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USE OF DIGITAL TECHNOLOGIES TO DEVELOP RESEARCH AUTONOMY OF TERTIARY STUDENTS

Abstract. The aim of the study is to determine the effectiveness of using personalized digital ecosystems to develop research autonomy of Doctors of Philosophy (PhD) students. The study employed the following methods: longitudinal observations, calculation of indices of reflective activity and coefficients of strategic flexibility, and convergent parallel design. The study found that the development of students' autonomy is possible due to the transition from structured to configured digital environments. Personalized digital tools (Zotero, Obsidian, ATLAS.ti, Voyant Tools, NVivo, Overleaf, Open Science Framework, etc.) were used to train three independent cohorts (2021–2025). The proposed digital ecosystems statistically significantly contributed to the development of key components of autonomy: the level of cognitive independence increased from 2.8 to 4.1 points (d=1.61), and the strategic flexibility indicator from 1.5 to 3.7 (d=3.22). Analysis of behavioural logs confirmed the formation of individual work processes, where the experimentation coefficient reached 0.8 in an open environment. Systematicians (31 people) demonstrated a stable growth of autonomy to 4.0 points, and Adaptive Researcher (13 people) reached a maximum index of 4.6, which indicates the effectiveness of free choice of tools. The final comparison of the 2021–2023 cohorts did not reveal statistical differences ($F(2,65)=0.45$, $p=0.64$), which confirms the stability of autonomy development at the level of 4.0±0.8 points regardless of the year of the start of the study. The scientific novelty of the research lies in the empirical comparison of open configurable versus structured digital environments using objective behavioural log-data, the identification of three distinct developmental trajectories, and the confirmation of effect stability across three independent cohorts.The practical significance of the research is identifying effective digital architectures that contribute to the professional development of the researchers at the third level of higher education.

Keywords: research subjectivity; configured digital environment; cognitive strategies; three-level autonomy model; longitudinal experiment; students' autonomy.

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1. INTRODUCTION

Problem Statement. The current paradigm of higher education has undergone fundamental transformations under the influence of the intensive digitalization of the academic space [1], which required a rethinking of approaches to the training of academic staff. The processes of professional development at the third level of higher education have now gone beyond the usual transmission of knowledge, focusing on the ability to deep self-regulation. This educational level was defined as the final stage of formal training, aimed at obtaining a doctorate degree through conducting one's own research [2]. At the third level of higher education, not only the mastery of professional competencies is assumed, but also the production of new knowledge that has fundamental academic novelty and practical value [3].

The relevance of this problem is determined, first of all, by the objective need to train researchers capable of autonomous functioning in a dynamic and information-rich academic environment. The third level of education involves the highest degree of independence, so the development of research autonomy has become a critical factor in the successful completion of PhD programmes within the specified time frame [4]. In a global dimension, research activity has increasingly been considered as a key tool for the innovative development of society, which directly depends on the subjectivity of each individual author [5]. The authors of our study identified the crucial role of the digital ecosystem as one of the main factors in ensuring the intellectual independence of a young scholar [6].

In view of the general trend of higher education development, the issue of integrating specialized digital technologies into the everyday academic practice of postgraduate students is of particular importance [7]. The use of complex electronic platforms and extensive knowledge management tools is becoming an obligatory component of the training of future PhDs in various fields of knowledge. Despite the developed technological infrastructure of modern universities, the mechanisms of transition from external stimulation to sustainable internal research autonomy remain poorly studied [8]. New didactic challenges that require thorough academic analysis and experimental verification arise at the intersection of digital literacy and the personal subjectivity of the researcher.

In our study, research autonomy is understood as the students' comprehensive ability to independently determine priorities, choose methodology, and reflect on their own activities [9]. Digital technologies are interpreted as a set of cloud-based tools for bibliographic management and data analysis, which form a holistic ecosystem to support intellectual work [10]. Special attention is paid to tertiary students as a specific group whose professional self-realization requires the highest degree of cognitive independence. The personalized digital environment is considered by the authors as an individually configured set of services that meets the unique thinking strategies and information needs of each scholar [11].

The analysis of the current educational discourse enabled the authors of our study to identify a significant contradiction between the wide possibilities of digital ecosystems and their real impact on students' independence. It was established that formal access to high-tech resources does not automatically guarantee the development of the ability to think critically or design research independently. According to the authors, there is a significant gap in understanding the role of digital tools in the intellectual emancipation of a graduate student. Most of the existing studies focus on describing technical skills in working with software, largely ignoring the transformation of research identity in the context of digitalization of education.

Traditional approaches to the development of autonomy are mostly based on a linear model of interaction between the research supervisor and the student, where the role of technology was purely supportive. Currently, active implementation of learning management systems is proposed to structure independent work, but such solutions are often reproductive.

Existing methodological approaches often limit the researcher's creative freedom with rigid platform algorithms, which prevents the formation of flexible academic research strategies. The aforementioned limitations emphasize the need to develop new ways to support autonomy that would take into account the nonlinear nature of current academic communication and individual trajectories of the researcher's development.

