Chapter 1
Using Physical and Virtual Labs for Experimentation in STEM+ Education: From Theory and Research to Practice

Yvoni Pavlou and Zacharias C. Zacharia

1.1 Introduction

Educational reform efforts in numerous countries (mostly since 2015) focus on the integration of science, technology, engineering and mathematics (STEM) policies in national curricula to promote interdisciplinary learning (Zhan et al., 2022). For example, the Next Generation Science Standards (NGSS; Next Generation Science Standards Lead States, 2013) endorse coherent and interconnected content and a coherent and interconnected approach to the STEM disciplines to support the development of students' scientific literacy. The NGSS include practices and core disciplinary ideas from engineering and the sciences that bring out the connections between the different domains, and facilitate their introduction in teaching and learning in an integrated way.

Even though inconsistencies in the definition of STEM education exist, it is nevertheless typically conceptualized as a teaching approach that incorporates skills from and knowledge of different disciplines, situated in real-world issues (Martín-Páez et al., 2019). The integration of other disciplines within STEM curricula is also a common practice in order to promote 21st century skills, such as creativity and entrepreneurship. For example, STEAM refers to the integration of arts and/or humanities in STEM curricula; STEAME additionally incorporates entrepreneurship. For the purposes of this article, the term STEM+ will be used from this point forward to represent all possible variations of STEM plus the additional disciplines that can be incorporated in STEM curricula. Educational approaches, such as inquiry-based (e.g., Pedaste et al., 2015), project-based (e.g., Capraro et al., 2013) and design-based learning (e.g., Crismond & Adams, 2012) are ideal for

Y. Pavlou (✉) · Z. C. Zacharia (✉)
Research in Science and Technology Education Group, Department of Educational Sciences, University of Cyprus, Nicosia, Cyprus
e-mail: pavlou.ivoni@ucy.ac.cy; zach@ucy.ac.cy

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implementing STEM+ initiatives because they are student-centered approaches that aim at addressing real-world issues through methods and practices like those of professionals (Martín-Páez et al., 2019; Thibaut et al., 2018). These approaches can facilitate the application of STEM+ concepts and practices in contexts that are relevant and interesting to students (National Academy of Sciences, 2014).

Laboratory experimentation is a fundamental aspect of science and engineering, and hence, the aforementioned educational approaches strive to provide relevant learning experiences to students. Laboratory work provides opportunities for students to implement scientific practices and skills (e.g., observation, hypothesis generation) to test theories and understand natural phenomena (de Jong et al., 2013; de Jong et al., 2014), and also to develop practical (e.g., handling equipment) and transferable (e.g., problem-solving, time management) skills (Reid & Shah, 2007). Traditionally, experimentation took place solely in physical laboratories (PL) that allowed learners to interact with real world physical/concrete materials and apparatus in order to observe and understand natural phenomena. This direct physical experience has been reported to be of pivotal importance during experimentation (e.g., Gire et al., 2010; Kontra et al., 2015; Zacharia, et al., 2012).

However, the exponential growth of technology has led to the need to rethink the practice of laboratory experimentation (Bybee, 2009; de Jong et al., 2013; National Research Council, 2006), with many studies in the past decades focusing on the use of virtual laboratories (VL) and the consequences for teaching, learning and research. Reeves and Crippen (2021) defined VL as "technology-mediated experiences in either two- or three-dimensions that situate the student as being in an emulation of the physical laboratory with the capacity to manipulate virtual equipment and materials via the keyboard and/or handheld controllers" (p. 16). The need for VL to be optimally integrated in STEM+ education became even stronger due to the COVID-19 pandemic and the subsequent rapid shift towards online/blended learning (European Commission, 2022), which inevitably promoted VL as an alternative to PL (Bazelais et al., 2022; Radhamani et al., 2021; Raman et al., 2021). Hence, it is not surprising that there is an increasing focus on the integration of technology to support learning in STEM education research (Zhan et al., 2022).

However, given that both PL and VL are available options for experimentation purposes, the dilemma persists as to which means of experimentation should be preferred for optimizing student learning. For instance, we are still looking for definite answers to questions such as, "Which means of experimentation under what circumstances optimizes student learning across grades K-16, PL or VL?" and "Should PL and VL be used alone or in combination across grades K-16?" The objective of this paper is to synthesize the theoretical and empirical perspectives emerging from the research concerning the exploration of effects of using VL and PL on students' learning during experimentation in order to contribute to the efforts of the community to answer these questions and to inform the research about and practice of laboratory experimentation in STEM+ education.

1.2 The Theoretical Perspective

Traditional views of cognition claim that the brain is made up of abstract functions and that it is a separate entity from the body, a notion that embodied theories currently challenge (Marmeleira & Duarte Santos, 2019). Embodied cognition theories differ in the degree of the effect of sensorimotor experience on cognition that is postulated (Wellsby & Pexman, 2014), but nevertheless, their overarching notion is the same: the interaction between the environment and the body influences cognition (Clark, 2008; Pouw et al., 2014; Wilson, 2002). As Pouw et al. (2014) mentioned, learning seems to depend on "gradual internalization of sensorimotor routines" (p. 65). Hence, researchers attempt to explain human motor, perception and cognition systems as dependent on the body (Farina, 2021). The mental representation of an object involves the sensory and motor regions of the brain, which are activated when the object is perceived or interacted with (Yee & Thompson-Schill, 2016). This mental representation encompasses not only the visual properties of an object, but also relevant actions (Barsalou, 2008; Gibbs, 2005). Neurological studies have shown that memory recall activates areas of the brain associated with the sensorimotor information experienced during an episode (Kiefer & Pulvermüller, 2012). For example, during the retrieval of haptically encoded stimuli, somatosensory and motor areas of the brain are activated, whereas for visually encoded stimuli, the activation of vision-related areas is observed (Stock et al., 2009). Embodied cognition theories tend to be appealing in terms of representing the organization of conceptual knowledge because they also predict how information is obtained (through sensorimotor experiences) and how and where it is processed (in the relevant sensorimotor systems; Yee et al., 2018).

For educational research, embodied cognition theories provide the opportunity to explore the impact of action on cognition throughout development and to utilize this knowledge to scaffold the teaching and learning process (Kontra et al., 2012). Hayes and Kraemer (2017) noted that embodied cognition theories can support our understanding of how students' STEM learning is enhanced, given the student-centered and hands-on nature of STEM education. In the study by Kontra et al. (2015), even brief physical experience with the forces related to angular momentum led to activation of the sensorimotor systems of the brain used to execute similar actions in the past, which resulted in the development of understanding about that concept. Rich sensorimotor experiences can support the presence of multimodal representations that facilitate learning (Kiefer & Trumpp, 2012) with a variety of ways to engage the body, from limited (e.g., gestures) to full-body movement (Skulmowski & Rey, 2018).

