Received: 30 July 2020 | Accepted: 1 March 2021

DOI: 10.1111/bjet.13083

British Journal of Educational Technology BERA

REVIEW

Learning by making: A framework to revisit practices in a constructionist learning environment

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Funding information
None

Abstract

Makerspaces are collaborative workspaces where people construct their ideas using a variety of materials and tools ranging from no tech to high tech, where components can be moulded and transformed into different projects depending on each maker's vision. Educational makerspaces allow educators to respond to the diverse interests of individual learners. This paper documents the learning of participants at an educational makerspace founded on constructionist principles. We analyse the characteristics of the Maker Movement and the features of an educational makerspace, identify learning dimensions, select a case, analyse field notes, photos and videos using an interpretivist paradigm and refine the practical framework guiding the facilitation of the case study discussed. Given that the investigators are also the facilitators of the activities, this framework allows an a posteriori analysis of the practices used to make learning visible.

KEYWORDS

constructionism, educational makerspace, framework, learning, learning by doing, mathetics, microworlds, objects-to-think-with

Practitioner notes

What is already known about this topic

- Makerspaces promote learning in STEM, developing 21st century skills such as effective communication and problem solving.
- Makerspaces accommodate diverse students and their interests.
- Makerspaces encourage DIY practices and design thinking.

What this paper adds

- New dimensions for analysing what has been learned in a constructionist educational makerspace.
- New indicators that illustrate the different dimensions of learning, which permit in-depth analysis of specific practices and promote reflection.
- A framework which can be applied in the analysis of learning in similar environments.
- Recognition that constructionist makerspaces can enhance learning in all disciplines, moving beyond the limits of STEM or STEAM.

Implications for practice and/or policy

- New ways to plan and execute activities in an educational makerspace and any constructionist education centre.
- A reference for identifying and making visible learning inside educational makerspaces and any constructionist education centre.
- Assurance of the quality of learning developed in educational makerspaces and any constructionist education centre.

INTRODUCTION

Makerspaces contain materials and tools that allow participants to solve problems as creators, rather than consumers (Dougherty, 2012). In Dougherty's words, "the maker movement has come about in part because of people's need to engage passionately with objects in ways that make them more than just consumers. But other influences are in play as well, many of which closely align the maker movement with new technologies and digital tools" (2012, p. 2). Characterised by a lack of formality, makerspaces allow people of all different ages to learn through discovery in both analogue and digital contexts, and develop the technological skills needed to create new products (Sheridan et al., 2014). Both individual needs and community concerns can be met by using low-cost digital technology to invent or fabricate solutions (Martinez & Stager, 2013). Participants are interest-driven and curious, and advance through trial and error, which fosters collaboration among peers in order to build a greater knowledge base. Originality and creativity is fostered in this kind of environment, allowing problems to be analysed from different perspectives and available materials to be repurposed, all in aid of finding the best result. From this creative environment, educational makerspaces have emerged that provide children and teens with the opportunity to learn by doing: to internalise and understand new concepts through small, concrete actions set in a "real life" context. As learning by doing is driven by a need to know, it permits a natural acquisition of "micro-scripts", or the abilities needed for achieving a desired goal (Schank, 1995).

Emerging in 2005, the Maker Movement applied the Do It Yourself (DIY) ethic to computers, electronics, carpentry and more, giving adult learners the opportunity to "engage passionately with objects" (Dougherty, 2012, p. 12). Papert is credited with founding the movement because he had created tools, theories and coercion-free learning environments by 1963. As he explained later, "my vision of a new kind of learning environment demands free contact between children and computers" (Papert, 1980, p. 16). He believed in allowing children to construct powerful ideas supported by their experiences, "supporting children as they build their own intellectual structures with materials drawn from the surrounding culture" (Papert, 1980, p. 32). His descriptions of the ideal learning environment prefigured makerspaces as they come to be known in educational circles, even though he did not use the name as such. As a researcher and educator, he showed how children could use computers and software to create cybernetic systems (Martinez & Stager, 2013). Educational makerspaces bring all these elements together, inviting learners to investigate, problem solve and construct with diverse materials (Stevenson et al., 2019). Projects are interesting and significant to the learners themselves, who break problems into smaller parts (Tucker-Raymond et al., 2016) and discover the vocabulary, methods and strategies employed in different fields. Papert's approach was "to make visible even to children that the fact of learning a physical skill has much in common with building a scientific theory" (Papert, 1980, p. 96).