The structured digital environment (Condition A) in the study was adopted as a necessary basis for the formation of research subjectivity. It provided a supporting algorithmic framework that satisfied the basic need for competence and security when performing complex tasks. The psychological mechanism of the self-determination model of prediction became the basis for the design of Condition B, where the open environment realized this freedom through the possibility of freely configuring tools. So, the two conditions represent successive stages of a single progressive process of autonomy development.

Within the scope of the study, three related constructs were identified. Research independence refers to the ability to perform specific research tasks without external supervision (task-oriented). Academic autonomy means institutional freedom to choose courses, topics, and study trajectories. Research autonomy acts as the central construct of this research and is defined as the integrative ability to independently determine research priorities, choose a methodology, build a research design, manage scientific work, and reflect on results. In contrast to research independence, research autonomy involves metacognitive regulation. Compared to academic autonomy, it is internally developed through practice, not provided by the institution.

The innovation of this study lies in shifting the focus from structured, algorithmically-driven digital environments to open, configurable ecosystems that foster research autonomy. Unlike prior research that emphasised technical skill acquisition, this study introduces objective behavioural log-data as indicators of metacognitive regulation. The scientific significance of the chosen direction is threefold: first, it bridges the gap between digital tool availability and actual autonomous research behaviour; second, it provides a longitudinal, cohort-sequential empirical validation of autonomy development; third, it offers a replicable model for PhD training in digitally rich environments.

The social significance of the problem is substantiated by the growing demand for highly qualified researchers capable of independent knowledge production in a rapidly changing world. Strengthening research autonomy directly enhances the quality of doctoral education, which in turn fuels scientific and technological innovation, economic competitiveness, and societal resilience. Thus, the study makes a tangible contribution to the development of education through evidence-based digital architectures, society by fostering self-regulated lifelong learning, and the state by improving the efficiency and output of national research systems. The implementation of a convergent parallel design ensures that quantitative and qualitative data are collected and analysed synchronously, providing depth to the statistical findings. Planning for a sample 20-30% larger at the initial stage further compensates for potential participant attrition during the longitudinal observation.

Several elements constitute the scientific novelty of this study. Open configurable digital environments were found to be associated with higher research autonomy than structured ones, as indicated by objective behavioural log-data (Cohen's d up to 3.22). Three developmental trajectories were identified, suggesting nonlinear growth dependent on metacognitive reflection. The effects proved stable across three cohorts ($F(2,65)=0.45$, $p=0.64$), and the large effect sizes are interpreted in terms of intrinsic motivation and self-determination theory.

Analysis of Recent Studies and Publications. The theoretical foundation of this study is based on the evolution of the concept of *Self-Directed Learning* in the context of the digital transformation of higher education. [12] consider autonomy as a multidimensional ability to

control one's own cognitive development. The study enabled the authors of this study to substantiate the structure of cognitive autonomy indices. The aforementioned approach is complemented by the ideas of [13],, who focus on the social nature of research independence, which is formed through active interaction in academic networks. Developing this idea, [14] points to the changing role of the academic mentor, who is transformed from a translator of knowledge to a facilitator of a complex technological environment.

The transition from guided to free academic research is impossible without taking into account the role of personalized learning environments (PLE), which are analysed in detail by [15] The researchers prove the dependence of the effectiveness of PhD training on the possibility of individual customization of the tools. In terms the theory of connectivism, [16] emphasize that modern autonomy consists in the ability to effectively navigate between information nodes, and not simply accumulate data. This thesis became the basis for the introduction of the strategic flexibility index, which was measured through the variability of the action algorithms of the participants in this study. At the same time, [17] employed the heutagogic approach and claimed that the highest level of autonomy is achieved only when the student independently builds the trajectory of his or her own academic research.

However, intensive digitalization carries certain risks, which [18] describes as "algorithmic pressure", which limits cognitive freedom through imposed templates. To overcome this determination, [19] propose to focus on reflexive activity within the landscapes of professional practice. The authors of our study transformed this position into a methodology for capturing reflexive indices through the analysis of return calls to their own content. The methodological guidelines of [20] confirmed the relevance of the chosen mixed design for capturing such complex intellectual constructs. Finally, [21] found a stable positive relationship between the use of open source software (OS) and the level of academic independence.

A critical synthesis of the available studies gives grounds to assert that there is a certain fragmentation in the understanding of the mechanisms of digital autonomy in the modern pedagogical discourse. Most researchers focus either on the psychological determinants of subjectivity or on the technical characteristics of individual platforms, ignoring the dynamic relationship between the architecture of the environment and the behavioural strategies of the researcher. Our study bridges this gap by introducing objective behavioural indices that enable measuring autonomy not as a static feature, but as a process of adaptive construction of research activity. So, the theoretical framework makes it possible to move from descriptive characteristics of digitalization to predictive modelling of the development of subjectivity of future PhDs. So, existing studies retain a validation gap of the long-term impact of the architecture of the digital environment on the dynamics of the development of autonomy. There is a lack of empirical data that would determine the impact of the configuration of tools on building of typical trajectories of research behaviour. This gap necessitates a longitudinal study that combines a controlled experiment with long-term observation of different cohorts of students.

