Coding Landmarks: A Programming Approach to Spatial Thinking

Programming as a Scaffold for Spatial Reasoning

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Abstract
While previous research has identified a correlation between spatial thinking and programming, little attention has been given to how programming can explicitly support students' spatial reasoning during learning activities. This study explores the role of programming as a scaffold in supporting spatial reasoning and conceptualization among primary students while they navigate the digitally simulated space within a programming microworld. Using a design-based research approach, we analyze how programming activity guided students' wayfinding in the digitally simulated space and supported the development of spatial concepts, providing them with the means to deploy computational thinking practices, like debugging, problem decomposition and abstraction to spatial problem solving.

Keywords and Phrases: Spatial Thinking, spatial concepts, programming, navigation, Computational Thinking

1. Introduction
Spatial thinking refers to the ability to use spatial concepts and representations effectively to support spatial reasoning processes (Jo & Bednarz, 2014) and it is considered fundamental not only regarding geography learning but also STEM domains, such as mathematics (Newcombe, 2010). Most research has focused either on examining the correlation between spatial thinking and cognitive achievement (e.g., Parkinson & Cytts, 2020) or on using factor analysis to define its core components (Bruce et al., 2015). However, research on the design of educational activities that support spatial reasoning development remains limited, mainly due to our limited understanding of how students develop their spatial reasoning and interact with spatial representations (Schulze, 2021). At the same time, according to scholars, students' difficulties in STEM fields, derive from students' inability to think spatially (Clements et. al., 2003). Especially regarding geography, where spatial thinking is essential for understanding key geographical concepts and activities, like map reading (Ishikawa, 2013), its neglect reduces the subject to mere memorization, disconnecting it from real-life applications (Bloom & Palmer-Moloney, 2004).

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Previous research suggests a positive correlation between programming and spatial skills; however, few studies have explicitly employed programming activities to study how it can foster spatial reasoning during learning activities. Rather than merely examining the link between spatial thinking and programming abilities, in this study we adopt a qualitative, design-based research approach (Bakker, 2018) to study and describe the processes under which primary students develop spatial reasoning processes when navigating the digitally simulated space in a programming environment. Through this design, we aim to gain insights regarding two research questions (RQ):

RQ1: How programming affects spatial reasoning during navigation in the digitally simulated space?

RQ2: What spatial concepts do students develop when using programming to navigate the digitally simulated space?

2. Spatial Thinking

Daily activities, such as estimating the capacity of a container, understanding maps, assembling furniture or packing a suitcase as well as understanding physical phenomena like the planetary motion rely on spatial thinking. According to Jo and Bednarz (2014) spatial thinking consists of three main components: spatial concepts, spatial representations and spatial reasoning processes. Spatial concepts, such as location, direction, distance, and pattern, provide the language for describing and analyzing spatial environments (Jo & Bednarz, 2014). Previous work from the field of geography education has proposed a progressive development of spatial concepts starting from basic archetypes (e.g., identity, location, size) and progressing to more advanced concepts like scale and connectivity (Golledge et al., 2008). Since spatial concepts are relative in nature, a crucial aspect of using them effectively is the use of spatial frames of reference (FoR). A FoR is a system or set of coordinates used to describe the position or orientation of objects within a space, which helps individuals describe locations relative to other objects or reference points. Levinson (2003) identifies three spatial FoRs that individuals use when they refer to spatial concepts: intrinsic, relative, and absolute. The intrinsic frame defines position based on the spatial properties of another object (f.e., the dog is in front of the house). The relative frame is viewer-based, describing position relative to the observer's viewpoint (f.e., the bag is to the right of the wardrobe). The absolute frame uses fixed coordinates, such as cardinal directions or the Euclidean Cartesian system, where positions are determined by measurements (e.g. the park is located five kilometers north of the city center).

