SECTION «PEDAGOGICAL SCIENCES»

ENHANCING THE EFFECTIVENESS OF DEVELOPING SPATIAL IMAGINATION IN TECHNICAL EDUCATION STUDENTS THROUGH AXONOMETRIC PROJECTION

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Abstract. The study substantiates an approach to enhancing the effectiveness of developing spatial imagination in students of technical fields through axonometric projection. The relevance of the study is determined by the difficulties students encounter at the initial stage of learning graphical disciplines when moving between a spatial object and its two-dimensional graphical representations. A methodological system of proactive axonometric projection is proposed, in which the axonometric image is used not only as a means of visually representing an object but also as an active intermediate link between spatial perception and orthographic projection. The methodology involves sequential spatial analysis, construction of an axonometric sketch, creation of orthographic projections, reconstruction of the spatial representation, and subsequent digital verification of the graphical solution. The experimental verification was conducted during the 2024-2025 academic year at Central Ukrainian National Technical University with first-year students enrolled in H7 "Agricultural Engineering" and G11 "Industrial Mechanical Engineering," who were divided into experimental and control groups. PSVT, MCT, and professionally oriented graphical tasks were used to assess effectiveness. The results demonstrated more pronounced positive dynamics in spatial imagination in the experimental group compared with the control group, supporting the appropriateness of systematic proactive

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use of axonometric projection. At the same time, the results characterize the studied sample and cannot automatically be generalized to all students in technical specialties. Promising directions for further research include expanding the sample, testing the methodology under different educational conditions, and further improving it.

INTRODUCTION

Modern training of technical specialists involves not only the acquisition of theoretical knowledge and mastery of digital design tools, but also the development of the ability to operate with spatial representations of technical objects. Spatial imagination enables learners to establish relationships between the shape, dimensions, and relative positions of structural elements, perform mental transformations of these elements, and move between different forms of graphical representation. Its development is an important prerequisite for successful learning of descriptive geometry, engineering graphics, computer modeling, and subsequent professional activity in technical fields.

This issue is particularly important at the initial stage of higher education, when students first systematically encounter the need to relate a spatial object to its graphical representation. Studies [1-4] show that some first-year students have insufficiently developed spatial representations and experience difficulties when studying graphical disciplines. At the same time, students' prior graphical preparation may be heterogeneous, which complicates the acquisition of material based on a rapid transition from a spatial object to a system of its two-dimensional projections.

One of the central problems at the initial stage of learning is the need to move between different forms of representation of the same object. Orthographic projections are a necessary and formalized means of conveying design information; however, their interpretation requires students to independently reconstruct an integral spatial representation from a set of planar images. For students with insufficiently developed spatial skills, such activity may create a substantial cognitive load. At the same time, modern digital visualization tools make it possible to perceive three-dimensional form directly, but they do not eliminate the need to develop the ability to independently transform spatial information and present it in a formalized graphical form.

Therefore, there is a need to identify instructional tools that can provide a gradual transition from an integrated spatial perception of an object to its formalized graphical representation. Axonometric projection is one promising means of facilitating this transition, as an axonometric image combines the visual clarity of spatial form with the possibility of graphically reproducing the structural features of an object. Importantly, this should involve not only perceiving a ready-made axonometric model, but also students' independent construction of an axonometric sketch, which requires the active transformation of a spatial representation into a graphical form.

Thus, a contradiction arises between the need for a high level of spatial imagination for successful mastery of technical disciplines and the difficulties involved in developing it at the initial stage of learning, on the one hand, and the availability of modern and traditional visualization tools that are not always integrated into a methodologically consistent system, on the other. Resolving this contradiction requires substantiating an approach to graphical training in which the axonometric image is used not merely as an illustrative or auxiliary tool, but as an active stage in the formation and transformation of a spatial representation before the transition to orthographic projection.

The aim of the study is to enhance the effectiveness of developing spatial imagination in students of technical fields by substantiating and applying axonometric projection as a means of actively developing spatial-graphical representations at the initial stage of learning.

1. Problem Statement

Modern professional activity in technical fields involves continuous work with spatial representations of technical objects, their elements, and their relative positions. Spatial imagination enables a person to perceive an object's shape, establish spatial relationships between its parts, perform mental transformations, and move from a graphical image to an integral spatial representation. For specialists in technical fields, this ability is an important component of professional training, since a substantial part of engineering activity involves reading, analyzing, and creating technical documentation, as well as designing and spatially analyzing machines and mechanisms [5-7].

The importance of spatial imagination is particularly evident in agricultural engineering and industrial mechanical engineering. An agricultural engineer works with complex technical systems whose structural elements have different spatial positions and interact during technological operations. Analyzing the design of agricultural machinery, selecting and adjusting working components, and determining the relative positions of parts and assemblies require the ability not only to perceive individual elements but also to form an integral representation of the machine's spatial structure [7-9].

In industrial mechanical engineering, spatial imagination is essential for reading assembly and working drawings, determining the shape of parts from their projections, analyzing the relative positions of structural elements, and creating new technical solutions. An engineer must be able to move from a graphical representation of an object to its spatial representation and, conversely, from an imagined or directly observed form of an object to its graphical representation. This ability enables the meaningful use of engineering graphics as a means of professional communication and design activity [10-12].

At the same time, spatial imagination does not develop automatically through learning the rules for constructing technical drawings. Research on students' graphical preparation indicates difficulties in developing spatial representations precisely at the initial stage of learning. In particular, Ukrainian researchers note that first-year students may have insufficiently developed spatial representations when studying descriptive geometry and graphical disciplines, which complicates the completion of graphical tasks and the acquisition of learning material [13; 14]. The problem of insufficient initial graphical preparation has also been identified in studies devoted to developing the graphical skills of future specialists [15; 16].

A particular difficulty is establishing correspondence between a spatial object and its two-dimensional graphical representation. When working with orthographic projections, students must correlate individual images, determine the relative positions of their elements, and use this information to reconstruct the spatial form of the object. Studies conducted with engineering students show that errors in working with orthographic projections are directly associated with difficulties in spatial visualization [17]. Similar difficulties have been identified in engineering drawing

instruction, particularly when moving between a two-dimensional graphical representation and a three-dimensional representation of an object [18].

Thus, at the initial stage of learning, students must simultaneously master graphical language, projection rules, and methods of spatial analysis of an object. This situation may create additional difficulties for students who lack sufficient prior experience with technical drawings and spatial models. From the perspective of cognitive load theory, acquiring a large number of interrelated new elements in the absence of sufficient prior knowledge may complicate learning activities [19]. Therefore, the problem of developing spatial imagination cannot be considered separately from the way graphical information is organized and presented.

The situation is further complicated by changes in the information environment of contemporary students. A substantial proportion of students have experience with digital graphics, three-dimensional models, and interactive visual representations before entering higher education. Prensky [20] associates the development of the contemporary generation of students with constant interaction with the digital information environment. At the same time, the widespread use of digital technologies does not automatically imply the ability to read technical drawings or perform spatial transformations. On the contrary, contemporary research points to the importance of how visual-spatial information is organized and of the nature of the cognitive operations students perform when interpreting it [21; 22].

Thus, a contradiction arises between the high demands of modern professional activity on the level of spatial imagination required of future specialists and the actual difficulties involved in developing it at the initial stage of higher education. On the one hand, students must learn to work with formalized orthographic projections, which form the basis of technical documentation; on the other hand, successful understanding of such projections already requires the ability to form an integral spatial representation of the object.

