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Embodied Cognition in the Intersection of Spatial Navigation and Computational Thinking

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Abstract: Cognition is not an exclusively mental process, but emerges from the continuous interaction between mind, body and environment. If cognition is strongly embodied, the ability to explore the environment could play a key role in the development of higher-level cognitive abilities, such as computational thinking. The ability to navigate space involves mental representations and the ability to manipulate these representations, which involve different cognitive processes such as learning sequences and forming associations. In this sense, spatial navigation and computational thinking share some cognitive mechanisms that this article aims to explore, as they could open up new perspectives and innovative educational methodologies.

Keywords: Embodied Cognition, Spatial Navigation, Computational Thinking, Cognitive processes.

1. Introduction

The mind has long been regarded as the result of complex representations based on computational procedures. This view gave rise to the mind-computer analogy, according to which "cognitive processes can be understood in terms of formal operations performed on symbolic structures" (Pylyshyn, 1980). From this perspective, sensorimotor processes were relegated to peripheral input and output devices (Wilson, 2002). The advent of the Embodied Cognition paradigm has introduced a radically different view that emphasizes the importance of the body for cognition that emerges from the interaction between mind, body, perceptual system, and environment (Di Paolo & Thompson, 2014). Within the Embodied Cognition paradigm, various contributions and theoretical approaches have emerged that refer to the 4Es framework of cognition (embodied, embedded, enacted, extended). According to this theoretical framework, cognition is inseparable from the body, embedded in the physical environment with which the subject's body interacts, and can extend itself through tools and technologies (Rowlands, 2010).

Thus, the concept of embodiment becomes crucial in the study of human cognition, taking shape as a key construct within the new direction pursued by cognitive science. Embodiment is not limited to perceptual experience, but represents an integration of motor, tactile and visual information that influences bodily representation and interaction with the environment (Ziemke, 2013).

Classical models of embodiment are increasingly being applied in educational contexts, giving rise to the concept of 'embodied learning' (Clughen, 2024; Shapiro & Stolz, 2019). Embodied learning represents a multimodal approach that engages students through sensory and motor experiences and, with recent technological advancements, often includes interaction with technology.

This approach utilizes bodily engagement to facilitate learning, with positive effects demonstrated in several areas, including language (Jusslin et al., 2022), reading and writing (Kiefer & Trumpp, 2012), STEM disciplines (Weisberg & Newcombe, 2017), and spatial skills. These skills are described as 'embodied skills' (Thom & Hallenbeck, 2022) and define the perception of space, the manipulation of surrounding objects and various ways of navigating the environment. Among these skills, spatial navigation is notable for its multimodal nature because it not only involves movement through the environment but also includes the mental representation of space and the ability to manipulate them involving different cognitive processes such as learning sequences and forming associations (Chrastil, 2013; Montello & Raubal, 2013).

Similar cognitive mechanisms sustain computational thinking, which is increasingly recognized as a fundamental skill in education as it develops essential problem-solving abilities. It is also closely related to higher-order cognitive functions such as decomposition, analysis, synthesis and evaluation (Baldassarre et al., 2017). A meta-analysis conducted by Uttal et al., (2013) found that spatial skills training has a positive impact on performance in computational and problem-solving tasks. Similarly, research by Buckley et al., (2019) suggests that training aimed at developing spatial skills significantly improves the ability to solve complex problems. The study conducted by Città et al., (2019) explored the link between spatial skills and computational thinking, demonstrating a relationship between mental rotation ability and higher-level cognitive processes related to computational thinking. Furthermore, Chan et al., (2024) demonstrated that computational thinking requires spatial reasoning, as students engage with multiple visual representations across various computational tasks. More recently, Berson et al., (2023) explored how robot programming can form a basis for the development of spatial reasoning and computational thinking in pre-school children. Their results show that children develop an understanding of spatial concepts and computational thinking while interacting with a programmable robot, navigating a path during a guided game.

Despite preliminary experimental evidence, there are still few studies that have explored the specific role of spatial navigation skills, mainly due to the challenge associated with conducting long and standardized real-world navigation experiments (Newcombe & Shipley, 2014). To overcome this challenge, recent research has utilized tangible technologies and virtual environment navigation paradigms offering new insights into understanding the relationship between spatial navigation and computational thinking (Nazareth et al., 2019). Therefore, identifying the cognitive intersections between spatial navigation skills and computational thinking could fill a gap in the literature and encourage the development of experimental research supported by technologies capable of overcoming the methodological limitations encountered so far. As described by Hajian (2019) learning can be transferred from one activity (e.g. orientation and movement in space) to the other (computational problem solving) if the two activities are very similar and share many common elements. This means that if spatial navigation and computational thinking share similar cognitive processes, it is possible to hypothesize that the former skill can act as a first exercise for the development of the latter. Considering the growing interest in the role of embodiment in education (Macedonia, 2019) the significance of computational thinking in learning processes (Mannila et al., 2014) and the gap in the literature regarding the potential of spatial navigation as a foundational step in the development of computational thinking, this study aims to explore the cognitive analogies between these two skills, to encourage the development of new and innovative educational practices.