The use of spatial frames of reference strongly depends on the kind of spatial representations used during communication about spatial meanings. Spatial representations, like maps or graphs, the second main component of spatial thinking, allow individuals to encode and interpret spatial relationships. Bruner (2006) categorizes representations into three types: enactive (action-based), iconic (image-based), and symbolic (language- or symbol-based). Effective spatial reasoning requires individuals to translate between these different kinds of representations, such as converting a map into verbal directions (Duval, 2017).

The kind of spatial representations used during spatial tasks affects the development of spatial reasoning. Spatial reasoning refers to cognitive processes that enable individuals to understand and manipulate spatial relationships (Atit et al., 2020). It involves various skills, such as mental rotation, perspective-taking, and visualization

(Newcombe, 2010). In geographic contexts, spatial reasoning facilitates geospatial problem-solving, such as interpreting topographic maps and navigating unfamiliar environments (Bednarz & Lee, 2019). A case of application of spatial reasoning is wayfinding, which involves identifying one's location and orienting while navigating (Ishikawa & Montello, 2006). Wayfinding relies strongly on the use of landmarks, distinctive locations in the city, such as monuments, that are used as reference points to indicate a location or a change in direction and to confirm the accuracy of the route. Landmark knowledge is the basis from which navigators progress to the development of route knowledge, meaning knowledge about the routes that connect the landmarks, and finally configural knowledge of the environment they navigate, meaning knowledge about the spatial relationships in the context of the broader spatial structure of the environment they navigate (O'Malley et al., 2018).

3. Spatial Thinking and Programming

Previous studies have explored the correlation between spatial skills and programming performance (Bockmon et al., 2020; Parkinson & Cutts, 2020; Fincher et al., 2006), showing that students with stronger spatial skills tend to perform better in coding activities. Cox et. al. (2005) elaborate on this positive correlation, explaining that navigating and structuring code requires building a mental map of its embedded concepts, a process analogous to wayfinding in physical environments, which they describe as code-to-concept mapping. They argue that programming environments resemble physical spaces in that they require spatial orientation and hierarchical organization. In both cases, programmers and navigators rely on distinctive elements of the environment as a basis for understanding the broader structure of the code or physical environment. Cox et al. (2005) call these elements 'beacons', while in the context of spatial navigation they are known as landmarks (Jones & Burnett, 2008). In programming, beacons are key pieces of code that indicate specific functionalities and help programmers organize and interpret the structure of a program (Reddivari & Kotapalli, 2017). Accordingly during spatial navigation, landmarks allow navigators to keep track of their paths or indicate locations where change of direction is needed, as part of the piloting wayfinding strategy (Allen, 1999), supporting the acquisition of configural/survey spatial knowledge (Ishikawa & Montello, 2006). Margulieux (2020) also suggests that the strong link between programming and spatial reasoning lies in the fact that computational practices mirror spatial reasoning processes. For example reorienting is a form of debugging. Existing research only refers to undergraduate students in computer science courses that aim to use spatial thinking activities to improve programming learning. In contrast, the role of programming in fostering spatial thinking with the aim of improving geography education remains unexplored. This study aims to address this gap by investigating whether and how programming activities can support the development and conceptualization of spatial thinking to improve spatial learning.

4. Methodology

Aiming to study in detail how programming activity stimulates students' spatial reasoning, this study employs a design-based research methodology (DBR) (Cobb et al., 2003), including the design of educational tools and classroom implementation. In DBR the primary focus is to deeply understand processes that emerge within specific contexts, generating new theoretical insights as well as informing educational practice (Cobb et al., 2003). Since theory development is about propensities and processes, rather than generalizing from a random sample to a population, DBR aims for generalization to a theory, model, or concept by presenting findings as particular cases of a more general model or concept (Bakker, 2018).