Therefore, there is a need for an approach to organizing initial graphical training that would provide a gradual transition from direct spatial perception of an object to its formalized graphical representation. One potentially effective means of such a transition is axonometric projection, since it makes it possible to represent several spatial coordinates

of an object simultaneously on a plane while preserving the integrity of its visual representation [10; 23]. Experimental studies of systematic practice in isometric and other spatial sketching also indicate the potential positive influence of such activity on the development of spatial visualization among engineering students [24; 25].

Therefore, the research problem lies in the need for a scientific and methodological substantiation of an approach to organizing the initial stage of graphical training in which axonometric projection is used not merely as an auxiliary means of depicting an already formed spatial representation, but as an active means of its formation, transformation, and consolidation before moving to more complex forms of graphical representation, particularly orthographic projections.

2. Analysis of Recent Research and Publications

The problem of developing spatial imagination in students of technical specialties is addressed in psychological and pedagogical research, methods of teaching graphical disciplines, and contemporary approaches to the use of digital visualization tools. Analysis of the scientific literature makes it possible to identify several interrelated areas important for substantiating effective means of initial graphical training: research into the mechanisms of spatial visualization, examination of difficulties in working with technical graphical representations, the use of sketching as a means of actively developing spatial representations, and the use of digital three-dimensional tools in education.

In psychological and pedagogical research, spatial imagination is viewed as a complex ability that enables operations with spatial objects and their graphical representations. Hegarty [5] considers spatial intelligence to be a set of interrelated abilities associated with encoding, storing, transforming, and using spatial information. This approach is important for technical education because engineering work involves not only perceiving the form of a real object but also continuously transforming information between different forms of representation.

Research by Ukrainian scholars confirms the importance of spatial thinking specifically for learning graphical disciplines. Karpiuk L.V. and Davidenko N.O. draw attention to the difficulty's students encounter when studying descriptive geometry and engineering graphics and emphasize the

need for purposeful development of spatial representations [13]. Similar issues are addressed in the study by Mamus H., where spatial thinking is defined as an important indicator of the intellectual development of higher education students [14].

Directly related to the training of future technical specialists is the study by Shostachuk A., devoted to developing the spatial imagination of future mechanical design engineers. The author considers graphical activity an important means of developing the future specialist's ability to operate with spatial representations and work with technical images [7]. The findings of Ukrainian researchers provide grounds for considering the development of spatial imagination not as an additional component of graphical training, but as one of its fundamental elements.

Also important is study [16], which examines the specific features of developing spatial imagination among bachelor's students at Ukrainian higher technical education institutions during a basic course. The authors emphasize difficulties associated with students' initial level of spatial preparation and the need for special organization of the educational process to develop it. This makes it possible to regard the initial stage of learning as a distinct methodological problem requiring a purposeful selection of means for developing spatial-graphical skills.

One of the central issues in engineering graphics research is the student's ability to establish correspondence between a three-dimensional object and its two-dimensional graphical representation. This ability is fundamentally important for reading technical drawings because individual orthographic projections contain only part of the information about an object's spatial form.

Study [17] examined the process of teaching spatial visualization using orthographic projection tasks, analyzed engineering students' errors when constructing orthographic projections, and showed that the nature of such errors may be associated with difficulties in spatial visualization. This confirms the need to view the teaching of orthographic projection not only as the acquisition of construction rules but also as the development of the ability to move between different spatial representations.

A similar problem is addressed in study [18], which focuses on students' difficulties in learning engineering drawing. The authors note the difficulty of visualizing three-dimensional objects from two-dimensional

images and, conversely, of moving from a graphical representation to a spatial representation. The use of an augmented reality environment in this study was considered a means of providing additional visual support for overcoming these difficulties. Thus, studies [17; 18] help specify one of the key problems of initial learning: students need not merely to know the rules for constructing projections but to develop the ability to move in both directions between a spatial object and its graphical representation. This ability should be taken into account when determining the sequence and means of teaching graphical disciplines.

A separate research area comprises studies examining the effects of targeted spatial training and graphical sketching on the development of students' corresponding abilities. One of the foundational studies in this area is the work of Sorby S.A. [26], which describes a specially designed course for developing three-dimensional spatial visualization among first-year engineering students. The course included tasks involving isometric sketching, multiview drawings, spatial transformations, object rotations, and sections. The results demonstrated the possibility of purposefully developing spatial visualization through specially organized instruction.

A further development of this approach is presented in study [12], devoted to developing three-dimensional spatial skills among engineering students. The author considers spatial visualization a skill that can develop as a result of systematic learning activity rather than merely a stable individual characteristic of a student.

The effectiveness of freehand technical sketching was directly investigated in study [24], where a controlled study of engineering students compared the results of groups receiving different amounts of freehand sketching instruction. The program included, among other activities, orthographic and isometric sketching exercises. The authors found a statistically significant improvement in spatial visualization performance among students who completed the extended sketching program compared with the control group.

A similar line of research is presented in study [27], which examined the effect of specially organized instruction in freehand sketching and spatial visualization for first-year engineering students. The results further support the value of combining spatial tasks with active graphical activity.

Of particular importance for our study is the fact that the cited works consider sketching not merely as a means of graphically recording an already formed representation, but as an activity in which students directly work with spatial information. The use of isometric and other axonometric representations is especially significant because they make it possible to combine spatial visualization with the need for students to independently construct a graphical representation.

At the same time, the cited studies focus predominantly on the development of spatial visualization and sketching as separate types of learning activity. This leaves open the question of the methodologically substantiated integration of axonometric projection into the structure of initial descriptive geometry instruction and its systematic use as an intermediate link between spatial perception of an object and formalized orthographic projection.

The development of digital technologies has substantially expanded the possibilities for representing spatial objects in the educational process. Three-dimensional computer models, interactive graphics, and augmented reality technologies make it possible to change the viewing angle, scale, and mode of representing an object, thereby creating additional opportunities for studying its spatial structure.

The cognitive aspect of using visual-spatial representations is examined in detail by Hegarty [21], who emphasizes that graphical representations can serve as external supports for spatial thinking; however, the effectiveness of their use depends on the structure of the representation, the nature of the task, prior knowledge, and the way it is interpreted. This point is particularly important for engineering graphics: the mere presence of a three-dimensional representation does not mean that students have developed the ability to independently operate with spatial representations.

Study [22] investigated different strategies of spatial thinking using diagrams and showed that different approaches to spatial transformation and reasoning may be applied when working with graphical representations. Therefore, in educational settings, graphics should provide not only access to a visual representation of an object but also conditions for students to actively perform spatial operations.

The use of digital visualization in engineering graphics is also examined in studies devoted to augmented reality. In particular, [18] demonstrated the

possibility of using an AR environment to support students in understanding the relationship between two- and three-dimensional representations. Study [24] also examines the influence of three-dimensional mobile augmented reality on engineering drawing learning outcomes among students with different levels of spatial ability.

Thus, digital tools provide substantial opportunities for visual representation of spatial form; however, they should be regarded as means of supporting learning activity rather than as substitutes for students' independent spatial-graphical operations. A ready-made three-dimensional model facilitates perception of spatial structure, whereas constructing one's own graphical representation requires students to actively transform the spatial representation.

The analysis shows that contemporary research pays considerable attention to the importance of spatial visualization for technical education [5; 11-15], difficulties in moving between two- and three-dimensional representations when learning engineering graphics [17; 18], and the positive effects of specially organized spatial training and freehand sketching [21; 25; 26].