The provision of high-embodiment experiences does not necessarily guarantee a positive impact on learning, but bodily experiences that relate to the task at hand seem to do so (Johnson-Glenberg, 2019; Skulmowski & Rey, 2018). For example, in a study by Mavilidi et al. (2017), preschoolers were engaged in activities related to the solar system in three experimental conditions: (1) integration of related physical activities, (2) integration of irrelevant physical activities and (3) no physical activities. It became apparent after an immediate and a 6-week assessment, that the preschoolers participating in tasks that incorporated meaningful physical activities outperformed the rest of the groups, and even the preschoolers participating in the irrelevant physical activities outperformed the students who were not involved in any type of physical activities. Zohar and Levy (2021) investigated whether an increase in bodily engagement (movie, simulation, joystick and haptic device with force feedback) subsequently leads to an increase in understanding of the concept of chemical bonding. The movie, simulation and joystick conditions resulted in similar conceptual development, whereas the participants in the haptic device condition, which offered the highest bodily engagement, had a significantly higher increase in knowledge. In a study by Qi et al. (2021), providing force feedback in a simulation to students with limited prior understanding of forces also facilitated learning, but providing additional visual cues (i.e., abstract arrows) did not improve performance. Hence, not all bodily experiences can enhance learning in the same manner; alignment between the manipulation and the learning objective is needed.

The active and meaningful interaction with materials and apparatus during experimentation is what enhances learning, and not physicality in itself (Han, 2013; Klahr, et al., 2007; Pouw et al., 2014; Triona & Klahr, 2003; Zacharia & Olympiou, 2011). Hence, embodied cognition theories do not necessarily favor a specific mode of experimentation (Rau, 2020). However, haptic perspectives on learning do favor the haptic manipulation of materials because, when combined with visual stimuli, it can support memory retrieval, minimize the likelihood of cognitive overload and support the conceptual grounding of abstract concepts (Rau, 2020). As stated by Van Doorn et al. (2010, p. 813), "[t]he term haptic refers to a perceptual system that combines both input from receptors in the skin and kinesthetic information." Through touch, we can gather information (e.g., about the properties of an object) and act (e.g., lift the object), but also, based on the sensory feedback received (e.g., the force used was not enough to lift the object), we attune our actions to fit our initial intentions (e.g., use more force; Reiner, 2008).

The haptic and the visual system are complementary in nature. In a study by Reiner et al. (2006), participants used a haptic interface to lift virtual cylinders marked with the labels "heavy", "light" or "###" (neutral condition), which were compatible, incompatible or neutral with regard to the actual weight of the cylinders. It became apparent that both the reaction time and error rate were lower for the cylinders with a label that was compatible with their weight, and higher when the label was incompatible. The haptic system has a higher processing cost than the visual system and hence it will be invoked when visual information is inadequate for addressing a targeted task (Hatwell, 2003; Klatzky, et al. 1993). Given that touch has an inherent bias towards how an object "feels" (e.g., texture, material) rather than its structural properties (e.g., size, shape; Klatzky et al., 1991; Klatzky et al., 1987; Klatzky et al., 1993), the haptic system will be activated only to assist vision when exploring structural properties (Hatwell, 2003), but it can be used for discriminating objects based on their surface textures (Heller, 1989). Thus, based on haptic perspectives on learning, it is expected that haptic manipulation, as an additional available modality, will augment the development of concept-specific understanding, particularly of concepts for which haptic cues can facilitate the development of multimodal representations, such as force (Han, 2013; Zohar & Levy, 2021) and mass (Lazonder & Ehrenhard, 2014; Pavlou et al., under review; Zacharia et al., 2012). For example, in the study by Lazonder and Ehrenhard (2014) regarding free fall, students who engaged with physical materials were able to develop scientifically correct understandings because the haptic sensory feedback available facilitated the correction of students' misconceptions and revision of mass-related beliefs. This process was not evident in the demonstration or VL groups.

Haptic sensory feedback simply cannot be offered in a virtual environment. Haptic technologies for providing sensory feedback (e.g., force feedback) in VL do exist, and studies investigating their impact on learning (e.g., Bivall et al., 2011; Han & Black, 2011; Jones et al., 2006; Magana et al., 2019; Zhuoluo et al., 2019) have reported positive findings, but the sensory feedback they provide is still quite limited in comparison to the haptic and dynamic feedback available when engaging with PL. Haptically enhanced simulations are also primarily focused on developing skills (e.g., related to surgeries; Qi et al., 2021), and the integration of such technologies, especially in formal education, is still very limited (Georgiou & Ioannou, 2019; Johnson-Glenberg, 2019; Malinverni & Pares, 2014).

As Pavlou et al. (under review) pointed out, when considering comparative studies in the field of science education from the haptic encoding and embodied cognition perspectives, findings of an equal or even negative impact of PL on learning can be attributed to a lack of significant perceptual differences between the VL and PL being compared (i.e., the perceptual stimuli and the available feedback offered in the PL did not differ significantly from the virtual environment; e.g., Han, 2013) and/or the participants' prior experiences/knowledge of the concepts under investigation. As far as the latter is concerned, it is evident that most studies in the field of science education focus on the primary school years and onwards (Wörner et al., 2022; Zacharia, 2015). For older students, knowledge of the concepts under investigation could have been grounded in the early years and hence, embodied experiences might not be a prerequisite for those students. As Yee et al. (2018) mentioned, as development progresses, the reliance on abstract knowledge increases, and direct sensorimotor experience is not as necessary as for young children. However, PL can be more beneficial than VL in the early years of education when considering the reliance on grounded experience, especially through the haptic manipulation of objects (Pavlou et al., under review).