4.1 The Travel Microworld

Taking into account the strong relationship between spatial thinking development, spatial language (Levinson, 2003), and embodied experience, we designed a digital LOGO programming microworld (Papert, 1980) (Figure 1), 'The Travel microworld', where students navigate a digitally simulated space using dynamically linked symbolic, iconic, and embodied representations (Morgan & Kynigos, 2014). The digital microworld was designed using MaLT2 (http://etl.ppp.uoa.gr/malt2/), a LOGO programming environment that combines symbolic expression with dynamic manipulation. One of the main strengths of LOGO programming, that makes it suitable for young learners, is that its commands correspond to bodily actions, supporting the connection between students' concrete embodied experience with abstract spatio-mathematical concepts (Papert, 1980), allowing them to express their intuitive ideas in symbolic ways. At the same time, the turtle's anthropomorphism enables body- syntonic learning, as students can synchronize with its movements to construct embodied spatial meanings (Papert, 1980). Previous research with MaLT2 has shown that primary students develop rich spatio-mathematical meanings, like angles as turns, when they are engaged with activities with LOGO (Latsi & Kynigos, 2022).

Spatial navigation was chosen as a context for studying students' spatial reasoning processes, as it inherently requires the effective synchronization of different types of representations. During navigation, one has to synchronize enactive representations which emerge as a result of movements with iconic spatial representations, like maps or building layouts, as well as with symbolic representations like verbal instructions. This synchronization requires a translation process between different representations of the spatial environment (Burgess, 2006), providing the context where spatial reasoning processes (Thom, 2018) emerge to achieve relative understanding (Gkreka & Kynigos, 2025).

The 'Travel Microworld' (Figure 1) consists of four main components:

A. The 3D Scene (Figure 1a), which simulated the geographical map, including hidden landmarks that represent countries' locations.
B. The LOGO editor (Figure 1b), where students type programming commands or execute already made procedures. In the LOGO editor ready-made procedures were available:
   a. 'you_are_here': it shows in the message window how many miles north or south, east or west is the entity located in relation to the starting pin point (green pin point) (Figure 2c).
   b. 'new_flight': it shows the sliders (Figure 1c) that move the entity towards the cardinal directions. It also shows on the 3D scene, a pin point whenever the entity is located on a country (Figure 1d, 1e). The two variables correspond to how many miles north or south, east or west is the entity located in relation to the starting pin point (green pin point).
   c. The sliders (Figure 1c), which move the entity on the digital scene.
   d. The message window (Figure 1d), which provides feedback on programming errors and confirms country locations.

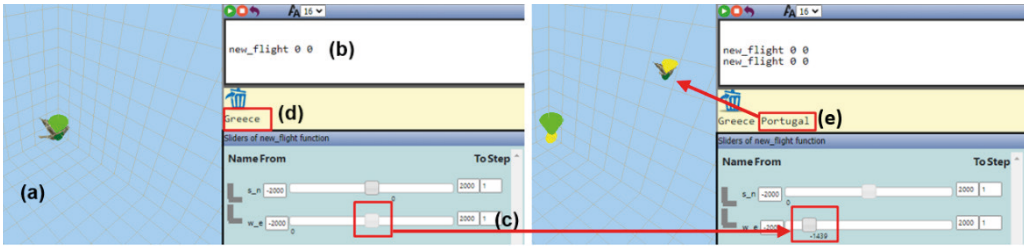

Figure 1: The elements of the Travel Microworld: (a) the 3D Scene where students navigate the digitally simulated space, (b) the LOGO editor where students input programming commands, (c) the sliders that allow students to move the entity using the cardinal directions (d) and (e) the message window providing feedback on location and errors.

Students worked in groups of 3-4. Each group used one computer and one supporting manual that included basic information regarding the interaction in the digital environment and explanations regarding LOGO programming commands and the procedures that were already create in the editor. They were tasked with locating various countries (e.g., Greece, Italy, Portugal, Algeria), on the 3D scene. They could either program the entity with simple commands in which they inserted values from measurements they did on Google Earth map (Figure 2a, 2b). They would then run the procedure 'new_flight' and use the sliders to place the entity on the point its path had previously ended, in order to see whether the landmark appears. They could also use the sliders directly to search for the landmarks using the four cardinal directions. The emphasis was placed on identifying and expressing the spatial relationships between the countries represented on the digital map, rather than precisely calculating distances or accurately simulating an airplane journey.