At the same time, the systematic use of axonometric projection specifically at the initial stage of learning as a means of forming a spatial representation followed by a transition to orthographic projections remains insufficiently explored. Most of the approaches considered either focus on the development of spatial visualization as a separate ability or examine the effectiveness of sketching, digital visualization, or augmented reality as individual instructional tools.

Accordingly, further substantiation is needed for an organization of graphical training in which the axonometric image performs not merely an illustrative function but becomes an active link in the transition from an integral spatial perception of an object to its formalized graphical representation. In this context, combining visual three-dimensional visualization, independent axonometric sketching, and subsequent transition to orthographic projection appears promising.

2.1 Barriers to Developing Spatial Imagination in Contemporary Learning Conditions

The analysis of scientific research provides grounds for considering difficulties in developing spatial imagination among students of technical

specialties not as the consequence of a single factor, but as the result of the interaction of several factors. At the initial stage of learning, students must simultaneously master a system of graphical symbols and projection rules, learn to establish correspondence between different types of images, and develop the ability to independently operate with spatial representations. With insufficient prior experience, this combination of requirements may create substantial difficulties [13; 16; 19].

One of the basic barriers is the heterogeneity of students' initial level of preparation. At the beginning of higher education, students may differ substantially in their experience with technical drawings, technical images, spatial models, and graphical software [13; 14; 16]. Under such conditions, the same sequence of material presentation may have different levels of difficulty for different students. A student who has already developed spatial analysis skills may focus on mastering projection rules, whereas a student with insufficient prior preparation must simultaneously master the very principle of spatial representation of an object. Therefore, at the initial stage, it is particularly important to create a system of learning activities that gradually develops spatial representations and provides a foundation for subsequent mastery of graphical language.

A second significant barrier is the need to reconstruct an object's spatial form from its two-dimensional projections. Orthographic projection is a necessary basis of technical documentation; however, an individual image represents only a particular aspect of a spatial object. To form an integral representation, students must correlate several projections, establish correspondences between their elements, and mentally integrate the information obtained [17; 18].

Research into students' errors when constructing orthographic projections shows that difficulties arise specifically when correlating a two-dimensional graphical representation with the spatial configuration of an object [17]. Similar problems have been identified in engineering drawing instruction, where students need to move between two- and three-dimensional representations [18].

Thus, the problem is not limited to a student's lack of knowledge of the rules for constructing a particular projection. Even with correct mastery of individual rules, students may experience difficulties when combining several planar images into an integral spatial representation. This determines

the need to include tasks in initial graphical training that are specifically aimed at developing transitions between different ways of representing an object.

Another barrier is the simultaneous acquisition of a large number of interrelated concepts and operations. When studying descriptive geometry, students must work with projection planes, the positions of geometric elements, rules for constructing images, conventional symbols, and spatial relationships between them. For a student who has not yet developed the relevant basic schemas, performing these operations simultaneously may place a substantial load on working memory. Within cognitive load theory, the effectiveness of learning new material is associated, among other things, with prior knowledge and established cognitive schemas [19]. Applying this principle to graphical training suggests that the difficulty of initial topics is determined not only by the amount of new material but also by the need to perform spatial and formal-graphical operations simultaneously.

Therefore, one methodological task is to reduce the gap between direct perception of spatial form and its formalized graphical description. The learning sequence should provide for a gradual increase in the complexity of spatial operations rather than require students to perform all necessary transformations simultaneously.

The contemporary educational environment is characterized by widespread use of digital graphics, three-dimensional models, and interactive visualization tools. Such tools enable direct observation of a spatial object, changes in its viewing angle, and examination of individual structural elements. Prensky's concept of "Digital Natives" links the contemporary learning experience of young people with continuous interaction with digital technologies [20].

However, experience interacting with digital three-dimensional objects does not automatically result in the ability to independently construct spatial representations. Hegarty [21] views visual-spatial representations as external tools that can support cognitive activity, but the effectiveness of their use depends on the nature of the task, the structure of the representation, and the way it is interpreted.

This makes it possible to distinguish between two types of learning activity. In the first, students observe a ready-made three-dimensional model and can explore it by changing the viewing angle. In the second,

they independently transform the spatial representation into a graphical representation. The first activity provides visual support, whereas the second requires active spatial transformation. The development of stable spatial imagination requires the presence of both components.

Another barrier may be the gap between mastering formal rules for constructing drawings and developing spatial operations. Mastering projection algorithms is a necessary condition for professional graphical training; however, knowledge of the construction sequence alone does not guarantee the ability to freely operate with spatial representations.

Hegarty [21] emphasizes the active role of the learner when working with graphical representations, and the effectiveness of external visualization is determined not only by its content but also by the cognitive operations performed during its interpretation.

In the context of engineering graphics, this means that instruction should not be limited to reproducing a prescribed sequence of graphical actions. Students should receive tasks that require them to analyze form, compare images, perform spatial transformations, and independently create a graphical representation of an object.

The issue of student activity is particularly important when digital tools are used. A ready-made 3D model considerably facilitates perception of an object's form, but by itself it may not require students to construct their own spatial representation. Therefore, digital visualization should be incorporated into the learning process so that observation of the model develops into active analysis and graphical reproduction. Active graphical reproduction of a spatial object is a fundamentally important complement to observing it. In constructing their own image, students must identify the object's main spatial characteristics, establish relationships between its elements, and transform the resulting representation into graphical form.

The barriers considered share a common feature: they are largely associated with the need to move between different ways of representing spatial information. Students must work with at least three interrelated levels: a real or digital three-dimensional object, its visual graphical representation, and a formalized system of orthographic projections.

The problem arises when these representations are learned as separate, insufficiently interconnected ways of working. In such a case, students may learn to perform individual graphical operations but experience difficulties

when moving from one type of representation to another. In this context, axonometric projection can be regarded as a potential intermediate link between an integral spatial representation and a formalized system of orthographic projections. Unlike an individual orthographic view, an axonometric image makes it possible to represent several spatial directions simultaneously while preserving the visual clarity of the object's form [6; 23]. When such an image is not only demonstrated but also constructed independently by the student, it can combine external visual support with active graphical activity.

Thus, the set of identified barriers makes it possible to define the main methodological problem at the initial stage of graphical training: it is necessary to provide a transition from spatial perception of an object to its formalized graphical representation in which students gradually develop the ability to independently create, analyze, and transform spatial representations. This substantiates the need for further investigation of axonometric projection as an active means of developing spatial imagination.

3. Presentation of the Main Material

3.1 Axonometric Projection as a Means of Developing Spatial Imagination

The results of the analysis indicate that one of the main difficulties in initial graphical training is the need for students to move between different ways of representing spatial information. A real or digital three-dimensional object is perceived as an integral spatial structure, whereas orthographic projections convey its form through a system of interrelated two-dimensional images. Establishing correspondence between these representations requires students to perform complex spatial transformations, which may not yet be sufficiently developed at the initial stage of learning [17; 18; 21; 22].

Therefore, it is appropriate to seek a graphical tool that could perform an intermediate function between the direct spatial representation of an object and its formalized projection representation. In this context, axonometric projection is of particular importance. An axonometric image makes it possible to represent several spatial directions simultaneously on a plane, allowing the structural form of an object to be perceived more holistically than in a single orthographic view [8; 23].

