Συνέδρια της Ελληνικής Επιστημονικής Ένωσης Τεχνολογιών Πληροφορίας & Επικοινωνιών στην Εκπαίδευση

Τόμ. 1 (2021)

12ο Πανελλήνιο και Διεθνές Συνέδριο «Οι ΤΠΕ στην Εκπαίδευση»


# Cultivating spatial thinking as a cross-cutting thread in STEM domains. Implications for the utilization of the educational robot construction procedure

*Vasiliki Sismani, Sofia Hadjileontiadou*

# Cultivating spatial thinking as a cross-cutting thread in STEM domains. Implications for the utilization of the educational robot construction procedure

**Vasiliki Sismani[1], Sofia Hadjileontiadou [2]**
bikhsism@gmail.com, schatzil@eled.duth.gr
[1,2] Department of Primary Level Education, Democritus University of Thrace, Greece

## Abstract

This work proposes the use of the educational robot construction procedure towards the cultivation of spatial thinking as a cross-cutting thread in STEM education. The work builds upon the idea that spatial thinking is malleable and initially presents a theoretical background to build upon. Then, an empirical case on the construction procedure of a robot, by a pair of primary school students using WeDo 2.0 blocks, is presented and spatialized in terms of construction actions and relevant argumentation. This exemplar case is used for the realization of the possibilities that stem from this spatialization to promote spatial thinking. The proposed work contributes at the metacognitive level to promote possible far transfer of spatial thinking in STEM domains.

**Keywords:** Spatial thinking, STEM, metacognition, educational robot, construction

## Introduction

In 2005 a "degree in STEM education" was created at the Virginia Tech University, which formalized the STEM movement that appeared in the 90s, as respond to the social needs of US (Martín-Páez et al., 2019). The nowadays well-known acronym STEM stands for the Science, Technology, Engineering, Mathematics, and a bulk of research work is being produced in the area of STEM education. Yet, due to differences in the epistemological origins and methodological tools of each one of the domains involved, so far there is lack of consensus concerning the conceptualization of the STEM education. Martín-Páez et al. (2019) cite five concepts that consider the integration of the STEM domains, i.e., integrated STEM, transdisciplinarity, interdisciplinarity, supradisciplinarity and multidisciplinarity. Based on this variety of approaches that are reported in the literature, there is a strong need for the clarification of the way the integration of the domains is proposed each time, along with the content that it refers to, in each domain (National Academy of Sciences, 2014).

Spatial thinking underpins our everyday life, work and science, thus it might be considered as a cross-cutting way of thinking within the STEM education. Such thinking is malleable and entails three elements, i.e., concepts of space, tools of representation and processes of reasoning (National Research Council & Geographical Sciences Committee, 2005). Research work supports the relationship between spatial thinking and specific STEM domains, e.g., mathematics, referring to the relationship between the visual-spatial reasoning ability and math and geometry problem solving (Markey, 2010). Uttal and Cohen (2012) explored the relationship between spatial thinking and performance and attainment in STEM domains and concluded that spatial training might increase the novices' performance in STEM-related tasks, which yet gets smaller as the expertise in the STEM field increases.

Θ. Μπράτιτσης (επιμ.), Πρακτικά Εργασιών 12ου Πανελλήνιου και Διεθνούς Συνεδρίου «Οι ΤΠΕ στην Εκπαίδευση», σ. 377-384
ΠΔΜ, Φλώρινα, 14-16 Μαΐου 2021. ISBN: 978-618-83186-5-6

Educational robotics has been used in many STEM-related tasks, putting in the forefront the technological domain. Typical procedures, while integrating educational robots, in such tasks are: a) the robot construction (depending on the technology that is used) and b) the robot use and programming according to the task. Research work in the area reveals that the efforts are usually put in the use and programming side (e.g., Anwar et al., 2019) and its contribution to the development of computational thinking (e.g., Angeli & Valanides, 2020).