For example, in the comparative study by Zacharia et al. (2012), preschoolers with scientifically correct prior understanding of the concepts under investigation (the function of a balance beam) who interacted with either physical or virtual manipulatives outperformed students with incorrect prior knowledge who engaged with the virtual environment. Their findings indicated that haptic sensory feedback, which is a unique affordance of PL, is a prerequisite for learning if participants do not have any previous understanding of the concepts. The study by Pavlou et al. (under review) validated and also expanded the findings by Zacharia et al. (2012). This study compared the conceptual understanding of preschoolers engaged in VL or PL in three subject domains (balance beam, springs and sinking/floating). In the balance beam and springs domains, the mass of the objects (a property that should be multimodally grounded to support learning) is a causal factor affecting the experimental output, but for the sinking/floating domain, the idea that mass affects the object's behavior in water is a common misconception children have (see, e.g., Havu-Nuutinen, 2005; Hsin & Wu, 2011; Pavlou et al., 2018). Preschoolers working in the balance beam and sinking/floating domains had prior understanding of the domains, but participants working in the springs domain did not. The mode of experimentation did not affect the learning outcome for preschoolers engaged in the balance beam domain, but preschoolers who engaged with PL during experimentation in the domain of springs outperformed the participants in the VL group because the haptic sensory feedback offered in the PL group seemed to facilitate the development of understanding of the causal effect of mass. However, in the sinking/floating domain, haptic sensory feedback available during experimentation with physical materials impeded the development of a scientifically correct understanding, and the mass-related idea that "heavy objects sink/light object float" was the most dominant idea used by preschoolers to explain the phenomenon both before and after experimentation. Similar findings were also found in the preliminary study (Pavlou et al., 2018). The authors concluded that although information about other object properties was available, especially through vision, and was at times more salient than mass, haptic cues related to the mass of the objects were the most dominant perceptual cues that led to the fixation/empowerment of relevant ideas. Hence, providing haptic sensory feedback during experimentation can be detrimental (for students holding relevant misconceptions, as in the sinking/floating domain), beneficial (for students with no prior understanding, as in the springs domain) or have no significant impact (as for the preschoolers with prior knowledge of the balance beam domain). To conclude, it seems that haptic sensory feedback, which is available through engagement in PL, is not always a prerequisite for learning (see also Zacharia, 2015). In other words, VL can be used under certain conditions as a means for experimentation because they can support or even augment the development of the understanding of scientific concepts.

1.3 The Empirical Perspective

VL carry a lot of affordances that can support learning, as highlighted by many researchers (e.g., Faulconer & Gruss, 2018; de Jong et al., 2013; Olympiou & Zacharia, 2012; Potkonjak et al., 2016; Zacharia, 2015). For example, VL provide the opportunity to experiment with unobservable phenomena (e.g., radiation), to manipulate variables (e.g., light rays) and other parameters (e.g., time, spatial dimensions, data displays) and to engage with abstract concepts (e.g., symbolic representations of light). In addition, VL provide access to multiple users, are cost- and safety-efficient and minimize trial errors. Therefore, the empirical literature initially focused on exploring whether VL can support teaching and learning and specifically, whether their impact can be similar to or even greater than that of

PL. There are studies showing an advantage of VL over PL (e.g., Akpan & Andre, 2000; Bell & Trundle, 2008; Finkelstein et al., 2005) and studies showcasing opposite findings (e.g., Gire et al., 2010; Marshall & Young, 2006). However, the majority of comparative studies do not indicate that one mode of experimentation dominates over the other (e.g., Chini et al., 2012; Evangelou & Kotsis, 2019; Klahr et al., 2007; Leung & Cheng, 2021; Reece & Butler, 2017; Triona & Klahr, 2003; Zacharia & Constantinou, 2008; Zacharia & Olympiou, 2011). Inconsistencies between these studies can in part be attributed to the varying affordances carried by PL and VL that were utilized, the varying methodological approaches employed (D'Angelo et al., 2014; Faulconer & Gruss, 2018; Ma & Nickerson, 2006) and the different theoretical perspectives (or in some cases the lack thereof) adopted to predict and explain the learning outcomes (Reeves & Crippen, 2021).

Nevertheless, literature reviews conducted over the years have pointed out that VL has an effect equal to or even greater than that of PL (Brinson, 2015; D'Angelo et al., 2014; Faulconer & Gruss, 2018) or other teaching approaches (Rutten et al., 2012; Smetana & Bell, 2012). Overall, the extant empirical research studies have revealed the potential of VL experimentation for enhancing students' learning across grades K-16 (e.g., Potkonjak et al., 2016; Triona & Klahr, 2003; van der Meij & de Jong, 2006; Zacharia & Anderson, 2003; Zacharia et al., 2008; Zacharia et al., 2012). Consequently, it can be argued that VL can provide learning experiences that are just as meaningful to students as PL and, considering the many more unique affordances carried by VL as opposed to PL, some could argue that under certain circumstances, VL could be less "messy", easier to manage, and more flexible and expandable than PL (Klahr et al., 2008), especially if we consider some of the "disadvantages" of PL (e.g., space and time restrictions, absence of abstract representations). Hence, should one mode of experimentation be preferred over the other?

VL and PL have complementary affordances and thus their combination can support presentation of multiple representations of science concepts (de Jong et al., 2013; Olympiou & Zacharia, 2012; Puntambekar et al., 2021; Zacharia, 2007; Zacharia & de Jong, 2014; Zacharia & Michael, 2016). The meaningful integration of multiple representations of a concept (e.g., a physical and a virtual/abstract representation) can enhance learning to a greater extent than stand-alone representations (Ainsworth, 2008). For example, in a study by Wang and Tseng (2018), third-graders who engaged in the combination condition (VL and then PL) outperformed the students who engaged in stand-alone modes of experimentation. Kapici et al. (2019) also reported an advantage of the combination of VL and PL for seventh-grade students for the concept of electricity. Even though some studies have showcased that the stand-alone use of VL and PL has a greater impact on learning than their combination during experimentation (e.g., Gnesdilow & Puntambekar, 2022), overall, their combination seems to be more beneficial than stand-alone use (de Jong et al., 2013; Wörner et al., 2022). Teachers from different educational levels also seemed to support the combination of the two modes of experimentation for teaching and learning practice (Tsihouridis, et al., 2019).

Studies investigating the combination of VL and PL (e.g., Achuthan et al., 2017; Fuhrmann, et al., 2014; Olympiou & Zacharia, 2012, 2014; Trundle & Bell, 2010;

Yuksel et al., 2019; Zacharia, 2007; Zacharia et al., 2008) and the different ways in which they can be combined (e.g., at the same time, blended, in sequence), have showcased their complementary nature, but nevertheless provide limited information on the preeminent affordances of each mode (Lazonder & Ehrenhard, 2014). Similarly, because most of the comparative studies focused on improving students' learning (Reeves & Crippen, 2021), VL and PL experimentation were generally compared (e.g., as instructional approaches) without necessarily accounting for the potential effect of specific affordances. This is a vital underpinning in order to achieve optimal combinations for learning (Rau, 2020; Wörner et al., 2022; Zacharia et al., 2008). Thus, identifying these unique affordances of each mode of experimentation and their effect on student learning across grades K-16, as well as understanding when and under what conditions a particular mode of experimentation, along with its unique affordances, becomes more effective is still a critical issue. For instance, the community focusing on PL and VL has not yet distinguished the circumstances under which a unique affordance optimizes learning and whether such an effect holds true across grades K-16. For example, does providing abstract representations – a unique affordance of VL – support student learning the same way across grades K-16? The community also lacks information on how different unique affordances interact with each other and how this interaction impacts student learning. Moreover, the theoretical perspective through which the issue of unique affordances is approached affects the predictions and explanations articulated with regard to the impact of VL on learning (Rau & Herder, 2021). In the next section, we attempt to synthesize the theoretical and empirical perspective presented in this article.

