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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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References

Abrahamson, D., & Sánchez-García, R. (2016). Learning is moving in new ways: The ecological dynamics of mathematics education. *Journal of the Learning Sciences, 25* (2), 203–239.

Abrahamson, D., Tancredi, S., Chen, R., Flood, V., & Dutton, E. (2021). *Embodied design of digital resources for mathematics education: Theory, methodology, and framework of a pedagogical research program.* Submitted toward publication. In B. Pepin, G. Gueude, & J. Choppin (Eds.), *(in preparation). Handbook of digital (curriculum) resources in mathematics education*. Springer.

Ackerman, J. M., Nocera, C. C., & Bargh, J. A. (2010). Incidental haptic sensations influence social judgments and decisions. *Science, 328*, 1712–1715.

Adams, N. E. (2015). Bloom's taxonomy of cognitive learning objectives. *Journal of the Medical Library Association: JMLA, 103*, 152.

Alban, M. W., & Kelley, C. M. (2013). Embodiment meets metamemory: Weight as a cue for metacognitive judgments. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 39*, 1628–1634.

Almarcha, M., Martinez, P., Balagué, N., & Hristovski, R. (2022). *Embodied transfer of knowledge using coordination dynamics concepts in high school: A preliminary study. [dataset] Open Science Framework (2022, April 11)*. https://doi.org/10.17605/OSF.IO/54A68

Anderson, L. W., & Krathwohl, D. R. (2001). *A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives*. New York, NY: Longmans.

Aubusson, P. J., Harrison, A. G., & Ritchie, S. M. (2006). Metaphor and analogy. In *Metaphor and analogy in science education (pp. 1-9)*. Dordrecht: Springer.

Boroditsky, L. (2000). Metaphoric structuring: Understanding time through spatial metaphors. *Cognition, 75*(1), 1–28. https://doi.org/10.1016/s0010-0277(99)00073-6

Boroditsky, L., & Ramscar, M. (2002). The roles of body and mind in abstract thought. *Psychological Science, 13*(2), 185–189. https://doi.org/10.1111/1467-9280.00434

Brucker, B., Ehlis, A. C., Häußinger, F. B., Fallgatter, A. J., & Gerjets, P. (2015). Watching corresponding gestures facilitates learning with animations by activating human mirror-neurons: An fNIRS study. *Learning and Instruction, 36*, 27–37.

Chiao, J. Y., Harada, T., Oby, E. R., Li, Z., Parrish, T., & Bridge, D. J. (2009). Neural representations of social status hierarchy in human inferior parietal cortex. *Neuropsychologia, 47*(2), 354–363. https://doi.org/10.1016/j.neuropsychologia.2008.09.023

Clary, M., & Wandersee, H. (2007). A mixed-methods analysis of the effects of an integrative geobiological study of petrified wood in introductory college geology classrooms. *Journal of Research in Science Teaching, 8*, 1011–1035.

Cone, T. P. (1999). *The interdisciplinary puzzle: Putting the pieces together. Teaching elementary physical education*. Champaign, IL: Human Kinetics.

Cone, T. P., Werner, H., & Cone, S. L. (2009). *Interdisciplinary elementary physical education*. Champaign, IL: Human Kinetics.

Ellis, R. (2001). Movement metaphor as mediator: A model for the dance/movement therapy process. *The Arts in Psychotherapy, 28*(3), 181–190. https://doi.org/10.1016/S0197-4556(01)00098-3

Forrester, J. W. (1994, June). Learning through system dynamics as preparation for the 21st century. In *Keynote address for systems thinking and dynamic modelling conference for K-12 Education. Concord, MA, USA*.

Goldstone, R., & Wilensky, U. (2008). Promoting transfer by grounding complex systems principles. *Journal of the Learning Sciences, 17*, 465–516. https://doi.org/10.1080/10508400802394898

Grissom, R. J., & Kim, J. J. (2012). *Effect sizes for research: Univariate and multivariate applications* (2nd ed.). New York, NY: Routledge/Taylor & Francis Group.