The presented work focuses on the construction procedure when block-based educational robotic technology is used and aims to seek for its potentiality to contribute as a means to project spatial thinking across STEM domains. In the next section, a theoretical background is presented, which then serves as a basis for the discussion of a case that exemplifies a proposed approach towards the aim.

## Theoretical background

### *Spatial thinking*

A spatially literate student has the habit of mind to think spatially (i.e., knows where, when, how, and why to think spatially), practices this type o thinking (based on concepts of space, tools of representation and processes of reasoning) and holds a critical stance that leads to the validity of reasoning upon spatial information (National Research Council & Geographical Sciences Committee, 2005). Spatial thinking is malleable, and is of evolutionally and adaptive importance (Newcombe & Frick, 2010). Students could benefit from its inclusion in the school curriculum from the early years (Gersmehl & Gersmehl, 2007).

Spatial thinking takes place in three contexts, in the context of the physical world we live in (cognition in the four-dimensional space-time), in the scientific context where natural phenomena are studied (cognition about space) and in the context of our thoughts when we assign locations to objects and concepts that are not always spatial, i.e., when we spatialize our thoughts about a particular problem. Moreover, it holds three fundamental elements (National Research Council & Geographical Sciences Committee, 2005), as summarized next.

The first fundamental element of spatial thinking is understanding the *space of reference*. "Spatial thinking is based on the structure of the space and the operations *in* and *on* this structure" (p. 30). In order to understand the structure of the space of reference, we need to use the following properties (primitives) of the objects in it (i.e., the things that we want to understand), in order to think and reason about them:

- The *identity or name*. Upon this, hierarchies, taxonomies, classification of the objects of interest can be spatially represented.
- The *location in space*. In order to realize the objects' location in space a set of three ideas can help: a) the *language of space* upon which we capture the spatial properties of objects, using relevant descriptions, b) the *spatial concepts* that are derived upon these (temporal or spatial) location properties of the objects, and c) the *operations* upon which we manipulate the space of reference and understand the relations among the objects of interest in it.
- The *magnitude*. It can be spatialized as an ordered series.
- The *temporal specificity and duration*. This primitive concerning time can be spatialized as, e.g., change, growth.

The second fundamental element of spatial thinking is the *representations*, i.e., procedures where entities and their spatial or conceptual relations of the real world are mapped to entities and their spatial or conceptual relations in the represented world. Towards this, attributes of the objects are mapped through encoding possesses that depend on the nature of the task and the previous experience. Moreover, the relations between the entities (comparisons to other entities or to a frame of reference) are also represented, either being static or dynamic. The representations might be internal (in the mind) or eternal. In the latter case, tools like images, diagrams, concept maps provide the bed-set for the spatial representation to be expressed.

The third fundamental element of spatial thinking is the *processes of reasoning*. The representations may be perceptually processed, e.g., transformed and supporting inference prediction, creativity and scientific reasoning. Moreover, enacting is a case of spatial motor-thinking imaginary transformations that are connected to actions as they are conceived trough the interaction of the spaces of body and world. Through this way, forces and the mechanics of actions, as they unfold in time, are understood. Complex spatial reasoning entails sequencies of mental transformations upon representations of the task. In this case the order of the transformations reveals the way the enactment of the specific mental task has been internalized and can be used in other tasks.

The more the learning of general principles of spatial thinking and of multiple examples, the farther transfer of spatial thinking can be achieved. The engagement of students in situations where they have to realize the general principles and relations that are required to produce a schematic spatial representation that cuts across different problems, may enhance their ability to solve new problems. In this way some common aspects of spatial thinking in different domains may be transferred (e.g., how to construct a spatial representation) (National Research Council & Geographical Sciences Committee, 2005).

The transferability of spatial thinking across domains of the curriculum is very important. Longitudinal research work has revealed that it serves as predictor for later STEM achievement (Newcombe, 2017). Yet, more research of longitudinal work is needed to justify possible causality between spatial skills and STEM outcomes (Stieff & Uttal, 2015). Towards this direction, two teaching practices that bond spatial thinking and STEM are proposed (Newcombe, 2017): a) *direct*, that focus directly on the improvement of spatial abilities by separately teaching spatial activities and wait to see later effects on STEM learning, and b) *indirect*, by spatializing the curriculum, i.e., use teaching techniques that elaborate spatial thinking along with the learning content.