4.2 Data collection and analysis

Twenty 12-year-old primary students participated in the study. The students had a little previous experience in block-based programming but they did not have any previous experience of navigation activities in the context of formal schooling. The data collected included screen and audio recordings during the activity. The analysis initially involved synchronizing and transcribing audio and screen recordings and then identifying in them critical incidents (Angelides, 2001), cases where students faced problems and came up with solutions, while expressing their spatial reasoning processes. Following, explanatory codes were assigned to incidents indicating computational and spatial thinking practices (e.g. debugging or path integration). These codes were grouped into thematic categories (Xu & Zammit, 2020) based on the computational practices students used during the activity to orient and locate the countries-landmarks in the digitally simulated space. In the results, we present indicative episodes where students use the computational practices of debugging, problem decomposition and abstraction (Brennan & Resnik, 2012).

5. Results

5.1 Debugging

Initially students used an egocentric approach in navigating the digitally simulated space. They thus programmed the entity using simple directional commands whose values were based in measurements they did on the Google Earth map (Figure 2a, 2b). For example, as shown in Figure 2, students want to reach France starting from

Italy. They use the Google Earth measurement tool to measure the distance (Figure 2b) and then the digital protractor to measure the angle that corresponds to the turn the entity has to make in order to head towards France (Figure 2a).

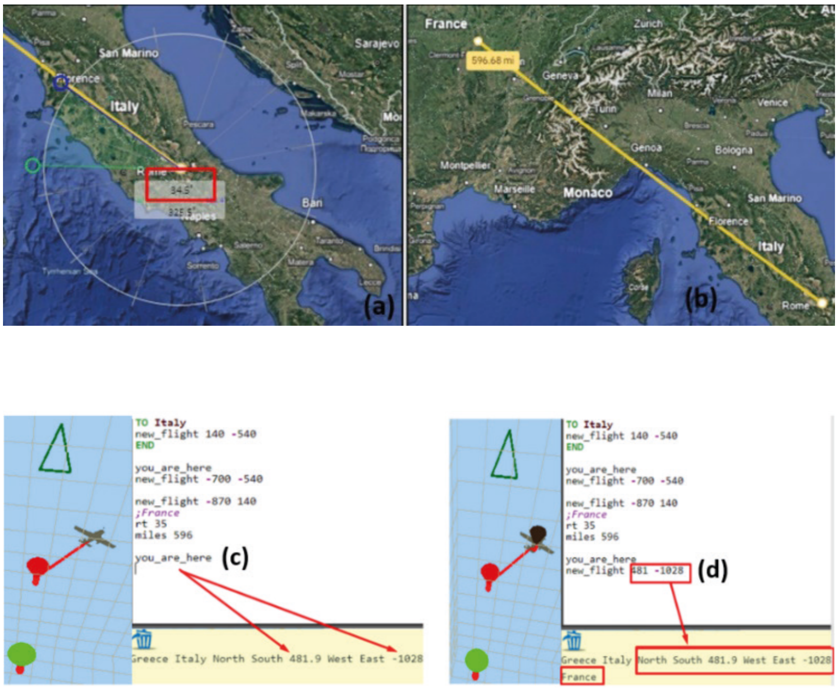

Figure 2: Figure 2 Students try to reach France: (a) measuring the turning angle and (b) distances, (c) running the 'you_are_here' procedure to retrieve coordinates, (d) running 'new_flight' to check whether France appears at the correct location.