Haken, H. (1978). *Synergetics. An introduction. Nonequilibrium phase transitions and self-organization in Physics, Chemistry and Biology*. Berlin-Heidelberg-New York: Springer.

Hristovski, R. (2013). Synthetic thinking in (sports) science: The self-organization of the scientific language. *Research in Physical Education, Sport and Health, 2*, 27–34.

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

Hristovski, R., Balagué, N., & Vázquez, P. (2014). Experiential learning of unifying principles of science through physical activities. In F. Miranda (Ed.), *Systems theory: Perspectives, applications and developments* (pp. 37–48). New York: Nova Science.

Hristovski, R., Balagué, N., & Vázquez, P. (2019). Science as a social self-organizing extended cognitive system. Coherence and flexibility of scientific explanatory patterns. In À. Massip-Bonet, G. Bel-Enguix, & A. Bastardas-Boada (Eds.) (1st ed.*,, Vol. 11. Complexity applications in language and communication sciences* (pp. 17–30). Cham: Springer.

Jacobson, M. J., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *The Journal of the Learning Sciences, 15*(1), 11–34.

Jamrozik, A., McQuire, M., Cardillo, E. R., & Chatterjee, A. (2016). Metaphor: Bridging embodiment to abstraction. *Psychonomic Bulletin & Review, 23*, 1080–1089. https://doi.org/10.3758/s13423-015-0861-0

Johnson-Glenberg, M. C., Megowan-Romanowicz, C., Birchfield, D. A., & Savio-Ramos, C. (2016). Effects of embodied learning and digital platform on the retention of physics content: Centripetal force. *Frontiers in Psychology, 7*, 1819.

Kaittani, D., Kouli, O., Derri, V., & Kioumourtzoglou, E. (2017). Interdisciplinary teaching in physical education. *Arab Journal of Nutrition and Exercise, 2*(2), 91–101. https://doi.org/10.18502/ajne.v2i2.1248

Kelso, J. A. S. (1984). Phase transitions and critical behavior in human bimanual coordination. *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology, 15*, 1000–1004.

Kelso, J. S. (1995). *Dynamic patterns: The self-organization of brain and behavior*. MIT press.

Kolb, D. A. (1984). *Experiential learning: Experience as the source of learning and development*. Prentice Hall Inc.

Lakoff, G., & Johnson, M. (1999). *Philosophy in the flesh. The embodied mind and its challenge to Western thought*. New York: Basic Books.

Lindgren, R., Tscholl, M., Wang, S., & Johnson, E. (2016). Enhancing learning and engagement through embodied interaction within a mixed reality simulation. *Computers & Education, 95*, 174–187.

