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Embodied Cognition in learning STEM disciplines. An overview on the role of spatial skills

L'Embodied Cognition nell'apprendimento delle discipline STEM. Una panoramica sul ruolo delle abilità spaziali

di

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Abstract:
From early childhood, children begin to explore and interact with the physical environment, gradually improving their spatial skills. Understanding how this process occurs is essential for teachers because they can effectively support the development of these skills in the educational context. Indeed, corporeity is an increasingly central dimension of educational experience and can be used as a pedagogical tool to foster active learning and skill acquisition, especially within the STEM disciplines.

The aim of this contribution is to thematize, within the theoretical framework of Embodied Cognition, how it is necessary to anchor the learning of concepts related to STEM disciplines to dynamics afferent to the bodily dimension. Indeed, this enables the pursuit of broader pedagogical goals: on the one hand, emphasizing the role of bodily experiences in shaping our cognitive processes, and on the other hand, encouraging the design of learning scenarios and educational technologies rooted in sensorimotor experience and action.

Keywords: Corporeity, Spatial Skills, Embodied Cognition, STEM.

Abstract:
Fin dalla prima infanzia, i bambini iniziano ad esplorare e interagire con il loro ambiente fisico, migliorando gradualmente le loro capacità spaziali. Comprendere come questo processo avviene è essenziale affinché gli insegnanti possano sostenere in modo efficace lo sviluppo di queste abilità anche all'interno del contesto educativo. La corporeità, infatti, è una dimensione sempre più centrale nell'esperienza educativa e può essere utilizzata come strumento pedagogico per favorire l'apprendimento attivo e l'acquisizione di competenze, soprattutto nell'ambito delle discipline STEM.
Obiettivo di questo contributo è tematizzare, all'interno del contesto teorico dell'Embodied Cognition, come sia necessario ancorare l'apprendimento di concetti legati alle discipline STEM a dinamiche e abilità pienamente afferenti alla sfera corporea. Ciò permette infatti di perseguire obiettivi pedagogici più ampi: da un lato, enfatizzando il ruolo delle esperienze corporee nel modellare i nostri processi cognitivi, dall'altro, favorendo la progettazione di scenari di apprendimento e tecnologie educative radicate nell'esperienza sensori-motoria e nell'azione.

Parole chiave: Corporeità, Abilità Spaziali, Cognizione Incarnata, STEM.

1. Introduction

Developing spatial abilities in children is crucial for their overall cognitive development (Alkouri, 2022). In the first few years of life, children's sensory abilities develop rapidly, allowing them to understand the surrounding world. Parallel to sensory development, children's motor interaction with the environment is characterized by exploratory agency in which objects are grasped, explored, moved.
The underlying mechanism of early spatial and motor development involves several components, such as natural maturation, environmental feedback, and active exploration (Newcombe et. al., 1999). According to Piaget's theory of cognitive development (Piaget, 1953) children actively construct their understanding of the world within a gradual process that develops through several stages. Moreover, the world in which they live is surrounded by several stimuli and, as a result, children are seen as dynamic thinkers who engage in the process of making sense of their experiences (Pitrella et al., 2023).
Cognitive development is thus a complex and multifaceted process shaped by several factors. Therefore, the importance of incorporating sensory and motor activities into daily educational practice