After having executed these commands, they run the procedure 'you_are_here' (Figure 2c) so that they get the values they have to insert in the procedure new_flight (Figure 2d) to test whether France landmark appears in the spot they have reached. However, this strategy proved complicated, often resulting to misorientation. For example in the next incident students have reached to the Atlantic ocean while they were initially searching for Libya.

> S11: From Portugal (Figure 3b), we went to Poland (Figure 3c), and now from Poland, we went to the Atlantic Ocean (Figure 3d).
>
> S12: Logically, look—since we went left from Poland, we should be here (Figure 4a) (shows on the Google Earth map).
>
> S12: Mmm, yeah... And basically, if we were here (shows Poland on Google Earth) and before we went right, then before we were (rotated the Google Earth map to show that they have to be in the north part of the ocean) (Figure 4b). Oh, I just realized, we didn't find Portugal earlier (Figure 3a). So erase that, it's wrong. (They erase 'Portugal').

In the above episode students use the code to review the movements that the entity made and resulted in the Atlantic Ocean. In order to figure out what went wrong students apply a dead reckoning reasoning process, recalling their previous movements. This process is supported the documentation of their commands in the logo editor. Through this process students identify the bug in their code they have mistakenly defined Portugal landmark so they erase it from the LOGO editor.

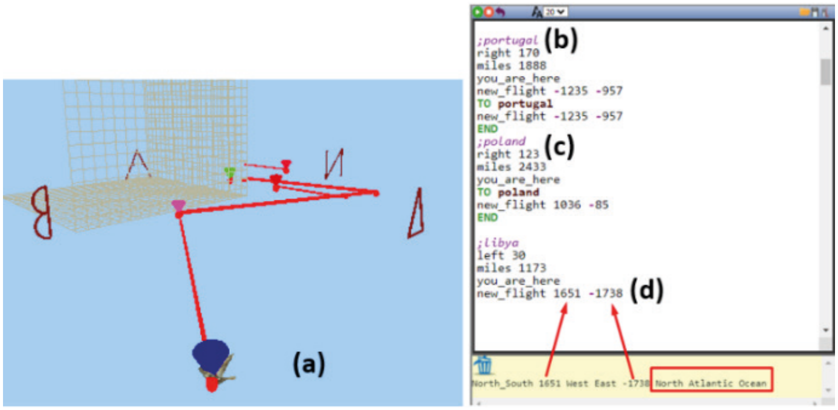

Figure 3: Students have reached Atlantic Ocean (a, d) and recall the commands that use to first go to Portugal (b), then Poland

Figure 4: Students rotate the Google Earth map to retrace their path and realize where the entity is located.

5.2 *Decomposing problems – calling landmarks*

Most of the students initially followed the step by step strategy to locate the landmarks on the scene. However as shown n the above episode, they soon realized that this process was time consuming and confusing. Gradually they adopted more practical ways of wayfinding. In the following incident students are still trying to locate Libya. When running the procedure new flight they do not get any landmark (Figure 5).

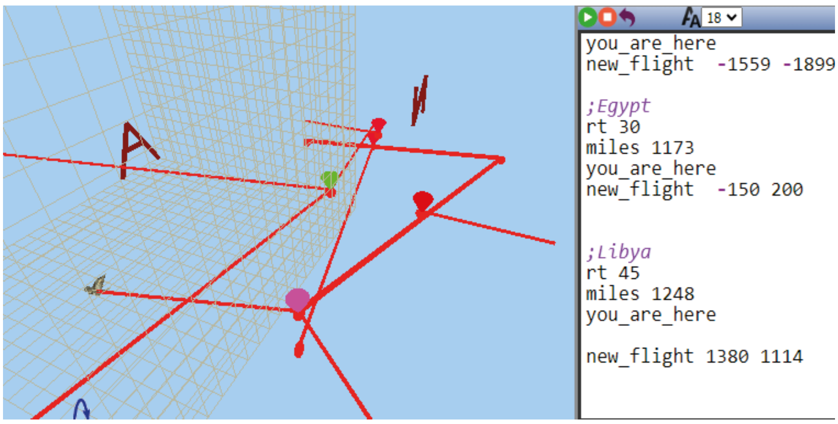

Figure 5: Students run the 'new_flight' procedure but do not find Libya

S14: I told you; we should have gone left. We're completely lost!