It is important to emphasize that axonometric and orthographic projection are not competing forms of graphical representation. They serve different functions in engineering practice. Orthographic projections provide a formalized representation of geometric and structural information required for manufacturing, inspection, and documentation of a product. An axonometric image, in turn, provides a more visual representation of spatial form and the relative positions of elements. Therefore, from a methodological perspective, these approaches should not be contrasted; rather, a stable relationship between them should be established.

For the development of spatial imagination, the student's ability to move from one representation of an object to another is of fundamental importance. In the simplest case, this process can be represented as a sequence (Fig. 1).

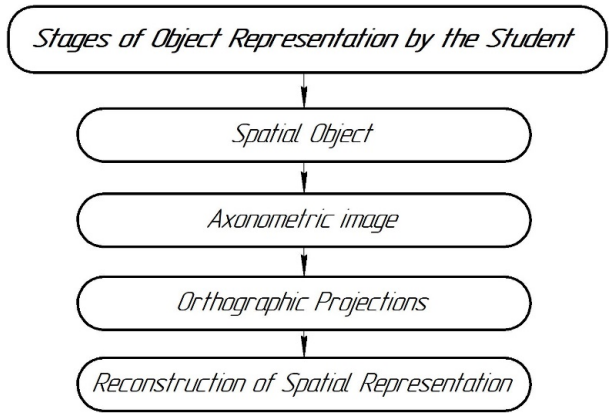


Figure 1. Stages of object representation by the student

Source: developed by the author

At the first stage, the student perceives the object's form as an integral spatial structure. At the second stage, it is graphically represented in axonometric projection, in which the main spatial directions and the relative positions of the elements are preserved within a single image. At the third stage, the spatial representation is translated into a formalized system of orthographic projections. At the final stage, the student must perform the

reverse transformation and reconstruct the spatial form of the object from the set of projections.

This sequence corresponds to the general nature of spatial thinking, in which people use both internal mental representations and external graphical representations [19; 22]. At the same time, a graphical representation can serve not only as a result of mental activity but also as a means of supporting it. For engineering graphics education, this means that a properly organized system of graphical representations can help students gradually establish connections between spatial form and its formalized representation.

Axonometric representation can occupy a special place in this system. Unlike an individual orthographic view, it allows several directions and surfaces of an object to be seen simultaneously. This gives students an opportunity to relate spatial form to its graphical representation without having to immediately reconstruct the entire object from several separate views. This constitutes the potential didactic value of axonometric representation at the initial stage of learning. Using axonometry as a means of developing spatial imagination should not be limited to demonstrating ready-made images. Students' active participation in independently constructing an axonometric sketch is of fundamental importance.

When performing such a task, students must identify the main spatial directions of the object, determine the positions of its elements, assess their relationships, and transfer the resulting spatial representation onto a plane. Thus, sketching involves the simultaneous interaction of spatial and graphical operations. Students do not merely observe a ready-made result but independently construct an external representation of the object.

The direct effect of systematic freehand sketching on spatial visualization was investigated in [25]; the results demonstrated a statistically significant improvement in spatial visualization performance compared with the control group. A subsequent study [27] also focused on combining freehand sketching and spatial visualization in the preparation of first-year engineering students and likewise showed a positive result.

Therefore, an axonometric sketch should be considered not only as a means of graphically recording a ready-made spatial representation but also as a learning activity in which students actively work with the spatial characteristics of an object. It is the active construction of the image that distinguishes this activity from passive observation of a ready-made model.

Developing spatial imagination through axonometric projection involves a set of interrelated mental operations:

– the first is holistic perception of spatial form – before beginning the construction, students must determine the overall configuration of the object, its main geometric elements, and the nature of their relative positions;

– the second is spatial correspondence of elements - when constructing an axonometric representation, it is necessary to determine how individual surfaces, holes, protrusions, slots, and other structural elements are positioned relative to the three main spatial directions;

– the third is spatial transformation – if an object has a complex shape or its position changes, students must mentally change the viewing angle, rotate the object, or determine the result of a particular structural modification. Such operations are typical components of spatial reasoning [6; 21; 22];

– the fourth is the transition from space to plane – students must transform the formed spatial representation into a graphical construction while following the selected axonometric system and the relative positions of the coordinate directions;

– the fifth is the reverse transition from plane to space – after completing the axonometric image, students should be able to use it to mentally reconstruct the spatial form. Subsequently, this operation is transferred to work with orthographic projections.

Thus, an axonometric sketch can facilitate not the development of a single isolated skill, but the sequential engagement of several spatial operations. This corresponds to approaches in which spatial thinking is viewed as a system of interconnected ways of processing spatial information [6; 21].

Modern digital tools make it possible to use a three-dimensional model as an initial visual support. Students can change the viewing angle, scale the model, examine individual structural elements, and observe their spatial relationships. At the same time, the digital model should not become the final outcome of spatial learning activity. If students only observe and rotate a ready-made object, some of the operations required for independent graphical representation remain unperformed. Therefore, it is appropriate to combine digital visualization with manual or digital axonometric sketching. In this sequence, the digital model serves as external visual support, the axonometric sketch as active transformation of the spatial representation, and orthographic projection as its formalization. This organization makes

it possible to combine traditional and digital tools rather than oppose them, using each according to different stages of learning activity. The proposed sequence can be schematically represented as shown in Fig. 2.

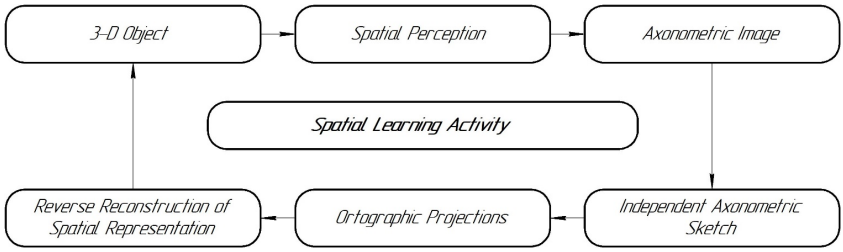


Figure 2. Model of spatial learning activity

Source: developed by the author

Each subsequent stage does not eliminate the previous one but builds upon it. Accordingly, students gradually move from perceiving ready-made spatial information to independently transforming it and producing a formalized graphical representation.

Based on the analysis, several principles for using axonometric projection at the initial stage of graphical training can be identified:

– the first principle is the gradual increase in the complexity of spatial tasks. Initial exercises should be based on simple geometric forms, gradually progressing to parts with more complex configurations, holes, steps, slots, and interconnected structural elements;

– the second principle is combining perception with independent construction. A ready-made axonometric image or 3D model should be used as initial support, after which students move to independently creating their own graphical representation;

– the third principle is the bidirectionality of spatial transformations. Learning tasks should include both the transition from a spatial object to an axonometric and orthographic representation and the reverse transition from a drawing to a spatial representation;

– the fourth principle is the connection between axonometry and orthographic projection. An axonometric image should not be taught as an

isolated topic. It should be used to explain how a single spatial object is represented by a system of interrelated orthographic projections;

– the fifth principle is student activity. The main focus should be not on the number of models demonstrated but, on the quantity, and quality of spatial operations performed by the student. This position is consistent with studies in which systematic sketching was considered an active component of spatial visualization development [25-27].