offers numerous opportunities, facilitating the exploration of the environment, and strengthening the neural connections necessary for later learning (Shonkoff & Phillips, 2000).
The acquisition of spatial skills is critical for cognitive development and learning, as it involves the ability to navigate the environment, manipulate objects, and understand relationships between different positions in space (Wang et al., 2014). In addition, spatial skills involve a combination of different abilities such as spatial visualization, spatial perception, and mental rotation which together enable to mentally manipulate two- and three-dimensional figures, understanding of one's position in relation to the surrounding environment (Buckley et al., 2018) and rotate an object in one's mind (Terlecki et al., 2008). Proficiency in spatial skills also provides better comprehension of abstract concepts and enhances problem-solving abilities (Netwong, 2018).
Additionally, some research indicated that males tend to outperform females in various aspects of spatial abilities (Reilly et al., 2016). To explain gender disparities, both biological differences and gender-based expectations have been considered. Often in early childhood, boys and girls are engaged in different activities and early socialization practices that can shape their understanding of what is considered appropriate behavior for their gender. Taken together, these factors can influence their self-perception, interests, and aspirations as they grow up.
Moè & Pazzaglia (2006) have investigated the influence of gender-related expectations on mental rotation abilities in which participants who were informed that their gender has superior spatial ability in this task, demonstrated improved performance. This manipulation of beliefs about gender differences in mental-rotation abilities, highlighted the impact of social cues on cognitive performance (Moè & Pazzaglia, 2006). Furthermore, children's interest in an activity can promote the corresponding cognitive competence and enhances their level of engagement during that activity. It's also possible that children's interest in certain spatial activities may play an important role in the development of their spatial skills (Xiao & Zhang, 2021).
In recent years, spatial skills have received relevant attention in the field of science, technology, engineering, and math education (Buckley et al., 2018., Weisberg & Newcombe, 2017).
Some research has shown that individual differences in spatial ability may also explain differences within STEM disciplines, where some individuals are less able to operate on spatial relationships (Lubinski et al., 2001). Spatial ability appears to be a key predictor of future career involvement in STEM fields (Kell et al., 2013) and the promotion of STEM education may also influence students' decisions to pursue these careers (Kearney, 2011).
In order to create a positive attitude toward STEM, it is important to develop students' spatial skills in a real-world learning scenario by anchoring the learning of concepts related to STEM disciplines to dynamics pertaining to the bodily dimension (Sisman et al., 2021). Although some research often discusses the impact of early spatial training on STEM education (Levine et al., 2012., Uttal et al., 2013), school curricula lack the knowledge needed to effectively focus on spatial activities in improving spatial skills, and students do not receive the training needed for developing STEM proficiency.
The aim of this paper is to explore the implications of embodied cognition framework for STEM education, emphasizing the integration of physical experiences into educational practices. By understanding this interplay, educators can design more effective and engaging learning experiences.

2. Embodied cognition and learning

Engaging in physical activities and manipulating one's body in space contribute to spatial awareness (Re et al., 2023). Additionally, hands-on experiences with manipulative activities, like building blocks or puzzles, further strengthen spatial skills by allowing individuals to physically interact with objects and understand spatial relationships.

The opportunities of applying embodiment in the educational context emerge from the close relationship between perception, action, and cognition. Consequently, the body is a dynamic knowledge system (Merleau-Ponty, 2003) in contrast to the traditional conception that primarily emphasizes the brain as the seat of cognition (Re et al., 2019). In fact, although classical cognitive science has made important contributions to the understanding of numerous phenomena, its conception has always been strongly based on the idea that mental processes are computational processes (Shapiro, 2012).

According to Macedonia (2019) this way of understanding cognition has had a strong impact on learning and education. On the contrary, embodied cognition revises some computational assumptions of traditional cognitive science, underlining the importance of the physical body of an agent in cognitive abilities (Shapiro et al., 2019). In this direction it is necessary to rethink teaching according to those perspectives that indicate the centrality of bodily experiences for development and learning (Gomez Paloma, 2017). This allows us to understand that there is no cognitive experience private to the involvement of the body and that learning is not a process that occurs in the mind, but rather, a dynamic and interactive process that takes place within a real and multisensory context. In this perspective, STEM education aims to combine theoretical knowledge with practical applications, recognizing the significance of the body as an active participant in the learning process. By anchoring the acquisition of STEM concepts to the dynamics of the bodily dimension, a process that requires rethinking the frontiers of pedagogy, boundaries between theory and practice dissolve.

Some disciplines, such as math and science, could be more effective if based on activities that arise from the physical world. Especially for children, it is necessary to present some abstract concepts related to real-life experiences and this can be achieved through various strategies:

1) Providing physical objects or manipulative tools for learners, improving spatial awareness.
2) Connecting spatial concepts to real-world scenarios, engaging students in activities.
3) Developing spatial skill in several ways, such as playing with puzzles, building with blocks, and engaging in mental rotation tasks.
4) Encourage learners to apply their knowledge in practical situations, by connecting STEM concepts to real-world scenarios.
5) Incorporate multiple sensory modalities in learning activities, to improve their motivation.

