UNIVERSITAT DE BARCELONA

Towards an Embodied and Transdisciplinary Education

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TOWARDS AN EMBODIED AND TRANSDISCIPLINARY EDUCATION

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To my Spanish, Catalan and Aussie family

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A wonderful harmony arises from joining together the seemingly unconnected.

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Nunca he sabido que responder a qué quiero ser de mayor porque quiero ser muchas cosas, quiero hacer muchas cosas y no solo una de por vida. Decidí estudiar Ciencias de la Actividad Física y del Deporte por mi pasión por el deporte y he salido con pasión por el conocimiento, por la fisiología, por la psicología, por la sociología, por la historia, por las matemáticas y por la física. Todo por aquella asignatura (*Fisiologia dels sistemes complexos adaptatius* – como la llamo yo) que estudié en segundo año de carrera impartida por la Dra. Natàlia Balagué donde descubrí las ciencias de la complejidad. De repente tenía mil preguntas y sentía la curiosidad por aprender que hacía años que había perdido.

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MariCarmen

Abstract

The educational landscape faces several challenges to uphold knowledge integration and the development of essential competencies in modern society. One prevalent issue lies in the dominant fragmentation and compartmentalisation of subjects that, enhanced by a specialised vocabulary, reinforces the disconnection among disciplines of the education curricula. Furthermore, the body is isolated from the learning process, marginalising movement and lived experiences. This approach fails to provide students with opportunities to engage meaningfully with the real world. Consequently, students struggle to apply the learnt topics to address real problems and develop essential competencies such as critical thinking, problem-solving, and collaboration skills. Although new educational approaches have emerged to promote the integration of disciplines (e.g., STEAM education), an embodied and transdisciplinary approach, which teaches general (non-specific or context-independent) scientific concepts, has yet to be introduced.

The doctoral thesis addresses the challenges of fragmented knowledge and disembodied education and proposes a transdisciplinary and embodied approach across elementary, high school, and higher education levels. Specifically, it evaluates the educational potential of experiencing the general concepts of Dynamic System Theory (DST) for enhancing the integration and transfer of knowledge at three academic levels. The hypothesis posits that learning DST concepts would enhance students' comprehension of phenomena and improve their ability to transfer knowledge across disciplines. The studies used a quasi-experimental design in elementary and high school and included a control group for the university intervention. Data was collected through questionnaires, interviews, and surveys. The results of the interventions showed that students could learn general DST concepts and principles through body experiences, integrate and transfer knowledge between different academic subjects, facilitate the understanding of diverse phenomena, and relate the learnt processes with their personal and social needs.

Additionally, students were satisfied with the intervention, expressing their will to continue learning the applications of DST concepts to phenomena. They also described that collaborative learning helped them deepen their knowledge. Teachers acknowledged the potential of learning general concepts through body movement experiences and valued the approach as a promising strategy for an integrated and embodied education. Overall, the thesis advocates adopting an embodied and transdisciplinary approach for enhancing knowledge integration and engagement in diverse educational settings.

Resum

El panorama educatiu s'enfronta a diversos reptes per defensar la integració dels coneixements i el desenvolupament de les competències essencials a la societat moderna. Un problema predominant rau en la fragmentació i la compartimentació de les assignatures que, potenciades per un vocabulari especialitzat, reforcen la desconnexió entre les disciplines dels programes educatius. A més, s'aïlla el cos del procés d'aprenentatge i margina el moviment i les experiències viscudes. Aquest enfocament no ofereix als estudiants oportunitats de relacionar-se de manera significativa amb el món real. En conseqüència, els estudiants lluiten per aplicar els temes apresos per abordar problemes reals i desenvolupar competències essencials com ara el pensament crític, la resolució de problemes i les habilitats de col·laboració. Tot i que han sorgit nous enfocaments educatius per promoure la integració de disciplines (per exemple, l'educació STEAM), encara no s'ha introduït un enfocament corporeïtzat i transdisciplinar, que ensenyi conceptes científics generals (no específics o independents del context).

La tesi doctoral, composta per cinc publicacions, aborda els reptes del coneixement fragmentat i l'educació descorporeitzada i proposa un enfocament transdisciplinar i corporeïtzat als nivells d'educació primària, secundària i superior. Concretament, avalua el potencial educatiu d'experimentar els conceptes generals de la Teoria de Sistemes Dinàmics (TSD) per millorar la integració i la transferència de coneixements en tres nivells acadèmics. La hipòtesi postula que l'aprenentatge dels conceptes de la TSD augmentaria la comprensió dels fenòmens per part dels estudiants i milloraria la seva capacitat per transferir coneixements entre disciplines. Els estudis van utilitzar un disseny quasi-experimental a primària i secundària i van incloure un grup de control per a la intervenció universitària. Les dades es van recollir mitjançant qüestionaris, entrevistes i enquestes. Els resultats de les intervencions van mostrar que els alumnes podien aprendre conceptes i principis

generals de la TSD mitjançant experiències viscudes, integrar i transferir coneixements entre diferents matèries acadèmiques, facilitar la comprensió de fenòmens diversos; i relacionar els processos apresos amb les vostres necessitats personals i socials.

A més, l'alumnat es va mostrar satisfet amb la intervenció i van expressar la voluntat de seguir aprenent les aplicacions dels conceptes de la TSD als fenòmens. També van descriure que l'aprenentatge col·laboratiu els va ajudar a aprofundir els coneixements. El professorat va reconèixer el potencial de l'aprenentatge de conceptes generals a través d'experiències de moviment i van valorar l'enfocament com una estratègia prometedora per a una educació integrada i corporitzada. En general, la tesi advoca per adoptar un enfocament corporeïtzat i transdisciplinar per millorar la integració del coneixement i el compromís en diversos entorns educatius.

Resumen

El panorama educativo se enfrenta a varios retos para defender la integración de los conocimientos y el desarrollo de las competencias esenciales en la sociedad moderna. Un problema predominante radica en la fragmentación y compartimentación de las asignaturas que, potenciadas por un vocabulario especializado, refuerzan la desconexión entre las disciplinas de los programas educativos. Además, se aísla el cuerpo del proceso de aprendizaje, marginando el movimiento y las experiencias vividas. Este enfoque no ofrece a los estudiantes oportunidades de relacionarse de forma significativa con el mundo real. En consecuencia, los estudiantes luchan por aplicar los temas aprendidos para abordar problemas reales y desarrollar competencias esenciales como el pensamiento crítico, la resolución de problemas y las habilidades de colaboración. Aunque han surgido nuevos enfoques educativos para promover la integración de disciplinas (por ejemplo, la educación STEAM), aún no se ha introducido un enfoque corporeizado y transdisciplinar, que enseñe conceptos científicos generales (no específicos o independientes del contexto).

La tesis doctoral, compuesta por cinco publicaciones, aborda los retos del conocimiento fragmentado y la educación descorporeizada; y propone un enfoque transdisciplinar y corporeizado en los niveles de educación primaria, secundaria y superior.

En concreto, evalúa el potencial educativo de experimentar los conceptos generales de la Teoría de Sistemas Dinámicos (TSD) para mejorar la integración y la transferencia de conocimientos en tres niveles académicos. La hipótesis postula que el aprendizaje de los conceptos de la TSD aumentaría la comprensión de los fenómenos por parte de los estudiantes y mejoraría su capacidad para transferir conocimientos entre disciplinas. Los estudios utilizaron un diseño cuasiexperimental en primaria y secundaria e incluyeron un grupo de control para la intervención universitaria. Los datos se recogieron mediante cuestionarios, entrevistas y encuestas. Los resultados de las intervenciones mostraron que los alumnos podían aprender conceptos y principios generales de la TSD a través de experiencias vividas, integrar y transferir conocimientos entre distintas materias académicas, facilitar la comprensión de fenómenos diversos; y relacionar los procesos aprendidos con sus necesidades personales y sociales.

Además, el alumnado se mostró satisfecho con la intervención y expresaron su voluntad de seguir aprendiendo las aplicaciones de los conceptos de la TSD a los fenómenos. También describieron que el aprendizaje colaborativo les ayudó a profundizar en sus conocimientos. El profesorado reconoció el potencial del aprendizaje de conceptos generales a través de experiencias de movimiento y valoraron el enfoque como una estrategia prometedora para una educación integrada y corporizada. En general, la tesis aboga por la adopción de un enfoque corporeizado y transdisciplinar para mejorar la integración del conocimiento y el compromiso en diversos entornos educativos.

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1. Introduction

"Marie was born with the characteristics of a scientist: she observed, explored, and manipulated what happened around her. Then, she started school and slowly diminished her freedom of exploration and manipulation. In primary school, Marie spent more than five hours sitting down and waiting for the best half-hour of the day: playground time. In high school, she learned disconnected contents of fragmented disciplines from often exhausted teachers. She stopped asking questions. She lost interest and curiosity to understand the world like the little scientist Marie did. Later, she started university and began a degree in chemistry. Although she specialised and collected a lot of information, she felt unable to understand and solve the complex problems of society. In a conversation with her friends, she realised that different disciplines share common principles but use other languages. Marie wondered... Can a science or theory integrate knowledge and help us understand different types of phenomena?

Through movement experiences like slackline, students learn general concepts of Dynamic Systems Theory (DST), like stability, instability, phase transition, and self-organisation. With these concepts, we can explain how water molecules transit from a solid to a liquid state, how a virus spreads, how a team is created or how a change in habits occurs. In fact, it is the ability to integrate different disciplines that have allowed the most relevant social and scientific advances.

Marie, also known as Marie Curie, won the Nobel Prize when she integrated two scientific disciplines, physics and chemistry, to discover radioactivity. Imagine what could happen if we promoted a unified and embodied education in school and life".

Figure 1*: Towards an Embodied and Transdisciplinary Education (TETE) project video.*

1.1. Justification of the thesis

Education is a fundamental pillar of society, shaping the minds and abilities of future generations. Over the past two decades, the educational system in Spain has been searching for effective teaching methods and has undergone several legal reforms influencing both curricula and teachers' careers (Arco-Tirado & Fernández-Balboa, 2003). Despite these efforts, the current fragmented and disembodied school curriculum faces several challenges. Firstly, it lacks experiential stimuli essential for comprehending and applying knowledge. Secondly, it leans towards subject-specific concepts rather than general concepts in science that can be applied across different areas of knowledge (Hristovski, 2013). Lastly, it falls short of meeting students' personal and social needs. As a result, students develop fragmented or superficial understandings of disciplines, hindering their capacity for critical and creative thinking across different scientific domains. Recognising this gap, there is a critical call for innovative educational strategies that can bridge the gap between general scientific concepts and the tangible experiences of learners.

The present thesis arose from the need to incorporate the body and the movement into the learning process and to integrate educational content for more meaningful learning. Specifically, it introduces the "Synthetic Understanding and Movement Analogies" (SUMA) educational framework to elementary, high school, and higher education curricula. The research involved creating three interventions tailored to different educational levels, their implementation, and assessing students' integration and knowledge transfer competencies. This comprehensive process unfolded over two years, aiming to initiate a transformative shift in the educational landscape.

1.2. Objectives and hypothesis of the thesis

Based on the problems detected and the questions described in the previous section, the doctoral thesis proposes a general objective: to develop a transdisciplinary and embodied approach across the three educational levels: elementary, high school and higher education. Concretely, aims to promote far-transfer analogical reasoning within and between different academic subjects, experiencing first with the body. This general objective will be achieved by developing several specific objectives connected to the publications that comprise the doctoral thesis.

Specific objectives

- To present the learning platform SUMA, a platform that apply movement analogies and lived experiences to learn the unifying concepts of science.
- To apply the SUMA Educational Framework in elementary school.
- To evaluate the impact of the intervention on the integrative and transfer of knowledge capacities of elementary school students.
- To design an intervention to apply the SUMA Educational Framework in high school.
- To evaluate the impact of the intervention on the integrative and transfer of knowledge capacities of high school students.
- To design an intervention to apply the SUMA Educational Framework in higher education.
- To assess the effects of the intervention on students' integrative and transfer of knowledge capacities.

We hypothesised that learning DST concepts through lived experiences would enhance students' comprehension of phenomena and improve their ability to transfer knowledge across disciplines.

1.3. Structure of the thesis

The doctoral thesis is presented as a compendium of articles and comprises six chapters. The first chapter includes the introduction, which justifies the research, the thesis objectives and hypothesis, the thesis structure, and the publications resulting from the project. The second chapter of the thesis presents the theoretical framework, starting with the state of the art in education and highlighting the problem of fragmentation and disembodiment. The chapter explores the need for integration, transitioning from a disciplinary approach to a transdisciplinary approach, which is the approach the thesis focuses on. Subsequently, the role of embodiment in education is discussed, followed by the SUMA Educational Framework. The third chapter presents the studies carried out as they have been published and one that has been submitted. Each article follows the journal's guidelines in which it was presented but follows the standard structure with sections on introduction, method, results, discussion and conclusions. The fourth chapter presents the results report, which summarises the research results. The fifth chapter provides a general discussion of the results obtained from the studies, some theoretical and methodological contributions to consider, a section on practical applications and another on limitations and future lines of research. The sixth chapter presents the conclusions derived from the doctoral thesis. Finally, the Bibliography and the Appendices are presented.

1.4. Publications

A total of four original articles and one book chapter constitute the main body of this thesis. One of the articles set the SUMA educational framework on which this thesis is based. The other three articles apply the SUMA framework in different education settings. The book chapter summarises the results derived from the elementary and high school interventions. Each study is presented as individual chapters: 3.1, 3.2, 3.3, 3.4 and 3.5. Below is a series of information regarding the title, the publication status, the name of the journal, its impact index, the authorship of the studies and, finally, the complete reference is included.

1.4.1. *Theoretical Article*

- Title: SUMA educational framework: The way to embodied transdisciplinary knowledge transfer.

- Status: article published.

- Journal: Research in Physical Education, Sport and Health.

- Quality index: The journal is indexed in the Directory of Open Access Journals (DOAJ) and indexed and presented in EBSCO databases.

- Author: Robert Hristovski, Natàlia Balagué, Maricarmen Almarcha and Pau Martínez.

- Reference: Hristovski, R., Balagué, N., Almarcha, M. C., and Martínez, P. (2020). SUMA educational framework: The way to embodied transdisciplinary knowledge transfer. *Research in Physical Education, Sport and Health, 9,* 3–7.

1.4.2. *Study I: SUMA in elementary school*

- Title: Transdisciplinary embodied education in elementary school: a real integrative approach for the science, technology, engineering, arts, and mathematics teaching.

- Status: article published.

- Journal: Frontiers in Education.

- Quality index: JCR: 2.3, Q2 (2022); SJR: 0.66, Q2 (2022).

- Author: Maricarmen Almarcha, Pablo Vázquez, Robert Hristovski and Natàlia Balagué.

- Reference: Almarcha. M., Vázquez, P., Hristovski, R., and Balagué, N. (2023). Transdisciplinary embodied education in elementary school: a real integrative approach for the science, technology, engineering, arts, and mathematics teaching. *Frontiers in Education.* 8:1134823. doi: 10.3389/feduc.2023.1134823.

1.4.3. Study II: SUMA in high school

- Title: Embodied transfer of knowledge using dynamic systems concepts in high school: A preliminary study.

- Status: article published.

- Journal: Human Movement Science.

- Quality index: JCR: 2.1, Q2 (2022); SJR: 0.64, Q2 (2022).

- Author: Maricarmen Almarcha, Pau Martínez, Natàlia Balagué and Robert Hristovski.

- Reference: Almarcha, M. C., Martínez, P., Balagué, N., and Hristovski, R. (2022). Embodied transfer of knowledge using dynamic systems concepts in high school: a preliminary study. *Human Movement Science.* 84:102974. doi: 10.1016/j.humov.2022.102974

1.4.4. Study III: SUMA in higher education

- Title: Integrating knowledge in higher education through experiencing the transdisciplinarity of Dynamic Systems Theory general concepts.

- Status: article under review.

- Journal: Apunts

- Impact index: JCR: 1.5, Q2 (2022); SJR: 0.4, Q1 (2022).

- Author: Maricarmen Almarcha, Lluc Montull, Natàlia Balagué and Robert Hristovski.

- Reference: Almarcha. M., Montull, L., Balagué, N., and Hristovski, R. (In press). Integrating knowledge in higher education through experiencing the transdisciplinarity of Dynamic Systems Theory general concepts. *Apunts.*

1.4.5. Book chapter

- Title: Hacia una educación corporeizada y transdisciplinar.

- Status: book chapter published.

- Editorial: Dykinson.

- Impact index: SPI-CSIC 2022 – General Ranking: Q1, Educación: Q1.

- Author: Maricarmen Almarcha and Natàlia Balagué.

- Reference: Almarcha, M., Balagué, N. (2023). Hacia una educación corporeizada y transdisciplinar en A. Vico, L. Vega (Eds.) *La innovación en el ámbito socioeducativo a través de las tecnologías y la atención a la diversidad*. Dykinson. https://www.dykinson.com/libros/la-innovacion-en-el-ambito-socioeducativo-a-traves-de-las-tecnologias-y-la-atencion-a-la-diversidad/9788411228220/

2. Theoretical Framework

2.1. State of the art

2.1.1 Fragmentation and specialisation of knowledge

The 21st century education is based on fragmentation and specialisation of knowledge, where the subjects are often compartmentalised and disconnected from each other (Hristovski et al., 2020). The major cause of the fragmentation is the specialised vocabulary in science, where each discipline uses a context-dependent vocabulary to explain the phenomena (Hristovski, 2013). Consequently, specialists struggle to understand each other when explaining basic processes (Hristovski, 2013). For instance, a cosmologist, cell biologist, sports scientist, and sociologist would hardly understand each other when they explained the basic processes within their fields, creating a communication barrier. The disconnection between disciplines is reflected in the curricula, and when it is not possible to connect knowledge across disciplines, learners miss opportunities to integrate and apply their knowledge to address real-world problems (Adams, 2015; Bautista et al., 2018). However, when the curriculum integrates real-world experiences, students develop crucial competencies such as critical thinking, transfer of knowledge, problem-solving, collaboration skills and creativity which have been found to enhance engagement and success (Darling-Hammond et al., 2017). Therefore, the educational curricula must address this limitation and incentivise the mentioned competencies among students.

2.1.2. Disembodiment

Another limitation of the actual educational curricula is its disembodied approach, which often neglects the body from the learning process (Macrine, 2002). In part because the model of knowledge prioritised in formal education has been centred on rational thinking and mental processes for a long time. Consequently, the body has been marginalised—including movement, physicality, perceptions and emotions (Gamelli, 2011), leading to a lack of engagement among students. Students learn sitting all the time, confined in a "desk jail", limited, restricted, and required not to move while concentrating on mental tasks (Standal 2016). A moving body in school is typically regarded as disruptive.

However, nowadays, it is evident that sitting too long during the day is prejudicial for youngsters and adults, and reducing physical movement is troubling for general health and cognitive performance (Biddle et al. 2010). Even standing is much better for learning than sitting (Mehta et al., 2015).

The mentioned disconnection of the body from the learning process comes from the influence of Dualism and the Cartesian dichotomy of mind versus body. Also, it follows the tradition of Plato to Descartes in assuming that the body gets in the way of cognition rather than being an indispensable part of it. Due to the assumption that the body has no role to play in cognition, the school curriculum privileges theory over practice (O'Loughlin 1998, 2006), which fails to provide students with opportunities to engage with the real world, limiting their ability to apply knowledge in meaningful ways.

More worrying is the current physical education model, which conceives the body as an object that must be maintained and preserved. The model treats the body as a machine that must function properly, promoting wellness and fitness diffused in society's values. Therefore, movement and physical activities are often seen as a means for increasing caloric expenditure and aesthetic development. In contrast, the use of movement at school plays a role not only in physical education classes but also in every school task—cognitive, experiential, socialisation processes, and the education of emotions—as it requires children to confront their bodies. Recognising the significance of the body in the learning process, an embodied approach seeks to bridge this gap by incorporating experiential learning. Engaging with the body allows students to connect theoretical knowledge with tangible experiences, fostering a deeper understanding beyond mere intellectual comprehension. This approach not only enhances retention and transfer of knowledge but also promotes meaningful learning experiences.

2.2. A plea for integration. From Disciplinarity to Transdisciplinarity

To address the problem of knowledge fragmentation in education, it is necessary to understand the different teaching approaches and break down the barriers between disciplines. Disciplinarity is the compartmentalisation of learning into system-defined units, which results in the acquisition of isolated concepts and skills (Mahan, 1970) without a comprehensive understanding of the broader picture. This has led to the creation of a diverse range of disciplines, each with its unique methodologies, paradigms, and problem areas. Based on disciplinarity, a multidisciplinary approach has been developed in schools where students learn concepts and skills from different disciplines separately, without any synthesis (Holbrock, 2020). However, disciplinary thinking can be problematic when attempting to understand global issues. The current information overload makes it essential to critically evaluate information from different sources, discern its relevance, and skillfully integrate and synthesise it. This can be achieved by developing competencies in critical thinking and knowledge integration. In fact, students who received a more integrated education demonstrated higher levels of understanding and transferred knowledge effectively (Hmelo-Silver et al., 2007). So, instead of focusing on learning specific skills from different disciplines, learning the common principles for a better understanding of the phenomena can be more practical and beneficial for students (Hristovski et al., 2014).

To bridge the gaps between disciplines and foster a more integrated understanding of complex issues, interdisciplinarity and transdisciplinarity were born with some differences between them. To understand the approach of the thesis, it is necessary to clarify the differences between interdisciplinarity and transdisciplinarity.

Interdisciplinarity refers to the collaboration and integration of knowledge and methods (but not theory) from different academic disciplines to address a specific problem or question. An interdisciplinary approach in education combines two or more traditional disciplines to give students a broader and more well-rounded perspective on a particular topic. It is often used to develop critical thinking and problem-solving skills. Recently, these approaches have gained popularity because they try to reduce the barriers within and between different areas of knowledge. One example is the STEM programs.

The acronym STEM comes from the curricular integration of Science, Technology, Engineering and Mathematics (Zollman, 2012; Bybee, 2013; Kelley and Knowles, 2016; García et al., 2017). STEM was born as a pedagogical movement initially proposed in the United States during the 1990s as part of a political strategy to give relevance to the disciplines with an emphasis on real-world applications (STEM Task Report, 2014). Currently, many other initiatives have recently been added to the conceptualisation of STEM, such as:

- STEAM, which refers to STEM + Arts (Kim and Chae, 2016),
- iSTEM, which includes "imagination" + STEM (Tsai et al., 2018),
- STREAM, used to describe proposals that integrate STEAM + Robotics (Stubbs and Yanco, 2009);
- ST®E(A)M(S), which refers to the broadest amalgamation of subjects in the same context: science, technology, engineering, mathematics, art, education for sustainability, and curricular integration (Krug and Shaw, 2016).

Despite the increasing adoption of STEAM teaching methodologies in educational centers, there still needs to be empirical evidence on their effectiveness in improving students' abilities to integrate and transfer knowledge. The lack of evidence can be attributed to the absence of a well-established integrative framework for educational curricula. Interdisciplinary programs aim to address one problem from different subjects simultaneously, thus, maintaining the boundaries of the disciplines.

Also, there needs to be more preparation for teachers related to the integration of STEAM disciplines (Radloff & Guzey, 2016). In a STEAM project, teachers typically contribute their expertise in a specific area of knowledge (García-Carmona, 2020) and collaborate on interdisciplinary projects. Still, they are unfamiliar with integrative or transdisciplinary concepts (see section 2.3). However, due to the fragmented nature of their academic training, which is divided into various specialties, teachers rarely understand all aspects of their field. Hence, the way they learn is a multidisciplinary approach, a non-integrative mix of disciplines with only sporadic and superficial links among the subjects.

In 2018, the U.S. government launched the Federal STEM Strategic Plan, a five-year initiative to promote STEM literacy and prepare the STEM workforce for future challenges. The new plan emphasises teaching academic concepts through practical real-world applications, integrating formal and informal learning in schools, communities, and workplaces, and incentivising critical thinking, problem-solving, cooperation, and adaptability skills among learners. Additionally, the plan highlights the need for the education transition from a disciplinary approach to a transdisciplinary approach, where different disciplines converge and teaching and learning move beyond traditional disciplinary boundaries:

"Problems that are relevant to people's lives, communities, or society, as a whole, often cross disciplinary boundaries, making them inherently engaging and interesting. The transdisciplinary integration of STEM teaching and learning across STEM fields and with other fields, such as the humanities and the arts, enriches all fields. It draws learners to authentic challenges from local to global in scale." (OSTP, 2018, p 20).

The concept of *transdisciplinarity* was first introduced to the world in 1972 at a Paris seminar held by the Organization for Economic Cooperation and Development (OECD) (Appel & Kim-Appel, 2018). Transdisciplinary thinking aims to overcome disciplinary boundaries and identify the knowledge voids and incompatibilities for knowledge unification (Madni, 2017). Achieving these objectives is key to fostering new relationships among traditionally independent disciplines, and in doing so, it is possible to address problems of national and global significance. Transdisciplinarity in education involves collaborating between, across and beyond disciplines to generate new knowledge (McGregor, 2015). However, transdisciplinarity has different interpretations and applications (Augsburg, 2014; Klein, 2004). For instance, according to the physicist Basarab Nicolescu and the philosopher Edgar Morin, transdisciplinarity is connecting the "multiple layers of reality". This means using knowledge from different fields to gain insights without the need to create a new subject. In this way, transdisciplinary approaches help to connect different disciplines to understand phenomena better (Nicolescu, 2002; Morin, 2002). Consequently, the most common practice consists of developing a project where students have to work during the semester. In the project, every teacher contributes from their area of knowledge (García-Carmona, 2020).

Here is an example to illustrate the difference between different mentioned approaches in education: Imagine you were teaching about virus infection. The topic requires fundamental disciplinary knowledge of chemistry, biology, math and sociology. What would moving along the path to convergence from disciplinary to transdisciplinary teaching and learning look like?