1.4 Bridging Theory and Research with Practice in STEM+ Education

Educational approaches that facilitate STEM+ learning, such as the inquiry-based learning approach or the engineering design learning approach, call for students' active engagement and involvement in the learning process (de Jong, 2019). Laboratory work is a focal aspect of these approaches, which can be productively enacted with virtual and/or physical means (de Jong et al., 2013; Zacharia & de Jong, 2014). The role of laboratory experimentation becomes even more crucial within STEM+ education, when science is used as the dominant discipline among all of the disciplines involved.

Given that both the theoretical and the empirical evidence support the idea that both PL and VL are viable means of experimentation for students (e.g., Finkelstein et al., 2005; Triona & Klahr, 2003; van der Meij & de Jong, 2006; Zacharia, 2015; Zacharia et al., 2008), including preschoolers (Pavlou et al., 2018, under review; Zacharia et al., 2012), the palette of experimentation possibilities available to teachers (i.e., use of PL, use of VL, use of combinations of PL and VL) needs to be expanded. In the past decades, research has shown that both VL and PL can support learning and that their meaningful combination can be conducive to developing multimodal representations of concepts (de Jong et al., 2013; Olympiou & Zacharia, 2012; Puntambekar et al., 2021; Zacharia, 2007; Zacharia & de Jong, 2014; Zacharia & Michael, 2016). However, identifying the situations in which PL and/or VL can be utilized to optimize student learning across grades K-16 is still a critical issue.

Olympiou and Zacharia (2012) developed a framework summarizing a series of considerations on how to combine/blend PL and VL. Based on their framework, contemplation of the affordances of each mode of experimentation (unique or not) in conjunction with the learning objectives of each experiment and students' background (e.g., prior conceptions, skills) is vital. The framework was validated in studies concerning undergraduate students (Olympiou & Zacharia, 2012, 2014) and primary school students (Zacharia & Michael, 2016) that exhibited the advantages of blending the two modes of experimentation instead of using VL or PL alone. The framework can support the decision-making process when designing laboratory experimentation activities for STEM+ initiatives with the integration of VL and PL. Below, we discuss – and extend – some of the key considerations integrated in this framework, in conjunction with the relevant literature.

Research has shown that despite the overlapping affordances of VL and PL offered during experimentation (e.g., manipulation of material, perceptual grounding for abstract concepts), their unique affordances can affect learning in a different manner (for more details, see Olympiou & Zacharia, 2014; Zacharia, 2015). On the one hand, the ability to visualize abstract concepts (e.g., light rays, particles, current flow) and modify parameters, such as time and dimensions, is a unique affordance of VL. For example, in a study by Finkelstein et al. (2005), university students working with a virtual laboratory for electrical circuits in which they could manipulate parameters (e.g., voltage) and visualize current flow outperformed the students working with physical materials, to whom such affordances were not offered. A study by Zacharia and de Jong (2014) highlighted the learning benefits of using VL prior to PL for the understanding of complex circuits because the virtual environment offers the additional visualization of the current-flow. The appropriate consideration of these affordances for this subject domain (see, e.g., Zacharia & Michael, 2016) can facilitate the appropriate blending of both modes of experimentation to support development of multimodal understanding.

On the other hand, the availability of haptic sensory feedback during manipulation is a unique affordance of PL. According to haptic perspectives on learning and empirical studies (e.g., Han, 2013; Lazonder & Ehrenhard, 2014; Pavlou et al., under review; Zacharia et al., 2012; Zacharia, 2015), the presence/absence of haptic sensory feedback can affect learning; hence, the identification of the conditions under which it can be beneficial or detrimental during experimentation can support the optimal integration of VL and PL in STEM+ education. The development of understanding of concepts such as forces (e.g., Han, 2013; Zohar & Levy, 2021), mass/weight (e.g., Lazonder & Ehrenhard, 2014; Pavlou et al., under review; Zacharia et al., 2012) and magnetic fields (e.g., Reiner, 1999) seems to benefit from interaction with haptic stimuli. Haptic sensory feedback is possibly even more essential for students with no prior embodied experience/knowledge of a domain, for whom haptic cues can enhance concept-specific understanding when visual cues alone are not adequate for solving a task (e.g., Pavlou et al., under review; Qi et al., 2021; Zacharia et al., 2012; Zohar & Levy, 2021). However, it should be taken into account that haptic cues related to a students' misconception might also hinder learning (i.e., lead to a fixation/empowerment of the misconception) as in the sinking/floating domain of the Pavlou et al. (under review) study.

In addition, based on the theoretical perspective in this article, the lack of embodied experiences with a domain seems to be a vital consideration when selecting/combining VL and PL. The initial sensorimotor grounding of scientific knowledge in STEM classrooms through hands-on approaches can support the development of abstract knowledge (Hayes & Kraemer, 2017). When prior knowledge/embodied experience with the concepts under investigation is lacking, then the use of PL during experimentation will most likely significantly improve the learning outcome (e.g., Pavlou et al., under review; Zacharia et al., 2012). For example, if students do not have any prior experience with a domain, PL can proceed VL to provide such experiences, especially when haptic manipulation (in combination with other modalities) can enhance conceptual understanding. To amplify the effect of embodiment, there should be a strong relation between the task at hand and the bodily movements enacted by the students working in a virtual or physical environment (e.g., Johnson-Glenberg, 2019; Mavilidi et al., 2017; Qi et al., 2021; Skulmowski & Rey, 2018; Zohar & Levy, 2021).

Of course, the need to provide embodied experiences (including haptic sensory feedback) might not be as vital for older students because such experiences were probably acquired during their early years through formal and/or informal learning, an argument that can even support the stand-alone use of VL (especially when considering the importance of distance/online learning). This argument agrees with empirical research that has shown an advantage or equal effect of VL on learning for a variety of domains and disciplines for students in primary school and older (Brinson, 2015; Zacharia, 2015). Nevertheless, the reliance of younger children on sensorimotor experience indicates the importance of using PL during experimentation. However, studies with preschoolers (Pavlou et al., 2018, under review; Zacharia et al., 2012) have shown that under certain conditions, the use of VL can also facilitate learning for younger children. Given that empirical research has focused on older students (for details, see Zacharia, 2015), our understanding of the situations in which VL can support learning in early childhood education is still limited.