The construction of the educational robots is considered a procedure that, depending on the robot's technology, may entail various degrees of complexity and experience, which, in turn, may have impact on the time-consumption and on the class control (Karim et al., 2015). These may be considered as disruptions towards finalization of the construction phase, in order to reach quickly the curricula centric activities with the robot, neglecting possible learning benefits from the construction procedure. Research work concerning Lego-like block spatial construction tasks have been used to analyze the spatial skills, trough the evaluation of, e.g., the time of the construction (Frick et al., 2013), the way of constructing (Verdine et al., 2016) and the way of following rules, in order to produce a stable construction (Zhang et al., 2017). However, Cortesa et al. (2017) argue that instead of studying intermediate or final points of the construction, an effort should be put in the study of the whole construction *process*. In fact, they propose a behavioral coding scheme to characterize this process and through it, to reveal the underlying cognitive process that are engaged. Through their analysis, they provide external representations of the construction paths that were observed.

To our knowledge, such spatial representations depicting research results have not been used as a metacognitive tool to cultivate the spatial thinking of the students; the lack of such approach has motivated the spatialization case that follows.

## A spatialization case

### *The sample*

In order to produce a spatialization of the construction procedure of a robot using WeDo 2.0 blocks (in this work the term block is used for all the types of the construction materials of the WeDo 2.0 kit), 15 primary level students that attended an informal class of educational robotics were video-recorded upon their parents' consent. They ranged from the second to sixth grade of primary school and they worked in groups of two or three, each group containing at least one more expert student in robotics than the others. An excerpt of 15min from the video-recordings of the collaboration of two students, one from the 2nd and the other from the 3rd grade, was analyzed, in order to showcase a spatialization of their construction effort.

### *Methodology*

The two-peers tried to construct a robot model upon given instructions, which depicted images of blocks of various types and sizes, along with their expected correct stepwise addition on the current state of the body of the model. Moreover, along with these instructions, they were given the WeDo 2.0 commercial kit, which includes blocks of different types and sizes, in order to choose what they needed according to the instructions.

The most expert student undertook the role of the builder (student A) and the second student, the role of the assistant (student B). Student A performed the construction procedure following the instructions, whereas student B was following the procedure and intervened verbally when needed upon the instructions. Thus, the construction procedure took place in a collaborative argumentative framework. A frame-by-frame analysis of the video-recording was manually performed. Content analysis was used to spatialize the construction of the robot model and the argumentation between the pair.

A micro-analysis of the construction procedure captured the sequencies of actions that were coded according to Table 1. Moreover, extending Socratous and Ioannou (2018) argumentation coding work, the following codes were used:

- Remark
- Questions/questions for verification
- Prompt for the addition of a block
- Denial
- Confirmation
- Encouragement
- Acceptance/agreement.

**Table 1. Coding of the construction actions (*coding by Cortesa et al., 2017)**

| Coding of construction actions | | Explanation |
|---|---|---|
| Addition | Simple (top-down*/down-top) | Simple, certain, straightforward addition of a block without trials for its correct positioning. Addition top-down/down-top in relation to gravity and the current state of the body of the model. |
| | Not simple (top-down/down-top) | Addition of a block after trials for its correct positioning. Addition top-down/down-top in relation to gravity and the current state of the body of the model. |
| | Simple (sideways)<br>Not simple (sideways) | Addition of a block in relation to its current state of the body of the model. |
| Rotation | Body (clockwise)<br>Body (anti-clockwise)<br>Body (forward) | Rotation of the body of the model in its current state from the student A perspective. |
| | Block (clockwise)<br>Block (anti-clockwise)<br>Block (forward) | Rotation of the block from the student A perspective. |
| Deconstruction | Body | Remove of a block |
| | Blocks* | Remove more than one blocks that leads to the deconstruction of the body in its current state |

Upon the aforementioned coding, a Q-COREA (Kazantzis & Hadjileontiadou, 2021) graphical representation of the specific case of the robot model construction procedure was constructed. It provides a simple depiction at a higher level of abstraction that can contribute to a more hermeneutical approach to the interpretation of the results of the micro-analysis approach.