The research goal. The aim of our study was to determine the patterns of influence of integrated digital ecosystems on the dynamics of development of research autonomy of tertiary students. The study is based on the conceptual idea of the role of digital technologies as a cognitive expansion of the student's research capabilities, and not just a means of automation. The authors proposed and tested a model of a personalized digital environment as an open space for making independent academic decisions. The aim involved the fulfilment of the following research objectives:

1. Compare the impact of a structured (*algorithmically specified*) environment and an open (*configurable*) environment on four specific indicators of autonomy in each of the three cohorts.

2. Classify typical trajectories of autonomy development according to three-year observation data.

3. Assess the stability of the identified patterns between three consecutive cohorts and to propose an optimal model of a personalized digital environment.

The hypothesis of the study is that an open digital environment leads to a higher level of research autonomy than a structured one.

The academic novelty of the study is deepening the understanding of the mechanisms of formation of autonomy of PhD candidates through a comparative analysis of activities in digital environments with different degrees of algorithmization. The study substantiates the use of objective log-data as reliable indicators of research subjectivity in order to verify the level of strategic flexibility beyond the subjective self-reports of the participants. New data were obtained on the dynamics of transformation of cognitive strategies of postgraduate students during the transition from structured to open ecosystems within the framework of long-term longitudinal observation. The reproducibility of the effects of autonomization was confirmed through the use of a cohort-sequential design, which allowed to identify stable patterns of students' behaviour regardless of the influence of contextual time factors.

2. RESEARCH METHODS

2.1 Research design

A cohort-sequential longitudinal design was used for combining the advantages of cross-sectional studies and long-term observation of the dynamics of students' development. The chosen approach provided the possibility of simultaneous comparison of different age cohorts of postgraduate students (1st and 2nd years of study) with parallel tracking of their research autonomy over several semesters. The choice of this design was justified by the need to distinguish the effects of the individual development of a scholar and the influence of external technological transformations within the educational process.

The first stage of the study was a conceptual justification of the mechanisms for the development of research autonomy in the context of intensive digitalization of the academic environment. The process was aimed at identifying the potential opportunities of digital technologies for ensuring the quality of training of tertiary students. *A cohort-sequential longitudinal design* was implemented in our study, which enabled combining the analysis of cross-sectional studies with long-term tracking of the dynamics of academic independence. At this stage, a theoretical framework was formed, which became the basis for conducting cyclical experimental interventions over several years.

The second stage of the study involved the implementation of sequential empirical data collection procedures using a convergent mixed approach. Quantitative and qualitative indicators were recorded in parallel for several independent streams of applicants who entered the experimental protocol at different time intervals. Each academic year was considered by the authors of our study as a separate cycle, which provided the opportunity to compare the experience of different groups of participants in the dynamics of their professional development. This approach verified subjective assessments of autonomy through objective indicators of activity in the use of bibliographic managers and academic networks.

The third stage of the study was devoted to the integration and comparative analysis of the results obtained throughout the longitudinal period. This made it possible to identify the advantages of personalized digital ecosystems for the development of research independence, taking into account long-term experience of academic activity. The final stage was a comparison of the performance of different cohorts was carried out, demonstrating variable levels of mastery of digital tools.

2.2 Sampling

The study involved 68 full-time postgraduate students of the humanities at Alfred Nobel University (Dnipro) and Kyiv National University of Culture and Arts (Kyiv). The main criterion for selecting respondents was academic status and the stage of work on the thesis. The study involved postgraduate students who began their studies in the period 2021-2023 to form three independent research cohorts. The choice of these categories of participants was determined by the need to have basic experience in academic activity for further improvement of research autonomy. The possibility of involving individuals at the stage of completing their thesis was considered, however, the high intensity of their final preparation could distort the results of the experimental impact. The level of proficiency in digital tools among the respondents ranged from medium to high, which was confirmed by the results of pre-testing and academic indicators.

The participants were divided into three groups according to the time of their entry into the experimental protocol, which ensured continuity of observation over several years:

a. *Cohort 1* (n=22) began participation in 2021, including 14 people from the social and humanitarian and 8 people from the artistic profiles.

b. *Cohort 2* (n=24) entered the study in 2022, bringing together 15 representatives of the humanities and 9 representatives of the arts.

c. *Cohort 3* (n=22) began the protocol in 2023, including 14 applicants from the social and humanitarian direction and 8 specialists in the field of culture.

Equal conditions were ensured for all participants and the principles of academic ethics were observed throughout the study period.