Using a *disciplinary approach*, a biology teacher might explain to students the virus components and properties, their structures, replication mechanisms, and how they interact with host cells. In this case, the teacher is identifying an isolated concept (fact, idea, or practice) that is aligned with only one discipline, in this case, biology. Using a *multidisciplinary approach*, a math teacher might explain to students who learned about the components of cells and properties to calculate the spread rate of a virus. The concept now involves multiple disciplines addressed independently on different aspects of the same concept. Using an *interdisciplinary approach*, multiple teachers—for example, one from biology, one from math and one from social science—might work together to have students elaborate a strategy to reduce the spread of a virus. Each teacher would ask students to contribute to the collective problem—studying virus properties in their biology class, calculating the spread rate of a virus in their math class, and finally, exploring the social aspects of virus outbreaks, such as the impact on communities and cultural practices affecting transmission and responses in their social science class to help decide where to act effectively. In this case, students and teachers across disciplines work together in an integrated way that makes the concept more authentic, but still, it is possible to identify the individual disciplines. Finally, using a *transdisciplinary approach*, a teacher would walk into any classroom and be unable to tell which discipline(s) are being taught because they have "converged." In this case, the teaching would integrate knowledge from different disciplines to educate students about virus infections. For instance, students would develop a strategy to address a hypothetical virus outbreak considering the biological factors that affect transmission, the chemical interventions that can be employed, the mathematical models that predict spread, and the societal aspects that impact the effective implementation of control measures. Table 1 illustrates the four different approaches discussed before.

Table 1. *Disciplinarity, multi_, inter_, and trans_ disciplinarity characteristics.*

Type of approach	Connotation	Description	Example
Disciplinarity	One	Focuses on a single discipline and its theories, methods, and practices	Biology
Multidisciplinarity	Many	Multiple disciplines working in parallel, but each discipline remains separate from the others	Biology, Maths
Interdisciplinarity	Among	Collaboration between different disciplines	Biochemistry
Transdisciplinarity	Beyond	Integration of knowledge	Bioinformatics

In resume, both *interdisciplinarity* and *transdisciplinarity approaches* (e.g., Cone et al., 2009; Stock & Burton, 2011; Yakman and Lee, 2012; Zamorano et al., 2018; Lage-Gómez and Ros, 2021) seek to promote a more comprehensive understanding of complex issues. Interdisciplinarity involves collaboration between different academic disciplines, while transdisciplinarity focuses on solving problems that require the interconnection of knowledge across disciplines. The key differentiating factor is that interdisciplinarity fails to transfer knowledge across disciplines to improve understanding of phenomena. In fact, confusion about their proper integration and true transdisciplinarity increases as STEM curricula gain momentum. Even though the approaches aimed to synthesise and integrate knowledge, it is still discipline-led, and each discipline employs skills and directions suited to that discipline. Interdisciplinarity focuses on a problem (phenomenon) and entails diverse theories, data acquisition, analysis techniques and modes of inquiry. It is a many-to-one mapping logic without any integrating factor that could engage the cooperation of different academic disciplines (Hristovski et al., 2017). However, "how" should the areas of knowledge mentioned before be integrated? Which areas or disciplines should be integrated? For what reasons? Furthermore, what is the significance of their integration? And moreover, how does an educator specialising in one discipline (e.g., maths, technology, social sciences, or art) bring together multiple disciplines to teach about complex socioscientific phenomena? The SUMA approach used in this thesis, explained in more detail in section 2.6, answers these questions.

2.3. How do we genuinely integrate different disciplines? The use of Dynamic System Theory concepts and principles in educational settings

Despite the rise of interdisciplinary and transdisciplinary teaching methodologies, there is a lack of complete integration among disciplines. To achieve a genuinely interdisciplinary or transdisciplinary approach, it is necessary to use a common language or "conceptual currency" that acts as a glue for the integration (Hristosvki et al., 2014, 2019).

Since the second half of the 20th century, there has been a growing recognition of the commonalities in the dynamics of various phenomena (Haken, 1977; Nicolis and Prigogine, 1977, Thom, 1969), and the pursuit of a minimal set of principles to explain a wide range of them has been an implicit objective in science (Hristovski, 2013). The emergence of complexity sciences has made it possible to comprehend diverse, complex phenomena, such as biological motion, through the synergetics framework (Haken, 1977; Kelso, 1995). In particular, Dynamic Systems Theory (DST) provides a theoretical framework to understand complex systems that evolve and change over time when interacting with the environment. This theory was initially rooted in the field of mathematics and physics; it applies to phenomena from elementary fields and particles to sociology and art and across disciplines such as psychology, biology, neuroscience, and linguistics. For instance, DST concepts can explain physical phenomena (Higgs, 1964), animal and human movement organisation (Kelso et al., 1979), the sociology of groups (Isnard & Zeeman, 1974), and neural networks and protein folding (Pollak & Chin, 2008), among others. Kelso's research focuses on how patterns of coordination emerge between different components within a system, such as brain regions, limbs, or individuals in a social group and how these patterns are established, maintained, and changed over time (Kelso, 1995).

Given that our world is characterised by dynamic processes, rather than timeless structures, DST approaches offer a more comprehensive explanation. With DST concepts, it is possible to integrate context-specific vocabularies from different scientific fields into a unifying framework, reducing the reliance on discipline-specific terminology (Hristovski, 2013). They can capture the processes across various phenomena, from micro to macro levels and explain the changes and structural transitions when interacting with the environment, which ultimately leads to a more unified understanding of the world. They can be taught using movement analogies, animations, simulations, and textual explanations and can be applied to teach students across different educational levels. Ultimately, understanding DST concepts enables students to apply and transfer their knowledge to real-world situations. Some of the fundamental principles and concepts associated with DST are developed belowd:

- ***Context (constraints) dependence:*** A set of critical constraints of the system's components and the environment within which it is embedded. For example, atoms in molecules, people in social relations, or cells in tissues all have properties that form the context. The interactions between individual components and their properties influence the collective properties. For example, the properties of people with different personalities determine how they interact and the social groups they form. Similarly, different cells form tissues with different properties and functions. The couplings/interactions between the components form networks with different structures that are an important part of the context. For example, neural, hormonal, and metabolic networks constrain our thoughts and behaviour.

  Environmental context is composed of the environmental constraints that affect the system. In physical systems, these may include temperature, radiation, pressure, or power input, whereas in social systems, they may involve economic ambience or ethnic and supporter polarisation. The context may destabilise the previously stable state and spontaneously rearrange system components into another ordered behaviour/structure. This is called a phase transition. The context, which includes a network of component properties, interactions, and internal and external perturbations, determines whether the behaviour will persist, how much it will persist, or how quickly it will decay and switch to another more persistent behaviour. The context generates the stability of the solution, i.e., behaviour, whether it is a social idea(l), a habit, or a cosmic object.

- ***Non-linearity:*** Dynamic Systems Theory suggests that the relationships between components within a system are often non-linear. This means that small changes can lead to significant effects and vice versa. The system's behaviour emerges from the interactions of its components rather than being directly determined by them.

- ***Emergence:*** Emergence is a phenomenon of formthe ation of collective properties in systems. These properties do not exist at the level of individual components but emerge from the interaction of such components. For example, a painting, music piece, or sculpture is not defined by its components, colours, notes, or spatial carvings but by the arrangement of these components. At a macro level, social collective properties like value systems, religions, ideologies, fashions, artistic tastes, and science research programs arise as emergent collective properties that guide the behaviour of the system's components, which are human beings. Because the components behave as the emergent collective variable dictates, they further stabilise its existence. What happens locally, i.e., how each component behaves, depends on the collective variable.

- ***Stability:*** Stability is the necessary and sufficient condition for any system to maintain its behaviour and structure. For a system to exist, it must be insensitive to perturbations. Indeed, some influences perturb the system to some extent. For example, low-energy ultraviolet radiation can perturb our skin cell structures. However, the system maintains its stability because the interaction between the components is strong enough to resist the perturbations. In other words, the bonds forming our cell structures are strong enough to persist even with light perturbations. Although the Earth's crust continuously trembles weakly, human-made buildings are stable. Only significant fluctuations or perturbations, such as earthquakes, can weaken the bonds between the components that stabilize these buildings.

- ***Instability:*** Instability refers to a system's inability to remain stable when subjected to perturbations from both internal and external sources. For instance, if our cell structures and functions are exposed to high-energy perturbations such as gamma radiation or extreme temperatures, they will quickly decompose. No system is entirely immune to all types or sizes of perturbations. The nature of things is such that instability often leads to the creation and destruction of structures while stability helps maintain them. Nature is inherently metastable. Some examples of how perturbations lead to instabilities include Rayleigh-Taylor instability, Plateau-Rayleigh instability, Kelvin-Helmholtz instability, Jeans' instability and liquid-solid transitions of supercooled liquids.

- ***Multistability:*** What happens when a system loses its stability? It can either dissolve into an unstructured stable state or transform itself into another stable, more ordered behavioru and structure. This property of systems, which allows them to have more than one stable state, is known as multistability.

- ***Metastability:*** Metastability is a phenomenon that requires a system to have at least two stable states (multistability). The duration of each stable state is closely related to the time scales of the system's changes. Sometimes, a system may remain in one state for an extended period and then quickly switch to another stable state that lasts for a relatively long time. If we observe the system for a short time, we may wrongly assume that the current state is the only stable state. However, if we wait long enough, we will witness a quick change to another relatively short-living state. These changes may occur due to external perturbations or intrinsic fluctuations that affect the system's organized behaviour. For example, our thoughts or attention may be focused on a particular subject for a brief period and then quickly switch to another one and then to another. Similarly, our conscious actions are continually switching as well. In some people, social or psychological perturbations may result in multiple personality changes. Even our Universe, with all of its laws, maybe a short-living metastable state in the big timescale of cosmic evolution.

- ***State variables:*** State variables capture the behavioural or structural state of systems. These variables can be positions, orientations or rates of change related to anxiety levels, body positions or orientations. They can be also, relational variables that show the relationship between two or more components in a system—for instance, interpersonal, inter-atomic, inter-molecular, or inter-galactic distances. Collective properties of a large number of components can also be state variables. These could be the average magnetization, density or concentration of particles, animals, or the collective direction of motion of players, flocks of birds, schools of fish, or fluid molecules. These variables have different names in different areas of science, such as *reaction coordinates* in chemistry and *order parameters* in physics, psychology, kinesiology, and neuroscience.

State variables are usually analysed for stability in two ways: first, how they behave when subject to perturbations, and second, how they behave under changes in context. Their stability provides information about the system's possible qualitative changes or phase transitions. The long-term states of these variables are called attractors, which attract the system's behavior toward them and maintain it. Conversely, unstable states are called repellers, which repel the system from them.

- ***Attractors:*** Attractors are stable states or patterns towards which a dynamic system tends to evolve. They represent the long-term behavior or tendencies of the system. Attractors can be fixed points, limit cycles (repetitive patterns), or strange attractors (complex, non-repeating patterns).

- ***Fluctuations – Perturbations:*** All systems experience deviations from their stable states, which can be either intrinsic to the system (fluctuations) or produced by external environmental influences (perturbations). These perturbations and fluctuations tend to weaken the bonds that integrate the system and maintain its stability. The behavioural variability of a system, whether physical, biological, psychological, or social, results from these omnipresent influences in nature. If the context changes, the fluctuations of the system increase and bring the system from stability to instability, close to phase transition, bifurcation, and critical or tipping points. Therefore, perturbations and fluctuations test the stability of the system. A highly stable system is indicated by small fluctuations, while enhanced fluctuations point to system instability. A quick recovery of the stable state indicates high stability, and vice versa.

- ***Phase transition/Bifurcation/ Critical point*:** Phase transitions are abrupt changes in the behaviour of a system as it crosses certain thresholds or boundaries. Even the tiniest perturbation can trigger significant changes when a system is close to its critical point. This critical point marks the transition from one stable state to instability and to another stable state. These transitions can occur in response to changes in system parameters or environmental conditions and often result in qualitative shifts in the system's behaviour. As the instability unfolds, a feedback loop amplifies the initial perturbation, leading to what is known as positive feedback. For example, transitions between solid, liquid, and gas, and phenomena like avalanches, magnetisation, societal shifts, and even warfare. These transitions happen relatively quickly compared to the broader context in which they occur. For instance, forming a new social order may take years, while the societal evolution that precedes it spans decades or centuries. Throughout these quick changes, there is a continual rearrangement of the system's components, whether it is the snow distribution in an avalanche, the orientation of microscopic magnetic moments, or the shifting social attitudes and values.

Depending on the circumstances, positive feedback can turn into negative feedback, which counteracts the initial change and restores the system to stability. Negative feedback is crucial in maintaining stability by suppressing any perturbations that threaten the existing stable structure or behaviour. When negative feedback takes effect, it stops the rearrangement of additional components supporting the transition process. For example, if a state government attempts to impose new social behaviours through legislation, negative feedback mechanisms within society can swiftly restore the previous stable behaviours, often through collective correction mechanisms such as peer pressure and conformity.

- ***Self-organisation:*** Systems with large number of components governed by DST principles may exhibit self-organisation, meaning patterns or structures emerge spontaneously from the interactions of the system's components without external instruction or control. These emergent patterns can be stable or undergo transitions depending on the numerical values of the key constraints. Symmetries are neatly connected with the existence or non-existence of *ordered structures* (spatio-temporal patterns). When there is no order or discernibile pattern the state is symmetrical.

When pattern (order) exists, the symmetry is broken. In self-organising systems, the constraints - driven change of interactions between the components lead to spontaneous formation of coherent patterns, structures, or behaviours on a larger scale. This process occurs when the previously spatially symmetrical state loses stability and rearranges its symmetry. Breaking the state's symmetry means forming a new stable *structure*. The stable structure is represented by an attractor. Self-organisation is observed in various natural and artificial systems. In biology, self-organisation is involved in morphogenesis, heart activity, brain activity, and the switch of locomotor patterns. In physical systems, this is seen in crystals and fluid dynamics. In social systems, this is observed in the behaviours of the ant colonies, shoals of fish, flocks of birds, and crowds of people. In geophysics, in mantle convection, cloud formation and development of fires, ocean currents, tropical cyclones and tornados. In technological systems, computer networks and traffic flow.

- ***Space-time scales:*** The order of magnitude of the spatial and temporal properties of a system's behaviour can be determined by its space-time scales. The smallest meaningful spatial scale is approximately 10^{-35} meters, while the minimum time scale is about 10^{-43} seconds. The largest spatial extent currently observable is around 10^{27} meters, and the largest time extent is approximately 10^{17} seconds, the extent of the observable Universe. This vast difference in spatial and temporal scales can be classified as micro and macro scales, with human beings falling in between these extremes. Our bodies have a spatial extent of about 1 meter and a lifespan of around 10^{9} seconds. The naked eye can perceive objects at least 0.01 degrees in size. Objects smaller than this size appear continuous to us. Additionally, any time gap between subsequent visual stimuli that ir than 0.04 seconds is indistinguishable from us, and we perceive the visual sequence as continuous.

However, despite the growing interest in the study of complex systems and their profound influence on various scientific disciplines, there is an evident absence of educational curricula or teacher training dedicated to incorporating these concepts. This gap underscores the opportunity to enhance educational practices through a more integrated approach that considers the principles of complexity science. Therefore, the thesis aims to teach the DST concepts in elementary, high school and university to promote the integration and transfer of knowledge among disciplines.

2.4. The role of embodiment in learning

Embodiment in education refers to using the physical body and experiences in the learning process. It recognises that learning, and hence our engagement with the world, is not solely cognitive but is deeply connected to physical actions, emotions, and interactions with the environment. Embodiment is an ongoing process and never ends because, as beings-in-the-world, we are in an open dialogue with the world we inhabit. We understand something when we experience it.

The current cognitive science perspective defines cognition as ecological, embodied and enactive, and emphasises body movement as a means to acquire abstract concepts (Abrahamson & Sanchez-García, 2016). The phenomenological movement and the Embodied Cognition (EC) theory provided one of the first philosophical and scientific attempts to seriously consider the role of the body in the human experience (Menary 2010; Shapiro 2011). They consider cognitive processes deeply rooted in the body's interactions with the world, suggesting that learning can be significantly improved when learners use their physicality to explore and understand new ideas. Both approaches try to move forward from the mainstreaming Western tradition, which is deeply metaphysical, dualistic, materialistic, and mentalistic. An EC approach to education redefines the role of the body in educational settings, promotes openness in classrooms and schools, and challenges the traditional model of modern schools. It supports outdoor learning, experiential education and similar proposals (Weare, 2002). Even though its effects have long been recognised by developmental psychologists Montessori (1989), Dewey (1991), and Piaget & Cook (1952), there is often confusion about what strategies are effective in the realm of education and how they relate to embodied cognition.

In some cases, the body is considered within educational settings through practices like embodied education and embodied learning (Smyrnaiou et al., 2016). Even though both practices view the learner as a whole being rather than separate its physical and mental qualities (Stolz, 2015), it is important to note the subtle differences between the two concepts.

Embodied learning involves instructional strategies that incorporate physical movement and sensory experiences to help students understand and remember concepts. This can include hands-on activities, gesture-based learning, physical simulations of concepts, and other kinesthetic experiences (Francesconi and Tarozzi 2012).

Embodied education, on the other hand, can be seen as a broader educational philosophy or framework that applies the principles of embodied cognition to the entire educational system. It encompasses not only the learning process of individuals but also the design of curricula, learning environments, and educational policies that support the integration of physical experiences in teaching and learning (Francesconi and Tarozzi, 2019). Embodied education might involve rethinking classroom layouts to allow for movement, incorporating dance or drama into various subjects, or designing outdoor learning experiences that connect students with nature and the physical world. It also considers the role of emotion and social interaction as integral to the learning process, recognising the embodied aspects of human experience.

In essence, while embodied learning focuses on the methods and activities that facilitate learning through bodily engagement, embodied education is a more holistic approach that considers how educational systems can be structured to support and enhance embodied learning practices. Embodied education seeks to create an environment and culture that values and uses the body as a tool for learning across all subjects and at all levels of education.

2.5. Embodied analogies: The impact of movement and lived experiences on learning

An analogy is a cognitive process of transferring information or meaning from a familiar domain to an unfamiliar domain to make a concept or idea more understandable (Gentner, 1983). It involves drawing a comparison between two different things based on a similarity they share. Analogies are often used in teaching to explain complex or abstract concepts by relating them to something familiar to the learner. An *embodied analogy* extends this concept by incorporating physical experiences or actions to reinforce the comparison. It involves using the body and sensory experiences to physically represent the analogy, making the abstract concept more concrete and relatable. For instance, to teach the principles of orbital mechanics, students can move around in ways that mimic the gravitational forces and orbital paths of celestial bodies. By physically playing and acting out the roles of planets or satellites, students can gain a more intuitive understanding of the forces at play. Similarly, in biology, to illustrate the immune response and the role of white blood cells in defending the body against pathogens, students can participate in a simulation where they take on the roles of different immune system components. Through physical interactions and movements, they can mimic the recognition of foreign invaders, the mobilisation of white blood cells, and neutralising or eliminating pathogens. Those examples only help students to learn and understand the concepts of a particular discipline but not to establish connections to other areas of study. The approach is explicitly disciplinary and, therefore, does not consider the interdisciplinary nature of certain fields. However, embodied analogies can be particularly effective in learning abstract concepts for several reasons:

1. Multisensory engagement: analogies engage multiple senses, which can lead to stronger encoding of information in memory (Guillund & Shiffrin, 1984). When learners use their bodies to explore an analogy, they are not just thinking about the concept but experiencing it through sight, touch, movement, and sometimes even sound.

2. Enhanced comprehension: the act of physically embodying an analogy provides a concrete understanding of an abstract concept (ref). By physically acting out abstract concepts, learners not only think about the ideas but also "feel" them.
3. Memory retention: embodied experiences create additional neural connections in the brain, which can help learners recall the concept more easily later on (Roig et al., 2012).
4. Cognitive Anchoring: The physical actions involved in an embodied analogy serve as cognitive anchors—concrete reference points that learners can use to ground their understanding of abstract concepts. The anchors help learners to integrate new information with existing knowledge (Hutto et al., 2015).
5. Active learning: the active participation required in embodied analogies promotes active learning, elevating motivation and interest—crucial factors for effective learning (Macedonia, 2019).
6. Bridging the gap: for some learners, abstract concepts can seem distant and disconnected from reality (Toghiani et al., 2008). Embodied analogies bridge this gap by providing a physical experience related to their everyday lives.
7. Social interaction: the collaborative nature of embodied analogies encourages social interaction and enhances understanding through discussion, observation, and shared experiences (Puntambekar, 2006).
8. Metaphorical thinking: analogies cultivate metaphorical thinking, which is a powerful way to grasp abstract ideas and promote a deeper understanding of the subject matter (Thibodeau & Boroditsky, 2011).
9. Emotional Engagement: The physicality of embodied analogies can evoke emotional responses, which play a significant role in learning (Brackett et al., 2019). Positive emotions associated with an engaging learning activity increase learners' attention and interest, further enhancing the learning experience (Cipriano & McCarthy, 2023).

In summary, embodied analogies are a powerful tool in education as they use physical experience and metaphorical thinking for understanding (Lakoff & Johnson, 1980). By grounding abstract concepts in bodily experiences, educators can create a more inclusive and effective learning environment that helps all students conceptualise and internalise abstract concepts. Some ideas have been applied to STEM learning (Hayes and Kraemer, 2017) under the name of interdisciplinary physical education (Cone et al., 2009). However, even if the interdisciplinary approach uses movement to learn some specific concepts of the subjects, it does not integrate the common principles and concepts nested in science. Instead of using physical activities to understand some specific context specific to the subject they are learning, the studies of the thesis have used movement analogies to connect different subjects by focusing on general concepts.

2.6. Synthetic Understanding through Movement Analogies: SUMA – the Transdisciplinary Unificatory Embodied Educational Framework

The Synthetic understanding through movement analogies (SUMA) learning framework (for the scientific basis of the framework, see Hristovski, 2013; Hristovski et al., 2014, 2019) approached the fragmentation of knowledge problem by discovering, extracting and using the general DST concepts and principles for a far transfer of knowledge among diverse phenomena studied by the disciplines. For instance, an integrated perspective of a virus infection problem can be approached from the perspectives of social, biological, psychological sciences, etc. However, also, many different phenomena or problems (including virus infections and spread) may be formulated or reformulated through common dynamic principles. These problems, then, can be further understood and ultimatelly solved as dynamic problems.

In this way, the SUMA framework provides a unified framework for science and technology, engineering and contribute to promote transdisciplinarity. The difference between the transdisciplinarity of SUMA approach and other trans- and multi-disciplinarity practices explained in section 2.2 is that SUMA provides a theoretical framework to integrate different subjects using the same general concepts and principles. Together with the above-mentioned feature, the embodied approach to learning (see Figure 2 and more details in 2.6.1) makes the second distinctive characteristic of SUMA with respect to other transdisciplinary, interdisciplinary and multidisciplinary approaches. The general concepts, principles, and different examples of applications have been developed in the SUMA learning platform (https://suma.edu.mk/general-concepts/). The concepts used in the interventions are defined in Table 2.

Figure 2. *Contrast between multidisciplinarity approaches and the transdisciplinarity of SUMA approach.*

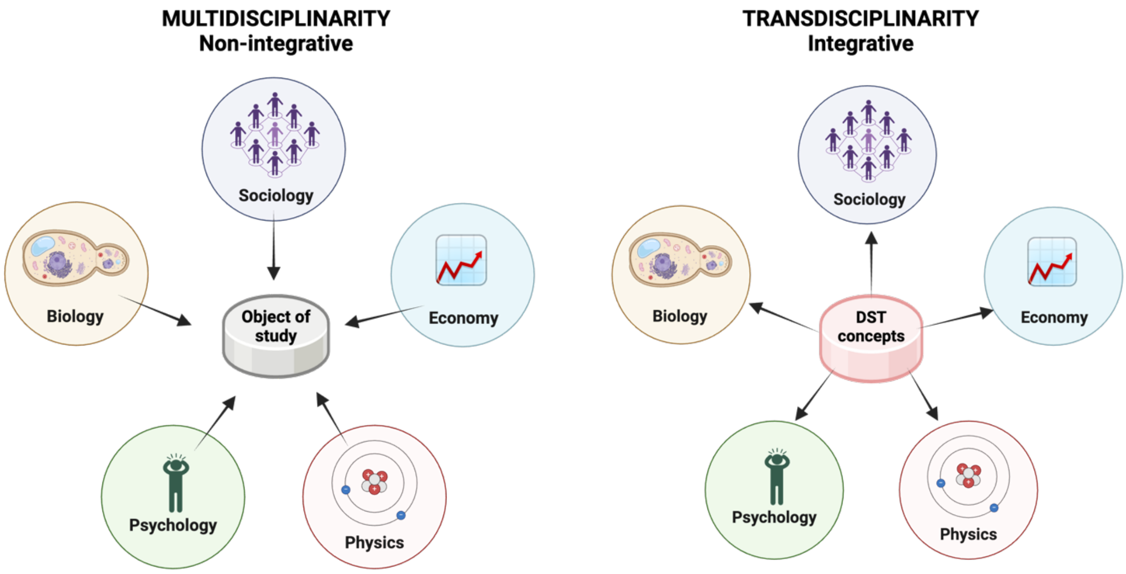

Table 2. *Definition of DST concepts used in the studies of the thesis.*

DST concepts	Definition
Stability	Resilience to perturbations. The necessary and sufficient condition for the existence of any system's behaviour/structure.
Instability	Lack of stability under perturbations coming from within or from outside the system
Phase transition (bifurcation)	A system destabilization produces a spontaneous rearrangement of system's components into another ordered behaviour/structure.
Self-organisation	A process by which the system components change their organization pattern under or without the influence of a perturbation.

Constraints (boundary conditions)	A limitation or restriction that destabilizes the previously stable state of order.
Order parameter (O.P.) (state variable)	Collective variable capturing the coordinative behavior of the system as a whole

2.6.1. The embodied part of SUMA Framework

The SUMA educational framework is based on embodied learning principles (Niedenthal, 2007; Stolz, 2015; Skulmowski and Rey, 2018), which means that body movement experiences can be used to understand complex and abstract concepts, particularly DST concepts. Several studies have shown the effectiveness of teaching through the body, the concepts from different subjects, including mathematics, physics, biology, music, and culture (Cone et al., 2009; Schwartz-Bloom et al., 2011). As a result, embodied interventions have become increasingly popular in elementary and secondary schools due to their effectiveness in enhancing cognitive abilities and improving knowledge retention (Clary and Wandersee, 2007; Spintzyk et al., 2016). However, the embodied approach in education has only been used to connect physical education with other subjects, known as interdisciplinary physical education (Cone et al., 2009).