## Results

Figure 1 depicts an excerpt from this Q-COREA.

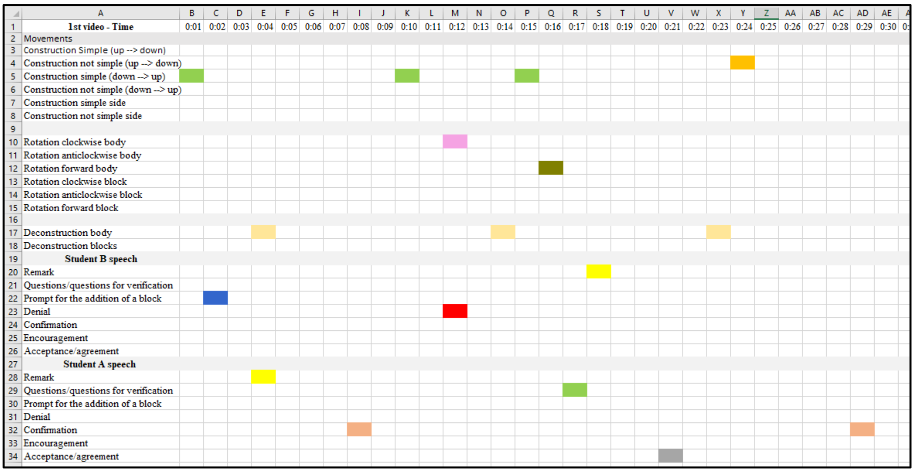


**Figure 1. An excerpt (30sec) from the Q-COREA graphical representation of the robot model construction process (same color palettes were used for the construction and the argumentation analysis, yet each color denotes different coding per analysis)**

The construction phase that was presented in the aforementioned case, entails all the three fundamental elements of spatial thinking (National Research Council & Geographical Sciences Committee, 2005).

The first element refers to understanding the *space of reference* and the construction procedure entails the four primitives of space, as students: a) *identify/name* and choose every time the block they need among other in the WeDo 2.0 kit, b) conceptualize each block's *location in space* using, the *language of space* to describe it to the peer, use *spatial concepts* to realize its temporal position (e.g., while holding it) and *operations* (e.g., rotations) to understand its relation to the body of the model, c) realize the *magnitude* of the blocks (e.g., as compared upon their length when they choose a block among other to fit in a specific position), and d) realize the time which is spatialized through the continuous *change* of the current state of the body of the model. The second element refers to the *representations*. Different representations are involved in the case construction procedure. The visual instructions that are provided to the students are external representations of the construction states towards the target model. However, student A (the builder) acts upon perceptual parsing of these representations, whereas student B keeps them as internal. Then upon each building action, argumentation gives the room for further elaboration of individual parsing. The Q-COREA is a spatialization tool that constitutes a graphical representation of the construction procedure after its completion, by mapping the original data (i.e., the construction actions that were coded) to the graphing entities. Towards this spatial representation, the attributes of the construction procedure need to be encoded and spatially represented. The construction of data visualization is not straightforward as it first has to be internally conceived (which data, how to encode them) and then externally expressed. The qualitative character of the Q-COREA however can support this effort as it simplifies the depiction of the attributes leaving the effort mostly to the collection of data. The third element is the process of *reasoning* upon the perceptual process of the representations. In particular, reasoning can refer, e.g., a) to the construction procedure of the model in the context of the physical world (e.g., as externalized through the language of space in the pair argumentation) and b) in the context of thoughts upon the spatialization of the construction procedure in the Q-COREA (e.g., detecting patterns and construction strategies as they evolve in time, indices of the enactment of the specific mental tasks like rotation, make predictions etc.). For example, the sequence of actions of the student A as depicted in Fig. 1 is: positioning from down-to-top, disassembling construction body, positioning again from down-to-top, rotating the body clockwise, again disassembling construction body, positioning from down-to-top, rotating the body in front, again disassembly of construction body and finally mounting from top-to-down (according to the law of gravity). Multiple experiences of construction of different robot models may reveal individual patterns of spatial thinking and acting. From the aforementioned it is evident that the construction procedure involves spatial thinking (Cortesa et al., 2017).