2. Cognitive correlates of spatial navigation and computational thinking

Spatial navigation is a complex cognitive skill essential for daily functioning that allows people to orient themselves and move through space (Moffat, 2009). It is not limited to the ability to physically move but includes the processing and manipulation of mental representations to solve complex spatial problems (Bocchi et al., 2019). The navigation process involves several steps, from encoding spatial information, to route planning and moving within the surrounding environment (Hegarty et al., 2006). It therefore includes the processing of a variety of information (visual, vestibular, proprioceptive, somatosensory and auditory) during movement, contributing to the development of cognitive strategies useful for reaching a given destination (Ekstrom et al., 2014). The spatial information obtained through navigation in an environment is organized through the creation of a cognitive map representative of the space in which one moves which allows individuals to determine the position of an object using landmarks (Tolman, 1948). Consequently, spatial navigation involves several cognitive processes that are crucial for a wide range of intelligent behavior, being strongly linked to memory, planning, attention and decision-making (Guariglia & Pizzamiglio, 2008) Chrastil's taxonomy (Chrastil, 2013) describes the main cognitive processes involved during each phase of spatial navigation, summarized in the following table:

Table 1. Cognitive processes involved in the different stages of spatial navigation according to Chrastil's taxonomy (Chrastil, 2013).

Stages of Spatial Navigation	Cognitive Processes
Landmark	Place recognition Forming associations Identifying decision points
Route	Sequence learning Forming associations

Graph	Locating the goal
Survey	Path integration

Due to its complexity, spatial navigation can be regarded as a transversal competence, whose impact goes beyond physical orientation in the environment, also influencing higher-order cognitive skills such as computational thinking Computational thinking is a key skill in education as it stimulates analytical and critical thinking skills and is strongly correlated with academic success in STEM learning (Swaid, 2015).

Wing (2006) defines computational thinking as a fundamental competence that includes problem-solving skills, algorithmic thinking and the generation of organized responses to complex problems. Promoting computational thinking skills from an early age allows students to be taught how to solve problems analytically, deconstructing them into subproblems and identifying the most appropriate solution (Barana et al., 2022).

Kalelioğlu et al., (2016) described the following stages of computational thinking, and the related cognitive processes involved:

Table 2. Stages of computational thinking and associated cognitive processes according to Kalelioğlu et al. (2016).

Stages of Computational Thinking	Cognitive Processes
Identify the problem	Abstraction Decomposition
Gathering, representing and analyzing data	Data collection Data analysis Data representation Pattern recognition Conceptualizing
Generate, select and plan a solution	Mathematical reasoning Building algorithms and procedures Parallelization
Implement solutions	Automation Modelling Simulations
Assessing solutions and continue for improvement	Testing Debugging Generalization

Some of these cognitive processes are particularly relevant to spatial navigation skills: both skills rely on the ability to construct dynamic mental representations that enable the prediction of paths, in spatial navigation, or effective solutions, in computational thinking. Education research has explored the relationship between spatial skills and computational thinking (Bruce & Hawes, 2015; Città et al., 2019; Moschella & Basso, 2020); however, few contributions have specifically addressed how spatial navigation skills can serve as an initial exercise in the development of computational thinking, making further investigation necessary.

3. Hypothesis of intersection between computational thinking and spatial navigation

To demonstrate the potential intersection between spatial navigation skills and computational thinking, it is essential to examine neuroscientific studies that, while analyzing the two domains separately, highlight the activation of common brain areas. For example, recent evidence suggests that regions of the prefrontal cortex (PFC) play a crucial role in various aspects of spatial navigation, such as route planning and environmental representation (Patai & Spiers, 2021); this area has also been found to be linked to executive functions, which are a set of complex mental activities essential for computational thinking (Robledo-Castro et al., 2023).