Another aspect that should be taken into consideration when selecting a means of experimentation for STEM+ enactments is factors related to the affective domain. For example, Justo et al. (2022) found that even though VL and PL had similar effects on the learning of basic engineering concepts, students' motivation increased with the use of physical materials. As Tsihouridis et al. (2019) also highlighted, primary students usually favor PL, whereas older students prefer VL. Hence, aspects other than learning (which were not the focus of this article, for example, the enhancement of students' skills or attitudes) can also guide the decision about which mode of experimentation is more appropriate.

The additional value of VL in education is no longer disputed, and research seems to be turning towards addressing the question of "which one is better" in what instances, how and for whom (de Jong, 2019). As noted in this article, the theoretical underpinning guiding how these questions are being examined does matter for the instructional design and the way the findings are explained (see Rau, 2020; Rau & Herder, 2021). Combining empirical and theoretical perspectives is essential. In addition, the current literature portrays the complex interplay between aspects, such as the affordances of each mode of experimentation, the concepts under investigation (e.g., haptic cues can augment concept-specific understanding) and students' prior embodied experiences/knowledge (including their misconceptions). However, the influence of this interplay on students' learning and the possible dominance of one aspect over others (e.g., whether students' misconceptions can impede concept-specific understanding in VL/PL) is yet unclear; research is still needed to develop a comprehensive framework for the optimal integration of PL and VL in STEM+ education.

References

Achuthan, K., Francis, S. P., & Diwakar, S. (2017). Augmented reflective learning and knowledge retention perceived among students in classrooms involving virtual laboratories. *Education and Information Technologies, 22*(6), 2825–2855. https://doi.org/10.1007/s10639-017-9626-x

Ainsworth, S. (2008). The educational value of multiple-representations when learning complex scientific concepts. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 191–208). Springer. https://doi.org/10.1007/978-1-4020-5267-5_9

Akpan, J. P., & Andre, T. (2000). Using a computer simulation before dissection to help students learn anatomy. *Journal of Computers in Mathematics and Science Teaching, 19*(3), 297–313.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology, 59*(1), 617–645. https://doi.org/10.1146/annurev.psych.59.103006.093639

Bazelais, P., Binner, G., & Doleck, T. (2022). Examining the key drivers of student acceptance of online labs. *Interactive Learning Environments*, 1–16. https://doi.org/10.1080/10494820.2022.2121729

Bell, R. L., & Trundle, K. C. (2008). The use of a computer simulation to promote scientific conceptions of moon phases. *Journal of Research in Science Teaching, 45*(3), 346–372.

Bivall, P., Ainsworth, S., & Tibell, L. A. (2011). Do haptic representations help complex molecular learning? *Science Education, 95*(4), 700–719.

Brinson, J. R. (2015). Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research. *Computers & Education, 87*, 218–237. https://doi.org/10.1016/j.compedu.2015.07.003

Bybee, R. W. (2009). *The BSCS 5E instructional model and 21st century skills*. BSCS.

Capraro, R. M., Capraro, M. M., & Morgan, J. R. (Eds.). (2013). *STEM project-based learning: An integrated science, technology, engineering, and mathematics (STEM) approach*. Springer Science & Business Media.

Chini, J. J., Madsen, A., Gire, E., Rebello, N. S., & Puntambekar, S. (2012). Exploration of factors that affect the comparative effectiveness of physical and virtual manipulatives in an undergraduate laboratory. *Physical Review Special Topics – Physics Education Research, 8*(1), 010113. https://doi.org/10.1103/PhysRevSTPER.8.010113

Clark, A. (2008). *Supersizing the mind: Embodiment, action, and cognitive extension*. Oxford University Press.
Crismond, D. P., & Adams, R. S. (2012). The informed design teaching & learning matrix. *Journal of Engineering Education, 101*(4), 738–797.
D'Angelo, C., Rutstein, D., Harris, C., Bernard, R., Borokhovski, E., & Haertel, G. (2014). *Simulations for STEM learning: Systematic review and meta-analysis*. SRI International.
de Jong, T. (2019). Moving towards engaged learning in STEM domains; There is no simple answer, but clearly a road ahead. *Journal of Computer Assisted Learning, 35*(2), 153–167.
de Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and virtual laboratories in science and engineering education. *Science, 340*(6130), 305–308. https://doi.org/10.1126/science.1230579
de Jong, T., Sotiriou, S., & Gillet, D. (2014). Innovations in STEM education: The Go-Lab federation of online labs. *Smart Learning Environments, 1*(1), 1–16. https://doi.org/10.1126/science.1230579
European Commission. (2022). *Impacts of COVID-19 on school education*. Publications Office of the European Union. Retrieved from https://data.europa.eu/doi/10.2766/201112
Evangelou, F., & Kotsis, K. (2019). Real vs virtual physics experiments: Comparison of learning outcomes among fifth grade primary school students. A case on the concept of frictional force. *International Journal of Science Education, 41*(3), 330–348. https://doi.org/10.1080/09500693.2018.1549760
Farina, M. (2021). Embodied cognition: Dimensions, domains and applications. *Adaptive Behavior, 29*(1), 73–88. https://doi.org/10.1177/1059712320912963
Faulconer, E., & Gruss, A. (2018). A review to weigh the pros and cons of online, remote, and distance science laboratory experiences. *The International Review of Research in Open and Distributed Learning, 19*(2), 155–168. https://doi.org/10.19173/irrodl.v19i2.3386
Finkelstein, N. D., Adams, W. K., Keller, C. J., Kohl, P. B., Perkins, K. K., Podolefsky, N. S., et al. (2005). When learning about the real world is better done virtually: A study of substituting computer simulations for laboratory equipment. *Physical Review Special Review Special Topics-Physics Education Research, 1*(1), 010103. https://doi.org/10.1103/PhysRevSTPER.1.010103
Fuhrmann, T., Salehi, S., & Blikstein, P. (2014). *A tale of two worlds: Using bifocal modeling to find and resolve "discrepant events" between physical experiments and virtual models in biology*. International Society of the Learning Sciences.
Georgiou, Y., & Ioannou, A. (2019). Embodied learning in a digital world: A systematic review of empirical research in K-12 education. In P. Díaz, A. Ioannou, K. K. Bhagat, & J. M. Spector (Eds.), *Learning in a digital world: Perspective on interactive technologies for formal and informal education* (pp. 155–177). Springer. https://doi.org/10.1007/978-981-13-8265-9_8
Gibbs, R. W. (2005). *Embodiment and cognitive science*. Cambridge University Press.
Gire, E., Carmichael, A., Chini, J. J., Rouinfar, A., Rebello, S., Smith, G., & Puntambekar, S. (2010). The effects of physical and virtual manipulatives on students' conceptual learning about pulleys. In *Proceedings of the 9th international conference of the learning sciences* (Vol. 1, pp. 937–943). International Society of the Learning Sciences.
Gnesdilow, D., & Puntambekar, S. (2022). Comparing middle school students' science explanations during physical and virtual laboratories. *Journal of Science Education and Technology, 31*, 191–202. https://doi.org/10.1007/s10956-021-09941-0
Han, I. (2013). Embodiment: A new perspective for evaluating physicality in learning. *Journal of Educational Computing Research, 49*(1), 41–59. https://doi.org/10.2190/EC.49.1.b
Han, I., & Black, J. B. (2011). Incorporating haptic feedback in simulation for learning physics. *Computers & Education, 57*(4), 2281–2290. https://doi.org/10.1016/j.compedu.2011.06.012
Hatwell, Y. (2003). Manual exploratory procedures in children and adults. In Y. Hatwell, A. Streri, & E. Gentaz (Eds.), *Touching for knowing: Cognitive psychology of haptic manual perception* (pp. 67–82). John Benjamins Publishing Company.
Havu-Nuutinen, S. (2005). Examining young children's conceptual change process in floating and sinking from a social constructivist perspective. *International Journal of Science Education, 27*(3), 259–279. https://doi.org/10.1080/0950069042000243736