## Discussion

The present work proposes the utilization of the construction phase towards the cultivation of spatial thinking following the second teaching practice by spatializing the STEM curriculum when educational robotics is involved. This proposal is presented as an envisioned teaching procedure where the Q-COREA is constructed by the students and scaffolded by the teacher. In particular, in this teaching/learning approach using the Q-COREA representation, the following merits may be fostered: As the Q-COREA reflects the construction path that every student followed, it can serve as loci where their construction experience is pinned, retained and easily recalled (National Research Council & Geographical Sciences Committee, 2005). Thus, cultivating the use of spatial representations this may entail the general idea that the spatial representation may encode any type of information, i.e., a cut-across idea that may be used in all the STEM domains. The construction of the Q-COREA may feed discussions about data literacy, e.g., how data are produced, how data are sampled from the video, what is a coding scheme, who may construct the Q-COREA, how data are spatially reported, what are the axes of the Q-COREA, why is it a dynamic representation, are there any issues of reliability and so on. These basic ideas about spatial representations (either internal or external) constitute again a cut-across idea that may be used in all STEM domains. Manipulations of the Q-COREA (either imaginary or externally expressed), may provide the space for practicing spatial skills of transformations, e.g., by changing the Q-COREA, in order to spatialize the rotation from the student's B perspective, by zooming out the Q-COREA information, in order to aggregate the frequency of each action, by detecting patterns of spatial thinking and acting, by reasoning on the construction experience while using the language of space. Translations of the experience may incorporate even further reflections to the STEM domains, e.g., top-down construction follows the law of gravity (physics and engineering (Zhang et al., 2017)), stepwise construction entails an algorithmic procedure (technology (Città et al., 2019)) encoding instructions to 3D, shape identification, mental visualizations and transformations of geometrical entities (mathematics, (Markey, 2010), realization of the different functionality of the WeDo 2.0 kit blocks (technology and engineering, (Cortesa et al., 2017)). Q-COREA constitutes a model of the student's experience; hence, there are increased possibilities that it may bridge the physical and intellectual spaces, the first being the real experience and the second reasoning about it, i.e., a procedure that may simulate problem solving approach when spatial representation fits to it. Modeling and reasoning on the basis of the model are again a common approach in all the STEM domains. Spatial thinking contributes to leaning by encoding new information, recalling old one and solving problems that can be solved with the aid of spatial representations. As the spatial thinking is malleable, the above ideas outline opportunities that may be revealed from the construction phase of the educational robot. They foster on helping students to practice spatial representations at the metacognitive level by focusing on metacognitive knowledge and skills on generic issues concerning the construction of representations and their transformations. Though this way, it is anticipated that far transfer may be achieved across the STEM domains where more specifications are needed for the representations of each domain, e.g., diagrams, maps (National Research Council & Geographical Sciences Committee, 2005). The case reported in this paper constitutes a paradigmatic basis for the proposed approach, i.e., to spatialize the educational robot construction procedure. Its implementation depends on the characteristics of the 'actors' and the educational context involved. As Karim et al. (2015) suggest, teachers should have specific training in incorporating robot-based activities in the classroom being in close interaction with the students.

## Conclusions

Literature reports relationship of spatial thinking with different domains of STEM and that spatial thinking is malleable. This work considers spatial thinking as a cross-cutting thread across STEM domains. A case on the spatialization of the procedure, while constructing an educational robot, is presented and discussed as a proposal for metacognitively cultivating generic spatial knowledge and skills that may facilitate far transfer of spatial thinking in the

STEM domains. The work contributes in the area of STEM education when educational robotics is involved.

