Spatial thinking in primary students’ educational robotics construction tasks: An exploratory study

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Abstract

The present work aims at exploring spatial thinking of primary students while they construct a robot with Lego WeDo 2.0 in groups of two. Towards this aim, content analysis of the videorecording of this procedure is performed on the basis of two proposed coding frameworks, i.e., for the spatial speech and the students’ hands gestures/movements, respectively. The results revealed varying enacted and spoken manifestations of the students’ spatial thinking and language upon which the potentiality of their scaffolding towards their further enhancement within the broader context of STEM education is revealed. Further implementations of the proposed approach at different contexts may justify the potentiality of exploration of spatial thinking during educational robotics construction tasks, providing additional domain of analysis for the enactment of spatial thinking and language expression.

Keywords: Educational robotics, spatial thinking, robotics construction, STEM, Lego WeDo 2.0

Introduction

Spatial thinking may be involved towards the interpretation and intervention to space from many everyday-life to work situations and even more to scientific approaches. According to the National Research Council & Geographical Sciences Committee (2005), spatial thinking involves three elements, i.e., understanding the space of reference, creating representations of it, and reasoning.

As far as understanding the space of reference, a series of properties is needed in order for someone to describe of an object in the space i.e., identity or name the object, identify its location in space, its magnitude, and its temporal specificity and duration. On the other hand, the representations refer to a procedure where the real objects and their spatial relations are mapped to objects and relevant relations in a represented world either it being internal or externalized through real artefacts, e.g., maps, diagrams etc. Finally, spatial reasoning is the process by which the representations may be perceptually processed. In particular, it is the process through which we form ideas about the objects and relationships in space, i.e., manage spatial information.

As argued by Whiteley et al. (2015), both the development and the externalization of spatial thinking are complex processes, inextricably intertwined: a) with the cognitive processes of the mind, and b) with the physical movements of the body, which usually follow them. Different means of expressing spatial thinking include: a) *Spatial speech,* which is the main mean that is used to describe spatial situations, externalizing the internal mental processes that take place throughout spatial reasoning (Georges et al., 2021), and b) *Gestures of spatial representations*, i.e., hand/arm movements that are produced when someone is engaged in cognitive activity. In particular, representational gestures may convey and communicate spatial information and enact spatial thinking. Examining the use of gestures as a tool for expressing spatial thinking, Alibali (2005) argues that both Iconic-representational (e.g., tracing a square in the air to mean “square”) and Deictic gestures (point at something) play a

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decisive role in the representation of spatial data as they are natural processes that are usually synchronized in time with the spatial speech.

Educational robotics is a technology that may be integrated in a learning task and, in parallel, it provides a cognitive potential towards enacting of spatial thinking. In particular, the integration of educational robotics in a learning situation follows two typical phases, i.e., the *robot construction* (depending on the technology that is used), and 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), which preceded and followed the application of spatial skills assessment tests (pre-post tests) (Dickson et al., 2022), or served as a means to study spatial reasoning paths while programming (Diago et al., 2021).

Under this perspective, the construction of the educational robots usually is considered as a time-consuming procedure that, depending on the robot's technology, may entail various degrees of complexity and experience, which, in turn, may have impact on the class control (Karim et al., 2015). Yet, focusing on the construction process of an educational robot, in a guided construction task, students are asked to read correctly the construction instructions (where the parts that make up the robot are depicted in two dimensions), and faithfully follow them, in order to capture the two-dimensional image in a three-dimensional physical-real construction. In fact, one of the most important stages of the robot construction process is the identification and selection of the appropriate part, which must comply with the corresponding instruction, taking into account the fact that its orientation and position in the construction kit may differ from the orientation which has in its virtual representation. Therefore, the process of choosing the appropriate part requires the constant comparison between image and physical object, regarding its size, shape and orientation in space (Francis et al., 2017). In particular, regarding the correct placement of a part, it is a process that includes different sub-actions, such as: a) location detection, b) transformations, c) part re-placement, and d) final part placement in the correct position.

Research work concerning Lego-like block construction tasks has 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). Cortesa et al. (2017; 2018) and Ramani et al. (2014), proposed an approach to study spatial thinking while constructing, yet with very small number of pieces of blocks (six and eight, respectively). Sismani & Hadjileontiadou (2021) studied spatial thinking as it was externalized through the hand/arm movements of the student while s/he was holding a part of educational robot and tried to use it during the construction procedure of a robot using Lego WeDo 2.0 kit. More specifically, they proposed a framework for coding these movements. The present work extends the work of Sismani & Hadjileontiadou (2021) by focusing at the analysis of spatial speech and gestures and construction movements.