To teach DST general concepts using the embodied approach, the educational principle of 'concreteness fading' can be applied (Terrace, 1963; Bruner, 1966; Goldstone and Son, 2005; Fyfe et al., 2014). Concreteness fading involves gradually transitioning from tangible and concrete experiences to more abstract ones. As proficiency develops, the concreteness gradually diminishes, leading to a foundational understanding of abstract concepts. Concreteness fading enables learners to understand context-free patterns that are more transferable to other areas of knowledge.

The integration of embodied learning and concreteness-fading principles in educational settings aims to offer a comprehensive and effective learning experience that recognises the significant contribution of physical engagement to the comprehension of complex concepts. Based on Kolb's (1984) experiential learning and embodied learning principles (Abrahamson & Sanchez-García, 2016), Hristovski et al. (2014) proposed four phases of embodied learning for learning abstract concepts or, in this case, DST concepts:

1. Embodied experience (a physical activity: perception-action or/and introspection).
2. Reflective observation of the embodied experience (paying attention to key perceived phenomena and their phases).
3. Abstract conceptualisation (see Table 2) is based upon the previous reflective observation phase but proceeds to conceptualisation, and relations of perceived phenomena.
4. Experiment with the acquired concepts and apply them to different fields and phenomena studied in the academic curriculum (i.e., transfer phase). (See Table 3).

These phases can be supported by various types of contexts, such as learning in natural settings, as well as by the use of educational technology, such as videos, augmented learning, virtual environments, etc. The learning process can also take various forms, such as individual or cooperative learning.

Table 3. *Examples of physical activities, their relation with DST concepts, and examples of transfer of knowledge to explain different phenomena.*

Physical activity	**Order parameter**	**Constraint**	**Phase transition**	**Transfer of knowledge**
Balance on a bench	Position (height) of the center of gravity with respect to the bench height.	Open eyes-to closed eyes; Body forward, inclination; Pushes	From balance to fall (i.e., sudden change of the value of the order parameter).	Transition from healthy to unhealthy state, based on the stability-instability concept
Acrosport	Position of the center of gravity of the figures shape formed by	Number of participants, number of supports	Changes of shape (structure of the system)	Transitions of the water state (solid, liquid, gas) based on the

	postures of individual participants.			concept of local interactions
The telephone	Network communication (length of communication)	Distance among nodes and properties of system's components.	From efficient to inefficient interaction	Transitions from spatially limited forest fire and spread of virus to a maximally spread. Based on the concept of local interactions
Quasi isometric 90º elbow flexion holding an Olympic bar at 80% of 1 RM until exhaustion	Elbow angle	Time on task	From stable 90º elbow flexion to 0º elbow flexion (task disengagement)	Transitions from a healthy tissue to an organic injury. (from microinjury to macroinjury). Based on the concept of connectivity

3. Publications

3.1. SUMA Educational Framework: The way to embodied transdisciplinary knowledge transfer

Robert Hristovski, Natàlia Balagué, **Maricarmen Almarcha**, and Pau Martínez.

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SUMA EDUCATIONAL FRAMEWORK: THE WAY TO EMBODIED TRANSDISCIPLINARY KNOWLEDGE TRANSFER

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(Original scientific paper)

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Abstract
Contemporary education, based on a fragmented structure of topics, limits reasoning and critical thinking in students, contributing little to the development of the integrative competencies and knowledge considered essential in modern society. Interdisciplinary approaches give raise to new specialties, but do not reduce the barriers within and between STEM (Science, Technology, Engineering and Mathematics), Humanities and Arts. The proposal of the SUMA (Synthetic Understanding through Movement Analogies) educational framework is applying movement analogies to learn the unifying concepts of science, that is, concepts that persist despite the changes of scientific paradigms or theories, and have a pluri-contextual character. This way, the SUMA framework aims to capitalize on the current perspective of cognitive science that defines cognition as ecological, embodied and enactive, and emphasizes body movement as a means to acquire abstract concepts. After explaining the origins, rationale, ongoing research and supporting tools (learning platform) of the SUMA educational approach, the proposed learning phases illustrate the differences between the more known interdisciplinary physical education and the current approach.

Key Words*: SUMA educational framework, STEM, Humanities, Arts, transdisciplinary mobility, movement analogies, general principles*

Introduction

The SUMA educational framework (Hristovski, 2013) stands for Synthetic Understanding through Movement Analogies and aims at developing an integrated framework for understanding phenomena spanning from physics to sociology and arts. The SUMA project, as a line of research within the SUMA educational framework, is a product of cooperation between the Faculty of Physical Education, Sport and Health, Ss. Cyril and Methodius University, Skopje, Republic of Macedonia, and the Complex Systems in Sport Research Group, INEFC, Univ. Barcelona, the project can be followed through the online Integrative education-learning platform (suma.edu.mk).

The SUMA project has participated in different editions of the Science Festival of the University of Barcelona under the auspices of UBICS (University of Barcelona, Institute of Complex Systems) and under the general theme of Discovering Complex Systems with different topics: "SUMA project: Synthetic Understanding through Movement Analogies", 2018; "Learning transdisciplinary concepts through movement analogies", 2019; "Move to discover complex systems", 2020. Its research line "Towards an embodied and transdisciplinary education" has been granted by the Ministerio de Educación y Formación Profesional of the Spanish government (FPU19/05693). As part of the research program, and in collaboration with the education institute INS María Rúbies from Lleida (https://agora.xtec.cat/iesmariarubies/) and the foundation Empieza x Educar (http://programaexe.org), a new curricular optional topic for secondary school "Move to understand the world" has been created. The project represents a first attempt to apply SUMA educational approach in the official education curriculum, and the ongoing research aims testing its impact: a) on the integrative competencies of students and teachers and b) on the knowledge transfer among topics related to STEM, Humanities and Arts. The final purpose of the program is enlarging the scientific-technical experience to all education levels (primary, secondary school and university) and diffusing the research results of the embodied and transdisciplinary education experiences among the education community.

Why an integrated understanding in education?

The search for minimum principles that explain the maximum number of phenomena is a tacit motive in science. Although integration of knowledge has been proved as a successful strategy for scientific development, the tremendous growth of science has mostly produced further specialization and fragmentation. Therefore, modern education from its initiation has been fragmented. Long before the onset of post-modern movement in the 1960es and 70es (e.g. Lyotard, 1979), during and after the period of Enlightenment, various education systems lend themselves to immersing young generations within fragmented narratives told by different academic subjects. Today the situation is not different.

In his UN manifesto 'Seven complex lessons in education for the future', Edgar Morin made a plea for an integrated approach in education. In his view, the contemporary education, based on a fragmented structure of topics, limits reasoning and critical thinking in students, contributing little to the development of the integrative competencies and knowledge considered essential in modern society. However, the problem relies on how to *genuinely* integrate STEM, Humanities and Arts.

Integration of STEM, Humanities and Arts

The integration and reduction of barriers within and between widely different areas as STEM, Humanities and Arts cannot be achieved by various forms of multidisciplinary and interdisciplinary approaches as usually considered. Most of the multidisciplinary, interdisciplinary and transdisciplinary approaches are *problem-centred* and entail diverse theories, data-acquisition, analysis techniques and modes of inquiry to study a problem (phenomenon), the object of research or applicative intervention. It is a kind of many-to-one mapping logic. In contrast, the transdisciplinarity underpinning the SUMA education approach is *unificatory-understanding-centred* and proposes that the same meta-theoretical framework (general concepts and principles) are used in diverse problems (phenomena), objects of research and practices studied by diverse disciplines. In short, it is a one-to-many mapping logic.

General concepts and principles, representing the spine of academic disciplines and defined in the learning platform of SUMA (https://suma.edu.mk/general-concepts/), have been first formulated in mathematics and physics, and concretely, they are ascribed to the Dynamic Systems Theory (DST) and Statistical Physics (SP), theories that capture, study and explain the system's changes over time as well as structural and functional transitions occurring in complex systems at different scales when interacting with the environment. In this way, DST and SP offer a common language, which can provide a unified framework for science, and thus, contribute to promote transdisciplinarity and unification of understanding of phenomena. It is worth to remark that DST and SP concepts are not physical although they were firstly applied in physics, but merely general. One can easily envision an alternate history of science in which e.g. sociologists first model the collective behaviour of humans or animals and then, 100 years later, physicists become aware that the same principle is valid for the emergence of e.g. macroscopic magnetism. Therefore, what is relevant in the SUMA educational framework and particularly, the SUMA project, is the generality of principles and concepts found in nature.

A common language for understanding Nature and Arts?

Science communities explore and strive to explain the immense diversity of processes observed at different levels and time scales of substance organization in nature. As the key properties of each level cannot be formal, i.e., mathematically, deduced from the laws that govern the behaviour of the more microscopic components (Hristovski, 2013, Hristovski, Balagué and Vázquez, 2014, 2019), different scientific disciplines have emerged (see Fig 1). The diversity of levels and phenomena constrains the scientific language of each discipline to form a specific vocabulary for naming and explaining the properties and processes under study, as well as communicating knowledge among scientists. This is how cosmologists speak about inflationary and electroweak epoch and space-time metrics, cell biologists about organelles, enzymes and metabolic pathways, psychologists about stress, emotions and personality, and sociologists about group formation, cohesion and leadership. These languages, thus, use context-dependent concepts to name and explain the processes under scrutiny. Context dependence is viewed essentially as a major cause of the fragmentation between the vocabularies of different scientific disciplines. While within specific scientific fields and subfields the communication of knowledge is made possible by a common vocabulary, the more distant disciplines are, the more difficult communication becomes. As this language fragmentation is also translated into science education, this inevitably leads to the formation of a fragmented worldview in learners and limits the possibilities of a learning transfer between different scientific subjects.

This is how the high disciplinary specialization and the development of context-specific science languages have entailed a lack of communication and transfer of knowledge among scientists (Hristovski, 2013). It is in such context that the SUMA educational framework suggests applying movement analogies (Hristovski, Balagué & Vázquez, 2014) to learn the unifying concepts of science provided by the DST and SP. Such concepts are increasingly used in a wide spectrum of scientific disciplines, and particularly, are useful to understand the behaviour of simple, as well as, of complex dynamic systems.

The tension arising from the coexistence of context-dependent and unifying tendencies in science can be seen as an opportunity rather than a problem: resolving it may result in patterns of understanding that are characterized by both a coherent explanatory skeleton coming from unifying tendencies and flexibility due to its context-dependent vocabulary. Their interplay is, what we consider, the necessary ingredient of building a coherent and yet flexible understanding of the world we live in.

From the point of view of scientific practice (in STEM areas but also Humanities and Arts), the importance of solid understanding and use of general unifying concepts cannot be overestimated. They are nested at each level of substance organization, persist despite the changes of scientific paradigms or theories, and have a pluri-contextual character, representing the spine of all sciences (Hristovski, Balagué & Vázquez, 2019).

The last 20-30 years witnessed immense disciplinary mobility of machine learning and dynamic systems approaches and modeling tools, which are thoroughly based on the application of the general (i.e. pluri-contextual) unifying concepts (e.g. stability, attractor, gradients, symmetry etc.), to areas that were separate before (see Figure 1). Today, one can find scientists who use these tools and hence principles and concepts, in a wide area of academic research areas, starting from physics, to molecular and cell biology, to neurosciences, psychology and exercise and sports sciences. In this way, many scientists can escape the confines of its discipline and join research in other, previously distant, domains. This capacity of evading and escaping the state of confinement and reduced possibilities of achieving the goal has been recently defined as a hallmark of the adaptive behaviour (Hristovski and Balagué, 2020).

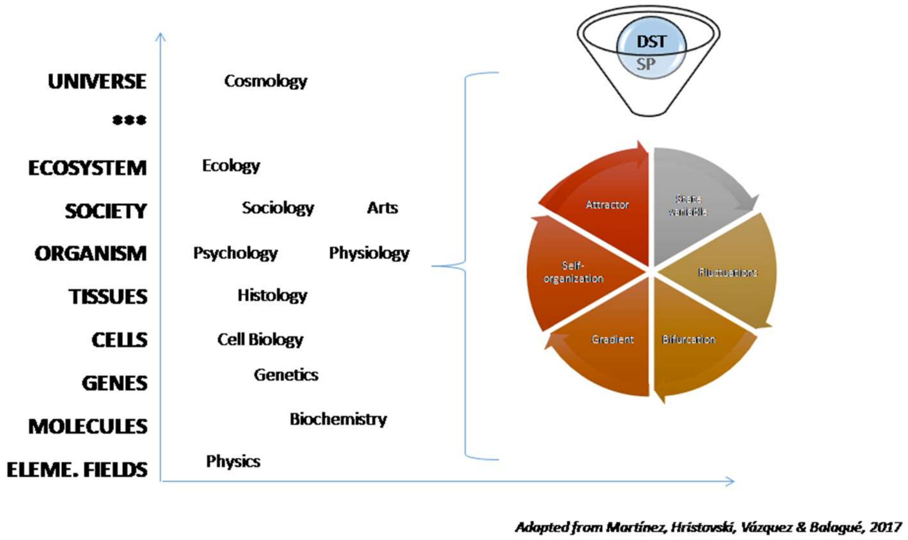

Figure 1. General concepts and principles from the Dynamical systems theory (DST) and Statistical Physics (SP) are at the heart of mathematical modeling and understanding in STEM and Humanities. Adapted from Martinez, Hristovski, Vazquez and Balague, 2017. With courtesy of Frontiers in Psychology).

What can be found in the Integrative education learning platform of SUMA?

The learning platform of SUMA educational framework aims to provide one strategy for building a synthetic understanding of the processes in Nature.The integrative focus is based on teaching common concepts and principles extant in various dynamical systems. Moreover, physical activities, in a form of movement analogies, are the pivot of such an integrative education which provides an embodied and experientially grounded understanding. The main aim is providing a helping tool for teachers, educators and students in their permanent striving to integrate their visions of the world. The visitor can find:

- *The Big Picture*: A general view on 'How Nature works' that leads to synthetic understanding and worldview.
- *General Concepts and Principles*: Integrative dynamic concepts used to teach and understand processes through textual explanations, simulations, animations and movement analogies;
- *Phenomena*: Understanding of phenomena existing at different levels of Nature's organization through textual explanations, simulations, animations and movement analogies, based on general concepts and principles.

Is integrated education becoming physical?

Why embodied education? The current perspective of cognitive science defines cognition as ecological, embodied and enactive, and emphasizes body movement as a means to acquire abstract concepts (Abrahamson & Sanchez-García, 2016). While currently, under the name of interdisciplinary physical education, there is a rich and elaborated learning strategy applied to disciplines like mathematics, physics, biology, music, or culture (Cone, Wernerand & Cone, 2009), such interdisciplinary approach is not integrative. It does not allow students to learn and experience the *common principles* and *concepts* nested in each of sciences and the relations that sciences have with arts. Instead to use physical activities for understanding processes and phenomena from different sciences, we propose using movement analogies to connect STEM (Science, Technology, Engineering and Mathematics), Social Sciences, Humanities and Arts by focusing on common principles and concepts.

Based on Kolb's (1984) experiential learning approach, and the ecological and embodied learning paradigms (Abrahamson & Sanchez-García, 2016) the proposed learning phases are as follows: 1.Concrete experience (a physical activity: perception-action and/or introspection) 2. Reflective observation on the experience (paying attention to key perceived phenomena and their phases) 3. Abstract conceptualization based upon the reflective observation (conceptualization, estimation and/or plotting of relations)
4. Experimenting with the new concepts and applying them to different fields and phenomena studied in the academic curriculum. These phases can be supported by various types of contexts such as learning in natural settings as well by use of educational technology, such as videos, augmented learning, virtual environments etc. Also, the learning process can take various forms such as individual or cooperative learning.

An example of a practical application of the method

A balance task can be used as a movement analogy to learn general concepts like stability, meta-stability, criticality (instability), search for stability and qualitative change; that may, afterwards, be transferred to diverse phenomena in nature, the social realm, and arts.

Keeping balance in the upright position is a basic motor skill in humans. It needs coordinated cooperation of the neuro-muscular system at many levels to negotiate the major environmental constraint (gravity) which tends to collapse the body. Due to gravity, for the human body, the ground state is the global energy minimum stable state (minimum metabolic rate). All other positions are metastable states that need active control to be stabilized. The degree of stability can be tested by applying external perturbations to the body and observing how it behaves. Rapid recovery of its previous state signifies stability, slow recovery signifies approaching instability, and no recovery at all signifies instability, i.e., loss of stability.

The learner stands with the feet parallel facing a target within reach/just out of reach. S/he is instructed to pay attention to a specific set of bodily sensations that will occur under different conditions. The distance from the target is divided into 10 equidistant intervals. The scaled target distance D is calculated as a ratio between the physical distance of the learner from the target to his/her arm length measured from the shoulder to the fingertips. The physical distance is measured from the tips of the toes to the vertical projection of the front part of the target on the floor. Starting from the closest scaled distance, the learner tries to reach and touch the target. Also, at each scaled distance, a partner applies a relatively constant mechanical perturbation to the learner's trunk in the direction of the target. As the scaled distance increases, typically close to $D = 1.4$, the learner loses balance and takes a step forward, i.e. transits to a more stable diagonal stance.

The learner is asked to provide several self-reports on the sensations of stability perceived at different scaled distances D, especially to the perturbations applied by the partner and the behavioural variability of the lower limbs and the centre of mass. The whole procedure may be videotaped and essential variables may be estimated, such as the centre of mass displacement and the leg displacement, and then put to further use. The concept of stability may be studied also in a perceptually grounded fashion with inanimate mechanical bodies as well, with learners acting and observing the effects produced on the body. However, important phenomena like the enhancement of fluctuations close to the critical point will not be obtained in this case.

The concept of stability exists because the behaviour or structure recovers quickly after a small perturbation. Hence, the behaviour/structure exists because it is insensitive (robust) to perturbations coming from within or out of the system. The competition of bond-forming couplings and perturbations is present in any system we see. Stability is reached if couplings between the components of the system are larger than the internal or external perturbing forces trying to decouple them, and vice versa. Nature creates and destroys through instabilities and maintains through stability. For instance, a human-made building is stable when the bond couplings resist the common earth crust tremblers. However, those stable couplings can be destroyed during an earthquake of high intensity. Some examples, of how perturbations induce instabilities which produce structures out of homogeneous stable state are Rayleigh-Taylor instability, Plateau-Rayleigh instability, Kelvin-Helmholtz instability liquid-solid transitions of supercooled liquids etc.

Conclusion

The SUMA approach can be used by physical education teachers or other specialists, though not necessarily during the physical education lessons, quite possibly through other forms of curricula (e.g. a *separate subject* (Hristovski, 2013) with the content of the SUMA educational framework), can contribute to 1) help teachers and students to discover and learn the unifying concepts common to STEM, Social Sciences, Humanities and Arts, 2) overcome the limits of fragmentation in education promoting an integrated scientific understanding, 3) overcome the lack of tune between contemporary scientific knowledge and educational practice,4) provide a transdisciplinary *transfer of knowledge* and enhance the *transdisciplinary mobility* of researchers in science, humanities and the arts, and 5) contribute to building a synthetic worldview and an integrated *feeling* of the world, a part that is thoroughly missing in current education. In this way, knowledge and the meaning it is supposed to provide may become genuinely physical through physical activities.

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3.2. Transdisciplinary embodied education in elementary school: a real integrative approach for the science, technology, engineering, arts, and mathematics teaching

Maricarmen Almarcha, Pablo Vázques, Robert Hristovski, Natàlia Balagué.

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Transdisciplinary embodied education in elementary school: a real integrative approach for the science, technology, engineering, arts, and mathematics teaching

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Introduction: Connecting academic disciplines and integrating knowledge is gaining popularity in elementary school. The relevant question is, how the targeted integration could be achieved? This research aimed to (a) evaluate the potential of teaching and learning Dynamic Systems Theory (DST) and Statistical Physics (ST) general concepts through embodied experiences in elementary school and, based on it (b) enable a far transfer analogical reasoning within and between different academic subjects.

Methods: Forty-eight elementary school students, aged 10.2 ± 0.82 y.o., followed an 8-week, 2-h/week intervention. The learning protocol contained a concreteness fading sequence of phases and consisted of four steps: (a) embodied experience, (b) reflective observation, (c) abstract conceptualization of DST/ST concepts, and (d) transfer of the DST/SP concepts to physical, sociological, biological and ecological phenomena. A validated questionnaire and an interview evaluated students' knowledge and analogical reasoning.

Results: The Wilcoxon Signed Ranks Test showed a general positive effect of the intervention on the understanding of DSP/SP concepts and on the far transfer competencies of students ($Z=-5.98$; $p<0.0001$). There was no association between the previous and newly acquired competencies (Spearman's $\rho=0.112$; $p=0.441$).

Discusion: The qualitative results showed that, in general, the suggested embodied learning protocol supports the acquisition of DST/SP general concepts and the far transfer competencies. However, students of this age are possibly highly sensitive to the balance of the focus between the embodied phases and the conceptualization/transfer phases of the learning protocol. The study points to the potential of learning the general DST/SP for elementary school students' integrative and far transfer competencies. The DST/SP concept-based transdisciplinary embodied education may offer a truly integrative approach to STEAM teaching.

KEYWORDS

dynamic systems, concreteness fading, transfer of knowledge, analogy, knowledge integration, trans-disciplinarity, embodied learning, complex systems

1. Introduction

Linking different disciplines and phenomena is crucial for developing reasoning and critical thinking (Anderson and Krathwohl, 2001; Cañal et al., 2013; Adams, 2015; Clapp and Jiménez, 2016; Bautista et al., 2018). However, contemporary education, traditionally based on a fragmented structure of subjects, limits students' integrating and knowledge transfer competencies (Goldstone, 2006; Jacobson and Wilensky, 2006; Hristovski, 2013).

Science education stands at the forefront of this endeavor by taking the active role of a pathfinder of connections in the complex landscape of academic disciplines. Indeed, integrating apparently disparate disciplines may be a crucial contribution to advancing science (Sengupta, 2019). In this line, there are exciting initiatives under the framework of STEAM (Science, Technology, Engineering, Arts, and Mathematics). However, the educational possibilities of integrating and transferring knowledge still need to be deeply explored.

STEAM education is a relatively new educational framework that aims to break down boundaries between disciplines taught in isolation and address actual-world problems (Dakers, 2006; Yakman, 2008; Baek et al., 2011). Typically, in STEAM, authors propose interdisciplinary models, integrating at least the contents of two of the acronyms (Stock and Burton, 2011; Yakman and Lee, 2012; Zamorano et al., 2018), and transdisciplinary models. Seeking to impact all educational fields, moving beyond specific disciplines and involving the space between disciplines, the transdisciplinary teaching of STEAM searches to produce new perspectives (Gibbs, 2015). Some examples include critical numeracy (Das and Adams, 2019), critical ecological sustainability (Kim et al., 2019; Lam-Herrera et al., 2019), and macroethics (Gupta et al., 2019).

Many countries are investing in STEAM learning at K-12 levels, for example, China (Li and Chiang, 2019), Australia (Sharma and Yarlagadda, 2018), England (Wong et al., 2016), and Canada (e.g., Science Technology and Innovation Council, 2015; Shanahan et al., 2016). Even South Korea has made STEAM the core of its education system (Yakman and Lee, 2012; Hong, 2016). However, there is still limited research on STEAM's validity and effectiveness in the classroom. In addition, STEAM's conceptualization is considered insufficient because the proposals and resources from specific disciplines do not provide acknowledgement of the commonalities between them (Zamorano et al., 2018; García-Carmona, 2020).

Although K-12 and high schools are adopting STEAM teaching methodologies, there is still limited empirical evidence about their benefits on students' abilities to integrate and transfer knowledge. The lack of a well-founded integrative framework of the education curricula and the lack of teachers' preparation to connect STEAM disciplines can explain such limitations (Radloff and Guzey, 2016). As suggested here, professionals from the STEAM disciplines work together on interdisciplinary projects but are rarely familiarized with accurate transdisciplinary approaches. Their academic training is usually fragmented into various specialties. The vast amount of different undergraduate and graduate degrees in science and engineering that universities offer each year proves it. The most common practice in a STEAM project is that each professional contributes to it through his/her area of knowledge (García-Carmona, 2020). This reveals STEAM primarily as a multidisciplinary approach, a non-integrative mixture of disciplines with only sporadic and superficial links among the subjects.

1.1. Early ideas and educational initiatives on understanding of complex systems

Intuitions about the educational benefits of using the commonalities between different phenomena and levels of organization have been expressed previously (e.g., Haken, 1977; Forrester, 1994). Early education initiatives have successfully used some concepts coming from the dynamical systems theory (DST) and statistical physics (SP) (from now on -DST/SP) concepts to understand complex systems' levels formation (e.g., Resnick and Wilensky, 1998; Wilensky and Resnick, 1999). Hence, the research on explaining complex systems phenomena was mainly focused on important concepts such as emergence and self-organization. For instance, some software packages allow students to manipulate computer-simulated environmental constraints to study the dynamic behavior of molecules, cells, etc. (Wilensky and Reisman, 2006) and integrate micro- and macroscopic chemical organizational levels (Stieff and Wilensky, 2003). The authors studied students' learning responses to computer agent-based-modeling relations between micro and macro–level phenomena on chemical, physical and social levels of substance organization. This line of research resulted in seminal reviews, position and prospect papers (Jacobson and Wilensky, 2006; Goldstone and Wilensky, 2008; Wilensky and Jacobson, 2015).

However, focusing solely on concepts and principles that are common for complex systems will still leave a fragmentation between systems that are defined as simple (e.g., pendulums, springs, elementary fields/particles, projectiles, mechanical tools, motion of artificial satellites, etc.), and truly complex systems that consist of a vast number of interacting components (e.g., fluids, cells, organism, societies etc.). Hence, the most crucial problem of fragmented education promised to be solved (Goldstone, 2006) would remain unsolved. This is especially relevant for STEM education since in the areas of technology and engineering, many sub-systems belong to the class of simple or, as a whole belongs to the class of complicated[1] systems. Hence, the set of concepts and principles that would satisfy the constraint of unifying simple, complicated and complex systems under the same umbrella was a new and challenging problem.

The second challenge to this goal is that the number of concepts/principles should not be too large and should not be level- or phenomenon-dependent. We explain in more detail this idea below.