## References

Angeli, C., & Valanides, N. (2020). Developing young children's computational thinking with educational robotics: An interaction effect between gender and scaffolding strategy. *Computers in Human Behavior*, 105, 105954.

Anwar, S., Bascou, N. A., Menekse, M., & Kardgar, A. (2019). A systematic review of studies on educational robotics. *Journal of Pre-College Engineering Education Research (J-PEER),* 9(2), 2.

Città, G., Gentile, M., Allegra, M., Arrigo, M., Conti, D., Ottaviano, S., Reale, F., & Sciortino, M. (2019). The effects of mental rotation on computational thinking. *Computers & Education*, 141, 103613.

Cortesa, C.S., Jones, J.D., Hager, G.D., Khudanpur, S., Shelton, A.L., & Landau, B. (2017). Characterizing spatial construction processes: Toward computational tools to understand cognition. In G. Gunzelmann, A. Howes, T. Tenbrink & E. J. Davelaar (Eds.), *Proceedings 39th CogSci 2017 annual meeting "Computational Foundations of Cognition"* (pp. 246-251), NY: Curran Associates, Inc.

Frick, A., Hansen, M. A., & Newcombe, N. S. (2013). Development of mental rotation in 3- to 5-year-old children. *Cognitive Development*, 28(4), 386–399.

Gersmehl, P.J., & Gersmehl, C.A. (2007). Spatial thinking by young children: Neurologic evidence for early development and "educability". *Journal of Geography*, 106(5), 181-191.

Karim, M. E., Lemaignan, S., & Mondada, F. (2015). A review: Can robots reshape K-12 STEM education? In *2015 IEEE international workshop on Advanced robotics and its social impacts (ARSO)* (pp. 1-8). IEEE.

Kazantzis, T., & Hadjileontiadou, S. (2021). Microgenetic analysis of the educational robotics as mindtools. A case in the construction of the concept speed. In T. Tsiatsos, S. Demetriadis A. Mikropoulos & V. Dagdilelis (Eds.), Research on E-Learning and ICT in Education (pp.219-237), Cham: Springer.

Markey, S. M. (2010). The relationship between visual- spatial reasoning ability and math and geometry problem solving. *Dissertation Abstracts International: Section B. The Sciences and Engineering*, 70, 7874.

Martín-Páez, T., Aguilera, D., Perales-Palacios, F. J., & Vílchez-González, J. M. (2019). What are we talking about when we talk about STEM education? A review of literature. *Science Education*, 103(4), 799-822.

National Academy of Sciences (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research*. Washington, DC: National Academies Press.

National Research Council & Geographical Sciences Committee. (2005). *Learning to think spatially*. National Academies Press.

Newcombe, N.S, & Frick, A. (2010). Early education for spatial intelligence: Why, what, and how. *Mind, Brain, and Education*, 4(3), 102-111.

Newcombe, N. (2017). *Harnessing spatial thinking to support STEM learning*. OECD Education Working Papers, No. 161, Paris: OECD Publishing.

Socratous, C., & Ioannou, A. (2018). A study of collaborative knowledge construction in STEM via educational robotics (2018). In J. Kay, & R. Luckin, (Eds.), *Proceedings 13th International Conference of the Learning Sciences (ICLS) "Rethinking Learning in the Digital Age: Making the Learning Sciences Count"* (Volume 1, pp. 496-503). London, UK: International Society of the Learning Sciences.

Stieff, M., & D. Uttal (2015). How much can spatial training improve STEM achievement? *Educational Psychology Review*, 27(4), 607-615.

Uttal, D. H., & Cohen, C. A. (2012). Spatial thinking and STEM education: When, why, and how? *Psychology of Learning and Motivation*, 57, 147-181.

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. S. (2016). *Links between spatial and mathematical skills across the preschool years*. Monographs of the Society for Research in Child Development.

Zhang, M., Igarashi, Y., Kanamori, Y., & Mitani, J. (2017). Component-based building instructions for block assembly. *Computer-Aided Design and Applications* 14(3), 293-300.