In particular, the present work is an explorative study that aims at detecting spatial thinking in a context where primary school students constructed a robot using the Lego WeDo 2.0 kit. The following research questions (RQs) were set:

- RQ1: How is spatial thinking expressed through students' speech, during their participation in the construction process of a robotic model?
- RQ2: How is spatial thinking expressed through students' gestures/movements, during their participation in the construction process of a robotic model?
- RQ3: Are patterns of synchronization of students' spatial speech and gestures/movements detected during the construction process of a robotic model?

The exploratory study

Setting and Participants

In the context of the Collaboration of the Department of Primary Education of the Democritus University of Thrace, Greece, with a primary school, the first researcher undertook an exploratory study on educational robotics construction tasks that took place during a weekly robotics club with 18 students of the 1st grade (6-7 years old) upon the consent of their parents and their teacher. The robotic kit Lego WeDo 2.0 was regarded as appropriate for this study as these tasks resemble to the construction of simple brick-toys that are used at this age. Initially, both the researcher and the teacher delivered two weeks training on the guided construction of «Milo» and «Spy» robots respectively from the unit "Getting started", upon the relevant two-dimensional visualizations that support the Lego WeDo 2.0 kit. In this way the students and the researcher were acquainted to each other and the procedure. Then the researcher focused on six students (three groups) that willingly followed her in the next two weeks. The students upon the same guided procedure constructed the "Speed" robot from the «Guided Projects-Science» unit. This exploratory study is based on an excerpt of 10 minutes from the video recordings of four students (three boys and one girl), i.e., the two more active working groups out of the three, that took place during the last two weeks.

The proposed coding frameworks

In this work, two coding frameworks for the manual video analysis are proposed at two levels. The first refers to the speech and the second to the gestures and the construction movements, respectively. A mixed approach that combined a content analysis procedure with elements of grounded theory (Bryman, 2017), resulted in a framework per coding level as described in the following sections. Inter-rater reliability was very high at both frameworks (Cohen's kappa coefficient κ >0.8).

Speech coding

Towards the speech coding on the basis of the transcribed text from the videos, two stages were foreseen. The aim of the first stage was to identify the areas of the text that contained elements of spatial speech using as 'unit of analysis the utterance', while the second was to further analyze these utterances with 'unit of analysis the word'.

In the utterance-based analysis, we took into account all the verbal sets (words, sentences, phrases), which were recorded as an uninterrupted chain of spoken language. The utterances were classified according to two coding categories depending on the context of the speech (Cannon et al., 2007), i.e., *purely spatial* and *non-spatial*. As purely spatial utterances were coded the cases of utterances where words, phrases, sentences were used in order to describe only spatial situations, construction instructions and functional features of the individual components-structural elements of the construction (Ferrara et al., 2011; Levine et al., 2012). On the other hand, as non-spatial utterances, were coded the utterances where 'spatial' words, phrases, sentences were used in the context of communication and cooperation between the students, i.e., this category includes utterances that do not have a pure spatial orientation, such as utterances made up of paralinguistic elements of speech, words-phrases that indicate admission or denial, call for attention, etc. (Socratous & Ioannou, 2019). From a ground to top perspective, based on the careful and iterative study of the transcribed text from the video recordings, the need to propose another coding category was highlighted, namely *mixed utterances*, which included utterances with both spatial and non-spatial use of speech.

In the word-based analysis, a content analysis of the purely spatial and mixed utterances was performed, with the unit of analysis being the word. Table 1 presents the coding framework that is proposed in this work. In particular, elements of the coding system of Cannon et al. (2007) were used in order to code speech at word level. Moreover, based on the careful and iterative study of the transcribed text, it was realized that a significant part of the words could not be correctly assigned to the specific coding categories, even though the content of the utterances to which they belonged was purely spatial and related to the development of the robot construction process. Therefore, the last four codes in Table 1 were added, with the aim of forming a more targeted coding tool for the data that stem in the context of an educational robot construction procedure.