Hayes, J. C., & Kraemer, D. J. (2017). Grounded understanding of abstract concepts: The case of STEM learning. *Cognitive Research: Principles and Implications, 2*(1), 1–15. https://doi.org/10.1186/s41235-016-0046-z

Heller, M. A. (1989). Texture perception in sighted and blind observers. *Perception & Psychophysics, 45*(1), 49–54. https://doi.org/10.3758/BF03208032

Hsin, C., & Wu, H. (2011). Using scaffolding strategies to promote young children's scientific understandings of floating and sinking. *Journal of Science Education and Technology, 20*(5), 656–666. https://doi.org/10.1007/s10956-011-9310-7

Johnson-Glenberg, M. C. (2019). The necessary nine: Design principles for embodied VR and active STEM education. In P. Díaz, A. Ioannou, K. K. Bhagat, & J. Spector (Eds.), *Learning in a digital world* (pp. 83–112). Springer.

Jones, M. G., Minogue, J., Tretter, T. R., Negishi, A., & Taylor, R. (2006). Haptic augmentation of science instruction: Does touch matter? *Science Education, 90*(1), 111–123.

Justo, E., Delgado, A., Llorente-Cejudo, C., Aguilar, R., & Caber-Almenara, J. (2022). The effectiveness of physical and virtual manipulatives on learning and motivation in structural engineering. *Journal of Engineering Education, 111*(4), 813–851. https://doi.org/10.1002/jee.20482thi

Kapici, H. O., Akcay, H., & de Jong, T. (2019). Using hands-on and virtual laboratories alone or together – Which works better for acquiring knowledge and skills? *Journal of Science Education and Technology, 28*(3), 231–250.

Kiefer, M., & Pulvermüller, F. (2012). Conceptual representations in mind and brain: Theoretical developments, current evidence and future directions. *Cortex, 48*(7), 805–825. https://doi.org/10.1016/j.cortex.2011.04.006

Kiefer, M., & Trumpp, N. M. (2012). Embodiment theory and education: The foundations of cognition in perception and action. *Trends in Neuroscience and Education, 1*(1), 15–20. https://doi.org/10.1016/j.tine.2012.07.002

Klahr, D., Triona, L. M., & Williams, C. (2007). Hands on what? The relative effectiveness of physical versus virtual materials in an engineering design project by middle school children. *Journal of Research in Science Teaching, 44*(1), 183–203. https://doi.org/10.1002/tea.20152

Klahr, D., Triona, L., Strand-Cary, M., & Siler, S. (2008). Virtual vs. physical materials in early science instruction: Transitioning to an autonomous tutor for experimental design. In J. Zumbach, N. Schwartz, T. Seufert, & L. Kester (Eds.), *Beyond knowledge: The legacy of competence* (pp. 163–172). Springer. https://doi.org/10.1007/978-1-4020-8827-8_23

Klatzky, R. L., Lederman, S. J., & Reed, C. (1987). There's more to touch than meets the eye: The salience of object attributes for haptics with and without vision. *Journal of Experimental Psychology: General, 116*(4), 356–369. https://doi.org/10.1037/0096-3445.116.4.356

Klatzky, R. L., Lederman, S. J., & Matula, D. E. (1991). Imagined haptic exploration in judgments of object properties. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17*(2), 314–322.

Klatzky, R. L., Lederman, S. J., & Matula, D. E. (1993). Haptic exploration in the presence of vision. *Journal of Experimental Psychology: Human Perception and Performance, 19*(4), 726–743. https://doi.org/10.1037/0096-1523.19.4.726

Kontra, C., Goldin-Meadow, S., & Beilock, S. L. (2012). Embodied learning across the life span. *Topics in Cognitive Science, 4*(4), 731–739. https://doi.org/10.1111/j.1756-8765.2012.01221.x

Kontra, C., Lyons, D. J., Fischer, S. M., & Beilock, S. L. (2015). Physical experience enhances science learning. *Psychological Science, 26*(6), 737–749. https://doi.org/10.1177/0956797615569355

Lazonder, A. W., & Ehrenhard, S. (2014). Relative effectiveness of physical and virtual manipulatives for conceptual change in science: How falling objects fall. *Journal of Computer Assisted Learning, 30*(2), 110–120. https://doi.org/10.1111/jcal.12024

Leung, P. K. Y., & Cheng, M. M. W. (2021). Practical work or simulations? Voices of millennial digital natives. *Journal of Educational Technology Systems, 50*(1). https://doi.org/10.1177/00472395211018967

Ma, J., & Nickerson, J. V. (2006). Hands-on, simulated, and remote laboratories: A comparative literature review. *ACM Computing Surveys, 38*(3), 1–24. https://doi.org/10.1145/1132960.1132961