Taking these principles into account, the process of developing spatial imagination through axonometric projection can be represented as a sequence of interrelated stages:

– at the first stage, students receive an integral spatial representation of a real or digital object. The main task is to identify its overall form and principal structural elements;

– at the second stage, the spatial representation is translated into an axonometric representation. Students determine the spatial axes, orientation of the object, and positions of its main elements;

– at the third stage, an independent axonometric sketch is produced. At this stage, external visual support is gradually replaced by the student's own graphical construction;

– at the fourth stage, orthographic projections are constructed on the basis of the formed axonometric representation. Spatial information is translated into a formalized system of graphical images;

– at the fifth stage, a reverse spatial transformation is performed: using the resulting orthographic projections, students must reconstruct the spatial representation of the object and relate it to the previously constructed axonometric representation.

Thus, the process becomes cyclical (Fig. 3).

As a result, students repeatedly move between spatial and graphical forms of representing the same object. The repetition of such transitions creates conditions for developing stable approaches to spatial analysis and graphical reproduction.

Thus, axonometric projection should be considered as one of the means of organizing initial graphical training, capable of combining the visual clarity of spatial representation with students' active participation. Its methodological value lies not only in the possibility of visually representing an object, but primarily in creating an intermediate link

between an integral spatial representation and a formalized system of orthographic projections. Combining axonometric representation, independent sketching, digital visualization, and subsequent orthographic projection creates conditions for gradually developing students' ability to independently create, transform, and analyze spatial representations.

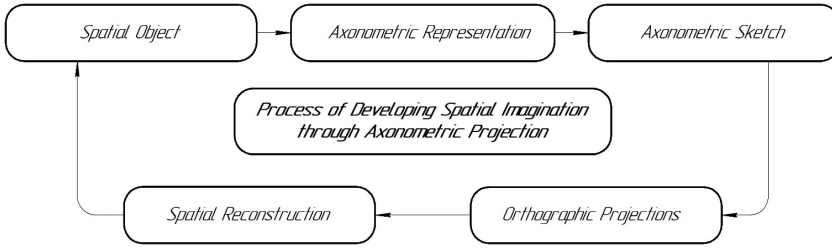


Figure 3. Process of developing spatial imagination through axonometric projection

Source: developed by the author

3.2 Methodological System of Proactive Axonometric Projection

The difficulties in developing students' spatial imagination identified in the preceding sections necessitate an approach to organizing initial graphical training in which the transition from perceiving a spatial object to its formalized graphical representation is carried out gradually. In this context, a methodological system is proposed based on the purposeful and proactive use of axonometric projection before mastering more complex orthographic projection operations.

The fundamental feature of the proposed approach is not the introduction of an additional section into the traditional engineering graphics course, but a change in the functional purpose of axonometric representation in the educational process. Axonometry is regarded not merely as one of the methods of graphically representing a technical object, but as a means of forming, refining, and verifying its spatial representation. This approach is consistent with research on the development of spatial skills among engineering students, in which effective development of spatial visualization is associated with specially organized work with three-dimensional forms,

their graphical representations, spatial transformations, and different types of projections [21; 22].

Accordingly, the starting point of the methodological system is the proposition that at the initial stage of learning, students should not only perceive a ready-made graphical image but also independently perform spatial-graphical operations. In this activity, they determine the form of the object, identify its main geometric elements, establish their relative positions, proportions, and directions, and then translate the resulting spatial representation into graphical form. The performance of these operations, rather than the mechanical reproduction of a ready-made image, constitutes the basis of the proposed methodology.

A special place in the system is occupied by the proactive use of axonometric projection. Its essence is that axonometric images are introduced at an early stage of graphical training, before complex orthographic projection tasks are performed. This makes it possible to first form an integral representation of the object's spatial form and only then proceed to its graphical decomposition into separate projections.

In this sequence, the axonometric image serves as an intermediate link between the spatial object and its system of orthographic projections. Students first determine the spatial structure of the object and represent it in axonometric projection, after which they establish how the same form is represented in individual orthographic projections. The reverse operation is then performed: the spatial representation is reconstructed from the orthographic projections and represented axonometrically. Thus, the result is not an isolated ability to construct a particular type of image, but the ability to move between different graphical representations of the same object. This bidirectionality is fundamental to the proposed system (Fig. 4).

Performing both types of tasks makes it possible to engage different spatial operations and avoid limiting instruction to a single construction algorithm. Research on spatial thinking demonstrates the importance of working with different representations of spatial information and using appropriate strategies for transforming it [5; 6]. For engineering graphics, this means that students need to develop the ability not only to read an individual drawing but also to establish correspondence between different ways of representing the same object.

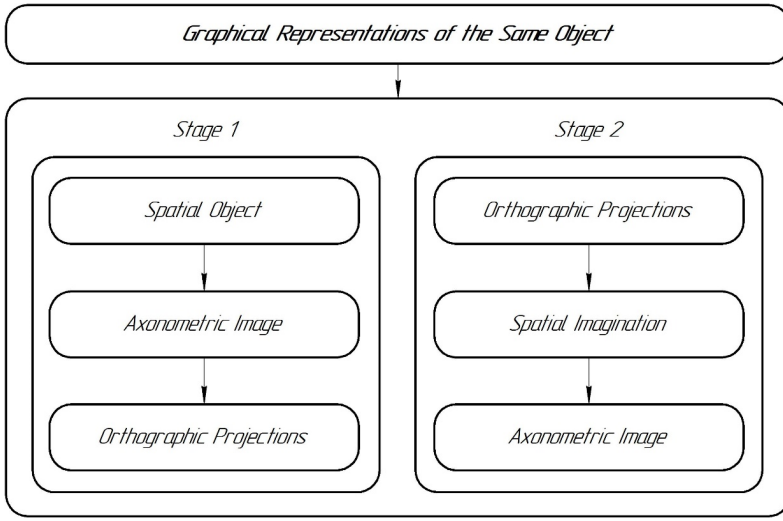


Figure 4. Graphical representations of the same object

Source: developed by the author

An important component of the proposed system is freehand axonometric sketching. At this stage, students do not receive a ready-made algorithmically constructed image to reproduce mechanically, but independently determine the main geometric characteristics of the object and represent them graphically. This activity promotes active spatial analysis because constructing even a simplified axonometric image requires determining the positions of the main elements, their relative locations, and spatial relationships.

At the same time, tasks should gradually become more complex. At the initial level, simple geometric solids and uncomplicated combinations of them should be used, making it possible to focus attention on the spatial position of elements. Subsequently, objects with cut-outs, holes, inclined surfaces, steps, sections, and the relative positioning of several structural elements are introduced. After the corresponding spatial analysis methods have been mastered, they can be transferred to technical parts and objects related to professional practice.

Another fundamental principle is the sequential combination of object-based, graphical, and digital visualization. At the initial stage, it is appropriate to use real objects, simple physical models, or visual representations of technical objects. This first establishes correspondence between a real object and its graphical representation. Students then produce their own axonometric sketch and proceed to construct orthographic projections. Thus, digital visualization does not precede independent spatial-graphical activity but is used after it has been completed.

The use of computer-aided design systems requires particular clarification. At the initial stage of learning, the CAD environment is not intended as a tool for students' independent three-dimensional modeling because first-year students do not yet possess the necessary software skills. During this period, its use is appropriately organized primarily at the level of teacher demonstration.

After students have completed their own axonometric sketches and orthographic projections, the teacher may demonstrate a previously prepared CAD model of the corresponding or an analogous object. By changing the viewing angle, rotating the model, and successively demonstrating its projections, the teacher enables direct comparison of the spatial form with its graphical representation. In this case, the digital model serves as a visual means of verification and explanation rather than replacing students' independent work.