Table 1. Framework for the spatial speech coding during the construction of a Lego-like robot

Code	Explanation	Examples
Spatial dimensions	Includes words that describe the size of an object, space, etc.	Small, big, tall…
Shapes	Includes words related to the description of the form-regularity of a two-dimensional-three-dimensional object, space	Circle, square, cube…
Location & Direction	Words used to describe the relative position of an object or points in space with respect to different reference systems.	In, out, down…
Orientation & Transformations	Words that describe the relative orientation and position of objects in space	Upward, below, upside down…
Continuous amount	Words that describe a three-dimensional object in terms of a continuous quantity	Whole, part, much, little, enough, even, extra, equal, length, width, meters, …
Deictics, pronouns, particles, locative adverbs	Words through which the local deictic is expressed and essentially marks the distance and proximity of an object in relation to the speaker's position in space, but their understanding depends on the general content of the sentence	Here, there, he, such...
Spatial Features & Properties	Words that describe the characteristic features and spatial properties of two-dimensional and three-dimensional objects, spaces, etc.	Straight, curve…
Pattern	Words indicating that reference is made to spatial patterns	Before, After, Repeat, Sequence, Row, Increment, Last, After…
Numerical designation of a robotic component	Words-Numbers through which a robotic component is described/named	"The one with the three holes."
Numerical designation of a robotic component with confirmatory character	Words-Numbers that are used as a measure to verify the designation of a robotic object through its mapping between the two-dimensional design (guidance design) and the three-dimensional space (robotic construction)	"That's right with the four holes."
Functional features & properties	Words used to identify mechanical and electronic components based on their function	Wheel, brain, cable
Construction Deconstruction	Words with which the attempt to connect-place the parts of the construction in space is expressed	put (add)….

Construction movements/gestures coding

The framework that is proposed here in order to code the gestures/movements while constructing an educational robot was formulated upon the adjustment of elements that were proposed/cited in previous research work, in similar contexts, as it is presented in Table 2. In particular, the code/s: a) Deictic and Virtual-Representational gestures (Hostetter & Alibali, 2008), b) Horizontal block placement (Ramani et al., 2014), c) Vertical block placement-location from top to bottom and from bottom to top, Horizontal and Sideways block placement, Rotation part clockwise/anticlockwise, Rotation body (clockwise/anti- clockwise) as used in Sismani & Hadjileontiadou (2021), d) Horizontal/Vertical inversion of block and body (as proposed in this work upon the empirical data of videorecording), and e) Deconstruction Block/s and Deconstruction Body to describe the movements related to assembly-disassembly (construction-deconstruction), highlighting in each code, the object to which each movement is related to (i.e. block for parts and body for a set of blocks) Cortesa et al. (2017).

Table 2. Framework for the spatial gestures/movements coding during the construction of a Lego-like robot

Code	Explanation
Deictic gestures	It includes movements such as the extension of the hand or fingers in order for students to point to objects, pictures, directions in space (without holding an object)
Iconic-Representational Gestures	It includes hand and body movements through which shapes, objects, spatial relationships etc. are represented (without holding an object)
Vertical block placement from top to bottom	Block placement vertically, with respect to the base of the structure from top to bottom
Vertical block placement from bottom to top	Placement of blocks vertically, with respect to the base of the structure from the bottom (from the base) to the top
Horizontal block placement	Block placement on the horizontal axis passing through the base of the structure
Sideways block placement	Block placement from left to right and the opposite in relation to the body of the structure
Rotation block clockwise	Clockwise component rotation according to the student's observation position
Rotation block anti-clockwise	Anti-clockwise rotation of a component according to the student's observation position
Rotation body Clockwise	Clockwise rotation of construction body according to the student's observation position
Rotation body anti-clockwise	Anti-clockwise rotation of construction body according to the student's observation position
Vertical Inversion block	Inversion of a component from bottom to top or vice versa on the horizontal mental axis
Vertical Inversion body	Inversion of a body of construction from bottom to top or vice versa in the horizontal mental axis
Horizontal Inversion block	Inversion of a component from right to left or vice versa on the vertical mental axis
Horizontal Inversion body	Inversion of a body of construction from right to left or vice versa in the vertical mental axis
Deconstruction Block/s	Disconnecting a part from the rest of the body of the structure
Deconstruction Body	Disconnecting several components together as a construction body

