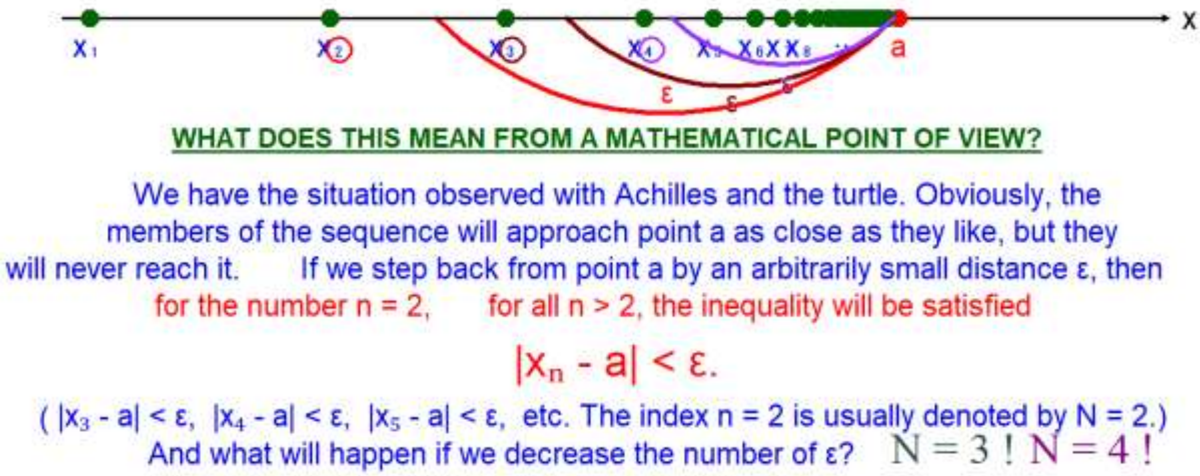

Fig. 10. Dependence of the number N on the choice of a specific ε

After all that has been studied, students are fully ready to perceive and assimilate the definition of sequence limit in verbal form and in the language of mathematics, which in turn removes all problems in determining of function limit.

3.2. Experimental results

The experiment, which lasted for 2021–2024, was carried out at the beginning of first half of the year during the study of discipline "Mathematics". In order to study the motivational factors of students, interests and taking into account the individual characteristics of personatity, representative control and experimental groups of 42 peoples were formed annually, and testing was conducted to assess the level of existing knowledge. After a certain period of time a repeated control survey was conducted for experimental groups were conducted with CPC using and in control groups are in traditional way. As a result of an experimental study the indicators values characterizing the degree of student's educational material mastering and learning material quality in mathematics were obtained. It corresponds to the formation of mathematical literacy parameters.

The leading indicators for first criterion is the degree of educational material mastering are *an assimilation parameter* of concepts volume ($\overline{K_p}$) and completeness parameter of an ability formation to operate with concepts when solving problems ($\overline{K_y}$). These parameters are determined by using the following formula:

$\overline{K_p} = \frac{\sum_{i=1}^{n} m_i}{nm}$, where m_i – number of an information module concepts learned by i-th student; m – number of key concepts needed to be learned in given information module; n – number of respondents who took part in testing.

$\overline{K_y} = \frac{\sum_{i=1}^{n} p_i}{np}$, где p_i – number of information block tasks correctly solved by *i*-th student; *p* – number of tasks that needed to be solved in given information module; *n* – number of respondents who took part in testing.

Table 1. Dynamics of changes in the values of indicators characterizing the degree of student's educational material mastering

Modules	Control group		Experimental group	
	$\overline{K_p}$	$\overline{K_y}$	$\overline{K_p}$	$\overline{K_y}$
1. Sequence limit	0,73	0,71	0,75	0,78
2. Function of single variable	0,71	0,72	0,78	0,79
3. Function limit	0,72	0,68	0,77	0,71
4. Continuity of function	0,60	0,73	0,76	0,82
5. Derivative	0,67	0,65	0,83	0,76
6. Applications of the derivative	0,59	0,68	0,81	0,75

For the purpose of analysis, Microsoft Excel TP and the Data Analysis add-in were used in conjunction with the "Paired Two-Sample t-Test for Means" function.

The average number of key concepts learned in each module of the course was selected as an independent variable. As a result of this analysis for an assimilation parameter $\overline{K_p}$ the following statistical data were obtained: $|t_{emp.}|$ = 6,3; which significantly exceeds $t_{cr.}(0{,}05)$ = 2,02 (in the condition of normal distribution samples and confirmation of H_0 – hypothesis). Therefore, we reject the null hypothesis. Therefore, the differences in the average values of knowledge acquisition indicators in the second sample are not random but systematic. Based on the completeness parameter $\overline{K_y}$ in the formation of skills for operating with concepts, the following statistics have been obtained: $|t_{emp.}|$ = 8,49, which significantly also exceeds the critical value $t_{cr.}(0{,}05)$ = 2,02.

The quality of learning of educational material in mathematics has been determined according to a methodology developed by the authors, using a coefficient that measures the depth of connections understanding between concepts. This indicator is calculated based on a definition of fractal dimension (D), which is an indicator of the interdisciplinary connectedness between concepts, and is calculated using the Hurst (H) indicator, which is related to the simple ratio D + H = 2, as presented in reference (Dvoryatkina, 2015). A detailed description of the algorithm for calculating the Hurst indicator can be found in that reference. The final formula for calculating this indicator is:

$$H = \frac{log(^R/_S)}{log(^n/_2)},$$

where S – standard deviation of learned concepts, R – scope of an accumulated deviation, n – number of respondents.