Lovejoy, S. (2022). Scaling and scale invariance. In S. B. Daya, Q. Cheng, J. McKinley, & F. Agterberg (Eds.), *Encyclopedia of mathematical geosciences. Encyclopedia of Earth Sciences Series*. Cham: Springer. https://doi.org/10.1007/978-3-030-26050-7_282-1).
Mavilidi, M. F., Okely, A. D., Chandler, P., Cliff, D. P., & Paas, F. (2015). Effects of integrated physical exercises and gestures on preschool children's foreign language vocabulary learning. *Educational Psychology Review, 27*, 413–426.
Meier, B. P., & Robinson, M. D. (2004). Why the sunny side is up: Association between affect and vertical position. *Psychological Science, 15*(4), 243–247. https://doi.org/10.1111/j.0956-7976.2004.00659.x
Montull, L., Vázquez, P., Rocas, L., Hristovski, R., & Balagué, N. (2020). Flow as an embodied state. Informed awareness of slackline walking. *Frontiers in Psychology, 10*, 2993. https://doi.org/10.3389/fpsyg.2019.02993
Morin, E. (2002). *Seven complex lessons for the education in future*. Unesco.
Niedenthal, P. M. (2007). Embodying emotion. *Science, 316*, 1002–1005.
Ping, R., Zinchenko, E., Larson, S., Decatur, M. A., & Goldin-Meadow, S. (2011). The relationship between gesture and speech predicts who will learn to solve a chemistry problem. In *Proceedings of the annual meeting of the cognitive science society (Vol. 33, no. 33)*.
Program for International Student Assessment. (2015). *PISA released items—Science*. Paris: OECD. Retrieved from: https://www.oecd.org/pisa/test/PISA2015-Released-FT-Cognitive-Items.pdf. (Accessed 31 December 2021).
Resnick, M., & Wilensky, U. (1993, April). Beyond the deterministic, centralized mindsets: New thinking for new sciences. In *Paper presented at the meeting of the American Educational Research Association, Atlanta, GA*.
Resnick, M., & Wilensky, U. (1998). Diving into complexity: Developing probabilistic decentralized thinking through role-playing activities. *The Journal of the Learning Sciences, 7*(2), 153–172.
Rhemtulla, M., Brosseau-Liard, P.É., & Savalei, V. (2012). When can categorical variables be treated as continuous? A comparison of robust continuous and categorical SEM estimation methods under suboptimal conditions. *Psychological Methods, 17*(3), 354.
Ruiter, M., Loyens, S., & Paas, F. (2015). Watch your step children! Learning two-digit numbers through mirror-based observation of self-initiated body movements. *Educational Psychology Review, 27*, 457–474.
Schwartz-Bloom, R. D., Halpin, M. L., & Reiter, J. P. (2011). Teaching high school chemistry in the context of pharmacology helps both teachers and students learn. *Journal of Chemical Education, 4*, 744–750.
Skulmowski, A., & Rey, G. D. (2018). Embodied learning: Introducing a taxonomy based on bodily engagement and task integration. *Cognitive research: principles and implications, 3*(1), 1–10.
Song, H. S., Pusic, M., Nick, M. W., Sarpel, U., Plass, J. L., & Kalet, A. L. (2014). The cognitive impact of interactive design features for learning complex materials in medical education. *Computers & Education, 71*, 198–205.
Spintzyk, K., Strehlke, F., Ohlberger, S., Gröben, B., & Wegner, C. (2016). An empirical study investigating interdisciplinary teaching of biology and physical education. *Science Education, 25*(1), 35–42.
Stieff, M., & Wilensky, U. (2003). Connected chemistry—Incorporating interactive simulations into the chemistry classroom. *Journal of Science Education and Technology, 12*, 285–302.
Stolz, S. (2015). Embodied learning. *Educational Philosophy and Theory, 47*(5), 474–487. https://doi.org/10.1080/00131857.2013.879694
Tisue, S., & Wilensky, U. (2004, May). Netlogo: A simple environment for modelling complexity. In *International conference on complex systems 21* (pp. 16–21).
Torrents, C., Balagué, N., Hristovski, R., Almarcha, M., & Kelso, J. A. S. (2021). Metastable coordination dynamics of collaborative creativity in educational settings. *Sustainability, 13*, 2696. https://doi.org/10.3390/su13052696
Wilensky, U. (1996). Modeling rugby: Kick first, generalize later? *International Journal of Computers for Mathematical Learning, 1*, 125–131.
Wilensky, U., & Reisman, K. (2006). Thinking like a wolf, a sheep, or a firefly: Learning biology through constructing and testing computational theories—An embodied modelling approach. *Cognition and Instruction, 24*(2), 171–209.
Wilensky, U., & Resnick, M. (1995, April). New thinking for new sciences: Constructionist approaches for exploring complexity. In *Paper presented at the meeting of the American Educational Research Association, San Francisco*.
Wilensky, U., & Resnick, M. (1999). Thinking in levels: A dynamic systems approach to making sense of the world. *Journal of Science Education and Technology, 8*(1), 3–19.
Wu, Y. C., Hsieh, L. F., & Lu, J. J. (2015). What's the relationship between learning satisfaction and continuing learning intention? *Procedia-Social and Behavioral Sciences, 191*, 2849–2854.