1.2. The SUMA-transdisciplinary embodied learning framework: conceptual approach

To solve the two main challenges discussed above and to achieve a conceptual integration of understanding among academic disciplines covering the whole spectrum of phenomena (from elementary fields/particles to sociology and art), including simple and complicated systems, there is a need for a "common conceptual currency" that can act as a glue for the integration. The Synthetic understanding through movement analogies (SUMA) learning framework (for the scientific

1 Complicated systems are defined as systems of simple components, each of which has a well-understood law of behavior and interaction with other elements (Grabowski and Strzalka, 2008).

basis of the framework, see Hristovski, 2013; Hristovski et al., 2014, 2019, 2020; Almarcha et al., 2022) approached this problem by putting forward a set of interconnected general concepts and principles coming from DST/SP which can play the role of a 'common conceptual currency.[2] However, extracting and verifying the general DST/SP principles/concepts from the above science fields, in which myriads of them vastly differ in generality, is an extraordinarily challenging problem. As said above, under the term 'truly general concepts', we mean concepts/principles instrumental in explaining dynamic phenomena of simple, complicated and complex systems in all levels of substance organization. More technically, truly general concepts represent level-independent '*invariants*' (Hristovski, 2013; Nathan and Alibali, 2021) encompassing all levels of substance organization. These truly general concepts/principles are necessary for achieving the far-transfer (Goldstone, 2006) goals of the SUMA educational framework. Although these concepts/principles are necessary, they cannot explain many phenomena comprehensively. Hence, in SUMA, the interplay between the truly general (the skeleton) and level dependent (the meat) concepts/principles forms the educational apparatus for achieving the far-transfer goals.

The empirical research with aim to extract and verify concepts of the broadest possible generality showed that 14 DST/SP concepts are explanatorily relevant for the whole set of academic disciplines ranging from physics of elementary fields/particles to sociology and art (Hristovski, 2013; Hristovski et al., 2019) (see footnote 2). These concepts and principles, such as stability and instability, gradients, mass-energy, information entropy, phase transitions, constraints, state variables, symmetry-symmetry rearrangement, etc., form the *transdisciplinary embodied approach* within the SUMA educational framework. They create the skeleton of the academic disciplines, playing the role of discipline-free concepts that are explanatorily involved in dynamic phenomena of all academic disciplines. On the other hand, each one of the disciplines also contains a large (in fact, much larger) set of discipline-dependent concepts. Discipline-free and discipline-dependent concepts interact to provide explanations for each set of phenomena.

We offer some examples to contrast the SUMA educational framework with similar approaches. For instance, concepts such as: adaptation, evolution, fitness, altruism and selfishness (Wilensky and Centola, 2007) or homeostasis (Jacobson, 2001) are certainly relevant for all biological and social systems but not non-biological ones. Thus, in order to enable a unified account of biological *and* non-biological systems, by using far transfer analogies, SUMA emphasizes more general concepts and principles, such as 'variability' (i.e., 'fluctuations' and 'perturbations'), 'constraints', 'interactions', gradient flow, and 'stability-instability', which are crucial in explaining adaptation, evolution, fitness and homeostasis as special instantiations of biological phenomena. Within the SUMA framework, concepts like altruism and selfishness are treated as biologically relevant constraints but not as general concepts. Because only stable entities survive (from elementary particles, planetary orbits to biological species), stability is the general precondition for natural selectivity. Hence, general concepts like 'stability-instability' are also crucial for explaining non-biological selectivity phenomena. The conceptual pair stability-instability plays a crucial role also in control theory which is fundamental to technology and engineering. Another concept, such as 'energy minimization' (e.g., Goldstone and Wilensky, 2008) is certainly of high generality, and in systems in thermodynamic equilibrium generates the system's stable behavior. However, in non-equilibrium (e.g., biochemical enzyme kinetics) systems, the principle of 'entropy production maximization' is often responsible for the stability of the system's patterns of behavior (e.g., Dobovišek et al., 2018). Hence, 'stability - instability' would appear as a more general concept/principle which may be generated either by energy minimization or entropy production maximization, depending on the concrete phenomenon. In this situation of far-transfer between equilibrium and non-equilibrium phenomena, this concept would have a role of deep analogy among the initial and target phenomena. Yet, another example are the concepts such as: 'fractal', 'power law and 'graph' (Lage-Gómez and Ros, 2021). In contrast, the DST/SP concept-based transdisciplinary embodied educational framework - SUMA uses concepts of a high level of generality to achieve these ends. For example, the concepts of fractals, power laws and graphs can be subsumed into the more general DST/SP concepts of 'symmetry - symmetry breaking' and 'interactions', respectively, because fractals and power laws are a special case of the concept of 'symmetry' (i.e., scale symmetry), and graphs are a unique representation of the concept of 'interaction'.

Hence, although SUMA transdisciplinary approach shares some similarities with other approaches (particularly those focused solely on complex systems education), it represents a distinct and genuine approach in important aspects. Hence, it offers powerful means for intersecting systems thinking, e.g., in biology with other STEM disciplines (Trujillo and Long, 2018; Momsen et al., 2022). First, it unifies (solves the fragmentation problem) among simple, complicated and complex systems; Second, but not less significantly, its reliance on truly general concepts/principles reduces their number and renders some concepts of narrower generality as level-dependent concepts/phenomena.

The extant interdisciplinary and transdisciplinary learning (e.g., Cone et al., 2009; Stock and Burton, 2011; Yakman and Lee, 2012; Zamorano et al., 2018; Lage-Gómez and Ros, 2021) is a phenomenon (problem)-based. In other words, the problem or phenomenon *is* the integrating factor that engages the cooperation of different academic disciplines. For instance, an integrated perspective of a virus infection problem can be approached from social, biological, psychological sciences, etc. On the other hand, in SUMA, the DST/SP general concepts *are* the integrating factor. The same DST/SP concept or principle (or one set of interdependent concepts and principles) integrates many phenomena (or problems). These concepts provide the 'integration substrate' needed to integrate processes and phenomena of different levels of organization (Martínez et al., 2017). For instance, the principle of 'tendency toward 'stability' in semantic relation with other general and phenomenon-dependent concepts can integrate many simple and complicated technological/engineering systems, as well as truly complex social and biological phenomena, such as damped oscillations of a spring, system of springs in vehicles, social stability, and path dependence of athlete's response to training stimuli, respectively. These two approaches have been explained in more detail for sports and exercise sciences (Hristovski et al., 2017). While the first has been called the "many (academic disciplines) to one (problem/phenomenon)" approach, the second is called the "one (concept/principle) to many (academic disciplines)" approach (see Figure 1).

2 https://suma.edu.mk/general-concepts/

1.2.1. The embodied part of the SUMA educational framework

The SUMA educational framework also pays serious attention to the importance of embodied learning principles (Niedenthal, 2007; Stolz, 2015; Skulmowski and Rey, 2018). The embodied approaches to learning emerging in recent decades reinvented Poincare's ideas of the central role movements have for cognizing the space and its geometry (Hristovski et al., 2014). Body movement experiences have already been used to study concepts in separate subjects such as mathematics, physics, biology, music, or culture (e.g., interdisciplinary physical education, Cone et al., 2009) and have gained some popularity in elementary and secondary school education due to their cognitive effectiveness and knowledge improvement (Clary and Wandersee, 2007; Schwartz-Bloom et al., 2011; Spintzyk et al., 2016). Recently, enactive and embodied approaches to STEM were successfully advocated on theoretical grounds (Hutto et al., 2015). The close link between movements and cognition has been innovatively elaborated (Abrahamson and Mechsner, 2022) with concrete applications in mathematics. On the other hand, preliminary research results have shown that DST/SP abstract general concepts can be mediated successfully using movement analogies (Almarcha et al., 2022). The embodied learning may show itself as an effective way of application of the educational principle of 'concreteness fading' (Terrace, 1963; Bruner, 1966; Goldstone and Son, 2005; Fyfe et al., 2014), in which the concreteness of the experience of learners gradually transits toward more abstract, and hence, context-free patterns of understanding, which are more transferable to new experiences (i.e., phenomena).

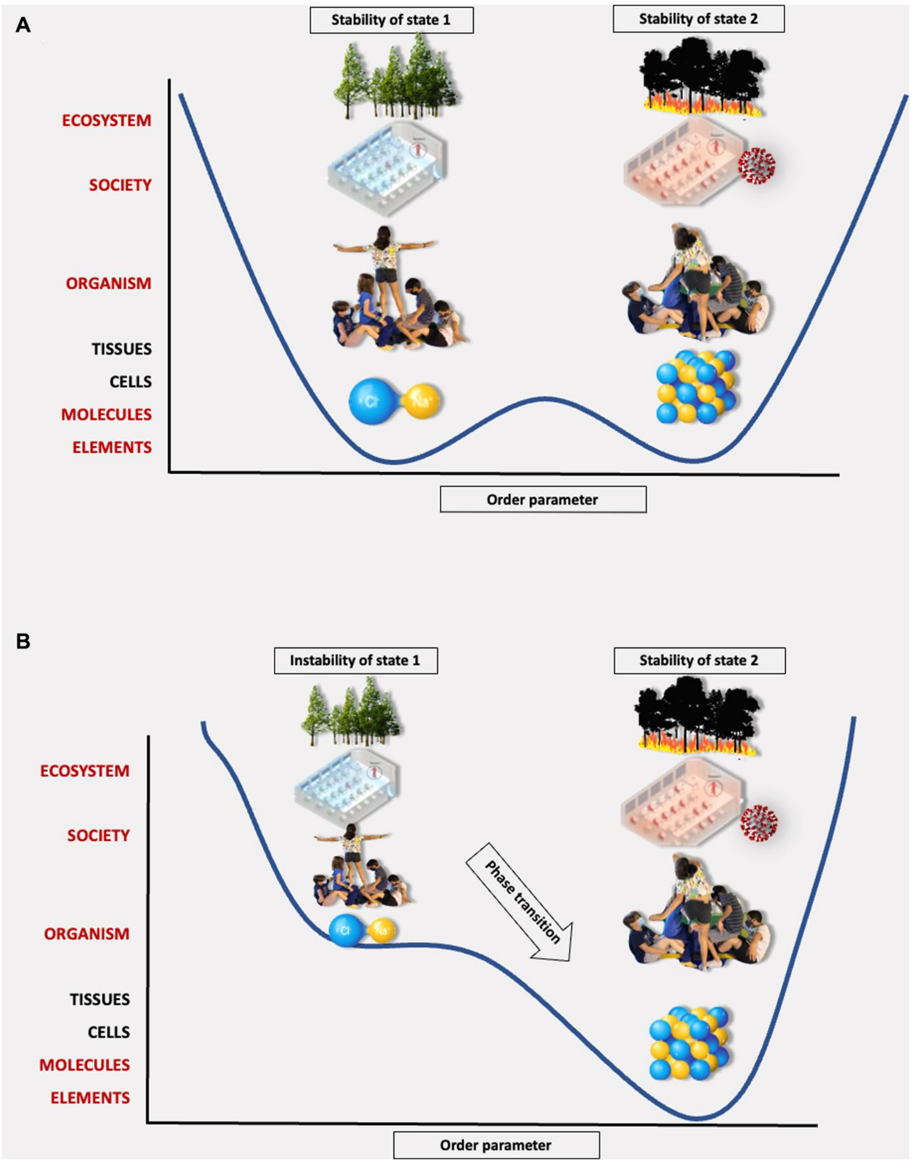

FIGURE 1
Stable states are represented as minima (bottom of the wells). Unstable states are represented as local maxima or inflection points. The order parameter (horizontal axis) represents the state of the system. **(A)** Representation of two stable states of an order parameter in phenomena of different organization levels. At the ecosystem level, it is represented by a green and burned forest; at the society level, a healthy and infected classroom; at the group level, a stable and collapsed acrosport figure; at the molecular level, the water is in the liquid and solid state. **(B)** Representation of the phase transition between the attractor states of the order parameter due to constraints (distance among trees, the distance among students, number of supports and temperature, respectively).

In order to apply the protocol of 'concreteness fading' Hristovski et al. (2014) proposed the following four phases of embodied learning of DST/SP concepts and their use in far or near transfer, based on Kolb (1984):

1. Embodied experience (a physical activity: perception-action or/and introspection).
2. Reflective observation of the embodied experience (paying attention to key perceived phenomena and their phases).
3. Abstract conceptualization (see Table 1) is based upon the previous reflective observation phase but proceeds to conceptualization, estimation and plotting of relations of perceived phenomena.
4. Experimenting with the newly acquired concepts and applying them to different fields and phenomena studied in the academic curriculum (i.e., transfer phase).

Note that, in the case of this protocol, the first two phases do not use the standard external representations (e.g., Bruner, 1966), but a first-person perspective concrete experience based either on perception-action cycles and/or on introspective judgments.

According to what has been discussed in the previous sections, we hypothesize that the embodied intervention will have a generally positive effect in acquiring general DST/SP concepts and their far transfer role among phenomena studied in different academic subjects of 5th grade elementary school. Particularly, we hypothesized that the four learning phases of the inbuilt concreteness fading protocol would (a) lead to the acquisition of the abstract meaning of the targeted general DST/SP concepts, and (b) enable a far transfer ability for connecting different phenomena.

2. Materials and methods

2.1. Participants

Forty-eight elementary school students of 5th grade (26 boys, 22 girls; 10.2 ± 0.82 y.o.) from two different class groups participated in the study. Ten (5 boys and 5 girls from each class) were randomly selected

TABLE 1 Definition and examples in physics and biology of the concepts explained and worked during the intervention.

DST/SP concepts	Definition
Stability	Resilience to small perturbations. The necessary and sufficient condition for the existence of any system's behavior/structure.
	Physics – A small temporary mechanical stress to a liquid water at room temperature and normal pressure will not produce ice (i.e., a solid state). The liquid state of the water is stable on room temperature and normal pressure.
	Biology – Under normal living conditions the immune system is constantly perturbed by environmental pathogens, however the non-infected (i.e., healthy) state is stable mostly due to the innate immune response.
Instability	Lack of stability under small perturbations coming from within or from outside the system.
	Physics – A small temporary mechanical stress on a supercooled liquid water will produce ice formation and a new stable solid state. The previous liquid state was unstable under supercooled (very low temperature) conditions.
	Biology - Immunodeficient immune system of a previously non-infected organism will yield under a small dose of pathogens and a new infected state will be stabilized. The previously uninfected state was unstable.
Phase transition (Bifurcation)	Transition from the previously stable state into another stable state through instability state. System's destabilization produces a spontaneous rearrangement of the organization of its components giving a way to another ordered behavior/structure.
	Physics – The transition from liquid water to ice (i.e., solid state). The ordered state of water molecules is being qualitatively changed. The short-range order of the liquid state transits to a long-range crystal lattice in the solid state.
	Biology – The transition from uninfected to infected state. The previous organization of the immune system which suppressed the pathogen replication, dominantly by means of the innate immunity, changes when the replication of the pathogens takes exponential growth. The adaptive immune response then is fully activated.
Self-organization	A process by which system's components change their organization pattern without external imposition of the organization pattern. It arises based on local interactions among the elements Examples:
	Physics – Water molecules spontaneously self-organize under the interactions and the external temperature and pressure constraints.
	Biology - The immune system spontaneously self-organizes under the interactions of many hierarchically organized sub-systems.
	In both cases, there is no external source imposing the organized patterns of behavior/structure.
Constraints (Boundary conditions)	A limitation or restriction that stabilizes or destabilizes the previously stable state of order, based on their numerical value.
	Physics – The temperature, the atmospheric pressure, the physico-chemical properties of water molecules, the presence of impurities etc.,
	Biology – The environmental stressors interacting with psychological traits and state, the state of the innate or adaptive immune response cells properties (vitamin D_3, levels, T-cells, B-cells), etc.
Order parameter (O.P.) (State variable)	Collective variable capturing the ordered/coordinated structure or behavior of the system as a whole. It is this variable whose states can be stable or unstable.
	Physics – The average density, or molecular bond orientation of water molecules;
	Biology – Pathogen concentration in the body vs. immunity response activation. On a psychological level – the self-assessed well-being.

and interviewed individually about the learnt DST/SP concepts. Students did not have prior knowledge or experience with the contents and procedure of the intervention. After explaining the procedures, the legal educator signed informed consent. The local ethic committee approved the study according to the Helsinki declaration.

2.2. Design

A quasi-experimental design comparing pre- and post-intervention results was applied. As DST/SP concepts are not included in the elementary education curriculum, a control group was considered unnecessary in this research.

2.3. Procedure

The study was conducted in a physical education facility. The intervention lasted eight weeks and had a frequency of two lessons/week of 1-h duration. It was developed during regular physical education lessons and was led by a PE teacher and researcher with more than ten years of experience, respectively, applying DST/SP concepts. One experimenter supervised the intervention *in situ*. The learning phases proposed by Hristovski et al. (2014) were the following:

1. Students performed the proposed physical activities focusing attention on relevant aspects of the body experiences for the association with the DST/SP concepts (see Table 2).
2. Reflection of previous body movement experiences.
3. Association of movement experiences with general DST/SP concepts (see Table 1) through videos and photographs.
4. Transfer of the DST/SP concepts to molecular, ecological and sociological phenomena (see Table 2; Figure 1).

Table 2 displays three examples of physical activities proposed to the students for learning DST/SP concepts of Table 1 and transferring them to ecological, molecular and biological phenomena. The transfer of knowledge was discussed with the students after each activity through audiovisual material projected in class. In the first activity, students had to maintain balance on a bench with open and closed eyes while a partner "pushed" them with different intensities. The order parameter (O.P.) was the body's center of gravity position with respect to the bench height. This O.P. kept stable under open eyes (released constraint) but destabilized with closed eyes enhanced constraint. The perturbations (pushes) affected the O.P. differently under stable and unstable conditions: the same push intensity that could be adequately compensated to keep the balance produced a fall under unstable conditions. The transfer to our healthy or unhealthy physiological state was done as follows: when our immune system is adapted to the environmental constraints, our organism is in a stable[3] healthy and uninfected state, and can control a pathogen attack. However, when it is constrained (e.g., by stress), the perturbation produced by a pathogen attack may destabilize the uninfected state and produce severe health consequences, i.e., a new stable state (disease, e.g., infection) (see, e.g., Krishnapriya and Pitchaimani, 2017; Shi et al., 2020; Su et al., 2022).

3 In dynamical systems approach the state of health is always a continuous variable. It is never a predefined categorical variable (Figure 1). This continuum, however, may have stable and unstable regions. It is the instability region that naturally induces category-like stable states (health vs. illness or uninfected vs. infected, states). Stable states do not mean the system is in one set-point. It may deterministically oscillate or stochastically fluctuate widely around some average value, however due to the negative feedback of the healthy organism, it dwells inside a wide, but nonetheless limited region. What is crucial to understand, though, is that this stable state can become unstable due to a slowly changing set of constraints (e.g., accumulated stress, weakened immune system), and eventually for a small perturbation (increased pathogen presence), it may spontaneously (by a positive feedback) switch to another stable (diseased, e.g., infected) region. For example, in: Shi et al., 2020; or Su et al., 2022, it is the ratio between virus elimination capacity of the immune system and the received pathogen load that defines the stability- instability of the healthy (uninfected) state. The set of interacting constraints acting on the immune system response, though, can be very intricate as in Antonovsky's model of salutogenesis (Antonovsky, 1979), or complex adaptive systems approach to health (Sturmberg et al., 2019).

TABLE 2 Examples of applied physical activities, their relation with DST/SP concepts and their transfer to molecular, ecological and sociological phenomena.

Physical activity	Order parameter (defines the level and type of organization or structure of the system)	Constraint (defines the influences to the extant organization of the system) (external and internal)	Phase transition (defines the qualitative change of the system's order)	Transfer of knowledge (defines the connection of the concept between different disciplines)
Balance on a bench	Position (height) of the center of gravity with respect to the bench height.	Open eyes-to closed eyes; Body forward, inclination; Pushes	From balance to fall (i.e., sudden change of the value of the order parameter).	Transition from healthy to unhealthy state, based on the stability-instability concept
Acrosport	Position of the center of gravity of the figures shape formed by postures of individual participants.	Number of participants, number of supports	Changes of shape (structure of the system)	Transitions of the water state (solid, liquid, gas) based on the concept of local interactions
The telephone	Network communication (length of communication)	Distance among nodes and properties of system's components.	From efficient to inefficient interaction	Transitions from spatially limited forest fire and spread of virus to a maximally spread. Based on the concept of local interactions

The following reflective observations were addressed to students: "What did you experience while maintaining the balance?," "What did you experience close to the fall? and when falling?"

In the acrosport activity, students had to build a stable acrosport figure in groups. Through instructions that manipulated some figure constraints (e.g., number of participants, number of supports and supporting surface), the figure destabilization was provoked and a change of its initial shape occurred; finally, additional constraints led to the figure collapse. The changes in the shape of the figure can be transferred to the changes of the structure of water (solid, liquid, gas) under slow unidirectional temperature variation (i.e., constraint changes).

In the telephone game, students sat in a circle touching their partners and transmitting messages with their hands. The initial stable communication was destabilized when the distance (acting as a role of constraint) among students increased until transmission was impossible. The experience was transferred to fire and virus infection spreading. In a forest, a fire spreads when the distance between trees is reduced, and in human societies, a virus infection spreads when the distance between unprotected (e.g., low D_3 vitamin concentration) persons is reduced.

2.4. Instruments

The understanding of the selected DST/SP concepts was assessed through a questionnaire administered through a Plicker's application.[4] It consisted of five closed questions with four answer options and only one correct answer. Surveys, case studies, interviews, and students' self-reporting questionnaires are among the most frequently chosen methods to investigate the effectiveness of transdisciplinary educational interventions (Takeuchi et al., 2020; Lage-Gómez and Ros., 2021). In particular, considering that knowledge transfer is difficult to measure objectively, close-structured interviews and questionnaires seem to be the most appropriate for children in elementary school.

2.4.1. Plickers questionnaire

Students responded to the Plickers questionnaire one day before and one day after the intervention. They were requested to answer honestly, emphasizing that their answers would be confidential and not affect their academic marks. They did not perform any additional learning activities (e.g., homework or additional lessons) during the intervention period. The content validity of the questionnaire was determined by two researchers with thirty years of experience in using CD concepts. Also, the students assessed face validity (clarity of the questions and the level of understanding). The internal consistency of the questionnaire was measured by Cronbach's alpha. The questions of the Plickers Questionnaire were the following:

1. When do we say that a system is stable?
2. When do we say that a system is unstable?
3. Does a burned forest represent a stable state?
4. Do a forest fire, and a virus infection spread in the same way?
5. Which of the following statements about self-organization are correct?

In order to enable the detection of the 'concreteness fading' effect (Goldstone and Son, 2005) for questions 1, 2, and 5, the answers contained incorrect, superficially correct and correct answers (please see Table 3). Although correct, the content of superficially correct

4 www.plickers.com

TABLE 3 Percentages of the answers to the Plickers questionnaire pre- and post-intervention.

		PRE		POST	
		5t A	5t B	5t A	5t B
Q1. When do we say that a system is stable?	a. When it is hard and does not break	15%	24%	8%	4,3%
	b. When it quickly returns to its initial state after it has been disturbed**	23%	29%	48%	34,7%
	c. When it does not fall because it maintains it's balance*	62%	47%	44%	66,6%
Q2. When do we say that a system is unstable?	a. When it is soft and breaks	38%	28%	13%	0%
	b. When it loses its initial state due to small disturbances**	38%	33%	75%	96%
	c. When it falls because it loses its balance*	24%	39%	22%	4%
Q3. Does a burned forest represent a stable state?	a. Yes**	15%	24%	50%	43%
	b. No	85%	76%	50%	57%
Q4. Do forest fires and virus infections spread in the same way?	a. Yes**	54%	38%	70%	78%
	b. No	46%	62%	30%	22%
Q5. Which of the following statements about self-organization are correct?	a. Self-organization is doing things by yourself*	32%	34%	4%	13%
	b. Self-organization is being very organized	16%	0%	0%	0%
	c. Self-organization exists when there is no external entity that imposes the internal organization**	32%	28%	57%	78%
	d. Self-organization is to organize automatically	20%	38%	39%	9%

The table shows the percentage of students that selected each answer for the two groups. *Superficially correct answer; **Correct answer.

answers was oriented toward the actual bodily experience and not toward the more abstract content of the correct answers. This allowed us to check whether students have acquired the deeper analogy enabling the far transfer or stayed stuck merely at the correct interpretation of the bodily experience.

2.4.2. Interview

To avoid bias, students conducted a semi-structured interview by an external researcher. The reliability of the interviews was guaranteed by the same researcher, the same design scheme of the questions, the same length of interrogation and the same time for all participants. The interviews were audio recorded and transcribed verbatim. Two education researchers validated the interview questions before the study. It consisted of the following questions:

1. 1.1. For you, what is a stable and an unstable state/1.2 Can you describe a situation in which you feel stable and unstable?
2. Do you know any phase transitions? What is the initial stable state before water crystals are formed and before a fire or a virus infection spreads?
3. What does self-organization mean to you?
4. What natural processes, such as the spread of a fire and the formation of water crystals, have in common with social processes, such as the spread of COVID-19?

2.5. Data analysis

2.5.1. Plickers questionnaire

The percentages of correct and incorrect answers for the five questions in pre- and post-intervention were calculated.

2.5.2. Interviews

The interviews were transcribed, and two researchers scored each response according to the rubric presented in Table 4. The data matrix was organized in 2 (pre- and post-intervention) columns × 50 (10 students × 5 scores) rows. Cohen's kappa analysis was performed to test the inter-observer agreement. The Kolmogorov–Smirnov test of normality tested the null-hypothesis of pre- and post-intervention scores' normal distribution. The Wilcoxon signed-rank test was used to compare pre-and post-intervention responses. To check for a possible association between students' pre- and post-intervention scores, we performed Spearman's ρ correlation. All quantitative data were analyzed using SPSS software (Version 28.0.1). The significance level for rejecting the null hypothesis claiming that the pseudomedian of the differences between pre-and post-intervention scores of students is located at zero was set on $p = 0.05$.

3. Results

3.1. Plickers questionnaire

Experts confirmed that all items were relevant to the target population and the intended purpose of the questionnaire. All students answered that the questions were clear and understandable. The assessed inter-item reliability of the questionnaire was $\alpha = 0.72$.