Magana, A. J., Serrano, M. I., & Rebello, N. S. (2019). A sequenced multimodal learning approach to support students' development of conceptual learning. *Journal of Computer Assisted Learning, 35*(4), 516–528. https://doi.org/10.1111/jcal.12356
Malinverni, L., & Pares, N. (2014). Learning of abstract concepts through full-body interaction: A systematic review. *Journal of Educational Technology & Society, 17*(4), 100–116.
Marmeleira, J., & Duarte Santos, G. (2019). Do not neglect the body and action: The emergence of embodiment approaches to understanding human development. *Perceptual and Motor Skills, 126*(3), 410–445.
Marshall, J. A., & Young, E. S. (2006). Preservice teachers' theory development in physical and simulated environments. *Journal of Research in Science Teaching, 43*(9), 907–937. https://doi.org/10.1002/tea.20124
Martín-Páez, T., Aguilera, D., Perales-Palacios, F., & Vílchez-González, J. M. (2019). What are we talking about when we talk about STEM education? A review of literature. *Science Education, 103*(4), 799–822. https://doi.org/10.1002/sce.21522
Mavilidi, M., Okely, A. D., Chandler, P., & Paas, F. (2017). Effects of integrating physical activities into a science lesson on preschool children's learning and enjoyment. *Applied Cognitive Psychology, 31*(3), 281–290.
National Academy of Sciences. (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research*. National Academies Press. https://doi.org/10.17226/18612
National Research Council. (2006). *America's lab report: Investigations in high school science*. National Academies Press.
Next Generation Science Standards Lead States. (2013). *Next generation science standards: For states, by states*. National Academies Press. Retrieved from http://www.nextgenscience.org/
Olympiou, G., & Zacharia, Z. C. (2012). Blending physical and virtual manipulatives: An effort to improve students' conceptual understanding through science laboratory experimentation. *Science Education, 96*(1), 21–47. https://doi.org/10.1002/sce.20463
Olympiou, G., & Zacharia, Z. C. (2014). Blending physical and virtual manipulatives in physics laboratory experimentation. In C. Bruguière, A. Tiberghien, & P. Clément (Eds.), *Topics and trends in current science education* (pp. 419–433). Springer.
Pavlou, Y., Papaevripidou, M., & Zacharia, Z. (2018). Can preschoolers develop an understanding of the sinking/floating phenomenon through physical and virtual experimental environments? In M. Kalogiannakis (Ed.), *Teaching natural sciences in preschool education: Challenges and perspectives* (pp. 76–95). Gutenberg.
Pavlou, Y., Zacharia, Z., & Papaevripidou, M. (under review). Comparing the impact of physical and virtual manipulatives in different science domains among preschoolers. *Science Education*.
Pedaste, M., Mäeots, M., Siiman, L. A., de Jong, T., van Riesen, S. A. N., Kamp, E. T., et al. (2015). Phases of inquiry-based learning: Definitions and the inquiry cycle. *Educational Research Review, 14*, 47–61. https://doi.org/10.1016/j.edurev.2015.02.003
Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V. M., & Jovanović, K. (2016). Virtual laboratories for education in science, technology, and engineering: A review. *Computers & Education, 95*, 309–327.
Pouw, W. T. J. L., van Gog, T., & Paas, F. (2014). An embedded and embodied cognition review of instructional manipulatives. *Educational Psychology Review, 26*, 51–72. https://doi.org/10.1007/s10648-014-9255-5
Puntambekar, S., Gnesdilow, D., Dornfeld Tissenbaum, C., Narayanan, N. H., & Rebello, N. S. (2021). Supporting middle school students' science talk: A comparison of physical and virtual labs. *Journal of Research in Science Teaching, 58*(3), 392–419.
Qi, K., Borland, D., Brunsen, E., Minogue, J., & Peck, T. C. (2021). The impact of prior knowledge on the effectiveness of haptic and visual modalities for teaching forces. In *Proceedings of the 2021 international conference on multimodal interaction, Montréal, Canada* (pp. 203–211). https://doi.org/10.1145/3462244.3479915
Radhamani, R., Kumar, D., Nizar, N., Achuthan, K., Nair, B., & Diwakar, S. (2021). What virtual laboratory usage tells us about laboratory skill education pre-and post-COVID-19: Focus

on usage, behavior, intention and adoption. *Education and Information Technologies, 26*(6), 7477–7495. https://doi.org/10.1007/s10639-021-10583-3

Raman, R., Vinuesa, R., & Nedungadi, P. (2021). Acquisition and user behavior in online science laboratories before and during the COVID-19 pandemic. *Multimodal Technologies and Interaction, 5*(8), 46. https://doi.org/10.3390/mti5080046

Rau, M. A. (2020). Comparing multiple theories about learning with physical and virtual representations: Conflicting or complementary effects? *Educational Psychology Review, 32*(2), 297–325. https://doi.org/10.1007/s10648-020-09517-1

Rau, M. A., & Herder, T. (2021). Under which conditions are physical versus virtual representations effective? Contrasting conceptual and embodied mechanisms of learning. *Journal of Educational Psychology, 113*(8), 1565–1586. https://doi.org/10.1037/edu0000689

Reece, A. J., & Butler, M. B. (2017). Virtually the same: A comparison of STEM students' content knowledge, course performance, and motivation to learn in virtual and face-to-face introductory biology laboratories. *Journal of College Science Teaching, 46*(3), 83–89.

Reeves, S. M., & Crippen, K. J. (2021). Virtual laboratories in undergraduate science and engineering courses: A systematic review, 2009–2019. *Journal of Science Education and Technology, 30*(1), 16–30. https://doi.org/10.1007/s10956-020-09866-0

Reid, N., & Shah, I. (2007). The role of laboratory work in university chemistry. *Chemistry Education Research and Practice, 8*(2), 172–185.

Reiner, M. (1999). Conceptual construction of fields through tactile interface. *Interactive Learning Environments, 7*(1), 31–55. https://doi.org/10.1076/ilee.7.1.31.3598

Reiner, M. (2008). Seeing through touch: The role of haptic information in visualization. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 73–84). Springer. https://doi.org/10.1007/978-1-4020-5267-5_4

Reiner, M., Hecht, D., Halevy, G., & Furman, M. (2006). Semantic interference and facilitation in haptic perception. In *Proceedings of the Eurohaptics conference*, *Paris* (pp. 41–35).

Rutten, N., van Joolingen, W. R., & van der Veen, J. T. (2012). The learning effects of computer simulations in science education. *Computers & Education, 58*(1), 136–153. https://doi.org/10.1016/j.compedu.2011.07.017

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), 6. https://doi.org/10.1186/s41235-018-0092-9

Smetana, L. K., & Bell, R. L. (2012). Computer simulations to support science instruction and learning: A critical review of the literature. *International Journal of Science Education, 34*(9), 1337–1370. https://doi.org/10.1080/09500693.2011.605182

Stock, O., Röder, B., Burke, M., Bien, S., & Rösler, F. (2009). Cortical activation patterns during long-term memory retrieval of visually or haptically encoded objects and locations. *Journal of Cognitive Neuroscience, 21*(1), 58–82. https://doi.org/10.1162/jocn.2009.21006

Thibaut, L., Ceuppens, S., De Loof, H., De Meester, J., Goovaerts, L., Struyf, A., et al. (2018). Integrated STEM education: A systematic review of instructional practices in secondary education. *European Journal of STEM Education, 3*(1), 2.