S7: Ok, look, I have an idea. Egypt is next to Libya, so let's go to Egypt (Figure 6a) since we know where it is, and then we move this (the slider) (Figure 6b). They student clears graphics and starts from the beginning.

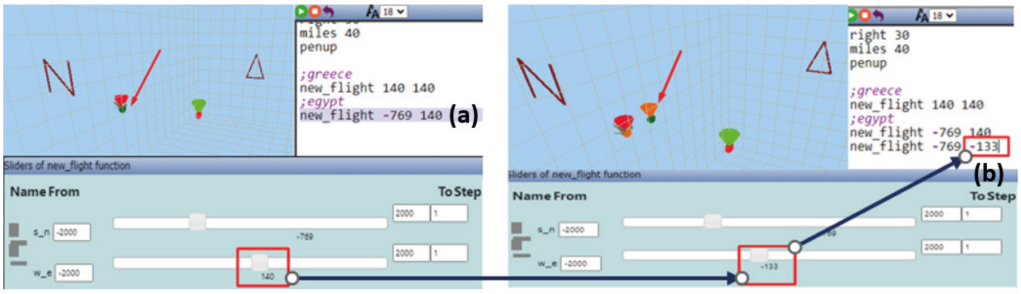

Figure 6: Students go to Egypt (a), move the slider and reach Libya (b)

Other groups followed the same strategy. For example in the next episode students of another group try to locate Ukraine. They start measuring the distance when the notice that Ukraine can be located if they head north while starting from Cyprus.

S17: We'll go to Cyprus (Figure 7a, 7b) and then straight up... It's on the same...

S18: Directly north from Cyprus (Figure 7c).

As shown in the examples this decomposing problem strategy was related with the use of geospatial frames of reference. Using the frame of reference of cardinal directions in combination with the code that placed the entity on a known landmark they managed to locate the hidden landmark they searched for.

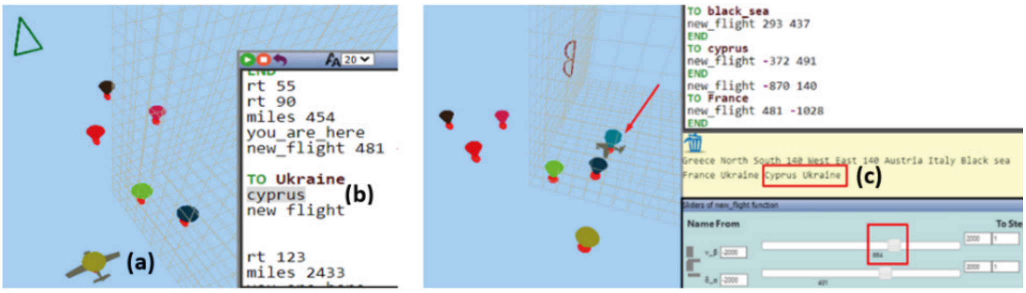

Figure 7: Students locate Ukraine using the 'cyprus' procedure, (a, b) and moving the entity towards the north using the slider

5.3 *Abstraction – coding Landmarks*

The ability to manipulate representations provided the children with a framework to extend their piloting strategy by defining their own landmarks. In this case, the children used the editor to create their own procedures that corresponded to the locations they often found by chance or by mistake. For example, in the following episode, the children are searching for Portugal. However, they end up finding the North Atlantic Ocean (Figure 8a).

S20: No, we arrived at the North Atlantic Ocean.