The detailed results from the Plickers questionnaire are given in Table 3. Before the intervention, the percentages of correct responses were 26, 35, 19, 45, 30, and 31% in each question, respectively. After the intervention, results improved, with question 1.1 having the lowest percentage of correct answers (41.5%) and questions 1.2 and 3 having the highest percentage of correct answers with 77 and 75%, respectively. Question 2 had 46% of correct responses.

3.2. Interviews

The Kappa analysis showed a high concordance of the interobserver scores (k = 0.81). Table 5 shows the student's results of the interview questions scored by researchers before and after the intervention. The two-tailed Kolmogorov–Smirnov test revealed a significant difference in the scores' data from the normal distribution at a significance level of $p < 0.0001$. The two-tailed Wilcoxon signed rank test revealed a clear effect of the intervention on students' knowledge and transfer abilities (pre-intervention mean rank = 1.28; mode = 1; vs. post-intervention mean rank = 4.06; mode = 4); $Z = -5.98$; $p < 0.0001$. The Spearman's ρ correlation showed no association between the pre- and post-intervention scores; $\rho = 0.112$; $p = 0.441$.

4. Discussion

This research aimed to evaluate if the SUMA embodied learning protocol with inbuilt concreteness fading structure: (a) will lead to the acquisition of the abstract meaning of the targeted general DST/SP concepts, and (b) will enable a far transfer ability for connecting different phenomena. The results showed that embodied transdisciplinary learning in 5th-graders can positively integrate topics of different STEM subjects, with some caveats. These findings are relevant because the learners age corresponds to the concrete operational stage in Piagetian classification of a child's cognitive development.

4.1. Plickers questionnaire

The questionnaire results showed that, in general, the applied DST/SP concepts are learnable and transferable among phenomena taught in different academic subjects in elementary school 5th graders. However, the first question from the questionnaire, concerning the meaning of the concept of 'stability', showed interesting and, to a degree, unexpected results. As said in the methods section, of the three possible answers, the first one was false, but the next two were true, one of which was the correct abstract definition. In contrast, the other one was a more superficial definition with a more immediate relation to the embodied experience.

In class A, the majority of students in the pre-intervention phase chose the more superficial definition as a correct answer migrated to the correct, more abstract definition in the post-intervention phase. This class showed a typical effect of 'concreteness fading' (Goldstone and Son, 2005). The contrary happened in class B. Although the

TABLE 4 Rubric used to score the responses obtained in the interviews.

Question 1.1. For you, what is a stable and an unstable state?	
0	S/he cannot define the concept with his/her words or give examples of situations, although erroneous.
1	Is not able to define the concept precisely but roughly with his/her words or give examples of situations, although erroneous.
2	Is not able to define the concept precisely but can describe it with their words and give an example, although erroneous.
3	Can define the concept with their words and gives some examples of the experienced situations.
4	Can explain the concept precisely and gives an example of the experienced situations.
5	Can define the concept precisely and offers concrete examples of the experienced situations.
Question 1.2. Can you describe a situation in which you feel stable and unstable?	
0	S/he cannot define the concept with his words or give examples of situations, although erroneous.
1	Cannot determine the concept precisely but roughly with his words or give examples of cases, although erroneous.
2	Cannot define the concept precisely, but he can explain it with his words and gives an example, although it is erroneous.
3	Can define the concept with his words and give examples of the situations experienced.
4	Can define the concept precisely and gives an example of the situations experienced.
5	Can define the concept precisely and gives concrete examples of the situations experienced.
Question 2. Do you know any phase transitions? Can you say which is the initial stable state before water crystals are formed and before a fire or a virus infection spread?	
0	S/he does not know any phase change, nor can he give an example.
1	Does not know any phase change, but he can give some bad examples.
2	Does not know any phase change, but can infer some experienced examples.
3	Does not know the definition of phase transition, but can infer the states of water and fire.
4	Does not know the definition of phase change, but he can infer the states of the three experienced systems.
5	Knows a phase change and can identify them in the three systems worked and experienced.
Question 3. What does self-organization mean to you?	
0	S/he cannot explain the concept, even in their own words.
1	Cannot explain the concept, but he can infer some examples
2	Cannot explain the concept, but he can give examples.
3	Can explain the concept, but in his own words.
4	Can explain the concept rigorously.
5	Can explain the concept rigorously and give concrete examples.
Question 4. What natural processes, such as the spread of a fire and the formation of water crystals, have in common with social processes, such as the spread of COVID-19?	
0	S/he cannot name or explain the similarities of the three processes or give examples.
1	Cannot name or explain the similarities between the three processes, but he gives an example, erroneous.
2	Can name the similarities between some processes but not explain them or give examples (although erroneous).
3	Can name some similarities between the three processes, but cannot explain or give examples.
4	Can name and explain the similarities between the three processes and give an example.
5	Can explain the similarities between the three processes and give concrete examples.

The researchers scored each answer according to the given response.

percent of the correct abstract definition increased, the percent of students who chose the more superficial definition increased, too. This apparent paradox of 'concreteness enhancing' may be possibly responsible for the slightly different emphasis on the 'embodied experience' and the 'reflection on the experience' phases instead of the 'association-conceptualization' and 'transfer phases' of the learning. Also, during the embodied and reflection phases, an emphasis to the 'balance' (present in the bench balancing) and the 'structure' (present in the acrosport experience) concepts may be possibly needed in order to make the 'stability-balance-structure-state' link more achievable for students. This is highly likely needed to emphasize the knowledge that what is 'stable' is the 'structured/organized' 'state' of the system itself.

Contrary to the concept of 'stability', the acquisition of the meaning of the concept of 'instability' did not show the paradox mentioned above. In both classes, the percent of incorrect and superficially correct answers from the pre-intervention phase substantially decreased and consequently, the number of correct answers increased. In this case, akin to class A for the concept of stability, the effect of 'concreteness fading' (Fyfe et al., 2014) was detected, as most students in classes A and B migrated from the

TABLE 5 Comparison of the pre- and post-intervention rubrics results obtained during the interview for each participant.

	Subject	Rubric score PRE	Rubric score POST
Q1.1. For you, what is a stable and an unstable state?	1	1	3
	2	0	4
	3	1	3
	4	1	3
	5	0	4
	6	1	2
	7	1	4
	8	1	4
	9	0	4
	10	0	4
Q1.2. Can you describe a situation in which you feel stable and unstable?	1	0	3
	2	0	4
	3	1	4
	4	2	4
	5	1	4
	6	1	4
	7	1	4
	8	1	4
	9	0	4
	10	0	4
Q2. Do you know any phase transitions? Can you say which is the initial stable state before water crystals are formed and before a fire or a virus infection spread?	1	0	5
	2	2	4
	3	2	4
	4	1	4
	5	0	4
	6	3	4
	7	2	5
	8	1	4
	9	2	4
	10	0	3
Q3. What does self-organization mean to you?	1	1	5
	2	1	5
	3	3	4
	4	2	5
	5	1	5
	6	2	4
	7	5	3
	8	2	4
	9	4	5
	10	1	4
Q4. What natural processes, such as the spread of a fire and the formation of water crystals, have in common with social processes, such as the spread of COVID-19?	1	0	5
	2	3	4
	3	4	4
	4	3	4

(Continued)

TABLE 5 (Continued)

	Subject	Rubric score PRE	Rubric score POST
	5	0	4
	6	1	5
	7	1	5
	8	3	5
	9	1	4
	10	0	5

The table shows an example given by one of the researchers.

incorrect and superficially correct answers to the correct generalizable answer.

The pre-intervention answers to question 3, "Does a burned forest represent a stable state?" which primes the link of the general concept of 'stability' to the phenomenon dependent 'state of burned forest', showed a strong bias toward the 'No' answer. This could be a consequence of the (metaphorical?) association between the concepts of 'stability' and 'life', in only living entities are stable. The post-intervention results showed that students generalized the concept of 'stability' to refer also to non-living states, such as 'burned forest'. Similarly, the far transfer question 4: Do forest fires and virus infections spread in the same way?; revealed a migration of students from the dominantly 'No' answer to the affirmative answer, showing that they have acquired the analogical link between the phenomena of pathogen spread and forest fire as depending on the constraints such as physical distance/interactions and the properties of the components (people and trees) of the system. Post-intervention results showed that relations between different phenomena were acquired based on the general concepts.

The acquisition of the concept of 'self-organization' also showed the same pattern of migration of students from the superficially correct and incorrect answers to the correct, more abstract statement. The process of self-organization was experienced through the acrosport activity in which students created macrostructures with their bodies through local interactions (support surfaces). Hence, the abstract insight of 'spontaneous organization' was immediately helped by the fact that neither teachers nor any other external agent imposed the shape of the macrostructure they succeeded in building. Instead, students built organized structures by finding local firm support surfaces on classmates' bodies. In this case, the 'concreteness fading' was much more closely related to the embodied experience than in the case of the concept of 'stability of a state' since the concept of 'state' has a more abstract meaning than the visually immediate concept of 'organization' or 'structure'. Among other things, this line of thought would support the claims expressed by Jaakkola and Veermans (2018), that there is no universal number of steps (phases) in concreteness fading protocols. It may well be possible that each pair of 'student's age - concept to be learned' has its own optimal number of phases for concreteness fading.

4.2. Interview

In order to more deeply analyze the level of understanding of the general concepts and abilities for far transfer in students, we interviewed 10 randomly assigned students in pre- and post-intervention conditions. The mean ranks and the mode differences of pre-and post-intervention scores showed that the intervention helped the students to learn the DST/SP concepts and identify them in molecular, ecological and sociological processes. The most expected (i.e., mode) answer characteristic in the pre-intervention phase was impossibility of, or vagueness of, explaining the concept and/or offering wrong examples. After acquainting them to DST/SP general concepts, on average, they formed a deeper understanding of phenomena acquired through body movement experiences. In the post-intervention phase, the most expected (i.e., mode) answers were characterized by students being able to explain the concept and giving examples of phenomena in which that concept plays essential role. In addition, students increased the capacity to show enhanced abilities of far transfer (i.e., to integrate) diverse phenomena studied in different academic disciplines (e.g., virus infection and forest fire transmission in infectology and ecology, respectively). The Spearman's correlation showed that students' previous state of knowledge did not significantly impact the post-intervention results. This is understandable since students' curricula did not contain any of the concepts or transfer contents that were applied during the intervention. Hence, students either gave random answers or used a kind of 'common sense' answers.

Although most students already used the far analogies as part of the intervention, only a few could provide new far transfer examples (not used or mentioned in class). For example, one student used the concept of phase transition to explain the phenomenon of mitosis: "When a cell is reproduced, it is a phase transition from one to two cells with the same genetic information." Another one connected the same general concept with the formation of the sun: "the collapse of a cloud of gas and the mass accumulated over time resulted in a phase transition from gas to the formation of the sun." These two students connected the previously acquired knowledge of these phenomena with the property of phase transitions to induce sudden and qualitative changes. The mitosis and star formation are phenomena of sudden qualitative change of the system's previous state. These phenomena in cell biology and astrophysics have already been modeled as such (e.g., Jeans, 1902; Spencer et al., 2013, respectively). The success of these two students to extrapolate the general concepts knowledge to phenomena that were not explicitly learnt during the intervention might be a consequence of a successful combination of embodied experiences of a sudden change, iconic thinking (e.g., Herlofsky, 2011) about the disruptive properties present both in mitosis and star formation, and the previously acquired knowledge in the school (e.g., the Kant-Laplace hypothesis of sun formation).

In general, before the intervention, the students had an inaccurate meaning of some concepts. For instance, the concepts of stability and instability as reflected in the scores of interview questions 1.1 and 1.2.

Also, four students could link questions 3, and 4 to prior (experiential or otherwise) knowledge and respond logically based on the implicit intuition of how local interactions may produce global outcomes. For example, a student recalled similarities between different phenomena (question 4): "In the case of the spread of a virus, if you reduce the distance from someone infected sufficiently, you can become infected too. In the case of forest fire propagation, if the distance among trees is reduced, the fire spreads burns; and in the case of water, by raising the temperature, an ice cube melts." However, in most cases, answers did not reflect a clear understanding of concepts. For example, (question 3) about the concept of self-organization, a representative explanation was the following one: "Self-organization is when you organize yourself." This is, of course superficially true but lacks a valid, i.e., non-circular explanation.

However, post-intervention, most students were able to: (a) explain DST/SP concepts, and (b) provide concrete examples and link them to body movement experiences. For example: "A healthy person is in a physiologically stable state, but this state can be destabilized under stressing factors (e.g., getting mad at friends, parent's divorce) and increase the susceptibility to disease, as another stable state." The majority of students connected the concepts of phase transition, stability, and instability: "Phase transition is when you go from one stable state to another stable state: from a green forest to a burned forest, from solid water to liquid water." In case of the concept of self-organization: "Nobody tells atoms what to do; they organize themselves," showing somewhat important understanding that for something to be called self-organized, there should be no external agent imposing the pattern of organization on the system's structure or behavior.

Also, for the phenomena of infection spread and forest fire, some students connected the previous knowledge of how other additional interaction constraints may change the 'local interaction', and consequently, the state of the system as a whole (human population or forest). For example, for infection spread, aside of the interpersonal distance, exposure to the sun and the levels of vitamin D may change the infection susceptibility. For the forest fires, aside from the tree-to-tree distance, some students mentioned the trees' moisture level, which may reduce the inflammability of the tree. These are pertinent cases in which one testifies how the interplay of phenomenon (i.e., level)-dependent concepts, such as: 'interpersonal physical distance', 'vitamin D', 'exposure to the sun', or 'inter-tree distance' and 'moisture' in semantic relation with the general (i.e., level-independent) concepts such as 'local interaction constraint', 'phase transition, may produce far transfer, analogy based, integration of seemingly unconnected phenomena.

5. General discussion

An eight weeks intervention teaching DST/SP concepts through embodied experiences enabled most 5th-grade students to (a) learn DST/SP concepts, (b) identify the general principles among physical, biological and sociological processes, and (c) enable far transfer between these academic subjects. Although most students developed an understanding of these basic concepts and showed abilities of far transfer, we need to be sure about the stability and depth of their understanding. Since students had no additional learning activities of DST concepts (e.g., homework) during the intervention period, all results were simply a product of their learning *in-situ*. Thus, it is likely that their understanding of the acquired concepts and analogies still needs to be improved, especially if we consider their age.

Embodied (transdisciplinary) learning may have potential advantages and disadvantages. A small difference in the emphasis of the concrete (i.e., embodied) experience vs. the association-conceptualization or the transfer phase may hamper the targeted concreteness fading (Fyfe et al., 2014) and result in its opposite effect – concreteness enhancement, as was the case with class B when learning the concept of 'stability'. On the other hand, concreteness fading success may vary from subject to subject or phenomenon to phenomenon (Kokkonen et al., 2022) and/or vary due to age (Jaakkola and Veermans, 2018).

Concerning this, the findings that two dimensions of embodied learning settings are highly relevant for its success: (1) the degree of task integration; and (2) the degree of bodily engagement (Skulmowski and Rey, 2018). The task integration level increases continually, from incidental cue-based bodily effects to fully integrated bodily activities into the learning task. On the other hand, the level of bodily engagement increases as bodily actions continually transit from seated activities to the performance of whole-body movements and locomotion.

Our learning protocol's characteristics (Hristovski et al., 2014) were: high bodily involvement and high task integration. By applying it, Almarcha et al. (2022) demonstrated the learnability of the general DST/SP concepts through embodied experiences in high school students aged 12–13 years. The findings of that and of the current study are in accordance with experimental results of other researchers which demonstrated that learning performance may be successfully molded by higher bodily involvement (e.g., Skulmowski and Rey, 2017), and by a higher level of task integration (Mavilidi et al., 2015). On the other hand, some authors have found that low bodily engagement and mere incidental cue-based bodily effects may not affect some learning performance measures (e.g., Alban and Kelley, 2013). However, Brucker et al. (2015) have found that low bodily involvement (e.g., sitting activities) may bring about high-performance gains for some tasks (e.g., in mathematics education: Abrahamson and Sanchez-García, 2016; Abrahamson et al., 2021; Shvarts and van Helden, 2021). On the other hand, although some authors (e.g., Johnson-Glenberg et al., 2016; Lindgren et al., 2016) have shown that a high bodily engagement may lead to higher learning performance, the possibility of a cognitive overload may minimize its effectiveness (Song et al., 2014; Ruiter et al., 2015). In general, our results of the intervention have revealed some subtleties of embodied transdisciplinary learning strategies, which point to the need of their further detailed investigation and careful implementation.

On a more prospective note, implementing the intervention proposed in this research is challenging for students and teachers, but its benefits may be tremendous for the entire school community. The school ceases to be where students go to learn, instead, it becomes an entire learning experience for establishing real-life connections. However, aside from the methodological issues discussed above, some challenges should be alleviated to implement the embodied transdisciplinary (SUMA) educational framework successfully. On the side of teachers, it may be challenging: (a) to promote the value of synthetic understanding of natural and societal phenomena under the same umbrella framework and hence, to motivate their accurate understanding of DST/SP general concepts, as well as the interconnectedness among them, and (b) to stimulate their imagination of creating embodied experiences for students that show as critical (Alberto et al., 2022). On the side of students, their personal constraints, such as age, cultural-value background and others, may play a crucial role. More important details that can enhance or hamper the 'learnability' of the DST/SP general concepts and the knowledge transfer among the academic disciplines must be researched before this educational framework can reveal its teaching potential. Future studies to compare the effectiveness of the teaching/learning strategies used in this study are warranted to use randomized controlled experimental designs, and a follow-up to verify the longer-term effects of the intervention. A particularly important line of research that directly stems from this research should be the age dependent 'depth of learning' of the general concepts as defined by the understanding of their *interconnectedness* and *interdependence*.

6. Conclusion

The study points to the potential of teaching and learning general DST/SP concepts through body movement experiences in elementary school, enhancing students' abilities to integrate and transfer knowledge among phenomena studied in natural and social sciences. The proposed transdisciplinary embodied education may offer a truly integrative approach to STEAM teaching. Future work is needed to distillate the full potential of the approach and its possible shortcomings. In this intervention, based on the transdisciplinary embodied learning framework- SUMA, students of 5th grade in elementary school were able to learn the targeted DST/SP concepts and use them for far transfer among different phenomena thought in separate academic subjects. The concreteness fading was shown to be an effective embodied learning strategy for the intervention. However, a part of the results showed that the strategy, at this age, may be fragile and somewhat sensitive to the differences in the degree of abstractness of the learned concepts, as well as to the differences in emphasizing the content of the embodied experience phases (phase 1 and 2) vs. the content of those phases focused on the abstract conceptualization and transfer (phase 3 and 4). Considering the findings of this study, our previous research, and the above-mentioned caveats, we conclude that the embodied transdisciplinary learning framework – SUMA has a substantial integrative educational potential in the area of the STEAM framework.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by 07/2015/CEICEGC. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. The local ethic committee approved the study according to the Helsinki declaration.

Author contributions

MA and PV conducted the intervention, collected the data, and organized the database. PV performed the statistical analysis. All authors wrote the first draft of the manuscript, contributed to the conception and design of the study, manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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3.3. Embodied transfer of knowledge using dynamic systems concepts in high school: a preliminary study

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Embodied transfer of knowledge using dynamic systems concepts in high school: A preliminary study

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ABSTRACT

The transfer of knowledge among academic subjects and linking different phenomena are crucial education competencies in Bloom's taxonomy of learning goals. From another side, modern cognitive science defines cognition and learning as embodied. The Synthetic Understanding through Movement Analogies (SUMA) educational framework proposes embodied learning of general scientific principles and concepts and knowledge transfer among academic disciplines encompassing sciences, humanities and arts. Accordingly, this research aimed to evaluate the educational potential of teaching a set of Dynamic Systems Theory (DST) concepts through body movement experiences in first-grade high school students. Five classes of high school students (*n* = 71; 23 girls, 46 boys and 2 non-binaries, aged 12–13 y.) followed a four-week intervention addressed to teaching five DST concepts (order parameter, stability, control parameter, instability and phase transition) and transfer them to biological and social phenomena. Students followed four teaching phases: a) embodied experience, b) reflective observation of the experience, c) abstract conceptualization of the experience using the five general concepts, d) transfer of knowledge through the concepts to different phenomena from biological and social science academic subjects. Students' integration and transfer of knowledge abilities were evaluated pre- and post-intervention through a questionnaire and three open-ended questions. Results were compared using non-parametric Wilcoxon matched-pairs test and effect sizes were calculated through PS_{dep} measures. Students' abilities to integrate and transfer knowledge increased post-intervention ($Z = 7.322$, $p < 0.0001$, $PS_{dep} = 1$). The effect of the intervention points to the potential of teaching general DST concepts through body movement experiences in high school students for achieving the goals of an embodied and unificatory transdisciplinary education.

1. Introduction

Linking phenomena manifested at different levels of substance organization and finding unifying principles is one of the crucial competencies of knowledge synthesis in Benjamin Bloom's taxonomy of learning goals (Adams, 2015; Anderson & Krathwohl, 2001). However, based on a fragmented structure of subjects, contemporary education limits students' integrating abilities, distorts their

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vision of the world, and contributes little to the development of competencies considered essential in modern society (Morin, 2002).

In the twenty-first century, the study of complex systems has generated a solid basis for integrating knowledge through unifying principles and concepts. The sciences of complexity were born due to the intuition that there is a set of common principles that may bring to the understanding of many complex phenomena and help the education of the 21st century (e.g. Forrester, 1994). However, despite the growing interest in studying complex systems and their profound impact on various scientific branches, there are no educational curricula including training on the topic.

Inspired by the Dynamical Systems Theory (DST) and Statistical Physics which form the mathematical basis of the Synergetics methatheory (Haken, 1978), the Coordination Dynamics paradigm (Kelso, 1984; Kelso, 1995) emerged. This paradigm has been formulated to study and explain the dynamic changes of neurobiological systems over time and structural and functional transitions occurring in goal-directed biological and sociological systems when interacting with the environment. These developments pointed to a possibility of using human movement systems to provide embodied learning experiences in education for linking different phenomena through general DST concepts.

Early studies on how students learn some concepts of complex systems and how they bring an understanding of micro-macro level correspondence were focused on the concept of emergence using the agent-based modeling to learn complex systems' dynamics (such as traffic jams and ant foraging) (Resnick & Wilensky, 1993; Wilensky, 1996; Wilensky & Resnick, 1995). Computer agent-based modeling has been used to foster the understanding of how microscopic interactions give rise to emergent macroscopic phenomena (Jacobson & Wilensky, 2006; Tisue & Wilensky, 2004; Wilensky & Resnick, 1999). This approach was also used in imaginative computer-based role-playing (Resnick & Wilensky, 1998; Wilensky & Reisman, 2006). In line with this, Stieff and Wilensky (2003) showed that, e.g. a chemistry modeling environment helped students connect micro-and macro-level phenomena and that an "emergent phenomena perspective developed a deeper understanding of chemistry concepts and processes. As a result, each student became less dependent on algorithms and more on conceptual approaches to problem-solving and justification. Students showed the most significant improvements when defining chemical concepts, characterizing the affecting factors and transferring knowledge between micro-and macro-levels during problem-solving. However, students' abstract understanding was often fragile, and when they tried to apply the learned concepts through modeling examples to new phenomena, they often found difficulties and returned to the previous learning rationale (Stieff & Wilensky, 2003).

In contrast, Goldstone and Wilensky (2008) stated that "complex system heuristics" are challenging to develop because they frequently run counter to "linear system heuristics", which seem to be more familiar to them. To improve the efficacy of interventions addressed to change students' way of thinking, it is necessary to generalize the "complex system heuristics" to all curriculum subjects.

1.1. The interdisciplinary embodied learning approach

Long before embodied cognition and learning became a lure in science and philosophy of mind, movement analogies[1] have been used to enhance the study of concepts and principles of separate subjects such as mathematics, physics, biology, music, or culture (see Cone, 1999; Cone, Werner, & Cone, 2009). Movement metaphors (Ellis, 2001), and hence movement analogies, are descriptions of movements attached to intellectual concepts that help students think about and abstract a concept (Jamrozik, McQuire, Cardillo, & Chatterjee, 2016). They are concrete in a physical sense but abstract at the level of the intellectual concept. For that reason, they are learned in a way that is usable by many intellectual domains. In other words, they can be used outside of the domain in which they were first encountered (Jamrozik et al., 2016), but so far, they have only been used in specific subjects.

Embodied learning is underpinned by the insight that human understanding of objects, principles, and concepts often involves somatosensory, perceptual or motoric re-experiencing, which is collectively referred to as "embodiment" of the relevant event in one's self (Niedenthal, 2007). In this sense, Lakoff and Johnson (1999, p.93) wrote: "what has always made science possible, is our embodiment, not our transcendence of it, and our imagination, not our avoidance of it". Embodied learning is educationally compelling because it possesses integrative characteristics of its own. It allows the learner to act and learn as a whole person, including feeling and thinking of being in the world, rather than segregating action and thinking processes as two unrelated realms (Stolz, 2015). Embodied learning has been studied from different perspectives. Of high importance are the findings that two dimensions of embodied learning settings are highly relevant for its success: the task integration and the degree of bodily engagement (Skulmowski & Rey, 2018). The level of bodily engagement continually increases as bodily actions transit from seated activities to the performance of whole-body movements and locomotion. The level of task integration, on the other hand, continually increases, starting from incidental cue-based bodily effects to fully integrated bodily activities into the learning task. Some authors (e.g. Alban & Kelley, 2013) showed that low bodily engagement and incidental cue-based bodily effects may not affect some performance measures. Higher bodily involvement may improve the learning performance in some cases (e.g. Skulmowski & Rey, 2018).