No traditional division into separate control and experimental groups was applied, because significant individual differences in baseline autonomy would have made homogeneous group formation difficult. Instead, a within-subjects crossover design was used, where each participant experienced both Condition A and Condition B in sequence. This means each person served as their own control, which helps eliminate selection bias. The sample size (n=68) may appear modest, but the statistical power for detecting large effects (Cohen's $d > 0.8$) exceeds 0.95. The evidence is further strengthened by the large effect sizes obtained (d up to 3.22) and the stable replication of results across three independent cohorts ($F(2,65)=0.45$, $p=0.64$).

Participants integrated specialized digital tools into their practice, selected based on their research objectives. The social and humanities profile used Zotero for bibliographic management, Obsidian for conceptual linkages, and ATLAS.ti for qualitative text analysis. The arts profile used Airtable for audio cataloguing, Tropy for organizing sheet music archives, and Sonic Visualiser for analysing sound patterns. All tools were integrated into a single workspace through platforms such as Notion or OSF, which allowed for the creation of a personalized digital ecosystem for each participant. The tools were selected based on a preliminary analysis of the functionality of over 30 different digital services for research work. The main criteria for selecting technologies were their ability to support autonomous search, bibliographic data management, and networked academic interaction. As part of the experimental approach, applicants used cloud platforms and citation managers to structure their own academic environment. The process of interaction with technologies involved separate stages, including the formation of a source database, systematization of materials, and presentation of intermediate results.

2.3 Methods

Two types of independent variables representing digital environments were defined in the study. The first condition (Condition A) involved working in a structured environment with an

algorithmically defined set of tools and a clear *workflow*. The second condition (Condition B) was based on the use of an open configurable environment, where researchers had the opportunity to freely choose the sequence of actions and customize interfaces. The dependent variables, which served as indicators of research autonomy, were measured through a system of behavioural patterns in the digital ecosystem.

Activity Log Module. This software module was integrated into the web portal for continuous registration of behavioural patterns of researchers by fixing the time stamps of each operation. The purpose of the tool was to objectify the process of academic research by counting the frequency of access to complex filtering and cross-referencing functions. Based on the obtained logs, the strategic flexibility index (the ratio of unique sequences of actions to the total number of attempts to complete typical research tasks) was calculated, which reflected the participant's ability to construct nonlinear algorithms for solving research tasks.

*Reflexive Analytics Dashboard***.** The tool was used to monitor metacognitive processes by tracking repeated access to created annotations and editing the structure of personal metadata. The depth of analysis was assessed by introducing a specific scale that differentiated technical editing from conceptual editing of research notes. Technical editing (changing the format, correcting errors) received 1 point, while conceptual editing (changing the structure of the argument, adding new connections) was evaluated at 3 points. The purpose of the panel was to identify the student's transition from reproductive accumulation of information to its critical and autonomous comprehension.

Cognitive Autonomy Scale.The intrinsic motivation to experiment compared to the default solutions was verified by using the reaction to new tools (Obsidian, ATLAS.ti, Airtable). The questionnaire was based on a 5-point Likert scale and contained subscales measuring the desire for innovation and resistance to algorithmic pressure. The purpose of the tool was to determine the readiness of the applicant to independently design the working environment in conditions of free choice (Condition B).

The effectiveness of the identified approaches to the development of autonomy was determined using the normative *coefficient(K_n)* developed by the authors.

$$K_n = \frac{V_{norm}}{V_{param}} \qquad (1)$$

Where V_{norm} – the maximum value accepted as normative for a specific cohort; V_{param} – the actual value of the autonomy indicator depending on the parameters of the digital environment. The calculations involved using *Cronbach's alpha* coefficient to assess the internal consistency of the indicators. A coefficient value > 0.9 indicated a strong influence of a single factor on the overall level of autonomy, while an indicator < 0.5 indicated low reliability of the indicator.

The study included three phases lasting 12 weeks for each cycle as part of longitudinal observation. At the baseline testing phase (T1), all participants performed a standardized task in a neutral environment to record baseline indicators. The experimental period involved the implementation of a *cross-over design*, where the first half of the group began work in Condition A, and the second – in Condition B (T2a). A complete switching of conditions was carried out after 6 weeks (T2b). At the final testing phase (T3), not only the productivity of academic search was recorded, but also the justification for the choice of specific tools in a free text field. The data were analysed in two planes: intra-cohort and inter-cohort. The intra-cohort analysis assessed the effectiveness of the intervention over one academic year using the paired *Student t-test* to compare values between phases. The inter-cohort analysis was based on the comparison of the results of the final testing between three independent cohorts of students. The *One-Way ANOVA* method was used for this purpose, which made it possible to confirm the stability and reproducibility of the results regardless of external time factors.