However, in addition to identifying a neuro-anatomical link between the two abilities, it is important to explore the possible functional relationship. Based on the identification of the cognitive processes involved in spatial navigation skills (Chrastil, 2013) and in the stages of computational thinking (Kalelioglu et al., 2016), we propose below a summary table of the cognitive functions involved in both skills:

Table 3. Comparison of cognitive processes involved in spatial navigation and computational thinking

Cognitive Processes	Spatial Navigation [12]	Computational Thinking [34]
Pattern recognition (1)	Place recognition	Pattern recognition
Sequential learning and strategy development (2)	Sequence learning and forming associations	Building algorithms and procedures
Identification of key points and problem decomposition (3)	Identifying decision points	Abstraction, Decomposition
Learning by response and generalization (4)	Response Learning	Conceptualizing, Generalization
Localization and representation of information (5)	Locating the goal and path integration	Data analysis and data representations

"Pattern recognition" (1) involves identifying similarities and recurring structures in the environment or available data. In spatial navigation, "Place recognition" allows individuals to identify locations based on landmarks and spatial patterns. Similarly, in computational thinking, “Pattern recognition” helps to identify recurring patterns in data, facilitating the development of algorithmic solutions (Léonard et al., 2022).

“Sequential learning and strategy development” (2) contributes to the construction of paths and the organization of solution procedures. In spatial navigation, “Sequence learning and forming associations” facilitates the establishment of an ordinal relationship between reference points in space. In computational thinking, “Building algorithms and procedures” relies on the ability to structure sequences of logical operations to solve problems (Csizmadia et al., 2015).

The “Identification of key points and problem decomposition” (3), facilitates the identification of essential landmarks simplifying the problem. In spatial navigation “Identifying decision points” enables the recognition of landmarks relevant to decision-making (e.g. where to turn). Similarly, in computational thinking, "Abstraction" and "Decomposition" help simplify the problem by reducing unnecessary details and breaking it down into manageable parts (Wing, 2008).

“Learning by response and generalization” (4) allows the adaptation and transfer of acquired knowledge to new situations. In the context of navigation, "Response Learning" involves associating each location with corresponding actions to follow a known path toward a goal; in computational thinking, "Conceptualizing and Generalization" allow solutions to be expressed in a way that it can be applied to multiple contexts (Selby, 2014).

Finally, “Localization and representation of information” (5) supports the organization and representation of data. In spatial navigation, it is expressed through “Locating the goal and path integration”, the ability to identify the destination and constantly update one’s position and orientation during movement; in computational thinking, “Data analysis and data representation” facilitate the understanding and representation of data (Berikan & Özdemir, 2020). These processes highlight how space navigation and computational thinking can be based on similar strategies for processing and structuring information. These analogies not only emphasize a potential intersection in their underlying cognitive processes but also suggest implications for educational practice. The following discussion explores how these insights can improve the design of learning experiences and guide future research directions.

4. Discussion

The purpose of this contribution is to identify the similarities between spatial navigation and computational thinking, proposing a theoretical framework that can stimulate further research on the hypothesis that spatial navigation skills can serve as an initial exercise in the development of computational thinking. The interest in this relationship stems from the growing importance of both skills in the educational context, especially in learning STEM disciplines. The overlap in cognitive processes allows us to hypothesize how the implementation of educational programs incorporating spatial navigation exercises can help strengthen computational thinking skills. However, the implementation of real-world navigation experiments has limitations that can be overcome using digital technologies and virtual reality (Jeung et al., 2022); these tools can simulate navigation scenarios that require the application of computational strategies in real-time, making learning more interactive. Future research could further investigate this relationship through experimental methods that assess the influence of individual factors, including gender, age, spatial memory and cognitive styles (Pazzaglia et al., 2018). Investigating how individual differences affect spatial navigation skills could provide useful insights into the design of personalized educational interventions. Furthermore, individuals adopt different orientation strategies in the environment during navigation: egocentric strategies are based on the individual perspective whereas allocentric strategies are based on the overall view (Lawton, 1994; Walkowiak et al., 2015).

These strategies of navigation involve different mental processes: the egocentric strategy tends to be more automatic, relying on subjective references; by contrast, the allocentric strategy requires more complex cognitive processing (Bohbot et al., 2007). Based on this evidence, it can be hypothesized that individuals who predominantly adopt allocentric strategies may demonstrate stronger computational thinking skills compared to those who rely on egocentric strategies. Supporting this hypothesis, a study conducted by Wang & Li (2023) found that high-achieving STEM students tend to favor allocentric strategies while lower-achieving students prefer egocentric ones.

In conclusion, this contribution is based on the hypothesis that spatial navigation could be an early exercise in computational thinking, due to shared cognitive processes involved. By analyzing the intersections between these skills, this study aims to fill a gap in the existing literature and highlights the educational potential of bodily engagement in supporting the development of complex cognitive functions, such as computational thinking, in line with the principles of embodied learning.

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