Sensory-motor engagement and physical interactions with the environment in children enhance higher cognitive processes such as thinking and learning (Shapiro & Stolz, 2018). Moreover, studies indicate a correlation between motor skills and spatial abilities, emphasizing the role of physical activity in cognitive performance (Bidzan-Bluma & Lipowska, 2018).

Among spatial skills, the ability of spatial reasoning is intrinsically linked to embodiment, as supported by Thom et al. 2021. Consequently, the efficacy of employing embodied tasks as a pedagogical strategy is rooted in the principles of embodied cognition (Thom et al., 2015). Thus, incorporating spatial elements into learning experiences positively impacts on spatial skill development (Newcombe, 2018) contributing to a holistic approach to learning.

3. Empirical evidence on embodiment and spatial skills

According to the embodied cognition perspective, cognitive functions are influenced by our bodily experiences and sensorimotor interactions with the world (Varela et al., 1991). Furthermore, this framework supports curriculum goals in the field of STEM disciplines (Weisberg & Newcombe, 2017) and enhances spatial reasoning (DeSutter & Stieff, 2017) which is associated with better performance in various disciplines and tasks, such as mental rotation (Città et al., 2019). More recently, Byrne et al. (2023) have reported evidence concerning the success of physical manipulatives interventions on children's spatial skills. Their findings highlight the several ways in which hands-on physical manipulatives activities can be incorporated into the early learning experiences of children, offering recommendations for educators in their teaching.

The positive effects of early spatial skills training with hands-on exploration and spatial activity support the importance of implementing spatially oriented curricula in childhood settings. Terlecki et al. (2008) have investigated the transfer effects of spatial experience on mental rotation abilities. They have found durable effects of spatial training, suggesting that training in one spatial task can positively impact performance in other spatial domains. Sorby (2007) has instead developed and assessed a course designed to enhance 3D spatial visualization skills among engineering students. The study has demonstrated positive outcomes, indicating that targeted training can enhance spatial abilities in specific domains.

The meta-analysis conducted by Uttal et al., (2013) has explored the malleability of spatial skills showing improvement through training interventions. However, these findings also suggest the importance of early spatial skill intervention in increasing students' spatial competencies. In line with these results and according to Levine et al., (2012) children who engaged in more puzzle play have shown better spatial abilities, suggesting that specific early activities can contribute to the enhancement of spatial skills.

A large number of studies also linked the early development of spatial skills to several domains requested in the field of STEM education such as math knowledge, problem solving abilities, mental rotation competence, and executive functions. Research conducted with young children has demonstrated the relation between gesturing and language learning (Iverson & Goldin-Meadow, 2005) as well as with mathematics education (Cook & Goldin-Meadow, 2006).

Gestures have been found to be also beneficial during complex learning, such as learning of abstract concepts (Malinverni &Pares, 2014) and mathematics domain (Macedonia, 2019).

Chu and Kita (2011) have reported that gesturing was more frequent during novel or complex tasks, while the frequency of gesturing decreased when the task became more familiar.

Other studies, instead, suggest that incorporating some action such as pointing and tracing with the index finger, can enhance learning performance and intrinsic motivation during the lesson (Agostinho et al., 2015) while Mavilidi et al., (2018) have shown that whole-body movements can make abstract thoughts easier to process.