Table 2. Dynamics of values changes in H-Hurst index and indicator D of fractal dimension

Modules	Control group		Experimental group	
	H	D	H	D
1. Sequence limit	0,5037	1,4963	0,3802	1,6198
2. Function of single variable	0,4862	1,5138	0,4380	1,5620
3. Function limit	0,4879	1,5121	0,4116	1,5884
4. Continuity of function	0,5373	1,4627	0,5233	1,4767
5. Derivative	0,5663	1,4337	0,4527	1,5728
6. Applications of the derivative	0,4879	1,5121	0,4272	1,5690

Comparative statistical analysis of an interdisciplinary connectedness distribution of concepts in control and experimental groups allowed us to reject the null hypothesis - there are no reliable differences between the average values of an interdisciplinary connectedness index of concepts in control and experimental groups (t_{emp}=4,66> t_{cr} (0,05)=2,02).

The obtained result allows us to suggest that the practical implementation of CPC leads to a significant increase in the fractal dimensionality of mathematics education content, and as a consequence, to the establishment of deep connections of different levels, enhancing the quality of learning material in mathematics.

As a result of an experiment, it was proved that CPCs with the function of teaching and active animation cause a lively interest contribute to the activation of cognitive activity and significantly improve the level of student's mathematical literacy. Another advantage of this method can be considered as its application in extracurricular time.

4. Discussion

According to the results of surveys of 74 British educational organizations, it turned out that information technologies are most often used for convenience rather than for the development of teaching effectiveness (Erdem, Kocyigit, 2019). In Germany, education have been conducted to show the level of effectiveness of digital media use by university teachers and students. It turned out that both were poorly prepared to work in a collaborative digital environment (Setwyn, 2016). Things are no better in Australia, Spain, New Zealand, and the USA (Lai, Hong, 2015; Ivanovsky, 2021). American scientists led by R.E. Mayer (Mayer, 2020) saw great prospects for multimedia learning and gave a definition of multimedia learning, developed the principles of coherence, signaling, redundancy, spatial and temporal contiguity, segmentation, modality, etc. The fact that the experience of applying multimedia technologies, for example, in a pandemic situation, is very valuable and that it should be developed and expanded, as it seems to be very relevant in the way of improving the educational process, is stated in (Vetlugina, Fominykh, 2021). Many Russian scientists see in the application of multimedia technologies a new, more progressive approach to learning (Tikhaeva et al., 2020; Shakhbanov, 2020; Bondarenko, 2017). The article (Tuzkova, Chernyavskaya, 2023) emphasizes the importance of digital technologies and systems applying in education, as it makes the learning process more effective and interesting.

Competently written computer-based training programs (CBT) with built-in animation, as mentioned above, make the learning process more visual, attractive, activate it. The effectiveness of this method is shown in the works (Bogdanov, 2023; Oleinik, 2023; Shpagina, Nesterova, 2021; Zaporozhtseva, Zvereva, 2019), CPCs (Zhabina, Milyutina, 2021; Schweigert, 2019; Bakhmetyev, 2015; Nazarenko, 2014). It should be noted that there are few effective TMCs in mathematics. This is due to the fact that programmers-professionals do not possess the appropriate methodology, and mathematics teachers are mostly not programmers.

Some scientists (Meseşan, Albulescu, 2019; Perry et al., 2017) look on this mathematical literacy problem using different aspects of practice-oriented questions (nature, society, infrastructure, science, production). However, the operationality of student's cognitive activity not always led to effective results (Smirnov et al., 2021). Such an original direction is the technology of student's mathematical literacy managing in the development of complex knowledge generalized constructs. The data obtained by us are consistent with the opinion of the authors (Hašková, Malá, 2019; Wenner, Campbell, 2017) about the weak readiness of teachers to innovate using. It is revealed that the integration of mathematics and informatics play a central role in determining the various levels of mathematical literacy success. Thus, in student's mathematical and digital literacy managing based on complex knowledge investigation, using a rich information and educational environment for mathematics teaching in the direction of computer resources involving to mastering of mathematics education becomes a priority in modern high school. This should be realized in the course of step-by-step study of complex knowledge generalized constructs with computer support and the ability to effectively interpret the tasks from real life. The priority for students become the ability to use the computer knowledge and skills to solve problems in mathematics and obtain a new information for effective growth of creativity and critical thinking.

5. Conclusion

In the course of investigation, the authors developed a computer-based mathematics learning complex system and knowledge with animation elements, which allows to comprehensively form the basic mathematical knowledge and ensure the effective development of mathematical literacy. The developed criteria and indicators are able to provide an objective assessment the dynamics of student's mathematical literacy development in the process of learning mathematics, which makes a significant contribution to the expansion of organizational and methodological support in process of teaching mathematics with using of an innovative digital technology. The analysis of an empirical results of the study using a set of mathematical and statistical methods has shown the positive dynamics of mastering level of key mathematical concepts and methods for mathematics learning in the experimental groups, ensuring the validity of theoretical conclusions obtained earlier about the improvement of mathematical literacy level in the conditions of implementation of computer-based training program.

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