This sequence has important methodological significance. If a ready-made 3D model is demonstrated before students perform a spatial-graphical task, it may effectively eliminate the need for them to independently form a spatial representation. If the digital model is demonstrated after the sketch and projections have been completed, it becomes a means of feedback: students can compare their own representation of the object with its three-dimensional representation, identify discrepancies, and understand the cause of an error.

Combining sketching and computer graphics corresponds to approaches that use computer visualization together with graphical and sketching tools to develop spatial skills in engineering education [23]. At the same time, in the proposed system, digital tools have a supporting function: they support the process of spatial analysis but should not perform it instead of the student.

As learning progresses and students master the fundamentals of computer modeling, the role of the CAD environment can gradually expand. At subsequent stages, when students have acquired the relevant digital competencies, they may independently create simple three-dimensional models and use them to verify their own graphical constructions. Thus, the digital component of the methodology is introduced gradually and corresponds to the actual level of students' preparation rather than presupposing skills that have not yet been developed.

Thus, the proposed methodological system is based on several interrelated principles:

– the proactive introduction of axonometric projection before complex orthographic projection operations;

– active axonometric sketching, during which students independently move from a spatial representation to a graphical representation;

– bidirectional transitions between axonometric and orthographic representations, including both the construction of projections from an axonometric representation and the reconstruction of a spatial representation from orthographic projections;

– gradual complication of objects and spatial operations, from simple geometric solids to technical parts and professionally oriented structures;

– stepwise use of digital tools, whereby at the initial stage CAD models are used by the teacher for demonstration, verification, and explanation, while independent modeling by students is introduced only after they have acquired the relevant skills.

In the proposed system, axonometric projection performs several functions simultaneously: it provides an integral graphical representation of a spatial object, creates a basis for the transition to orthographic projections, activates students' independent spatial-graphical activity, and makes it possible to verify the formed representation using visual and digital tools.

The overall logic of the proposed approach can be represented as a sequence (Fig. 5). This sequence provides a gradual transition from direct perception of the object to its formalized graphical representation and the reverse reconstruction of its spatial form. Each subsequent stage builds on the spatial actions formed at the preceding stage.

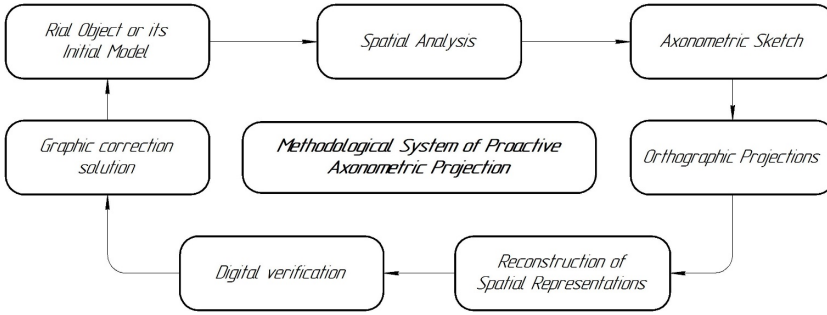


Figure 5. Methodological system of proactive axonometric projection

Source: developed by the author

Implementation of the proposed approach requires specification of the content of learning tasks, their sequence, the balance between individual and demonstrative work, and methods for monitoring results at different stages of learning. Therefore, the next task is to define the structure of the methodological system and the step-by-step organization of its implementation in the graphical training of students in technical fields.

4. Experimental Verification of the MSAAP

To verify the effectiveness of the developed Methodological System of Advanced Axonometric Projection (MSAAP), a pedagogical experiment was conducted to determine changes in the level of spatial imagination development among students in technical fields. Unlike the preceding sections, which substantiated the theoretical principles, structure, and implementation stages of the system, this section considers the conditions for practical implementation of the MSAAP and the results of its experimental verification.

4.1 Organization and Conditions of the Experimental Study

The experimental work was conducted during the 2024-2025 academic year at Central Ukrainian National Technical University, in the Department of Agricultural Engineering, which provides training in the specialties H7 “Agricultural Engineering” and G11 “Industrial Mechanical Engineering.” The study involved 52 first-year full-time students.

For the experiment, an experimental group and a control group of 26 students each were formed.

The experimental group (EG) studied according to the developed MSAAP, in which axonometric projection was introduced at the initial stage of graphical training and used as an active link in the transition from spatial representation to formalized graphical representation. The control group (CG) studied according to the traditional sequence, in which the initial stage focused primarily on complex drawing, while axonometric representations were introduced later.

The groups were formed taking into account the results of initial diagnostic testing and the general level of pre-university graphical preparation. At the beginning of the study, no statistically significant differences between the groups were found in the main indicators of spatial preparation. This made it possible to use them as comparable groups for subsequent assessment of changes in performance.

This approach corresponded to the logic of the previously developed methodological system. Its basis is not the replacement of orthographic projection with axonometric projection, but a change in the sequence in which spatial-graphical actions are developed. Axonometry is used as an intermediate form of representation that makes it possible to connect an integral spatial representation of an object with its subsequent formalized presentation in a system of orthographic projections.

During the formative stage, the amount of classroom instruction was identical in both groups and comprised 8 hours of lectures and 16 hours of practical classes. Thus, the difference between the groups was determined not by the amount of instructional time but by the organization of graphical activity and the sequence in which spatial-graphical operations were introduced.

4.2 Implementation of the Methodological System of Proactive Axonometric Projection

The practical implementation of the Methodological System of Advanced Axonometric Projection (MSAAP) was carried out in accordance with its structure and the logic of organizing learning activities defined in the preceding section. The main feature of the proposed approach was moving axonometric projection from the final stage of processing graphical

material to the initial stage of forming a spatial representation of a technical object. The axonometric image was used not only as a ready-made way of presenting the object but also as a means of students' active work with its spatial form.

During instruction of the experimental group, primary attention was given to the sequential performance of interrelated spatial-graphical actions. The work began with perception of a real technical object, its physical model, or a visual representation. Students were asked to determine the overall form of the object, the relative positions of its main parts, the nature of its surfaces, and the presence of holes, slots, protrusions, and other structural elements. This preliminary spatial orientation provided the basis for subsequent graphical representation of the object.

The next step was to produce an axonometric sketch. At this stage, students did not receive a ready-made drawing to reproduce mechanically; instead, they independently transferred the formed spatial representation onto a plane. Particular importance was attached to freehand sketching because it required simultaneous control of spatial form, coordinate-axis directions, proportions, and the relative positions of elements.

After the skill of forming an integral axonometric representation had been developed, students moved to orthographic projection. They were asked to determine the necessary views and construct the corresponding orthographic projections from the created or provided axonometric image. Thus, the transition to the multiview drawing took place after a spatial representation had been formed rather than preceding its formation. This changed the nature of the learning activity: students had not merely to master the rules for constructing individual projections but to establish the spatial correspondence between the object and its system of planar images.

An important component of implementing the MSAAP was the reverse transition from orthographic projections to a spatial representation. Students were asked to reconstruct the form of a part from two or three projections, determine the relative positions of its elements, and verify the correspondence of the resulting representation with the axonometric representation. This work ensured repeated switching between different ways of representing the same object. The need for such transitions between graphical representations corresponds to the contemporary understanding

of spatial visualization as the ability not only to perceive spatial information but also to transform it between different forms [12; 28].