Triona, L. M., & Klahr, D. (2003). Point and click or grab and heft: Comparing the influence of physical and virtual instructional materials on elementary school students' ability to design experiments. *Cognition and Instruction, 21*(2), 149–173. https://doi.org/10.1207/S1532690XCI2102_02

Trundle, K. C., & Bell, R. L. (2010). The use of a computer simulation to promote conceptual change: A quasi-experimental study. *Computers & Education, 54*(4), 1078–1088. https://doi.org/10.1016/j.compedu.2009.10.012

Tsihouridis, C., Vavougios, D., Batsila, M., & Ioannidis, G. (2019). The optimum equilibrium when using experiments in teaching – Where virtual and real labs stand in science and engineering teaching practice. *International Journal of Emerging Technologies in Learning, 14*(23), 67–84.

van der Meij, J., & de Jong, T. (2006). Supporting students' learning with multiple representations in a dynamic simulation-based learning environment. *Learning and Instruction, 16*(3), 199–212. https://doi.org/10.1016/j.learninstruc.2006.03.007

Van Doorn, G. H., Richardson, B. L., Wuillemin, D. B., & Symmons, M. A. (2010). Visual and haptic influence on perception of stimulus size. *Attention, Perception, & Psychophysics, 72*(3), 813–822.

Wang, T., & Tseng, Y. (2018). The comparative effectiveness of physical, virtual, and virtual-physical manipulatives on third-grade students' science achievement and conceptual understanding of evaporation and condensation. *International Journal of Science and Mathematics Education, 16*(2), 203–219.

Wellsby, M., & Pexman, P. M. (2014). Developing embodied cognition: Insights from children's concepts and language processing. *Frontiers in Psychology, 5*, 506. https://doi.org/10.3389/fpsyg.2014.00506

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review, 9*(4), 625–636. https://doi.org/10.3758/BF03196322

Wörner, S., Kuhn, J., & Scheiter, K. (2022). The best of two worlds: A systematic review on combining real and virtual experiments in science education. *Review of Educational Research, 92*(6), 911–952.

Yee, E., & Thompson-Schill, S. (2016). Putting concepts into context. *Psychonomic Bulletin & Review, 23*(4), 1015–1027. https://doi.org/10.3758/s13423-015-0948-7

Yee, E., Jones, M. N., & McRae, K. (2018). Semantic memory. In J. T. Wixted & S. Thompson-Schill (Eds.), *The Stevens' handbook of experimental psychology and cognitive neuroscience* (4th ed., pp. 1–23). Wiley Online Library.

Yuksel, T., Walsh, Y., Magana, A. J., Nova, N., Krs, V., Ngambeki, I., et al. (2019). Visuohaptic experiments: Exploring the effects of visual and haptic feedback on students' learning of friction concepts. *Computer Applications in Engineering Education, 27*(6), 1376–1401. https://doi.org/10.1002/cae.22157

Zacharia, Z. C. (2007). Comparing and combining real and virtual experimentation: an effort to enhance students' conceptual understanding of electric circuits. *Journal of Computer Assisted Learning, 23*(2), 120–132.

Zacharia, Z. C. (2015). Examining whether touch sensory feedback is necessary for science learning through experimentation: A literature review of two different lines of research across K-16. *Educational Research Review, 16*, 116–137.

Zacharia, Z., & Anderson, O. R. (2003). The effects of an interactive computer-based simulation prior to performing a laboratory inquiry-based experiment on students' conceptual understanding of physics. *American Journal of Physics, 71*(6), 618–629. https://doi.org/10.1119/1.1566427

Zacharia, Z. C., & Constantinou, C. P. (2008). Comparing the influence of physical and virtual manipulatives in the context of the physics by inquiry curriculum: The case of undergraduate students' conceptual understanding of heat and temperature. *American Journal of Physics, 76*(4), 425–430. https://doi.org/10.1119/1.2885059

Zacharia, Z. C., & de Jong, T. (2014). The effects on students' conceptual understanding of electric circuits of introducing virtual manipulatives within a physical manipulatives-oriented curriculum. *Cognition and Instruction, 32*(2), 101–158. https://doi.org/10.1080/07370008.2014.887083

Zacharia, Z. C., & Michael, M. (2016). Using physical and virtual manipulatives to improve primary school students' understanding of concepts of electric circuits. In M. Riopel & Z. Smyrnaiou (Eds.), *New developments in science and technology education* (pp. 125–140). Springer. https://doi.org/10.1007/978-3-319-22933-1_12

Zacharia, Z. C., & Olympiou, G. (2011). Physical versus virtual manipulative experimentation in physics learning. *Learning and Instruction, 21*(3), 317–331. https://doi.org/10.1016/j.learninstruc.2010.03.001

Zacharia, Z. C., Olympiou, G., & Papaevripidou, M. (2008). Effects of experimenting with physical and virtual manipulatives on students' conceptual understanding in heat and temperature. *Journal of Research in Science Teaching, 45*(9), 1021–1035. https://doi.org/10.1002/tea.20260

Zacharia, Z. C., Loizou, E., & Papaevripidou, M. (2012). Is physicality an important aspect of learning through science experimentation among kindergarten students? *Early Childhood Research Quarterly, 27*(3), 447–457. https://doi.org/10.1016/j.ecresq.2012.02.004

Zhan, Z., Shen, W., Xu, Z., Niu, S., & You, G. (2022). A bibliometric analysis of the global landscape on STEM education (2004–2021): Towards global distribution, subject integration, and research trends. *Asia Pacific Journal of Innovation and Entrepreneurship, 16*(2), 171–203. https://doi.org/10.1108/APJIE-08-2022-0090

Zhuoluo, M. A., Liu, Y., & Zhao, L. (2019). Effect of haptic feedback on a virtual lab about friction. *Virtual Reality & Intelligent Hardware, 1*(4), 428–434.

Zohar, A. R., & Levy, S. T. (2021). From feeling forces to understanding forces: The impact of bodily engagement on learning in science. *Journal of Research in Science Teaching, 58*(8), 1203–1237. https://doi.org/10.1002/tea.21698