Furthermore, involving elementary school kids in collaborative movement learning, where they create geometric shapes with their bodies, was found to enhance their understanding of angles during geometry lessons (Shoval, 2011).
Research has also focused on integrating physical activity in children (Gao et al., 2018) and to academic time through psychical activity and active lessons to enhance executive functioning (Norris et al., 2019). This body of research encompasses investigations into both the immediate impacts of physical activity during single sessions and the enduring effects observed across multiple sessions. Positive outcomes on children and executive functions, specifically planning, problem solving (De Greef et al., 2018) inhibition and cognitive flexibility (Benzing et al., 2016) were found.
More recently, Zhang et al. (2022) have investigated the efficacy of self-management of cognitive load, specifically finger pointing, in enhancing learning from spatially separated text and pictures in online settings. The research extended prior work by investigating the impact of finger pointing, mouse pointing, and a combination of both on learning outcomes. Results support the effectiveness of finger pointing for improved retention, while mouse pointing, and the combined strategy showed no significant benefits. In conclusion, finger pointing emerges as a straightforward and practical self-management approach in online learning, contrasting with the less effective nature of mouse pointing.
Empirical research on learning has less considered the role of kinesthetic and tactile sensory modalities. Hu et al., (2015) have found that kinesthetic modalities, including movement and bodily activity, are involved in learning and allow us to reflect on elements of geometry. Tactile modalities instead, engage learners through physical interactions with educational materials, such as running their finger over a paper-based lesson for a hands-on experience. (Macken & Ginns, 2014).
Glenberg's research (2017) emphasizes the significance of a multisensory learning environment in which students who engaged in manipulating toys while reading, have demonstrated more comprehension compared to those only reading the text. This empirical evidence underscores the importance of incorporating embodied experiences into educational contexts, suggesting that learning environments benefit from a more embodied structure.
Additionally, advancements in neuroimaging methodologies have provided insights into the neural mechanisms that underlie spatial skills. Vingerhoets et al., (2002) have used functional magnetic resonance imaging (fMRI) to analyze brain activation patterns during mental rotation tasks. The findings have revealed the activation of areas associated with motor planning and execution, implying a significant interplay between spatial processing and regions of the brain linked to motor functions.
Taken together, these studies collectively contribute to the understanding of spatial skills and their implications for learning, offering valuable insights into effective educational strategies and interventions. Additionally, research incorporating embodied tools contributes to a more effective learning experience and fosters greater comprehension by linking abstract concepts to familiar bodily experiences. This connection enhances the overall understanding of spatial concepts in the field of STEM education.

4. Conclusion

Spatial skills involve cognitive processes facilitating individuals in navigating their environment (Wang et al., 2014) solving problems and understanding spatial relationships. Moreover, these skills play a significant role in STEM disciplines (Stieff & Uttal, 2015) by facilitating a deeper

understanding of geometric and spatial concepts, enabling individuals to manipulate spatial information, and enhancing problem-solving abilities.
Empirical evidence on the positive effects of movements on learning, in particular in the field of STEM education, suggests not only the central role of the body in cognition but the opportunities of an embodiment-based education into several learning domains (Mavilidi et al., 2018).
By incorporating spatial skills within an embodied cognition framework promotes a holistic understanding of spatial concepts through physical interaction, thus learners can deepen their comprehension of intricate concepts, and construct knowledge more efficiently. Understanding the importance of spatial skills for STEM education also allows educators to design interventions that resonate with the diverse ways students acquire information, fostering an effective educational environment.
Starting from the analysis of the body as a source of knowledge and learning, the embodied cognition framework focuses on its role in shaping cognitive processes, highlighting the significance of physical interactions with the environment. In essence, embodied cognition introduces a novel perspective on learning, suggesting that integrating physical experiences into the educational process can create more effective learning experiences for students.
Especially in STEM disciplines, numerous studies have consistently demonstrated a positive correlation between spatial skills and academic achievement (Stieff & Huttal, 2015). Despite recent literature having focused on the exploration of the connection between spatial skills and embodied experiences with results confirming this interplay, these findings need to be substantiated with future research.
Adopting the embodied cognition framework for enhancing spatial skills in both learning and STEM education encourages a shift in research focus towards understanding the interplay between the body and cognitive processes, offering significant opportunities for improving spatial skills and advancing the convergence of research in these interconnected domains. Promoting an active learning environment implies rethinking how learning takes place and how it can be improved within an embodied dimension. Despite recent technological advancements, such as the utilization of motion sensors that enable a rich sensory interaction, creating a learning context grounded in the principles of embodied cognition means considering various levels of interaction between students and teachers within a multisensory environment.
Fostering a dynamic learning environment in which students actively participate is the best approach to increase curiosity and motivation for STEM concepts.

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