Digital tools were used as an additional instrument for verifying and refining spatial representations. After students completed their own graphical solution, a corresponding three-dimensional model was demonstrated or created in a CAD environment. Comparing the sketch, orthographic projections, and three-dimensional model made it possible to identify discrepancies, determine the cause of an error, and correct the graphical solution. This approach is consistent with the idea of combining manual sketching and computer graphics, in which digital modeling does not replace students' spatial-graphical activity but supports and verifies it [28].

As the main spatial operations were mastered, the learning material became more complex, progressing from simple geometric solids and their combinations to technical parts and objects characteristic of the professional activities of future agricultural engineering and mechanical engineering specialists. This ensured a gradual transfer of developed spatial skills from instructional exercises to professionally oriented graphical tasks. Thus, implementation of the MSAAP in the educational process was based on a sequential cycle of spatial-graphical actions (Fig. 6).

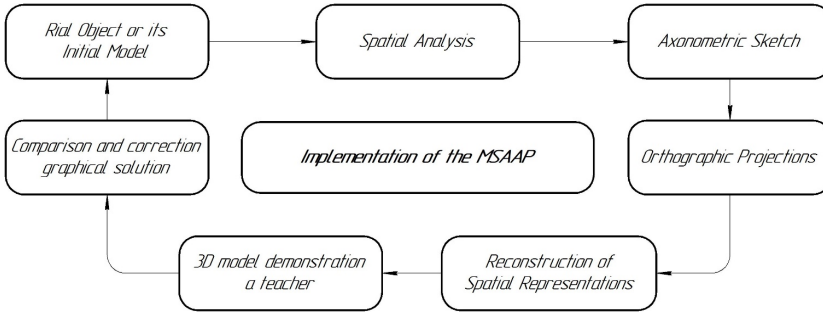


Figure 6. Implementation of the MSAAP

Source: developed by the author

This cycle constituted the operational core of the methodological system and determined the difference between the organization of learning in

the experimental group and the traditional approach, in which multiview drawing was studied before axonometric projection. As a result, in the MSAAP, axonometry performed not a final illustrative function but served as an initial and intermediate means of forming, transforming, and monitoring students' spatial representations.

4.3 Diagnostic Instruments and Assessment Procedure

To assess the effectiveness of the MSAAP, a set of diagnostic tools was used that combined standardized spatial-thinking tests with original professionally oriented tasks.

Within this study, spatial imagination is considered an integrated ability to perceive, mentally transform, correlate, and graphically reproduce spatial objects, while the PSVT, MCT, and professionally oriented tasks are used to assess individual components of this ability.

The main quantitative instrument was the Purdue Spatial Visualization Test: Rotations (PSVT) [30], adapted for use in the training of students in technical specialties. The test contains 30 tasks requiring participants to mentally rotate a three-dimensional object and determine its position after rotation. The use of the PSVT is appropriate for assessing dynamic spatial visualization, which is an important component of engineering spatial activity. A substantial body of research confirms the possibility of purposefully developing spatial skills, and the meta-analysis [29], which covered 217 studies, demonstrated an overall positive effect of specialized spatial training compared with control conditions.

The Mental Cutting Test (MCT) [12] was additionally used to assess the ability to mentally determine the shape of a cross-section of a spatial object. Studies of mentally determining two-dimensional cross-sections of complex three-dimensional structures confirm the importance of such operations in the study of spatial abilities [31].

To bring the assessment closer to actual graphical activity, three original tasks were developed:

– the first task, "Axonometry from Description," required students to receive a verbal description of a technical object and independently produce an axonometric sketch. The correspondence of the drawing to the specified object, proportionality, and accuracy in conveying the structural form were assessed;

– the second task, "Projection Transition," required students to construct three orthographic projections based on a ready-made axonometric image of a part. Particular attention was paid to the correct selection and construction of views and the absence of projection errors;

– the third task, "CAD Verification," provided students with axonometric and orthographic representations of the same technical object containing a discrepancy. The task was to identify the error and verify it using a three-dimensional digital representation. Thus, the assessment concerned not only the ability to create a graphical image but also the ability to verify the correspondence between different representations of the same object. This type of task is consistent with approaches to using computer graphics and sketching to develop engineering visualization skills.

For interpretation of the results, three levels of spatial imagination development were distinguished: low, medium, and high. At the same time, the PSVT thresholds (<15, 15-23, 24-30 points) used in this study should be regarded specifically as an author-developed system for interpreting the results rather than as universal normative thresholds of the test. This approach makes it possible to use the levels to analyze changes within the sample without assigning the proposed thresholds the status of a generally accepted standard.

The pedagogical experiment consisted of three stages: diagnostic, formative, and control. At the diagnostic stage, during the first two weeks of September, initial testing of both groups was conducted. Statistical analysis revealed no significant differences between the groups at the beginning of the study ($p > 0.05$).

The formative stage lasted 12 weeks, from October to December. The experimental group studied according to the MSAAP, while the control group followed the traditional program. The amount of instructional time was identical for both groups.

At the control stage, during the final week of the semester, both groups completed the same set of diagnostic tasks. Statistical processing included testing normality of the distribution using the Shapiro–Wilk test, Student's t-test for comparing means, and Pearson's χ^2 test for analyzing frequency distributions [32-35]. Data were processed using Statistica 12 software by StatSoft.

5. Results of Experimental Studies

5.1 PSVT Test Results

The test results demonstrated positive dynamics in spatial visualization in both groups (Table 1); however, the magnitude of the increase was substantially greater in the experimental group.

Table 1

PSVT test results

Indicator	EG, n=26 pre-test	EG, n=26 post-test	CG, n=26 pre-test	CG, n=26 post-test
Mean score	13.4	22.8	13.6	17.9
Standard deviation	3.8	4.1	3.7	4.5
Increase	-	+9.4	-	+4.3

In the experimental group, the mean score increased from 13.4 to 22.8 points, i.e., by 9.4 points. In the control group, the increase was 4.3 points, from 13.6 to 17.9 points. Thus, the absolute increase in the EG was more than twice that in the CG. Based on the final results, the difference between the groups was statistically significant ($t = 4.1$; $p < 0.001$). An important complement to the analysis of mean values is the distribution of students across the levels of spatial imagination development defined within the study (Table 2).

Table 2

Distribution of students by levels of spatial imagination development

Level	EG / before experiment	EG / after experiment	CG / before experiment	CG / after experiment
Low	15 (57.7%)	2 (7.7%)	15 (57.7%)	8 (30.8%)
Medium	8 (30.8%)	12 (46.2%)	9 (34.6%)	13 (50.0%)
High	3 (11.5%)	12 (46.2%)	2 (7.7%)	5 (19.2%)

After completion of the experiment, the proportion of students with a high level in the EG increased from 11.5% to 46.2%, whereas in the CG it increased from 7.7% to 19.2%. At the same time, the proportion of students with a low level in the EG decreased from 57.7% to 7.7%, while in the CG it decreased from 57.7% to 30.8%. Differences in the final distribution were statistically significant ($\chi^2 = 6.52$; $p = 0.038$).

The observed dynamics are consistent with the general conclusion of contemporary research that spatial skills are sufficiently malleable and can develop under specially organized instruction. The meta-analysis [29] demonstrated a positive effect of targeted spatial training compared with control conditions. At the same time, the results presented in this study are original experimental data and should not be equated with the findings of previous studies.

5.2 Mental Cutting Test Results

A similar trend was identified in the MCT results (Table 3).