3. THE RESULTS AND DISCUSSION

Analysis of data from three longitudinal cohorts revealed a systemic impact of digital environment architecture on the dynamics of research autonomy development. The results demonstrate statistically significant differences between experimental conditions and stability of the effect over time. Each of the following conclusions is supported by rigorous inferential statistical methods. Intra-cohort analysis demonstrated the advantage of an open environment for all measured components of autonomy. The statistical power of the repeated-measures analysis of variance exceeded the recommended level of 0.95 for large effects. The size of the detected effects indicates the practical significance of the architectural solutions of the digital ecosystem (Table 1).

Table 1

Comparison of research autonomy indices in structured and open digital environments

Autonomy Index	Condition A (Struct.)	95% CI for A	Condition B (Open)	95% CI for B	t(67)	p	Cohen's d
Cognitive autonomy	2.8 ± 0.7	[2.6, 3.0]	4.1 ± 0.9	[3.9, 4.3]	9.34	<0.001	1.61
Strategic flexibility	1.5 ± 0.5	[1.4, 1.6]	3.7 ± 0.8	[3.5, 3.9]	18.71	<0.001	3.22
Reflexive activity	3.1 ± 0.6	[3.0, 3.2]	3.9 ± 0.7	[3.7, 4.1]	7.13	<0.001	1.23
Experimentation coefficient	0.3 ± 0.2	[0.25, 0.35]	0.8 ± 0.2	[0.75, 0.85]	21.55	<0.001	2.50

Note: The data are presented as M ± SD; CI – confidence interval; Cohen's d is interpreted as: 0.2 – small, 0.5 – medium, 0.8 – large effect. All calculations are performed for paired samples (n=68)

Source: Developed by the authors (2025)

The large effect sizes (Cohen's d > 0.8) indicate that open environments qualitatively transform research behaviour, not just improve scores. The high experimentation coefficient (d=2.50) suggests that free choice of tools fosters intrinsic motivation – a key psycho-pedagogical driver of autonomy. Narrow confidence intervals for Condition B indicate low variability in the participants' response to the open environment.

Hierarchical cluster analysis identified three statistically significant trajectories of the development of research behaviour. Validation of the cluster structure using the k-means method confirmed the stability of the grouping (sylus = 0.92). Each cluster represents a unique pattern of adaptation to the digital ecosystem, which is determined by the level of intrinsic motivation (Figure 1).

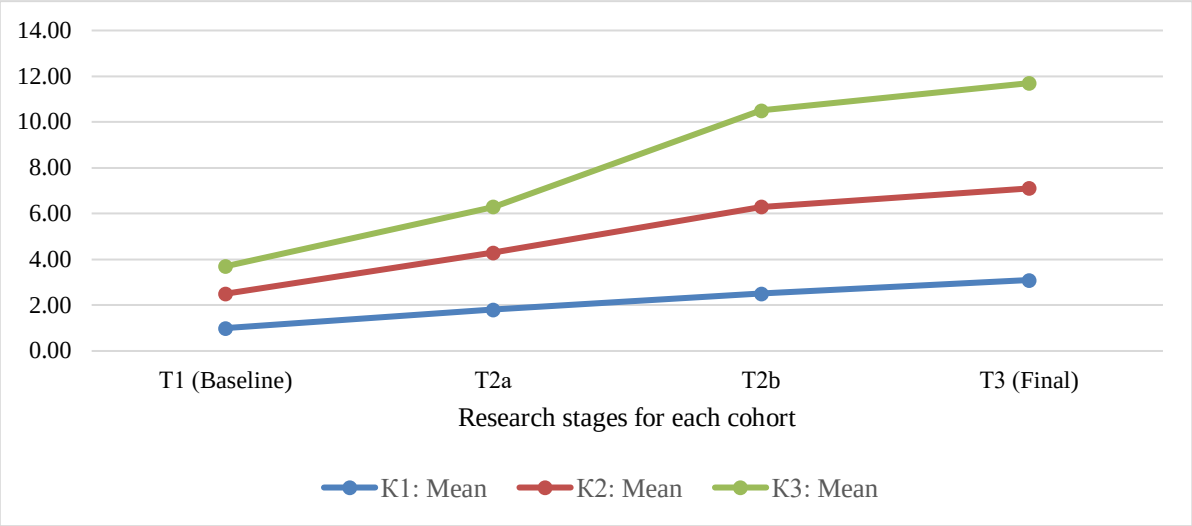

Figure 1. Dynamics of the integral autonomy index for the three identified clusters
Note: The dotted lines represent the 95% confidence intervals of the mean values for each measurement within the cluster
Source: Developed by the authors (2025)

The visualization demonstrates statistically different trajectories between clusters. The Adaptive Researchers cluster shows nonlinear accelerated growth after the adaptation phase. Non-linear accelerated growth in Cluster 3 after the adaptation phase indicates a threshold effect: once strategic flexibility reaches a minimum level, further gains occur autonomously through reflection and practice.