Similarly, low task integration may fail to significantly improve the performance, while a higher level of integration may remedy this shortcoming (Mavilidi, Okely, Chandler, Cliff, & Paas, 2015). Low bodily involvement (implemented dominantly through sitting

[1] At this point it is useful to shortly address the commonalities and differences between analogies and metaphors. In the foreword of their influential book, Aubusson et al. (2006) explain: "It seems the term metaphor can be applied to *all* comparisons that feature the identification of some similarity between two things. While not always the case, there appears to be a tendency to use the term analogy when the comparison is extended highlighting a range of similarities and differences between two things. Thus, all analogies are metaphors but not all metaphors are extended into analogies." (p.3)Hence, acknowledging that movements are not 'per se' analogies or metaphors, we use the term 'movement analogy' as a subclass of movement metaphors (e.g. see Ellis, 2001), which can help students to understand targeted concepts or principles.

activities) may bring about high-performance gains (Brucker, Ehlis, Häußinger, Fallgatter, & Gerjets, 2015). On the other hand, a high bodily engagement may lead to higher learning performance (Johnson-Glenberg, Megowan-Romanowicz, Birchfield, & Savio-Ramos, 2016; Lindgren, Tscholl, Wang, & Johnson, 2016). However, due to the possibility of a cognitive overload, its effectiveness may be minimal (Ruiter, Loyens, & Paas, 2015; Song et al., 2014). So far, the research has not been able to crystalize a simple relation between the two dimensions and the embodied learning performance, which can be used to guide educational praxis. However, the high level of task integration with varying levels of bodily integration may be crucial for successful learning gains. As in many other areas of education, it is highly likely that other factors such as age, gender and culture may be involved in successful applications.

Current interdisciplinary embodied approaches, which have gained popularity in primary and secondary school education due to their cognitive effectiveness and knowledge improvement (Clary & Wandersee, 2007; Schwartz-Bloom, Halpin, & Reiter, 2011; Spintzyk, Strehlke, Ohlberger, Gröben, & Wegner, 2016), consist of associating physical education with other subjects of the curriculum (Kaittani, Kouli, Derri, & Kioumourtzoglou, 2017). However, the embodied learning approach has never been used to comprehend unificatory concepts of science, humanities, and art to enable knowledge transfer among academic disciplines (unificatory transdisciplinary approach). To start a research program in that direction, we hypothesized that DS concepts would have an integrative role in learning phenomena from biological and social sciences, enabling a transfer of knowledge among disciplines.

While the educational potential of physical activities for learning academic concepts from different disciplines has been tested and recognized (Cone et al., 2009), their application for the transfer of the understanding by using unifying concepts in science (unificatory transdisciplinary approach) has not been scientifically evaluated yet. In other words, to our knowledge, the embodied learning approach has not been used so far to promote an integrative understanding of phenomena manifested at different levels of substance organization through learning transfer, using DS concepts and principles.

1.2. Synthetic Understanding through Movement Analogies: SUMA – the Transdisciplinary Unificatory Embodied Educational Framework

A significant problem for a systematic and grounded approach to a successful integrative transdisciplinary educational framework in previous works was the lack of a clearly defined set of general concepts and principles, which would play the role of a ‘common currency’ in academic subjects. Indeed, it is pretty challenging to determine the subset of concepts and principles sufficiently general to be explanatory valid in the broadest sense (i.e. starting from elementary physical fields to sociology). This is understandable because concepts may have a different level of generality, and one has to assume that the most general ones will form a tiny subset of the total number. To define the relevant set of concepts and principles used for the transfer of understanding of phenomena between the broadest set of organizational levels of nature, Hristovski and col. provided evidence that school and university textbooks do not follow up-to-date modeling and interpretative theoretical frameworks (Hristovski, 2013; Hristovski, Balagué, & Vázquez, 2014, 2019). Notably, this is particularly the case in modeling frameworks used in scientific research, especially in sciences of systems that are more organizationally complex, such as biology, psychology, and sociology. Using text analysis, the authors extracted thirteen concepts and principles (or themata) that were explanatory relevant for the whole spectrum of levels of substance organization, starting from elementary physical fields to sociological systems (see the learning platform of SUMA (https://suma.edu.mk/general-concepts/). To show how the generality of transfer is enhanced within SUMA framework in comparison to other approaches, we use the example from Goldstone and Wilensky (2008). Whereas in this work the power-law was used as a learning transfer concept, in the SUMA educational framework the power-law is subsumed to the more general concept of symmetry-symmetry breaking (e.g., Lovejoy, 2022). This is because although the power-law which do not possess characteristic scale (i.e. it is scale-free) has a significant degree of generality, there also exist processes with a characteristic scale (e.g. periodic oscillations). Hence, both the scale-free and processes with characteristic scales can be understood by symmetry- symmetry breaking principles.

The embodied learning in SUMA educational framework is based on Kolb’s (1984) experiential learning approach (Hristovski et al., 2014), and it consists of the following teaching phases:

1. Embodied experience (a physical activity: perception-action and/or introspection)
2. Reflective observation on the embodied experience (guiding attention to key perceived phenomena related to DST concepts)
3. Abstract conceptualization based upon the reflective observation (conceptualization, estimation and/or plotting of relations)

Table 1
DST concepts (visit https://suma.edu.mk/).

DST concepts	
Stability	Resistance to perturbations. The necessary and sufficient condition for the existence of any system’s behaviour/structure. |For example, a standing person restoring the previous position after another person’s push (perturbation).
Instability	Being not stable under the perturbations coming from within or outside the system. For example, a standing person cannot restore its previous position (s/he changes it) after push (perturbation) by another person.
Phase transition	A system destabilization produces a spontaneous rearrangement of system components into another macroscopically ordered behaviour/ structure. For example, a spontaneous change in the stance from parallel (unstable, under certain conditions) to diagonal (a more stable) stance.
Control parameter	A limitation or restriction that can destabilize the previously stable state of order. For example, the degree of forwarding or backward inclination of the upper body of a standing person in a parallel stance.
Order parameter	A measure of the degree and type of order across the boundaries in a phase transition system. For example, the floor projection angle of the center of body mass with respect to the feet of standing subject in a parallel stance.

4. To experiment with the new concepts and apply them to different fields and phenomena studied in the academic curriculum.

The introspection in the first phase is not necessarily movement-based because it can be based on any life experience, but it is further scaffolded using a movement activity. These phases can be supported by various contexts, such as learning in natural settings or using educational technology, such as videos, augmented learning and virtual environments, and individual or group arrangements (Hristovski, Balagué, Almarcha, & Martínez, 2020; Torrents, Balagué, Hristovski, Almarcha, & Kelso, 2021). The SUMA educational framework is based on the three pillars: 1. Education-based on a comprehensive set of concepts and principles of broad generality (used in the full spectrum from quantum field theory to sociology); 2. Experiential learning through embodied experiences; and 3. The integration of Science, Technology, Engineering, Mathematics (STEM), humanities, and art phenomena under the same educational umbrella.

In this research, a relevant subset of the comprehensive set of general DST concepts within the SUMA project is used to convey the empirical investigation of the potential of the educational framework.

Hence, this research aimed to evaluate the educational potential of teaching five DST concepts (see Table 1) through movement analogies for integrating and transferring understanding among some ecological and sociological processes in first-grade high school students.

2. Method

2.1. Design

A quasi-experimental design comparing pre-and post-intervention results has been applied.

2.1.1. Participants

Five classes of first-grade students of a public high school (n = 71, 23 girls and 46 boys, two non-binaries, aged 12–13 y.) participated in the study. All students and their teachers confirmed that they were not previously introduced nor familiar with DST general principles and concepts. The legal educators were informed about the intervention procedures and signed an informed consent.

2.1.2. Instruments

The integration and transfer of knowledge questionnaire evaluate the students' integrative and knowledge transfer skills (Table 2). According to the PISA reports, it consisted of 5 closed questions scaled from 0 to 10 (Program for International Student Assessment, 2015). Participants had to respond how much they agreed with the statements: from totally disagree (0) - to agree (10). The wide range of the scale allowed treating the data as continuous (Rhemtulla, Brosseau-Liard, & Savalei, 2012) and detecting more effectively differences between pre-and post-intervention. The content validity of the questionnaire was determined by two researchers with 30 years' experience using DST concepts. The inter-item reliability of the questionnaire was Cronbach's alpha: 0.72.

In the case of rating six or more in each item of the questionnaire, an open question was requested to justify the response using DS concepts with their correct meaning (see Table 1). A researcher of the SUMA project performed the evaluation. Because learning satisfaction is a mediating factor in the relationship between teaching quality and academic performance (Wu, Hsieh, & Lu, 2015), in the post-intervention data collection, an additional question was added to the questionnaire in order to test the student's learning satisfaction degree.

2.1.3. Procedure

All students responded to the integration and transfer of knowledge questionnaire before the intervention. Students were requested to respond as honestly as possible, emphasizing that their answers would be kept confidential and would not affect their grades.

The intervention lasted eight weeks (one-hour session, two times per week). The following steps were followed:

(1) Students performed two types of movement-based experiences which were video recorded (two lessons):

a) Slackline walking: walk on a slackline placed at 0.85 m from the floor with a tension of 5.28 ± 0.65 kN (according to Montull, Vázquez, Rocas, Hristovski, & Balagué, 2020). Students had to walk under two different conditions: (1) with arms moving freely, (2) with arms close to the body. Students were previously familiarized (3 weeks) with slackline walking during physical education lessons and during school free time. After this period most of them were able to walk 25 m on the slackline. During the intervention they did a minimum of 5 trials and a maximum of 10 trials per session in each condition. In this task the order parameter was the position of the center of mass with respect to the slackline, and the control parameter the freedom of

Table 2
Questionnaire items.

Item 1	I can explain why species become extinct.
Item 2	I can explain how infections spread.
Item 3	Social and natural phenomena are related.
Item 4	I can relate environmental issues with personal relationships problems.
Item 5	I can relate a movement experience with ecological and social processes.

movement of the upper extremities. The degree of stability was assessed through the time spent on the slackline without falling (the phase transition).

b) Acrosport task: four different acrosport figures were proposed to groups of 5–6 students. Once the stability of the figure was achieved, students were requested to reduce three supports (contacts of extremities with the ground or with the partners) and rebuild the figure. For example, one support is a foot on the ground or a hand on a partner's back (see Fig. 1). They were repeating the procedure until the stability of the figure was lost (phase transition). In this task the order parameter was the position of the group center of mass with respect to the ground, and the control parameter the number of supports.

(2) Projection of the video recorded movement experiences and discussion about the bodily experiences) (two lessons)
(3) Explanation of the DST concepts through videos and photographs in connection with the bodily experiences (two lessons) (see Table 1).
(4) Transfer of the DST concepts to ecological (sudden extinction of species due to water pollution and infection spreading) and sociological (sudden cancelling out of social network relationships) phenomena (three lessons). In this phase, students' attention was focused on DST concepts that change their content (order parameters and control parameters) in different phenomena (social or biological), and those remaining invariant (stability, instability and spontaneous transitions).

Participants did not do any other learning activity during the intervention (e.g. homework or additional lessons).

2.1.4. *Data analysis*

The Shapiro-Wilk test of normality of distributions of the pre-and post-intervention scores revealed a significant violation of the normality condition in most of the items. Hence, the non-parametric Wilcoxon matched-pairs test compared pre-and post-intervention responses. Effect sizes were calculated as PS_{dep} measures (Grissom & Kim, 2012).

All quantitative data were analyzed using STATISTICA Software (Version 10.0).

3. Results

a) *Integration and transfer of knowledge questionnaire*

Seventy-one students responded to both pre-and post-intervention questionnaires. Wilcoxon matched-pairs test showed high and significant pre- to post-intervention differences in all items (see Table 3). Students' self-evaluation for explaining and relating phenomena increased after the intervention.

Pre-intervention, all students were unable to score >6 in all questionnaire items and thus, were not eligible for responding to the open questions. However, post-intervention, they answered correctly the following open questions: a) why species become extinct (73.24%), b) how infections spread (83.33%), c) the relationship between social and biological sciences phenomena (87.32%), d) the relationship between environmental issues and personal relationship problems (63.38%), e) the relationship between their personal experiences during the pandemic and ecological and social processes (74.65%).

All the research data is available in the Open Science Framework repository (Almarcha, Martinez, Balagué & Hristovski, 2022).

4. Discussion

A short intervention teaching DST concepts through movement experiences helped high school students to a) learn DST concepts, b) identify the general integrative principles among ecological and sociological processes, and d) transfer the knowledge between such academic subjects. However, although students could transfer knowledge to phenomena already explained during the intervention, few were able to provide other examples to the open questions. It is important to emphasize that they had no additional learning activities of DST concepts during the intervention period, and all results were simply a product of their learning in-situ.

Students' high school teachers considered the embodied learning induced by the slackline and acrosport tasks as motivating and

Fig. 1. Movement-based experiences: Slackline walking and acrosport figures.

Table 3
Intra-group differences in pre-post intervention questionnaire results.

Item	N	Z	PS_{dep}
1	71	7.322***	1.00
2	71	7.323***	1.00
3	71	7.167***	1.00
4	71	6.567***	1.00
5	71	7.008***	1.00
All ítems	71	7.323***	1.00

*** $p < 0.001$.

relevant for interconnecting different academic subjects. This is probably due to the fact that the bodily experiences of these tasks directly link to the DST concepts of stability, instability and phase transition, and make these tasks highly compelling for students.

These are some commentaries extracted from the post-intervention questionnaire:

> *'I have never enjoyed a class like this* (Aaron), *'Now, I understand the spreading of virus infections, which also helps me understand how social relationships spread'* (Xènia).

The intervention has contributed to removing the barriers of formal education, connecting more directly to students' embodied experiences and enabling a deeper understanding of general concepts. As extracted from the questionnaire:

> *'When carrying out the acrosport activity, I understood the phase transitions occurring in nature, which are preceded by perturbations and phases of instability*. (Joshua).

These results further support the findings in the extensive literature on the effects of embodied interventions on specific cognitive capacities (Boroditsky & Ramscar, 2002), such as decision making (e.g. Ackerman, Nocera, & Bargh, 2010); perception of social status (e.g. Chiao et al., 2009); time flow (Boroditsky, 2000); affect and body perception (Meier & Robinson, 2004), as well as in learning of abstract concepts belonging to specific academic disciplines such as biology (Spintzyk et al., 2016), physics (Johnson-Glenberg et al., 2016), mathematics (Abrahamson & Sánchez-García, 2016; Abrahamson, Tancredi, Chen, Flood, & Dutton, 2021), chemistry (Ping, Zinchenko, Larson, Decatur, & Goldin-Meadow, 2011). These are, of course, only some examples of the vast literature on embodied cognition and learning and making a more systematic review was not the goal of this paper.

However, to our knowledge, this is the first study that experimentally shows how the DST explanatory concepts can be used to achieve a transdisciplinary integration of high school academic curricula. Hence, the SUMA educational framework can foster the understanding and transfer the knowledge among academic subjects, in general and through embodied practices in specific.

Due to the study's novelty, there are numerous limitations to it. One of our concerns is that the novelty of the DST concepts and the embodied approach may induce weak retention effects. Research on more intensive and long-lasting interventions involving teachers of different subjects and students of different grades is warranted. Implementing this kind of intervention requires teachers to value embodied and transdisciplinary learning approaches and acquire technical and pedagogical competencies related to general concepts. This task may require specific changes, which are hard to achieve due to social inertia.

This is a preliminary study with a quasi-experimental design. Using a control group and establishing other metric characteristics of the used instruments, such as the reliability (inter-item and test-retest) and their discriminatory power, is warranted in future interventions to give more consistency to the current results.

Furthermore, the potential of movement-based experiences to promote knowledge transfer through general concepts should be further investigated. For example, is there a trade-off between the attentional load and the degree of bodily integration in the learning task? Future research should also inspect in much more detail the different ways academic disciplines encompassing STEM, humanities and arts can be put into interaction and the academic and practical benefits that may stem from it. Finally, it is warranted to adapt and extend this type of intervention to all educational levels and study their long-term effects.

The current results can have other significant practical consequences. The SUMA educational framework enables the understanding and transfer of knowledge among phenomena belonging to different levels of organization in nature and society, revealing its potential in education itself and fostering educational and professional policies. In particular, the authors of this paper envision its crucial role in the professional mobility of experts, practitioners and scientists between different fields of expertise (Hristovski et al., 2020).

The effect of the intervention points to the potential of teaching DST concepts through body movement experiences in high school students for achieving the goals of an embodied and unificatory transdisciplinary education.

Authors' contributions

All authors listed have made a substantial, direct and intellectual contribution to the work and approved it for publication.

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Authors' statement

The legal educators were informed about the intervention procedures and signed informed consent.

Declaration of Competing Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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3.4. Integrating knowledge in higher education through experiencing the transdisciplinarity of Dynamic Systems Theory general concepts

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Apunts (submitted, accepted)

Integrating knowledge in higher education through experiencing the transdisciplinarity of Dynamic Systems Theory general concepts

La integración del conocimiento en la educación superior a través de la experimentación de la transdisciplinariedad de los conceptos generales de la Teoría de Sistemas Dinámicos

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Integrating knowledge in higher education through experiencing the transdisciplinarity of Dynamic Systems Theory general concepts

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Abstract

This study aimed to determine the effectiveness of experiencing general concepts from Dynamic Systems Theory (DST) for enhancing integrative knowledge among higher education students. Two class groups of first-cycle students were assigned to the experimental (EG, n: 147) and control (CG, n: 140) groups, respectively. The EG followed a specific intervention consisting of learning DST general concepts and experiencing their transdisciplinarity, while the CG followed the regular lessons. Integration and transfer of knowledge were evaluated using questionnaires and oral presentations. Post-intervention, the EG group improved significantly their integrative and transdisciplinary knowledge, while the CG showed no change. Experiencing the transdisciplinarity of DST concepts effectively fostered integrative knowledge among higher education students.

Keywords: complex systems, transfer of knowledge, embodied learning, education innovation

Resumen

Este estudio pretendía determinar la eficacia de experimentar conceptos generales de la Teoría de Sistemas Dinámicos (TDS) para mejorar el conocimiento integrador entre estudiantes de enseñanza superior. Se asignaron dos grupos clase de estudiantes de primer ciclo al grupo experimental (EG, n: 147) y al grupo control (CG, n: 140), respectivamente. El EG siguió una intervención específica que consistía en aprender conceptos generales de TSD y experimentar su transdisciplinariedad, mientras que el CG siguió las clases regulares. La integración y la transferencia de conocimientos se evaluaron mediante cuestionarios y presentaciones orales. Tras la intervención, el grupo EG mejoró significativamente sus conocimientos integradores y transdisciplinares, mientras que el CG no mostró ningún cambio. Experimentar la transdisciplinariedad de los conceptos de DST fomentó eficazmente el conocimiento integrador entre los estudiantes de enseñanza superior.

Palabras clave: sistemas complejos, transferencia de conocimientos, aprendizaje corporeizado, innovación educativa

Introduction

In the traditional educational curricula, subjects are often taught in isolation and disconnected from each other (Hristovski et al., 2020). By failing to recognise the interconnectedness of knowledge across disciplines, learners miss opportunities to apply what they have learned to real-world problems (Adams, 2015; Bautista et al., 2018). Research shows that students who were taught in a fragmented manner had limited transferability of knowledge to new contexts (Ball, 2000). More concretely, standard instructional practices in undergraduate teaching, such as traditional lectures, laboratory, or recitation courses, are ineffective at helping students to master and retain important concepts of the disciplines over the long term (Wood & Gentile, 2003). Moreover, these practices do not adequately develop the integrative knowledge and collaborative problem-solving that we need to face the problems of the modern world.

In contrast, students who received a more integrated education (e.g, problem-based learning or inquiry learning) demonstrated higher levels of understanding of the topic and could better apply their knowledge effectively (Hmelo-Silver et al., 2007). However, the use of subject-specific vocabulary in different disciplines makes it challenging to implement transdisciplinary approaches (Hristovski, 2013; Hristovski et al., 2020). For example, in sports science, experts such as physiologists, biomechanists, sports coaches, and data analysts may face communication barriers due to differences in scientific terminology and approaches. In such cases, a common scientific language could facilitate a shared understanding and the integration of knowledge, which are crucial for the progress of science and society.

To understand and unify approaches in sciences, general concepts and principles that can explain different phenomena are needed. The Dynamic Systems Theory (DST) offers a comprehensive set of interconnected general concepts and principles that have been empirically identified (Hristovski, 2013; Hristovski et al., 2014; Hristovski et al., 2019). Using DST concepts can help us to understand phenomena from a broad spectrum of scientific disciplines (i.e., elementary particles and fields to sociology) and unify knowledge. This includes the sports sciences (Balagué et al., 2017; Vázquez, 2017; Hristovski, 2013) and its multilevel nature (from sports genetics and epigenetics to sport sociology). In this sense, they have a potential for simple integration of basic understanding of phenomena from various academic disciplines.

When researching the effectiveness of transdisciplinary educational interventions, short questionnaires completed by students are commonly used (Takeuchi et al., 2020; Lage-Gómez & Ros., 2021). In particular, questionnaires tailored to the content appear to be the most suitable since knowledge transfer is challenging to assess objectively. In this case, constructed-response items provide students with opportunities to justify their answers seems helpful (McCarthy, 2005). This activity is similar to scientific reasoning in real-life science inquiries. The questionnaire used in the research is based on the knowledge integration theory. It follows the criteria proposed by Liu et al. (2011) for developing assessments to measure student knowledge integration.

On the other hand, learning by experiencing first can be more effective in consolidating theory for students. For example, body movement experiences have been used to study concepts in mathematics, physics, biology, music, or culture (e.g., interdisciplinary physical education, Cone et al., 2009) or transdisciplinary concepts in primary and secondary education (see Almarcha et al., 2022; Almarcha et al., 2023). These experiences have shown better outcomes when working in groups because of the extent of collaborative peer learning (Magin, 1982). One example of practical experience to explain the theory in university settings is the study conducted by Hernández (2019), where students learned the kinematics of bicycle physics by riding a bicycle as an authentic experience. Another experimental study has shown that creating a centre for "learning how to learn" at university based on learning through teaching reduces attrition by improving tutoring and student skills (Wankowski, 2007).

The SUMA educational framework (see Hristovski et al., 2020) arises from the need to integrate disciplines by and embodied principles in the learning environment (Niedenthal, 2007; Stolz, 2015; Skulmowski & Rey, 2018). Based on this framework, we hypothesised that learning through embodied experiences will have a positive effect in acquiring general DST concepts and their transfer role among phenomena in university settings.

This research aimed to evaluate the educational potential of experiencing some DST concepts (see Table 1) for enhancing integration and transfer of knowledge among higher education students.

Methods

Participants

Two hundred eighty-seven first-cycle degree program students of sports science aged between 18 and 36 years old ($M = 20.07 \pm 3.85$) from the same faculty participated in the study. Two class groups with no significant differences in average sex, age, and educational interest were selected for the study. A hundred forty-seven students (37 women and 110 men) were assigned to the experimental group (EG) and 140 (34 women and 106 men) to the control group (CG). The female representation reflected the gender distribution of the whole degree program. Students were not previously introduced to or familiar with DST concepts. Once the intervention was explained, the students provided their informed consent to participate. The institution and the local research ethics committee approved the research. The data was coded anonymously to ensure confidentiality, adhere to university ethics, and comply with relevant guidelines and the principles of the Declaration of Helsinki.

Procedure

The study was conducted in a university faculty and integrated into the teaching general program. The intervention lasted 12 weeks and had a frequency of two theoretical lessons and one practical lesson per week of 90 minutes each. It has been led by an experienced teacher applying DST concepts and two researchers working in the same field.

During class time, on the first day and at the end of the intervention program, all participants filled out a demographic form and the Integrative Knowledge Questionnaire (see Instruments section below). Then, the EG followed the intervention while the CG continued with the regular lessons.

Intervention program

The intervention program consisted of two phases: a) preparatory and b) group work participation in a symposium.

a) Preparatory

The preparatory phase consisted of four learning phases (adapted from Hristovski et al., 2014 and Kolb, 1984):

1. Experiencing the dynamics of embodied phenomena through physical activities (11 sessions).
2. Reflecting on the dynamics of previous body experiences with the help of teacher questions after the performed physical activities.
3. Following theoretical lessons on general DST concepts (11 sessions) (Table 1).
4. Relating the body experiences with the general DST concepts (11 sessions).

b) Group work participation in a symposium

With the purpose of applying and experimenting with the transdisciplinarity of general DST concepts, students prepared group works to be presented in a symposium. Students with common theoretical and practical interests (4-5 members) selected a topic or phenomenon related to health, sports performance, or education to be explained using DST general concepts. Moodle platform chats were used to avoid topic overlaps in selecting topics. Once the topics were assigned to the groups, students worked collaboratively to submit an abstract (including authors, title and references) to participate in a symposium. When the abstract was accepted, they could present their works orally. A period of two weeks was left for correcting and resubmitting abstracts. During the process, the teachers offered additional support, providing regular tutoring and follow-up discussions to ensure that every group had the necessary resources to excel in the oral presentation.

The symposium program was scheduled to be six sessions that covered the following general topics: nutrition, health, injuries, performance, team sports, and education. Each presentation was 12 minutes duration plus 10 minutes of questions. After each presentation, all students and teachers scored the oral presentations and discussions following a rubric (Hafner & Hafner, 2003) (see Table 3) and added a comment or feedback to justify the score.

DST Concepts	Definition
Self-organisation	Spontaneous process where some form of overall order arises from local or global interactions between parts of an initially disordered system
Synergies	Spontaneous formation of structural and functional couplings among components to achieve task goals
Emergence	Radical novelty in the higher-level behaviour of systems resulting from interactions in the lower-level components within those systems.
Embededness	Nested structure. Smaller modules, each of them providing a certain function, are used within larger modules that perform more complex functions.
Dynamic system	System changing over time
Stability	Resilience to perturbations. The necessary and sufficient condition for the existence of any system's behaviour/structure.

Instability	The behavior/structure of a system which tends to vanish and switch to a stable state.
Phase transition	The spontaneous qualitative change of the system as a result of the instability of the previous state.
Attractor	Behavioural or structural states toward which, under some specific context, the system converges over time.
Repeller	Unstable state of system's behaviour.
Constraint/ context	Boundary conditions, limitations that apply restrictions to the degrees of freedom of a system.

Table 1. DST principles and general concepts

Evaluation

Integration and transfer of knowledge Questionnaire

Students had to answer the following questions:

1. Do you think it is scientifically interesting to explain any natural phenomenon using the same general DST concepts?
2. Can you identify common principles of DST in biological, psychological, and sociological processes? Which ones?
3. Can you use the general DST concepts to explain a phenomenon such as a social revolution? Please justify it.

4. And for explaining an organic injury? Please justify it.

The content validity of the questionnaire was established by two researchers with 30 years of experience in using DST concepts and evaluated by a researcher from the SUMA project (Hristovski et al., 2020). The internal consistency of the questionnaire was measured by Cronbach's alpha.