Results and Discussion

Upon the content analysis of the speech with the proposed framework (RQ1), 53% of the utterances included 34% pure and 19% mixed spatial utterances, which might be considered sufficient, taking account the pre-training weeks were direct scaffolding of spatial words took place. Further content analysis of these utterances using the word as a unit of analysis, revealed two classes of results. In the first class, Deictics appear with greater frequency (42%), quantitatively prevailing in the speech of the students, while in combination with the frequency of occurrence of words expressing the Numerical designation of a robotic component (23%), they constitute 64% of the words with spatial content. The second class refers to: Construction-Deconstruction 8%, Location & Direction (7%), Functional features & properties (7%), Numerical designation (confirmatory) (4%), Continuous amount (4%), Spatial Features & Properties (3%), Spatial dimensions (1%), Orientation & Transformations (0.5%), Pattern (0.5%) and Shapes (0%). Form the difference between the two classes of the results, it is evident that the students lacked the vocabulary to name the Shapes of some the Lego WeDo 2.0 components or their functionality. To overcome this difficulty, they used some external characteristics (e.g., number of holes). Regarding the quantitative analysis of all the students' gestures/movements during their participation in the construction process (RQ2), 32% were Deictic gestures, whereas 5% Iconic-representational ones. The Deictic gestures were used by students in order not only to express spatial information, but also it seems to be the case that they intended them to communicate such information (Alibali, 2005). A total percentage of 20% referred to the four sub-categories of placement movements, with the Vertical block placement dominating with 11%, followed by the Sideways block placement at 7%. In particular, the prevailing top-down mounting strategy entails spatial reasoning procedure according to the law of gravity. Moreover, this procedure is also manifested in a 37% of the sum of gestures/movements through all eight different sub-categories of rotations and inversions, almost uniformly split in all the sub-categories of rotations around 6% and the inversions around 3%. It seems that this elaboration of movements towards mounting the blocks in order to construct the robot externalizes an effort to manage the spatial information. Finally, 6% referred to Deconstruction Blocks movements whereas no Deconstruction Body movements were recorded, the latter being an indicator of successful straightforward route towards the robot construction.

By analyzing the occurrence of speech and gestures/movements (RQ3) it seems that two main patterns are detected. The first pattern can be identified in the use of Deictic expressions along with Deictic gestures. It seems that in this pattern the gestures convey spatial information that is not expressed in the speech, and, thus, it is accompanied by the gestures (Alibali, 2005). This pattern reveals the lack of spatial vocabulary and the Deictic gestures function as a means to communicate the content. The second pattern refers to the time that the aforementioned synchronization of the Deictic speech and gestures takes place, i.e., it appears to precede or follow block mounting movements. The use of Deictic expressions, in synchronization with the manifestation of Deictic gestures, constitutes elements of cognitive processes of spatial reasoning, through which the spatial internal representations are externalized (Alibali, 2005).

From the aforementioned it is evident that this exploratory study revealed aspects of all the three spatial thinking elements as they were enacted during the construction procedure of a robot. More specifically, as far as space understanding is concerned, the students managed to identify the blocks they needed and conceptualized their position on the body upon operations on the blocks, but they had difficulties in the language of space and enhanced it through the gestures and sideways in order to name them. Moreover, they realized the magnitude of blocks on the basis of comparisons with the pictorial aid, and they realized the construction process evolving in time. Representations seemed to be employed through the broad perspective of translating the 2D visual instructions to 3D construction through operations on each block towards the enactment of this effort. Finally, processes of reasoning were manifested in speech and gestures/movements throughout the construction procedure. On the basis of the proposed coding frameworks the present exploratory study extended previous work in the area (Sismani & Hadjileontiadou, 2021), by extracting a more fine-grained information concerning spatial thinking though the construction procedure of a Lego WeDo 2.0 robot. Such information reveals the construction phase in educational robotics as a space to cultivate spatial thinking. For example, this exploratory study revealed that although students managed to perform the construction task upon only pictorial support, it seemed that they needed more scaffolding with spatial vocabulary words by the teacher, combined with the specific robotic technology (Cohen & Emmons, 2017). From this perspective, beginner students could benefit from their teachers who might use spatial vocabulary while introducing the robot kit and demonstrating the construction procedure. Moreover, the pictorial support could be further enhanced with relevant vocabulary and the students could be asked to speak aloud about their construction movements. Such an approach might increase the possibilities for a student to enhance the spatial vocabulary towards externalizing spatial thinking yet, under the limitations that stem from his/her age and sociocultural background and the social-emotional context where the construction takes place (Cohen, 2015). Future uses of the proposed approach may further underline the contribution of this study to reveal the opportunities that are hidden in the construction procedure when Lego-like educational robotics is used towards triggering spatial thinking, and cultivating a more refined spatial (mathematics) and technical (engineering) language in the broad area of STEM education.

Conclusions

The presented exploratory study managed to capture manifestations of spatial thinking, while a Lego WeDo 2.0 robot is constructed upon a proposed coding framework of spatial speech and gestures/movements. The proposed analysis framework showed sufficient sensitivity and specificity to identify the different facets of spatial thinking, showcasing a potentiality to extend it further as a tool that could facilitate the educator to deep into the students' way of thinking. Implications from the utilization of this information towards scaffolding of students in further STEM domains relate with new means of understanding students' embodied perception of space.

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