Analysis of the final results revealed structural differences between clusters, which is confirmed by strict statistical criteria (Table 2). The clusters demonstrate significant differentiation on key indicators of autonomy and experimentation. Comparison of groups using ANOVA and calculation of effect sizes confirm the significance of these differences.

Table 2

Comparative characteristics of clusters on final indicators (stage T2)

Parameter	**K1: Pragmatists (n=24)**	**95% ДІ**	**K2: Systematicians (n=31)**	**95% ДІ**	**K3: Adaptive Researchers (n=13)**	**95% CI**	**F(2, 65)**	**p**	**η^2**
Autonomy Index	3.1 ± 0.5	[2.9, 3.3]	4.0 ± 0.4	[3.8, 4.2]	4.6 ± 0.3	[4.4, 4.8]	58.7	<0.001	0.64
Experiment. Coefficient	0.4 ± 0.1	[0.35, 0.45]	0.7 ± 0.1	[0.66, 0.74]	0.9 ± 0.1	[0.85, 0.95]	102.3	<0.001	0.76
Cohen's d (K1 vs K3)	-	-	-	-	-	-	-	-	3.28

Source: Developed by the authors (2025).

Significant inter-cluster differences (η^2=0.64) reveal that learners with similar initial levels diverge due to metacognitive ownership, not just skill acquisition. Adaptive researchers actively reconfigure their workflows, which aligns with self-determination theory.A comparative analysis of three independent cohorts demonstrated a high degree of reproducibility of the experimental effect. One-way inter-subject ANOVA did not reveal systematic differences in the final results between years. Convergence of the confidence intervals of the integral index confirms the stability of the influence of the digital environment regardless of external factors (Table 3).

Table 3

Comparison of the results of the final testing (T2) between the three cohorts

Indicator	Cohort 2021 (n=22)	95% CI	Cohort 2022 (n=24)	95% CI	Cohort 2023 (n=22)	95% CI	F(2,65)	p
Integral index	4.0 ± 0.8	[3.7, 4.3]	3.9 ± 0.7	[3.6, 4.2]	4.1 ± 0.9	[3.7, 4.5]	0.45	0.64
Total performance	1.7 ± 0.3	[1.55, 1.85]	1.6 ± 0.4	[1.44, 1.76]	1.8 ± 0.3	[1.66, 1.94]	1.12	0.33
Cohen's d (max min)	-	-	-	-	-	-	0.25	-

Source: Developed by the authors (2025).

The absence of statistically significant inter-group differences ($p > .05$) and minimal Cohen's $d < 0.3$ effects for pairwise comparisons of cohorts confirm the stability hypothesis. Overlaying the 95% confidence intervals for the integral index in all three cohorts visualizes their statistical indifference. This indicates that the effect of the open environment is reliable and does not depend on the specific year of participation in the study.

The grouped bar chart visualizes the results of the comparative inter-cohort analysis at four key stages of the study (Figure 2). It clearly demonstrates the parallel dynamics of the growth of research autonomy in independent groups. The statistical similarity of the results is confirmed by the visual overlap of the confidence intervals at each stage.

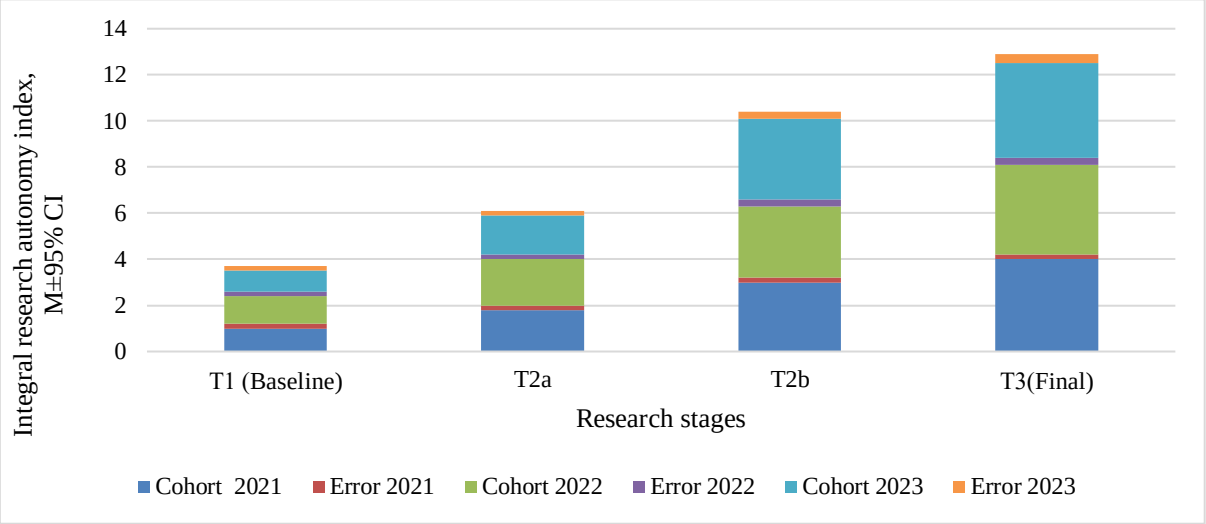

Figure 2. Dynamics of the mean values of the integral autonomy index with 95% confidence intervals for the three cohorts

Source: Developed by the authors (2025)

The diagram shows grouped columns for each cohort (2021, 2022, 2023) at four measurement stages (T1, Stage 1, Stage 2, T2). The vertical lines on the columns show 95% confidence intervals. The absence of statistically significant differences between the cohorts at each stage is confirmed by partial or complete overlap of the confidence intervals. The same positive dynamics of autonomy growth in all three groups is clear, confirming the stability of the intervention effect regardless of the year of participation in the study.