Group work presentations assessment

All students were required to assess the work of the other groups using an online form linked to a rubric. The rubric had three items - "integration of concepts", "collaborative work", and "originality and quality" - each of which was evaluated on a 4-point scale ranging from 1 (deficient) to 4 (excellent). Table 2 displays the rubric items along with the percentage of grades used to evaluate the team's presentations.

Punctuation					
Items	Excellent (4)	Good (3)	Adequate (2)	Deficient (1)	% of qualification
Integration of concepts	Good domain of the concepts and respond coherently to the questions.	Understand the phenomenon that explain but have difficulties to link some concepts.	Need some rectifications about the usage of the concepts.	Have no understanding of the concepts.	40%
Collaborative work	The exposition shows planification	The exposition shows planification,	The exposition shows some planification,	There is no collaboration or even no participation	40%

	and collaborative work. All the members participate actively.	but some members present deviations from the group's framework.	but with different levels of participation among the members.	by the members.	
Originality and quality	Original topic. Adequate and attractive visual support.	Original topic. Adequate but few attractive visual support.	Non-original topic. Adequate visual support.	Non-original topic. Inadequate visual support.	20%

Table 2. Group presentations rubric embedded in the form used to evaluate the team's presentations.

Student's satisfaction survey

Post-intervention, a student satisfaction survey was administered to collect the acquired competencies in integrating and transferring knowledge and the collaborative learning benefits (see Table 5).

Data Analysis

Integration and transfer of knowledge Questionnaire

Descriptive statistics were used to interpret the quantitative data. The percentages of Yes/No answers for the numbers 1 and 2a and the correct/incorrect answers in 2b, 3 and 4 questions in pre- and post-intervention were calculated for the EG and CG. A chi-square test of independence was performed to compare the differences between the groups, while McNemar's test was used to compare the results within groups each group for each question.

Group work presentation assessment

The mean and standard deviation (SD) of students' and teachers' marks (out of 10) associated with the first item of the rubric (use of general DST concepts to explain the phenomenon under study) was calculated to evaluate their integrative and transdisciplinary knowledge. The mean and SD of the student's and teachers' marks (out of 10) associated with the other three items, respectively were calculated. The mean final marks provided by students for the team presentations and the consensual marks of the teachers for each presentation were compared through Spearman's rank correlation.

Student's satisfaction survey

The percentage of responses to every question of the student satisfaction survey was calculated.

Results

Knowledge Integration Questionnaire

Experts confirmed that all items were relevant to the students and the intended purpose of the questionnaire. The assessed inter-item reliability of the questionnaire was $\alpha = 0.92$. Table 3 displays the % of responses for both groups.

Before the intervention, as neither group had been exposed to the general DST concepts, they could not answer questions 2.2, 3, and 4. However, both groups shared similar responses in questions 1 and 2: 31% and 16% for the CG and 33% and 15% for the intervention group. After the intervention, the CG maintained the responses (34% in Q1 and 18% in Q2), while the EG showed significant changes: 86, 90, 80 and 74% in each question, respectively.

Comparing both groups, there were no significant differences pre-intervention in the responses to every question (Q.1, Q.2.1, Q.2.2, Q.3 and Q.4): Q.1 (χ^2 = 0.119, p = .82705), Q.2.1 (χ^2 = 0.733, p = .85854), Q.2.2, Q.3 and Q.4 (χ^2 = 0.289, p = .96611). However post-intervention the differences were significant in every question Q.1 (χ^2 = 81.428, p < .00001), Q.2.1 (χ^2 = 152.821, p <. 00001), Q.2.2 (χ^2 = 186.998, p < . 00001), Q.3 (χ^2 = 163.596, p < . 00001), and Q.4 (χ^2 = 181.583, p < . 00001).

When comparing differences within groups, the CG did not differ between pre and post Q.1 (χ^2 = 3.00, p = .083), Q.2.1 (χ^2 = 2.00, p = .157), Q.2.2, Q.3 and Q.4 (χ^2 = 1.00, p = .317). In comparison, the EG presented significant differences Q.1 (χ^2 = 77.00, p < .001), Q.2.1 (χ^2 = 111.00, p < . 001), Q.2.2 (χ^2 = 118.00, p < . 001), Q.3 (χ^2 = 109.00, p < . 001), and Q.4 (χ^2 = 116.00, p < . 001).

KIQ questions	CG (n=140)		EG (n=147)	
	Pre	Post	Pre	Post
	Yes	*Yes*	*Yes*	*Yes/correct*
1. Do you think it is scientifically interesting to explain any natural phenomenon with the same concepts?	44 (31%)	47 (34%)	49 (33%)	126 (86%)***

2.1 Can you identify common principles of CAS and general concepts of DST in biological, psychological and sociological processes?	23 (16%)	25 (18%)	22 (15%)	133 (90%)***
2.2 Which ones?	1 (0.71%)	1 (0.71%)	2 (1.36%)	118 (80%)***
3. Can you use the general concepts (attractors, instability, variability, synergies, etc.) to explain a phenomenon such as a social revolution? Justify	1 (0.71%)	1 (0.71%)	2 (1.36%)	109 (74%)***
4. And for explaining an organic injury? Justify	1 (0.71%)	1 (0.71%)	2 (1.36%)	116 (79%)***

*Significant differences when comparing with the post-CG data
**Significant differences when comparing with the pre-EG data

Table 3. Percentages of responses to the Knowledge Integration Questionnaire

Team presentations assessment

A total number of 54 works with different topics of interest were evaluated. Integration of knowledge (item 1) was assessed with a mark of 8.43 ± 0.88, the team's collaborative work (item 2) with a mark of 8.91 ± 0.45, and the originality of the work (item 3) with a mark of 8.52 ± 0.55. Teachers' and students' marks showed a positive correlation (rho = 0.8, $p < 0.01$) and confirmed the objectivity of the judges (Table 4).

Items	Mean± SD	Min	Max	Spearman's rho
Integration	8.43 ± 0.88	5.35	9.7	
Collaborative work	8.91 ± 0.45	7.55	9.55	
Originality and Quality	8.52 ± 0.55	6.72	9.47	
Students Qualification Final Mark	8.18 ± 0.96	3.88	9.43	
Teachers Qualification Final Mark	7.36 ± 01.65	4	10	0.8

Table 4. Team presentations assessment results

Student's satisfaction survey

The survey was responded to by 115 students, of which 77.19% were satisfied with the intervention, 72.81% expressed the will to continue learning to apply DST concepts to different psychobiological and sociological phenomena, and 74.56% expressed that collaborative learning helped them to deepen their knowledge.

	Students responses				
Survey questions	Nothing at all	A little	Neutral	Very	Very much
1-Are you satisfied with what you learnt in the course?	10 (8.78%)	5 (4.38%)	11 (9.65%)	60 (52.63%)	28 (24.56%)
2- Would you like to keep learning these	6 (5.26%)	7 (6.4%)	18 (15.79%)	55 (48.25%)	28 (24.56%)

concepts as well as their application at different levels?					
3- Do you think that collaborative learning (symposium, co-evaluation, etc.) has helped you to go deeper into the course's knowledge? Why?	8 (7.02%)	5 (4.38%)	16 (14.04%)	35 (30.70%)	50 (43.86%)

Table 5 Percentages of responses to the Student's satisfaction survey

Discussion

The intervention's results revealed that by experiencing the general DST concepts, students could integrate and transfer knowledge effectively, leading to an increased interest in explaining natural phenomena using the same concepts. Their grades supported this outcome and demonstrated their ability to apply the general DST concepts to the selected topics of interest. The positive correlation between the marks awarded by the students and teachers confirmed the objectivity of the assessment. Additionally, the students agreed that the team's collaborative dynamics of working in groups was an efficient strategy to achieve the purpose of the intervention.

The intervention significantly impacted the EG's integration and transfer of knowledge abilities. Meanwhile, the CG showed no improvement, which can be attributed to their lack of exposure to learning DST concepts. In turn, the increase of integrative and transfer knowledge abilities of EG can be attributed to several aspects of the intervention program. First, the sessions were designed to experience the DST concepts through physical activities, which have gained some popularity in education due to their effectiveness in enhancing cognitive abilities and improving knowledge retention (Clary & Wandersee, 2007; Schwartz-Bloom et al., 2011; Spintzyk et al., 2016). When general concepts were experienced, explained and identified in different phenomena, the capacity to transfer knowledge among disciplines improved. Then, the reflective observation of these experiences enhanced the comprehension, abstract conceptualisation, transference and retention of the general DST concepts. These results are consistent with those Almarcha et al. reported (2022, 2023) in primary and secondary school.

The organisation of the symposium created an ideal environment among students to understand different phenomena, transfer the knowledge to topics that may not have previously crossed their minds, and thus acquire transdisciplinary competencies. According to Cabrera et al. (2017), allowing students to work on a meaningful topic contributes to improving their motivation. Prince (2004) agreed that optimal learning comes from active engagement with the material being taught.

Also, a supportive and pleasant classroom atmosphere contributed to the emergence of students' questions and arguments, which can often be more valuable than the lessons themselves. Classroom interactions between teachers and students seem more effective than traditional teaching methods and active learning situations in promoting participatory engagement (Bartlett & Ferber, 1998; Smith & Cardaciotto, 2011; Yoder & Hochevar, 2005).

The Knowledge Integration Questionnaire and satisfaction survey results showed that students believed they had improved their knowledge integration and transfer skills, become more interested in science, had a positive experience with collaborative learning, and that working on a relevant topic had boosted their motivation and creativity. The satisfaction survey data showed that the discussions and tutoring during the entire learning process helped students consolidate their learning. The teachers' tutorial guidance and internal group discussions were key to the intervention's success, as Ko and Mezuk (2021) found.

Despite the strengths of this study, some limitations must be considered. First, the long-term effects of the intervention have yet to be evaluated, and future research is warranted to be investigated. Also, as suggested by Hristovski et al. (2020), most educational interventions ignore the importance of the experiences in learning. Future interventions may enhance the learning process of general DST concepts using an experiential learning approach, as proposed in this study (Hristovski et al., 2014, Almarcha et al, 2022, 2023).

Additionally, we did not conduct a gender analysis of the results due to the small number of female participants compared to male participants. We suggest incorporating interviews throughout the academic program to understand better how students developed transfer of knowledge competencies during the intervention. The intervention highlighted the potential of experiencing and applying the DST concepts to foster integrative knowledge and transdisciplinarity among higher education students.

Conflicts of interests

The authors declare no conflicts of interest regarding the publication of this paper.

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3.5. Towards an Embodied and Transdisciplinary Education

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Capítulo XIV

HACIA UNA EDUCACIÓN CORPOREIZADA Y TRANSDISCIPLINAR

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1. INTRODUCCIÓN

Vincular disciplinas científicas y relacionar fenómenos biológicos y sociales, entre otros, es esencial para desarrollar competencias integradoras de conocimiento y pensamiento crítico (Adams, 2015; Bautista et ál., 2018). Aun así, el modelo educativo imperante, promovido por una progresiva especialización y subespecialización científica que caracterizó el siglo XX, sigue siendo dominantemente multidisciplinar y fragmentado (Hristovski et ál., 2020).

Para favorecer la integración de conocimiento han surgido enfoques como la educación STEAM, que tiene como objetivo difuminar las barreras entre disciplinas (Baek et ál., 2011). Sus seguidores proponen un modelo interdisciplinar donde se integran al menos dos disciplinas (Zamorano et ál., 2018). Así, países como Australia, Canadá, China o Inglaterra ya apuestan por el aprendizaje STEAM en los niveles de primaria y secundaria (Sharma y Yarlagadda, 2018; Shanahan et ál., 2016; Li y Chiang, 2019; Wong et ál., 2016). Sin embargo, la investigación sobre la validez y eficacia de la perspectiva STEAM en el aula resulta todavía insuficiente. Además, su conceptualización y aplicación carece de propuestas y recursos que reconozcan los puntos en común entre las disciplinas científicas que la componen (García-Carmona, 2020; Zamorano et ál., 2018).

Desde una perspectiva integradora, otro problema destacable en la educación actual es el aislamiento del cuerpo del proceso de aprendizaje. Todo el contenido se aprende fundamentalmente en el aula y sin movimiento, lo que supone una menor implicación en el aprendizaje (Clary y Wandersee 2007). Por eso, enfoques corporeizados interdisciplinares, que conectan la educación física con otras asignaturas del plan de estudios (Kaittani et ál., 2017), han ganado popularidad en primaria y secundaria (Spintzyk et ál., 2016; Schwartz-Bloom et ál. 2011).

Sin embargo, el aprendizaje corporeizado aún no se ha utilizado con un enfoque transdisciplinar, es decir, con el objetivo de comprender conceptos científicos generales o unificadores que permitan conectar diferentes disciplinas. Las primeras ideas para unificar la ciencia surgen del estudio de los sistemas complejos y su introducción en las disciplinas académicas (Forester 1994, Jacobson y Willensky 2006, Goldstone, 2006).

Basándose en la Teoría de Sistemas Dinámicos (TSD) y la Física Estadística (FE), Hristovski (2013) extrajo trece conceptos y principios relevantes para todo el conjunto de disciplinas académicas, desde la física hasta la sociología y el arte (Hristovski, Balagué y Vázquez, 2019) pero sus aplicaciones al currículo escolar están aún poco exploradas. La plataforma educativa "Synthetic Understanding through Movement Analogies" (SUMA) (Comprensión sintética a través de analogías de movimiento), ofrece dichos conceptos y principios generales con el objetivo de contribuir a la integración del conocimiento y del cuerpo en la educación. Conceptos como los de estabilidad e inestabilidad, transición de fase, parámetro de control, parámetro de orden, y principios como el de auto-organización, tienen el potencial de formar un esqueleto común para la comprensión de fenómenos y procesos que se estudian en diferentes disciplinas académicas. (https://suma.edu.mk/conceptos-generales/). Resultados preliminares de investigación han demostrado que dichos conceptos generales se pueden enseñar y aprender con éxito utilizando analogías de movimiento (Almarcha et ál., 2022).

Las fases de aprendizaje que se proponen para promover una educación corporeizada y transdisciplinar, propuestas por Hristovski et ál. (2014) e inspiradas en el marco de aprendizaje experiencial de Kolb (1984), son las siguientes:

1. Experiencia de movimiento (actividad física).
2. Observación reflexiva de la experiencia prestando atención a los procesos de cambio y sus fases.

3. Relación de la experiencia y la observación reflexiva con los conceptos y principios generales de la TSD/FE (ver tabla 1).
4. Aplicación de los conceptos y principios a diferentes fenómenos estudiados en otras disciplinas del currículo académico.

El objetivo de este estudio fue evaluar el potencial de las intervenciones dirigidas a la enseñanza y el aprendizaje de conceptos generales de la TSD/FE a través de experiencias de movimiento en educación primaria y secundaria.

2. METODOLOGÍA

2.1. PARTICIPANTES

Dos clases de primaria (n= 48, 26 chicos y 22 chicas, 10-11 años) y 5 clases de secundaria (n= 71, 23 chicas y 46 chicos, 2 no binarios, 12-13 años), respectivamente, participaron en 4 semanas de intervención (4 h/semana) como parte de su contenido lectivo regular. Todos los estudiantes desconocían los principios y conceptos generales de la TSD/FE, que no aparecen en los planes de estudio, y no fueron previamente introducidos ni familiarizados con los mismos. Todos los estudiantes y tutores legales/educadores recibieron una explicación previa sobre el objetivo y procedimiento a seguir durante la intervención y firmaron un consentimiento informado.

2.2. DISEÑO

Se siguió un diseño cuasi-experimental comparando resultados pre y post intervención. Como los conceptos de TSD/FE no están incluidos en el currículo de educación primaria y secundaria, se consideró innecesario añadir un grupo control en esta investigación.

2.3. PROCEDIMIENTO

La intervención duró ocho semanas con una frecuencia de dos lecciones/semana de 1 hora de duración. Las clases se desarrollaron dentro de la asignatura de educación física y fueron dirigidas por un profesor de educación física con más de diez años de experiencia en la aplicación de conceptos de la TSD/FE en investigación no educativa. Una investigadora supervisó la intervención in situ. Las fases de aprendizaje fueron las siguientes (Hristovski et ál.2014):

1. Los estudiantes realizaron las actividades físicas propuestas (ver Tabla 2).
2. Reflexión sobre las experiencias de movimiento.
3. Presentación de los conceptos TSD/FE (ver tabla 1) a través de videos y fotografías visualizando sus propias experiencias de movimiento.
4. Aplicación de los conceptos TSD/FE a fenómenos moleculares, ecológicos y sociológicos (ver tabla 2 y figura 1).

TABLA 1. *Conceptos generales TSD/FE (visit https://suma.edu.mk/)*

Conceptos	**Definición**
Estabilidad	Resiliencia a las perturbaciones. Condición necesaria y suficiente para la existencia del comportamiento/estructura de cualquier sistema.
Inestabilidad	Falta de estabilidad ante perturbaciones provenientes del interior o del exterior del sistema.
Transición de fase	Reorganización espontánea de los componentes del sistema en otro comportamiento/estructura estable.
Autoorganización	Un proceso por el cual los componentes del sistema cambian su patrón de organización bajo o sin la influencia de una perturbación.

Parámetro de control	Llimitación o restricción que desestabiliza un orden previamente estable.
Parámetro de orden	Variable colectiva que captura el comportamiento coordinativo del sistema como un todo

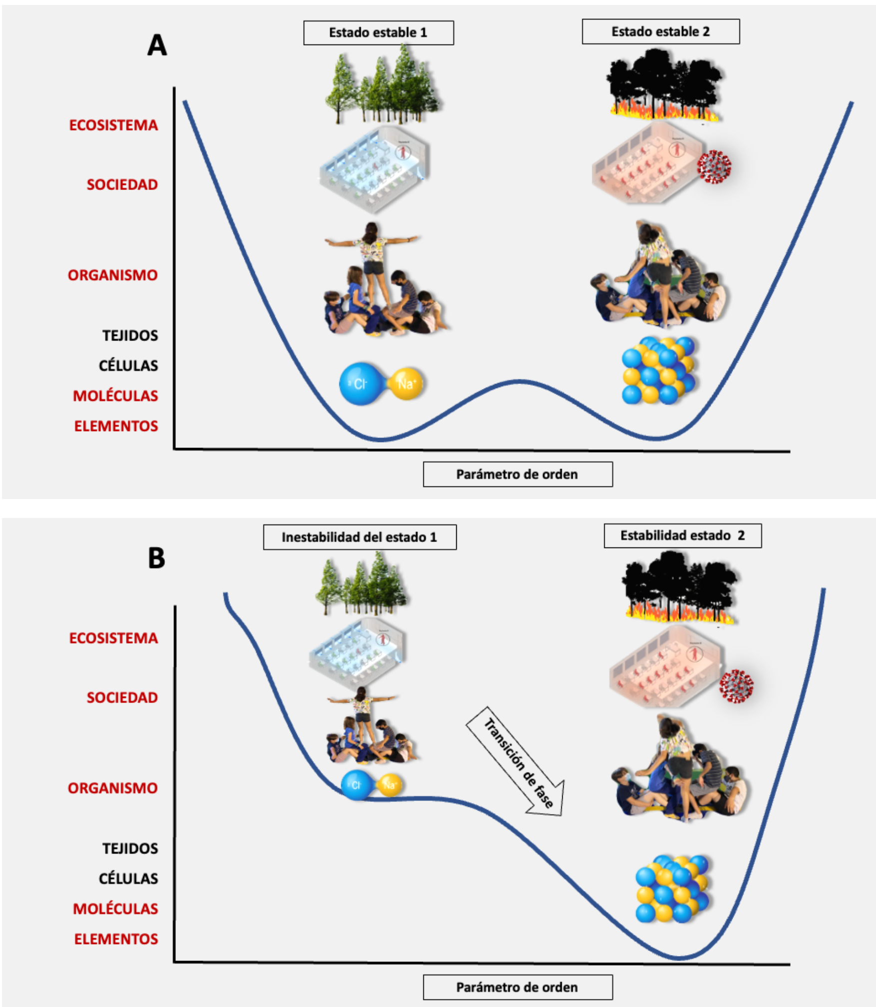
Fuente: elaboración propia

TABLA 2. Ejemplos de actividades físicas propuestas, su relación con los conceptos TSD/FE y su transferencia a fenómenos moleculares, ecológicos y sociológicos

Experiencia de movimiento	Parámetro de orden	Parámetro de control	Transición de fase	Transferencia de conocimiento
Slackline	Posición del centro de gravedad con respecto del suelo	Manos enganchadas al cuerpo	Del equilibrio en el slackline a la caída al suelo	Del estado saludable al no saludable
Acrosport	Posición del centro de gravedad de la figura	Número de participantes y de apoyos	Cambios de forma, configuraciones	Cambios del estado del agua: sólido, líquido, gas
Teléfono	Comunicación en red	Distancia entre los nodos	De una comunicación efectiva a ineficaz	Propagación de un incendio en el bosque, propagación de la infección por un virus

Fuente: Elaboración propia

FIGURA 1. Transferencia de conocimiento a través de experiencias de movimiento corporal. (A) Representación de dos estados estables de un parámetro de orden en fenómenos de distintos niveles de organización. El nivel de ecosistema, está representado por un bosque verde (estado estable 1) y quemado (estado estable 2); el nivel de la sociedad, por un aula sana (estado estable 1) y contagiada (estado estable 2); el nivel grupal, por una figura de acrosport estable (estado estable 1) y por una deshecha (estado estable 2); a nivel molecular, por agua en estado líquido (estado estable 1) y sólido (estado estable 2). (B) Representación de la transición de fase entre los estados atractores del parámetro de orden debido a parámetros de control (distancia entre árboles, distancia entre estudiantes, número de apoyos de la figura y temperatura, respectivamente).



Fuente: Elaboración propia

2.4. INSTRUMENTOS

Las encuestas, los estudios de casos, las entrevistas y los cuestionarios de autoinforme de los estudiantes se encuentran entre los métodos elegidos con más frecuencia para investigar la efectividad de las intervenciones educativas interdisciplinarias (Lage-Gómez y Ros., 2021; Takeuchi et ál., 2020). En particular, considerando que la transferencia de conocimiento es difícil de medir objetivamente, las entrevistas y cuestionarios de estructura cerrada parecen ser los más apropiados para estudiantes de primaria y secundaria. Por ello, la comprensión de los conceptos TSD/FE se evaluó a través de cuestionarios y entrevistas.

Los estudiantes respondieron al cuestionario un día antes y un día después de la intervención, respectivamente. Se les pidió que respondieran con la mayor honestidad posible, enfatizando que sus respuestas se mantendrían confidenciales y no afectarían a sus calificaciones académicas. No realizaron ninguna actividad de aprendizaje adicional (por ejemplo, tareas o lecciones adicionales) durante el período de intervención.

2.4.1 Primaria

El cuestionario constó de cinco preguntas cerradas con cuatro opciones de respuesta y una única respuesta correcta:

1. ¿Cuándo decimos que un sistema es estable?
2. ¿Cuándo decimos que un sistema es inestable?
3. ¿Un bosque quemado representa un estado estable?
4. ¿La propagación de un incendio forestal y la infección de un virus tienen la misma dinámica de transmisión?
5. ¿Cuáles de las siguientes afirmaciones sobre la autoorganización son correctas?

Las preguntas de la entrevista fueron las siguientes:

1. 1.1. Para ti, qué es un estado estable e inestable / 1.2 ¿Puedes describir una situación en la que te sientes estable e inestable?

2. ¿Conoces alguna transición de fase? ¿Puede decir cuál es el estado estable inicial antes de que se formen cristales de agua y antes de que se propague un incendio o una infección por virus?

3. ¿Qué significa para ti el principio de autoorganización?

4. ¿Qué procesos naturales, como la propagación de un incendio y la formación de cristales de agua, tienen en común con procesos sociales, como la propagación del COVID-19?

2.4.2 Secundaria

El cuestionario fue validado por dos expertos y constó de 5 preguntas cerradas escaladas de 0 a 10 según los informes PISA (PISA, 2018). Los participantes respondieron qué tan de acuerdo estaban con las afirmaciones: totalmente en desacuerdo (0) - totalmente de acuerdo (10). El amplio rango de la escala permitió tratar los datos como continuos (Rhemtulla, Brosseau-Liard y Savalei, 2012), así como detectar las diferencias pre/post intervención.

En el caso de calificar con una puntuación de seis o más en cada ítem del cuestionario, se solicitó a los estudiantes que justificaran su respuesta respondiendo a una pregunta abierta que debía ser respondida utilizando los conceptos aprendidos (ver Tabla 1). El criterio para decidir sobre la corrección de las respuestas fue el uso de conceptos generales con su correcto significado. Un experto del proyecto SUMA evaluó las respuestas.

2.5. ANÁLISIS DE DATOS

Los resultados se compararon mediante la prueba t de Student y la prueba de Wilcoxon para datos apareados en los estudiantes de primaria y secundaria, respectivamente. Los tamaños del efecto se calcularon a través de las medidas d de Cohen y PSdep. Todos los datos cuantitativos se analizaron utilizando el software SPSS (Versión 28.0.1).

En primaria se transcribieron las entrevistas, y dos investigadores calificaron cada respuesta de acuerdo con la rúbrica presentada en la Tabla 3. Se realizó un análisis Kappa para testar la coherencia inter-observadores.

TABLA 3. Rúbrica de evaluación de la entrevista.

Preguntas 1.1 y 1.2. Relacionado con el concepto de estados estables e inestables (Estabilidad-Inestabilidad)	
0	No puede definir el concepto con sus palabras ni dar ejemplos de situaciones, aunque sean erróneos.
1	No es capaz de definir el concepto de forma precisa sino aproximada con sus palabras o dar ejemplos de situaciones, aunque sean erróneos.
2	No es capaz de definir el concepto con precisión pero puede describirlo con sus palabras y dar un ejemplo, aunque erróneo.
3	Puede definir el concepto con sus palabras y da algunos ejemplos de las situaciones vividas.
4	Puede explicar el concepto con precisión y da un ejemplo de las vividas.
5	Puede definir el concepto con precisión y ofrece ejemplos concretos de las situaciones vividas.
Pregunta 1.2. Relacionado con el concepto de estado inestable (Inestabilidad)	
0	No puede definir el concepto con sus palabras ni dar ejemplos de situaciones, aunque sean erróneos.
1	No es capaz de definir el concepto de forma precisa sino aproximada con sus palabras o dar ejemplos de situaciones, aunque sean erróneos.
2	No es capaz de definir el concepto con precisión pero puede describirlo con sus palabras y dar un ejemplo, aunque erróneo.