S21: Wait, add this in now that we found it. Make one like the one we have for Italy (means the procedure that locates the entity directly on Italy) so we can write it down and go there if we want to find something else nearby (Figure 8b).

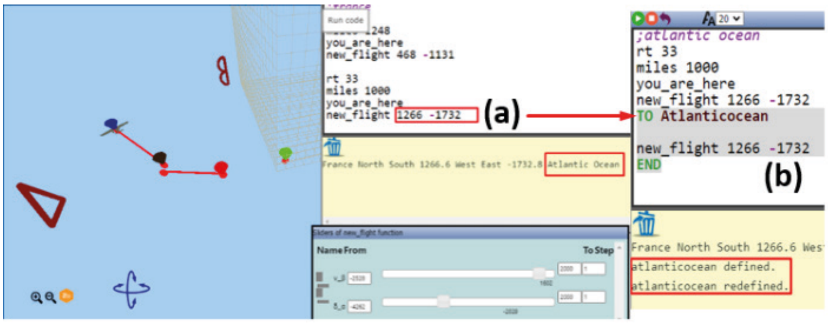

Figure 8: Students create a new landmark procedure for Atlantic Ocean (a, b)

Another indicative episode is the following where students have reached the Poland while searching for Libya (Figure 9a).

S7: Why are we in Poland (Figure 9a)?

S10: Great, save it at least, now that we have it (Figure 9b).

S7: How?

S8: Give it a name, like here (shows the “Austria” procedure).

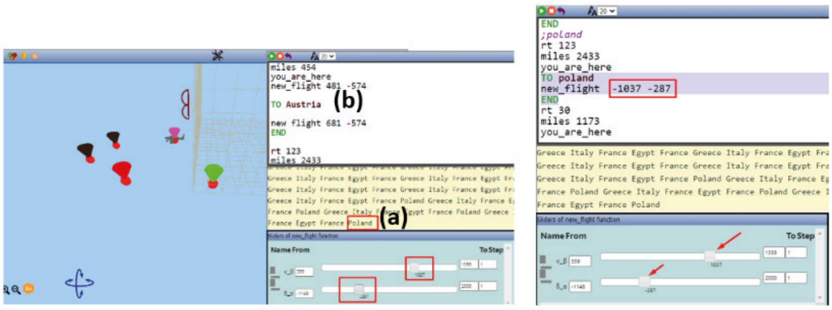

Figure 9: Students reach Poland while searching for Libya, (a, b) and they create a procedure for Poland to use it as a reference.

The students’ creation of procedures like “Atlantic Ocean” and “Poland” is an example of the computational practice of abstraction because students created named procedures that represent specific locations for future reference, transforming complex navigation steps into reusable commands.

6. Discussion

In our study programming served as a context for students to express their spatial reasoning process based on computational practices, in relation to which students developed geospatial concepts. Initially, students relied on relative frames of reference, using simple programming commands to move the entity. They used the computational practice of debugging in relation to dead reckoning reasoning by reviewing the commands they had inserted in the editor. Gradually though, they adopted landmark-based navigation, using known reference points to orient themselves in space progressing finally to the use of absolute frames of reference in relation with the computational practice of decomposing navigation in relation to the piloting wayfinding strategy, using the known landmarks as starting points to locate the hidden landmarks. Finally they deployed abstraction practices, defining their own procedures, creating reusable reference points for navigation. As students engaged in programming-based navigation, they naturally began to develop and apply key spatial concepts. They initially relied on relative frames of reference (e.g., moving "left" or "right"), expressing the concept of relative location, but through programming commands such as 'new_flight', they started incorporating absolute/geographical frames of reference to define locations as absolute or geographical. using cardinal directions. The study highlights the value of computational thinking for spatial thinking development especially in relation to geography education, suggesting the integration programming activities and spatial tasks, that allow students to express their spatial reasoning processes in a structured way. Future research is needed to further explore how programming and computational thinking based approaches can support spatial learning.

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