The results demonstrate a statistically confirmed predominant effect of the open digital environment on the development of all components of research autonomy, with large effect sizes (Cohen's d from 1.23 to 3.22). Cluster analysis revealed three stable typical development

trajectories, where Adaptive Researchers achieved significantly higher results compared to Pragmatists (d=3.28). Inter-cohort comparison confirmed high reproducibility and stability of the effect over time, as no statistically significant differences were found between the results of the three independent cohorts ($p > 0.05$). So, the architecture of the digital ecosystem as a cognitive extension determines not only the level, but also the nature of the dynamics of students' research autonomy development.

The introduction of personalized digital ecosystems into the training of PhD students is considered as a mechanism for stimulating autonomous research strategies. This approach is focused on giving participants the right to independently choose the tools for solving academic research tasks. The analysis of behavioural patterns made it possible to increase the level of cognitive independence and reflection. [22] this process ensures the active researchers' involvement in overcoming the problems of autonomization. The synchronization of individual and network work formats is realized through the effect of digital presence. It is emphasized that high-quality training of scholars is based on reflexive adjustment of interaction with methodological content. According to [23], the creation of adaptive environments guarantees equal opportunities for students' professional development.

Existing studies focus on the perception of information through the telepresence effect [24]. In our study, the emphasis is shifted to the effectiveness of combining Condition A (structured environment) and Condition B (configured environment). It was found [25] that the integration of strategic planning and action logging contributes to the development of an individual *workflow*[26]. An increase in autonomy indices was achieved in three independent cohorts through the consistent combination of algorithmic and free learning. The data on cluster K3 (Adaptive researchers) confirm a positive correlation between the level of self-regulation and willingness to experiment in Condition B.

At the same time, the literature notesthat hybrid environments can cause additional burden on moderators [27]. In contrast to the results of [28] the data refute the risk of critical cognitive overload for applicants. It is shown that the previous stage of work in a structured environment (Condition A) minimizes the negative effects of subsequent free choice. The risk of disorientation is confirmed only if algorithms are completely absent in the initial stages [29]. However, the study verified the possibility of a successful transition to full autonomy thanks to a cross-sectional design. In our study, the main attention is paid to the personalization functions, which led to an increase in the strategic flexibility of the participants.

An analysis of the publications indicates their focus on the study of virtual technologies for storing information [30]. The issue of autonomy has often been considered as a static characteristic, rather than a dynamic process [31]. Our study recorded longitudinal changes that were implemented through a web portal with different architectures. Approaches that contribute to the development of skills for autonomous management of digital tools were identified. The practical significance of the results is the possibility of introducing open ecosystems into the educational process of PhDs. The presented criteria for working in configurable environments ensure an increase in the quality of academic training.

4. CONCLUSIONS AND PROSPECTS FOR FURTHER RESEARCH

This study aimed to determine the effectiveness of personalized digital ecosystems for developing research autonomy in PhD students. The main hypothesis – that an open digital environment leads to higher autonomy than a structured one – was supported by the data. The open configurable environment (Condition B) produced significantly higher scores on all autonomy components compared to the structured environment (Condition A), with large effect sizes (Cohen's d from 1.23 to 3.22). The experimentation coefficient reached 0.8 in the open environment, suggesting that free choice of tools fosters intrinsic motivation. Three distinct

developmental trajectories were identified: Pragmatists (n=24), Systematicians (n=31), and Adaptive Researchers (n=13). Adaptive Researchers achieved the highest autonomy index (4.6), indicating that metacognitive reflection and willingness to experiment are key drivers of autonomous research behaviour. The effects proved stable across three independent cohorts (2021–2023), with no statistically significant differences between them ($F(2,65)=0.45$, $p=0.64$). This confirms that the observed patterns are reproducible and not dependent on the year of study entry. The practical significance of the study lies in identifying effective digital architectures (Zotero, Obsidian, ATLAS.ti, etc.) and principles for configuring open ecosystems that support research autonomy. Prospects for further research. Further research may focus on comparing traditional environments with AI-supported ecosystems, expanding the sample to more higher education institutions, and investigating the long-term sustainability of autonomy gains after the completion of the PhD programme.