3	Puede definir el concepto con sus palabras y da algunos ejemplos de las situaciones vividas.
4	Puede explicar el concepto con precisión y da un ejemplo de las vividas.
5	Puede definir el concepto con precisión y ofrece ejemplos concretos de las situaciones vividas.

Pregunta 2. Relacionada con el concepto de transición de fase.

0	No conoce ningún cambio de fase, ni puede dar un ejemplo.
1	No conoce ningún cambio de fase, pero puede dar algunos malos ejemplos.
2	No conoce ningún cambio de fase, pero puede inferir algunos ejemplos experimentados.
3	No conoce la definición de transición de fase, pero puede inferir los estados de agua y fuego.
4	No conoce la definición de cambio de fase, pero puede inferir los estados de los tres sistemas experimentados.
5	Conoce un cambio de fase y puede identificarlos en los tres sistemas trabajados y experimentados.

Pregunta 3. Relacionada con el concepto de autoorganización.

0	No puede explicar el concepto, ni siquiera con sus propias palabras.
1	No puede explicar el concepto, pero puede inferir algunos ejemplos.
2	No puede explicar el concepto, pero puede dar ejemplos.

3	Puede explicar el concepto, pero con sus propias palabras.
4	Puede explicar el concepto con rigor.
5	Puede explicar el concepto con rigor y dar ejemplos concretos.

Pregunta 4. Relacionada con los puntos en común entre la formación de cristales de agua, el fuego y la propagación de virus.

0	No puede nombrar ni explicar las similitudes de los tres procesos ni dar ejemplos.
1	No puede nombrar ni explicar las similitudes entre los tres procesos, pero da un ejemplo, erróneo.
2	Puede nombrar las similitudes entre algunos procesos pero no explicarlos ni dar ejemplos (aunque sean erróneos).
3	Puede nombrar algunas similitudes entre los tres procesos, pero no puede explicar ni dar ejemplos.
4	Puede nombrar y explicar las similitudes entre los tres procesos y dar un ejemplo.
5	Puede explicar las similitudes entre los tres procesos y dar ejemplos concretos.

4. RESULTADOS

Las habilidades de los estudiantes para integrar y transferir conocimientos aumentaron después de la intervención, tanto en primaria ($t=-7.24$, $p<.0001$, $d=0.8$) como en secundaria ($Z= 7.322$, $p< .0001$, PSdep = 1 en todos los ítems).

4.1. PRIMARIA

4.1.2 Cuestionario

Según los expertos, el cuestionario mostró una excelente validez de contenido. La fiabilidad test-re-test fue $\alpha = .72$.

Antes de la intervención, los porcentajes de aciertos fueron del 26%, 35%, 19%, 45%, 30% y 31% en cada pregunta, respectivamente (ver tabla 4). Antes de la intervención, los resultados mejoraron, siendo la pregunta 1.1 la de menor porcentaje de aciertos (41,5 %) y la pregunta 1.2 y 3 la de mayor porcentaje de aciertos con un 77 % y 75 %, respectivamente. La pregunta 2 tuvo un 46% de respuestas correctas. El porcentaje de respuestas correctas aumentó después de la intervención ($t(9)=-7,24$, $p<0,001$).

TABLA 4. Porcentajes de respuestas correctas al cuestionario pre y post-intervención.

Preguntas	*1.1*	*1.2*	*2*	*3*	*4*	*Reporte final*
PRE	*26,00*	*35,50*	*19,50*	*45,00*	*30,50*	*31,00*
POST	*41,50*	*77,00*	*46,50*	*75,50*	*68,00*	*64,50*

4.1.3 Entrevista

El análisis Kappa mostró una alta concordancia de las puntuaciones inter-observador ($k = 0,81$). Tras la intervención, los alumnos fueron capaces de encontrar similitudes entre diferentes fenómenos (pregunta 4): “En el caso de la propagación de un virus, si me acerco a alguien infectado y reduzco mi distancia, puedo infectarme. En el caso de la propagación del fuego, al reducir la distancia entre árboles, el fuego se propaga más rápido y el bosque se quema; y en el caso del agua, al elevar la temperatura se derrite un cubito de hielo".

Incluso, proporcionaron ejemplos concretos vinculados con las experiencias de movimiento corporal: “Una persona sana se encuentra en un estado fisiológico estable, pero este estado puede desestabilizarse ante factores estresantes (por ejemplo, enfadarse con los amigos, divorcio de los padres) e incluso desarrollar enfermedades”. También fueron capaces de conectar los conceptos de transición de fase, estabilidad e inestabilidad: “La transición de fase es cuando pasas de un estado estable a otro estado estable: de un bosque verde a un bosque quemado, de agua sólida a agua líquida”; y de autoorganización: "Nadie les dice a los átomos qué hacer; ellos mismos se autoorganizan".

4.2 SECUNDARIA

4.2.1 Cuestionario

Los estudiantes mejoraron sus competencias para explicar y relacionar fenómenos después de la intervención: ítem 1 (Z (71) = 7,322; p = 0,0000001, PSdep = 1); Ítem 2 (Z(71) = 7.323; p=0.0000001, PSdep=1); Ítem 3 (Z(71) = 7.167 p=0.0000001, PSdep=1); Ítem 4 (Z(71) = 6.567, p=0.0000001, PSdep=1); ítem 5 (Z(71) = 7,008; p=0,0000001, PSdep=1); Total para los 5 elementos (Z(71) = 7,323, p=0,0000001, PSdep=1)..

En la fase previa a la intervención, todos los estudiantes no pudieron obtener una puntuación superior a 6 y no fueron elegibles para responder a las preguntas abiertas. Sin embargo, tras la intervención, los participantes respondieron correctamente a las preguntas abiertas de por qué se extinguen las especies (73,24 %) y cómo se propagan los virus (83,33 %). También fueron capaces de relacionar fenómenos de las ciencias sociales y biológicas (87,32%), cuestiones ambientales con problemas de relación personal (63,38%) y experiencias personales con procesos ecológicos y sociales (74,65%).

5. DISCUSIÓN

De acuerdo con los resultados de los cuestionarios y entrevistas, la intervención ayudó a los estudiantes a comprender los conceptos TSD/FE e identificarlos en procesos moleculares, ecológicos y sociológicos. Después de conectarlos con sus experiencias de movimiento, los estudiantes reconocieron una mayor comprensión de dichos procesos.

Además, aumentaron la capacidad de integrar diversos fenómenos estudiados en diferentes disciplinas académicas (por ejemplo, infección por virus y transmisión de incendios forestales en biología y ecología, respectivamente). Las entrevistas identificaron cómo los estudiantes fueron capaces de transferir los conceptos generales vivenciados a través del movimiento con dichos fenómenos. Sin embargo, solo unos pocos estudiantes pudieron proporcionar nuevos ejemplos de transferencia no mencionados en clase. Nuestros resultados apoyan la hipótesis de que los estudiantes aprenden mejor cuando experimentan conceptos abstractos a través del propio cuerpo. Este hallazgo resulta particularmente relevante para el futuro de las metodologías STEAM y para promover una educación verdaderamente integradora que facilite una mejor comprensión de los fenómenos relacionados con la vida.

Pese al auge de metodologías de enseñanza STEAM en la escuela, la evidencia sobre sus beneficios es limitada. La práctica más común en un proyecto STEAM es que cada profesional contribuya desde su propia área de conocimiento (García-Carmona, 2020). Por ello, es necesario un marco integrador fundamentado científicamente para ayudar a los docentes a conectar las disciplinas STEAM. La actual fragmentación académica en especialidades y subespecialidades dificulta la transferencia de conocimiento en el aula.

Los conceptos TSD/FE suponen una moneda de cambio conceptual común necesaria para integrar procesos y fenómenos de diferentes niveles de organización (Martínez et ál., 2017). Por lo tanto, se sugiere incluir dichos conceptos en los proyectos STEAM (Shin y Han, 2011; Zamorano et ál., 2018) para promover una integración real de conocimiento.

Otras iniciativas han utilizado conceptos de TSD/FE para aprender, a través de simulaciones en ordenador, los comportamientos de moléculas, células, sociedades, ecosistemas, etc (Jacobson y Wilensky, 2006; Stieff y Wilensky, 2003). Más recientemente, Lage-Gómez y Ros (2021) desarrollaron un proyecto transdisciplinar en educación primaria conectando, a través de fractales y gráficos, las matemáticas y el arte, mostrando resultados de aprendizaje significativos y niveles más altos de motivación. En contraste con este enfoque, el marco educativo SUMA utiliza conceptos con un elevado nivel de generalidad, que los hace aplicables a múltiples disciplinas científicas, no solo a unas pocas. De hecho, las imágenes de fractales y gráficos pueden incluirse en los conceptos más generales de TSD/FE de ruptura de simetría-simetría e interacción, respectivamente, porque los fractales son un caso particular de simetría de escala y los gráficos son una representación única de interacciones.

Algunos autores han mostrado también la efectividad de experiencias corporeizadas en el aprendizaje (Abrahamson et ál., 2021; Abrahamson y Sanchez-García, 2016; Cone et ál., 2009), y sobretodo, en el aprendizaje de conceptos abstractos (Boroditsky, 2000; Boroditsky y Ramscar, 2002). Sin embargo, estos autores se centran en conceptos específicos de cada disciplina, y no en conceptos generales capaces de explicar un espectro mayor de fenómenos.

Implementar la intervención propuesta en esta investigación supone un desafío para alumnado y profesorado, pero sus beneficios pueden ser tremendos para toda la comunidad escolar. De hecho, los profesores de primaria y secundaria de ambos centros educativos definieron las actividades realizadas durante la intervención como motivadoras e inspiradoras, no solo para los alumnos sino también para todo el claustro y el entorno escolar, destacando las ventajas de interconectar diferentes materias. Además, se consigue reducir la distancia entre teoría/ciencia y práctica, desarrollar un pensamiento crítico, facilitar una mayor comprensión de los fenómenos relacionados con la vida y afrontar con mayor criterio los retos actuales.

El marco teórico del proyecto SUMA permite conectar los diferentes niveles de organización de la materia, proporcionando unas bases para abordar el estudio de otros niveles organizativos, como el nivel astronómico, ecosistémico, molecular o subatómico, que aún están por descubrir para los estudiantes de primaria y secundaria. Como consecuencia, la escuela deja de ser el lugar donde se adquiere información para convertirse en una experiencia de aprendizaje conectada con la realidad.

Sin embargo, una intervención como la llevada a cabo, requiere de un conocimiento previo riguroso de los conceptos generales de TSD/FE y de su interconexión. La comunicación y colaboración del profesorado desempeñan un papel crucial en el éxito de este tipo de intervenciones.

6. CONCLUSIONES

Los efectos de las intervenciones realizadas apuntan al potencial educativo de la enseñanza y aprendizaje de conceptos y principios generales de la TSD/FE a través de experiencias de movimiento en primaria y secundaria. Después de la intervención, los y las estudiantes fueron capaces de integrar y transferir conocimiento entre diversos fenómenos estudiados en ciencias naturales y sociales. El enfoque corporeizado y transdisciplinar ofrece nuevas posibilidades para la educación STEAM. Se precisa de una formación adecuada del profesorado y de una investigación extensiva que involucre a profesorado de diferentes materias y alumnado de diferentes etapas educativas para desarrollar todo el potencial del enfoque.

7. AGRADECIMIENTOS/APOYOS

Agradecemos al alumnado y profesorado que han hecho posible ambas experiencias educativas.

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4. Results report

This thesis reveals that embodied and transdisciplinary interventions based on the SUMA framework can be used to integrate and transfer knowledge between different disciplines. The results show that learning DST concepts through embodied experiences in elementary, secondary and higher education is possible. These general concepts, i.e., self-organisation, order parameter, control parameter, stability, instability and phase transition, were proved to be useful to connect the disciplines in the curricula, such as biology, mathematics, chemistry, technology, social sciences, and arts, ultimately unifying knowledge. Table 4 summarises the general findings of all experiments included in this thesis.

Table 4. *Summary of the results obtained applying the SUMA Framework in elementary, high school and university settings.*

Article	Results
Theoretical	The aplication of the SUMA Educational Framework, an online learning platform to facilitate the implementation of the approach in the teaching environment. It can be found at: https://suma.edu.mk/.
Study I. SUMA in elementary school	The applied DST/SP concepts are learnable and transferable among phenomena taught in different academic subjects in elementary school Most students were able to: (a) explain DST/SP concepts, and (b) provide concrete examples and link them to body movement experiences.
Study II. SUMA in high school	High school students improved their ability to explain scientific phenomena by relating them to personal experiences. Which has led to an enhancement in their understanding of the concepts.

Study III. SUMA in higher education	The intervention proved to be effective in developing integrative knowledge through collaborative settings in higher education students. The experimental group showed an improvement in integration and transfer of knowledge capacities, greater interest in science, and an increased motivation and creativity for the topic. Finally, they were able to identify common principles in psychobiological and sociological processes and used the general DST concepts properly.
Book chapter	Students recognized a greater understanding of molecular, ecological, and sociological processes when they learn trough movement experiences. Furthermore, they were able to transfer the general DST concepts with such phenomena.

Table 5. *Summary of the main characteristics of the articles included in the thesis.*

Article	**Demographics**	**Embodied experiences**	**DST general concepts**	**Transfer of knowledge (phenomena)**	**Instruments**
Theoretical	-	-	-	-	-
Study I: SUMA in elementary school	Two classes of 5th grade elementary public-school students (n= 48, 22 girls and 26 boys aged 10-11 y.)	Balance on a bench, acrosport, collective games	Stability, instability, phase transition, self-organisation, constraints, order parameter	Molecular (water state from liquid to solid), ecological (from green to a burnt forest) and sociological (from a healthy to a infected classroom)	Plickers questionnaire Interviews

Study II: SUMA in high school	Five classes of 1st grade public high school students (n = 71, 23 girls and 46 boys, 2 non-binaries, aged 12–13 y.)	Slackline walking Acrosport	Stability, instability, phase transition, control parameter, order parameter,	Ecological (sudden extinction of species due to water pollution and infection spreading), and sociological (sudden cancelling out of social network relationships)	The integration and transfer of knowledge questionnaire
Study III: SUMA in higher education	287 1st cycle students of sports science (EC= 37 women, 110 men; CG=34 women, 106 men) aged between 18-36 y.)	Incremental cycling task, dyadic task on a slackline, quasi-isometric arm curl exercise	Self-organisation, synergies, emergence, embeddedness, dynamic system, stability, instability, phase transition, attractor, repeller, constraint/context	Nutrition, health, injuries, performance, team sports, and education	Knowledge integration questionnaire, team's oral presentation, satisfaction survey
Book chapter	Study II and Study III	-	-	-	-

**CG= control group, EG= experimental group.

5. Discussion

The discussion is structured in three different sections. The first presents the theoretical, methodological and practical contributions. The second section explains the benefits of comprehending general principles and concepts in education. Finally, the limitations and future perspectives are presented in the last section.

5.1. Theoretical, methodological and practical contributions of the thesis

5.1.1. Theoretical contributions

This research has made significant theoretical contributions by exploring the transformative potential of **incorporating a common language in education**. Dynamic system theory provides a set of general concepts and principles that can unify the subjects taught in elementary school, high school, and university.

The results from the studies have shown that students can learn abstract concepts effectively when they experience them through their bodies, providing valuable insights about **integrating the body to learn DST concepts.** Embodied interventions have also been found to have a positive impact on cognitive capacities (Boroditsky & Ramscar, 2002), including decision-making (e.g. Ackerman et al., 2010), perception of social status, (e.g. Chiao et al., 2009); time flow (Boroditsky, 2000); affect and body perception (Meier & Robinson, 2004), as well as improving learning outcomes (Abrahamson et al., 2021; Abrahamson and Sanchez-García, 2016; Cone et al., 2009) and knowledge retention (Clary and Wandersee, 2007; Schwartz-Bloom et al., 2011; Spintzyk et al., 2016), especially for abstract concepts (Boroditsky, 2000; Boroditsky and Ramscar, 2002) of the academic disciplines such as biology (Spintzyk et al., 2016), physics (Johnson-Glenberg et al., 2016), mathematics (Abrahamson & Sánchez-García, 2016; Abrahamson et al., 2021), or chemistry (Ping, et al., 2011). The embodied interventions applied in the studies of the thesis have consisted of several classes where physical activities were prepared to help students experience the theoretical concepts and principles. When general concepts were embodied, explained and identified in different phenomena, the capacity to transfer knowledge among disciplines improved. Then, the reflective observation of these experiences enhanced the comprehension, abstract conceptualisation, transference and retention of the general DST concepts. Students could connect topics that may not have previously crossed their minds and relate the concepts to personal experiences. For instance, in primary school, a student relates the phases of the phenomena learnt in class with the phases of how he goes from a healthy state to an unhealthy state. The evidence supports that when students relate the new knowledge to a personal experience, the learning process becomes more relevant and impactful as it allows a better understanding of the information (Oller et al., 2021).

Additionally, applying **the SUMA Framework across different educational levels** showcases an innovative approach to education that transcends traditional subject boundaries, paving the way for a more interconnected and integrative learning experience. In contrast with interdisciplinary and transdisciplinary approaches in education that focus only on the specific concepts of each discipline, the SUMA educational framework uses concepts with a high level of generality, making them applicable to multiple scientific disciplines, not just a few. For example, Lage-Gómez and Ros (2021) developed a transdisciplinary project in elementary education connecting mathematics and art through fractals and graphics, showing significant learning results and high motivation levels. However, fractal and graph images can be included in the more general DST concepts of symmetry breaking-symmetry and interaction, respectively, because fractals are a particular case of scale symmetry, and graphs are a unique representation of interactions. Similarly, the work of Wilensky and colleagues, who used computer simulations to study the behaviours of molecules, cells, societies, and ecosystems (Wilensky, 1996; Wilensky and Resnick, 1999; Wilensky and Reisman, 2006) use concepts of different level of generality, which can be ultimately reduced to some more general concepts from the SUMA framework (Almarcha et al., 2023). However, these works have shown that for example, when teachers teach chemistry, a subject with abstract concepts conceived as difficult for students, using complex system concepts, students rely less on memorisation and more on conceptual understanding (Stieff and Wilensky, 2003). Also, students have shown they could apply micro- and macro-level concepts of different level of generality during problem-solving. In summary, those interventions help students to achieve a solid understanding of *some* complex system principles across different levels of organization (Jacobson and Wilensky, 2006).

The improvements students show in their integrative and knowledge-transfer capacities are particularly relevant to the future of education methodologies. It is important to emphasise that, in contrast to the above-discussed approach, the SUMA concepts and principles of maximal generality can be used in STEM (Science, Technology, Engineering and Mathematics) education exactly because they are fundamental for understanding not only the complex systems, but also the simple and complicated systems which are particularly studied in Technology and Engineering disciplines (Almarcha, et al., 2023). Thus, the DST concepts and principles, as extracted and defined in the SUMA framework, are suggested to be included in the projects to **promote a better understanding of the dynamics of complex systems sciences and a real integration of knowledge** (Martínez et al., 2017). Finally, the development of **the role of the teacher** in facilitating embodied and transdisciplinary learning experiences is a matter of importance in this thesis.

5.1.2. Methodological contributions

The methodological contributions of the thesis have been:

- The development and application of specialised **Knowledge Integration Questionnaires** to measure students' degree of knowledge integration.
- The **application of learning phases** derived from Kolb's experiential learning model (1984) to structure the educational process.
- The design and development of a comprehensive **rubric for assessing students' integration and transfer of knowledge** competencies. Which have resulted in a valuable tool for educators and researchers alike.
- The emphasis on fostering **participatory engagement** within the school community.
- The methodology used in the research, which puts emphasis on **interactions between teachers and between teachers and students**,

has played a pivotal role in the learning process. As a result, an interactive and engaging classroom environment has emerged, drawing on relevant literature (Bartlett & Ferber, 1998; Smith & Cardaciotto, 2011; Yoder & Hochevar, 2005).

5.1.3. Practical contributions

On a practical level, this research offers **tangible strategies to enhance the integration and transfer of knowledge** competencies among students. It proposes **practical activities** designed to teach DST concepts and connect subjects at all educational levels. These activities aim to break down subject boundaries within educational curricula, foster a more interconnected and collaborative learning environment, and provide actionable steps for educators. By emphasising the importance of participatory engagement and suggesting strategies to **improve teacher communication**, the study provides practical insights for educators seeking to **create a cohesive and supportive classroom atmosphere**. This thesis provides **hands-on tools based on embodied activities for reinforcing the understanding of general DST concepts** and enhancing the overall learning experience.

5.2. Benefits from comprehending general principles and concepts in education

Implementing an embodied and transdisciplinary intervention in educational settings is challenging for students and teachers, but the benefits can be tremendous for the entire school community. In fact, the different educational centres and teachers defined the activities conducted during the intervention as motivating and inspiring for the students and the entire school environment. The school is no longer just a place where students go to learn; rather, it becomes an entire learning experience for establishing real-life connections.

Comprehending DST concepts is not just about acquiring knowledge but also about a better understanding of the different phenomena in the world. This approach fosters a more profound scientific culture and a broader perspective on science. Because of the transdisciplinary nature of DST concepts, students can connect the different levels of matter organisation: the astronomical, ecosystemic, molecular, or subatomic levels. Connecting the levels allows learners to develop integrative and critical thinking competencies, which are valuable in any profession. Integrating knowledge competence allows students to grasp theoretical concepts more effectively and apply them in different practical scenarios. With critical thinking competence, students can question and evaluate information, make informed decisions, and deal with practical problems.

On the other hand, using a common language among professionals from different disciplines encourages truly interdisciplinary collaborations. Professionals who understand the underlying dynamic principles of their field can think beyond conventional boundaries and contribute to the reinvention of their profession by introducing novel ideas and approaches. When ideas are applied across different domains, they can lead to groundbreaking innovations and scientific advancements, ultimately enhancing the professional prestige of the individuals involved.

In higher education, allowing students to work on a meaningful topic improves their motivation and contributes to creating debates, which can often be more valuable than the lessons themselves (Llamas & Quiles, 2013). According to Prince (2004), active engagement with the material being taught is the key to optimal learning, and creating active learning situations for students could be an option. As Smith & Cardaciotto (2011) and Yoder & Hochevar (2005) argue, participatory engagement has numerous benefits. Also, a collaborative, supportive and pleasant classroom atmosphere contributed to the emergence of students' questions and arguments, which can often be more valuable than the lessons themselves. Classroom interactions between teachers and students seem more effective than traditional teaching methods and active learning situations in promoting participatory engagement (Bartlett & Ferber, 1998; Smith & Cardaciotto, 2011; Yoder & Hochevar, 2005).

In a rapidly changing world, adapting to new contexts is crucial. So, an education based on general principles gives individuals a versatile skill set to navigate new environments and challenges successfully.

5.3. Limitations and Future Perspectives

It is important to mention some limitations of this thesis. First, the results from the elementary and high school studies suggest that the intervention may be fragile at this age and somewhat sensitive to differences in the degree of abstractness of the concepts learned. Depending on how much emphasis is made on the content of the embodied learning phases (phase 1: the movement activity or introspection, and phase 2: the reflective observation of the embodied experience) is emphasised compared to the content of abstract conceptualisation (phase 3) and transferring knowledge to other disciplines (phase 4), the effectiveness of the intervention's effectiveness may vary. Therefore, the emphasis on either the "embodied" part or the conceptualisation part can significantly impact the results.

Second, teachers often lack familiarity with DST concepts and embodied experiences. It is difficult to design embodied activities to make analogies with the content of the subjects. Moreover, the curriculum design does not promote inter-subject transdisciplinarity, and most classrooms do not provide enough space for movement. Due to the novelty of this approach and the limited exposure of educators, it is a challenge to develop such interventions effectively. It is also important to explore whether there is a trade-off between the attentional load imposed and the extent of bodily integration required when learning a new task.

Third, the studies have used a quasi-experimental design because the group's classes were already stipulated in educational settings. To provide more consistency to the results, future interventions should use a randomised experimental and control group and establish metric characteristics of the instruments used, such as reliability (inter-item and test-retest) and discriminatory power. Also, incorporating interviews throughout the academic program could be a suitable solution to capture better the changes occurring at different process stages. As for the analysis, we did not conduct a gender analysis of the results since the number of female participants was significantly lower than that of male participants.

Fourth, to implement this intervention, teachers must (a) value the use of embodied and transdisciplinary learning methods, (b) acquire technical and pedagogical competencies related to DST concepts and (c) collaborate with other teachers to cross boundaries between subjects. Consequently, it is necessary to address a formation for teachers to learn how to create more integrative interventions (i.e., with projects, interdisciplinarity, and transdisciplinarity) and how to evaluate them. In short, new assessments that align with the learning format must be developed. However, changing the current methodologies that have been used for ages can be challenging due to the rigid structure of the educational system.

For future research, it is crucial to delve into how academic disciplines can interact with each other and the benefits that may arise from such interactions. Also, the potential of movement-based experiences in the learning experience should be addressed. Finally, more intensive and long-lasting interventions involving teachers of different subjects and students of different grades are warranted.

6. Conclusions

This thesis shows the potential of teaching and learning general concepts and principles of DST through movement experiences to foster integrative knowledge across elementary, secondary and higher education levels. Based on the experience of the researchers who created the SUMA educational framework and online learning platform, the creation of adapted interventions for each of the three education centres, and the contact of the teachers, it was possible to (a) learn general DST concepts and principles through body experiences, (b) integrate and transfer knowledge between different academic subjects through DST concepts, (c) develop critical thinking in higher education (d) facilitate a better understanding of different phenomena and (d) relate the content with the personal and social needs of the students. In particular, the studies presented are pioneers in applying the SUMA educational framework to achieve transdisciplinary integration in different academic curricula through embodied practices.

By learning general scientific concepts and principles through physical experiences, educators can create a more engaging, effective, and meaningful learning environment. However, adequate training must be provided to ensure that educators and students benefit from this approach. Moving forward, future research must involve educators from diverse disciplines and students from diverse educational backgrounds to fully realise its potential. In conclusion, the adoption of an embodied and transdisciplinary approach, grounded in the SUMA educational framework, emerges as a promising and innovative strategy for the future of education.

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Annexes

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