Table 3

MCT results

Indicator	EG, n=26	CG, n=26
Mean score before experiment	10.2	10.4
Mean score after experiment	18.6	13.7
Increase	+8.4	+3.3

In the EG, the mean score increased by 8.4 points, whereas in the CG it increased by 3.3 points. The difference between the final group results was statistically significant ($t = 3.91$; $p < 0.001$).

This result is important for graphical training because performing sections requires a transition from an external graphical representation to the internal spatial structure of an object. Accordingly, the positive dynamics in the MCT complement the PSVT results and indicate that the changes concerned not only mental rotation operations but also other forms of spatial manipulation of an object.

5.3 Results of Professionally Oriented Tasks

The results of the original tasks are presented in Table 4.

Table 4

Results of professionally oriented tasks

Task	EG	CG
Axonometry from description	76.9%	50.0%
Projection transition	80.8%	65.4%
CAD verification	84.6%	61.5%

The experimental group demonstrated higher performance on all three tasks. The largest difference was observed in the "CAD Verification" task – 23.1 percentage points.

This result is particularly significant in the context of the structure of the MSAAP. In this system, the digital environment does not replace the preceding spatial-graphical activities but is used to verify them. Therefore, the higher EG result on the verification task may be regarded as an indication of a developed ability to compare different representations of the same object and identify discrepancies between them. The need to work with different types of representations and select an appropriate spatial-analysis strategy is an important component of spatial thinking.

5.4 Qualitative Analysis of the Results

The quantitative results were complemented by pedagogical observation, analysis of typical errors, and a brief survey of students concerning their perception of the learning material.

At the diagnostic stage, the most frequent difficulties in both groups involved distinguishing visible and hidden contours in axonometric representations, confusing frontal dimetric projection with isometric projection, and conveying proportions during sketching. According to the data recorded in the study, the frequency of these errors was approximately 45%, 60%, and more than 70%, respectively.

At the control stage, the frequency of these errors in the EG decreased to less than 10%. In the CG, errors associated with conveying proportions and distinguishing hidden contours persisted in approximately 25% and 20% of cases, respectively.

These results provide grounds for associating the positive dynamics not only with mastery of individual construction rules but also with a change in the nature of learning activity. Within the MSAAP, students systematically performed transitions between the spatial object, axonometric representation, and orthographic projections. Thus, the same structural information was processed in different forms of representation. This type of activity corresponds to approaches according to which spatial thinking involves using different strategies and external representations depending on the nature of the task.

The survey results also revealed differences in the perception of the learning material. In the experimental group, 82% of students reported that the material was easier to understand when the explanation began with a three-dimensional representation. Only 5% of respondents reported discomfort associated with the sequence of learning being unfamiliar to them. In the control group, 47% of students described the initial multiview drawing classes as difficult or very difficult.

These data should be considered specifically as results of subjective perceptions of learning rather than direct evidence of changes in cognitive load or motivation. At the same time, they complement the objective test results and indicate that, for a substantial proportion of students, initial reliance on a three-dimensional representation was understandable and acceptable.

5.5 Generalization of the Results and Verification of the Working Hypothesis

The experimental study made it possible to compare the results of two groups that worked with the same amount of classroom instruction but under different arrangements of graphical activity. The main difference in the experimental group was the proactive introduction of axonometric projection, its systematic combination with manual sketching, bidirectional transitions between axonometric and orthographic representations, and subsequent use of a digital model for verification.

According to the PSVT results, the mean score in the EG increased from 13.4 to 22.8 points, whereas in the CG it increased from 13.6 to 17.9 points. The increases were 9.4 and 4.3 points, respectively, indicating more pronounced positive dynamics in the experimental group. According to the MCT results, the mean increase was 8.4 and 3.3 points, respectively. The final EG results exceeded those of the CG, consistent with the PSVT data. Analysis of the level distribution also showed a substantially larger proportion of students with a high level of spatial imagination in the experimental group, 46.2% compared with 19.2% in the control group, whereas the proportion with a low level was 7.7% compared with 30.8%, respectively.

The results of the original tasks confirmed a similar trend in professionally oriented graphical activities: performance in the EG ranged from 76.9% to

84.6%, whereas in the CG it ranged from 50.0% to 65.4%. This is important because the effectiveness of the proposed system was assessed not only through psychometric test results but also through students' ability to apply spatial operations when performing specific graphical tasks.

The findings are consistent with previous studies demonstrating the possibility of purposeful development of spatial skills among engineering students. In particular, Sorby S.A. [12] considers spatial visualization a skill that can be improved through specially organized instruction, while [26] demonstrated the effectiveness of a specialized spatial-training course for first-year engineering students. The meta-analysis [29] also indicates the general possibility of developing spatial abilities through targeted training.

It is also important that the proposed system was not reduced to increasing the number of three-dimensional visualizations. Its fundamental feature was the organization of active student activity: first spatial analysis, then an independent axonometric sketch, transition to orthographic projections, reconstruction of the spatial representation, and only then digital verification. This structure is consistent with the proposition that external graphical representations can support spatial thinking, but their effectiveness depends on how they are used and on the nature of the operations performed by students.

Thus, the results of the pedagogical experiment support the working hypothesis of the study and provide grounds to consider that the systematic proactive use of axonometric projection, combined with active sketching, transitions between different graphical representations, and the stepwise use of digital visualization, provides greater effectiveness in developing spatial imagination among students of technical specialties compared with the traditional sequence of instruction.

At the same time, the results should be interpreted within the framework of the pedagogical experiment conducted. They confirm the effectiveness of the proposed organization of instruction for the studied sample, but by themselves do not provide grounds for automatically generalizing the obtained indicators to all higher education institutions and all categories of students. Further research may focus on testing the MSAAP on a broader sample, across different educational programs, and with delayed assessment of the retention of the developed spatial skills.

CONCLUSIONS

1. It was determined that developing spatial imagination among students of technical specialties is an important component of graphical training because engineering tasks require transitions between a spatial object, its axonometric representation, and orthographic projections.

2. A methodological system for developing spatial imagination through axonometric projection (MSAAP) was substantiated and developed, based on the sequence shown in Fig. 5.

3. Experimental verification involving 52 students (EG – 26, CG – 26) demonstrated positive dynamics in spatial skills in both groups, but more pronounced dynamics in the experimental group. According to the PSVT, the mean EG result increased from 13.4 to 22.8 points, while the CG result increased from 13.6 to 17.9 points; according to the MCT, the increases were 8.4 and 3.3 points, respectively.

4. The level distribution results demonstrated a positive effect of the proposed methodology: after the experiment, a high level was demonstrated by 46.2% of EG students compared with 19.2% of CG students, while a low level was demonstrated by 7.7% compared with 30.8%, respectively; the differences between the final distributions were statistically significant ($\chi^2 = 6.52$; $p = 0.038$).

5. It was established that the MSAAP provides not only improved standardized test results but also better performance on professionally oriented graphical tasks. EG performance across the three tasks ranged from 76.9% to 84.6%, whereas CG performance ranged from 50.0% to 65.4%, supporting the appropriateness of systematic use of axonometric projection as an active component in developing spatial imagination.

6. The results should be regarded as findings of the pedagogical experiment within the studied sample and therefore cannot be directly generalized to all students in technical specialties. To confirm the stability and generalizability of the observed effect, further studies are needed on broader and more heterogeneous samples, together with further refinement of the proposed methodological system and verification of its effectiveness under other learning conditions.

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