5. LIMITATIONS

Despite the obtained results, the authors of our study identified a number of methodological limitations related to the design and sampling parameters. In particular, it was decided to abandon the traditional division into stationary EG and CG. This limitation was determined by significant individual differences in the basic level of autonomy of PhD students, which made it difficult to form groups identical in all parameters. The influence of personal characteristics on the result was eliminated by using an *within-subjects design*, where each participant was consistently in the role of a control object and a subject of experimental influence.

An important limitation was the localization of the research base, which covered only two higher education institutions (HEIs) – Alfred Nobel University and Kyiv National University of Culture and Arts. Although the involvement of institutions of various profiles enabled taking into account the interdisciplinary specifics, the limited geographical and institutional coverage prevents a broad generalization of the conclusions to the entire higher education system. The number of participants (n=68) was also a certain limiting factor for the application of multivariate analysis methods with a large number of variables. However, the use of three independent cohorts partially compensated for this aspect by checking the reproducibility of effects in different time frames.

The established limitations on the sample size were minimized by implementing a *cross-over design*, which provided high statistical power with a relatively small number of respondents. The distribution of participants at the level of the sequence of stages enabled the authors of this study to assert a causal relationship between the structure of the digital environment and the autonomy indices. In further research, it is planned to expand the circle of HEIs involved to verify the obtained patterns in a broader academic context. The indicated limitations do not reduce the academic value of the results, but only outline the boundaries of their interpretation and indicate promising directions for future studies.

6. RECOMMENDATIONS

The authors recommend integrating practical modules on building digital ecosystems into postgraduate curricula. Academic supervisors should move from instruction to facilitation of the process of researcher’s digital self-organization. The postgraduate student evaluation system should be supplemented with monitoring of objective indices of research autonomy. The creation of interdisciplinary laboratories will provide methodological and technical support

for experimental research processes. It is necessary to transform separate computer literacy courses into a system of continuous digital support at all stages of academic research.

AUTHOR CONTRIBUTIONS

Iryna Oliinyk: Conceptualization; methodology; formal analysis of longitudinal observations; writing – original draft preparation.

Andrii Bondarenko: Investigation; data curation and processing of behavioral logs; visualization of statistical data (Figures 1 and 2); writing – review and editing.

Nataliia Volkova: Project administration; supervision of the PhD student training cycles; theoretical validation of the research subjectivity model; validation of the cluster structure.

Olha Lebid: Resources; software selection and criteria development (Zotero, Obsidian, ATLAS.ti, etc.); validation of cognitive autonomy indices; revision of the practical recommendations.

Oleh Lavnikov: Investigation; data collection during experimental phases T1, T2, and T3; formatting and technical preparation of the manuscript.

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ВИКОРИСТАННЯ ЦИФРОВИХ ТЕХНОЛОГІЙ ДЛЯ РОЗВИТКУ ДОСЛІДНИЦЬКОЇ АВТОНОМІЇ СТУДЕНТІВ ЗАКЛАДІВ ВИЩОЇ ОСВІТИ

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Анотація. Метою дослідження є визначення ефективності використання персоналізованих цифрових екосистем для розвитку дослідницької автономії студентів-докторантів. У дослідженні використовувались такі методи: поздовжні спостереження, розрахунок індексів рефлексивної активності та коефіцієнтів стратегічної гнучкості, а також конвергентний паралельний дизайн. Дослідження показало, що розвиток автономії студентів можливий завдяки переходу від структурованих до конфігурованих цифрових середовищ. Для навчання трьох незалежних когорт (2021–2025) використовувались персоналізовані цифрові інструменти (Zotero, Obsidian, ATLAS.ti, Voyant Tools, NVivo, Overleaf, OpenScienceFramework тощо). Запропоновані цифрові екосистеми статистично значуще сприяли розвитку ключових компонентів автономності: рівень когнітивної незалежності зріс з 2,8 до 4,1 балів (d=1,61), а показник стратегічної гнучкості — з 1,5 до 3,7 (d=3,22). Аналіз поведінкових журналів підтвердив формування індивідуальних робочих процесів, де коефіцієнт експериментування досяг 0,8 у відкритому середовищі. Систематики (31 особа) продемонстрували стабільне зростання автономності до 4,0 балів, а адаптивні дослідники (13 осіб) досягли максимального показника 4,6, що свідчить про ефективність вільного вибору інструментів. Остаточне порівняння когорт 2021–2023 років не виявило статистичних відмінностей ($F(2,65)=0,45$, $p=0,64$), що підтверджує стабільність розвитку автономії на рівні 4,0±0,8 балів незалежно від року початку навчання. Практичне значення дослідження полягає у визначенні ефективних цифрових архітектур, що сприяють професійному розвитку дослідників третього рівня вищої освіти.

Ключові слова: суб'єктивність досліджень; сконфігуроване цифрове середовище; когнітивні стратегії; трирівнева модель автономії; поздовжній експеримент; автономія студентів

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