Papert defined learning as "building knowledge structures through progressive internalization of actions" and believed it happened when children constructed public entities, or "Objects-to-think-with" (Papert, 1991, p. 1 *as cited in* Ackermann, 2001, p. 4). Herein lies the constructionist roots of learning by doing, as opposed to learning as a reflection of a student's intellectual potential. Learning is "how ideas get formed and transformed when expressed through different media, when actualized in particular contexts, when worked out by individual minds" (Ackermann, 2001, p. 4).

A common misconception is that learning in an educational makerspace is of less consequence, as it differs conceptually and physically from a traditional classroom. Conventional schooling tends to compartmentalise knowledge into disciplines, with separate physical spaces and rigid scheduling. Learning is approached more in theory, from the singular perspective of the teacher and the textbook. Concepts are covered sequentially inside a predetermined time frame (Kumpulainen & Kajamaa, 2020). From a learner's perspective, it is almost impossible to associate "fun" with "learning" (Petrich et al., 2013). Learning must be repositioned so that participants are motivated, free to generate new ideas, encouraged to choose projects that have personal significance, supported by diverse materials and technology, and permitted to learn from mistakes.

Learning through making has been justified pedagogically for years. Dewey (1960) argued that learning should be contextualised, connecting content to a physical environment through student-directed investigation in an environment that stimulates curiosity. These experiential learning spaces promote interaction between "an individual and objects and others" (Dewey, 1960, p. 86), where roles can be exchanged depending on the objectives, activities and tools in an iterative process of investigation and making (Bevan et al., 2015). These dialectic interactions between materials, participants and context facilitate learning. In the words of Freire (2014), this process of discovery is promoted by the ebb and flow between action and world, world and action with posterior reflection. Learning emerges within a context of liberty through experience and social interaction, according to Vigotsky (1979) and Lave and Wenger (1991). It is cultivated by the relationship between ideas, materials and an environment that has been carefully designed to prompt the discovery of "Objects-to-think-with", where objects become cognitive artefacts that facilitate the construction of new knowledge (Papert, 1980).

This paper provides an analytical framework to help practitioners make learning visible in a context that does not feature traditional methods of evaluation. To begin, we discuss the concerns linked to learning in constructionist contexts, then propose different learning dimensions and apply them in the analysis of a case developed in the Creative Garage, an educational makerspace in Costa Rica. Using the interpretivist paradigm, we apply our framework to reveal the students' learning, from the analysis of photographs, videos and field notes collected by the investigator/facilitators, as well as concurrent research into different learning dimensions.

Our research attempts to answer: What are the characteristics of a constructionist educational makerspace? What is learned in this environment? How do we make this learning visible for participants?

LEARNING IN A CONSTRUCTIONIST ENVIRONMENT

Papert's definition of learning makes the learner's initiative and ideas central to the process of knowledge construction. A constructionist environment is one where learners have sufficient time and opportunity to share their ideas with a wider community.

In this environment, learning is self-directed, as students create solutions with tools that help them reach the desired information. Even when the externalisation of what they have learned is not an original product, constructionism is marked by three characteristics (Ackermann, 2001):

1. The externalisation stimulates higher cognitive functions;
2. Externalisation may involve a range of media;
3. The initiative of the learner is apparent in design.

Learning is a continual process of construction where we connect to concepts through our experiences. Learning is also incremental, as our knowledge about the self and our world deepens with each interaction. Finally, Papert recognised that **intelligence** is defined in situ, as it is determined by the state of being immersed in the context, connected and sensitive to the changes in milieu. "Knowledge is formed and transformed within specific contexts, shaped and expressed through different media, and processed in different people's minds" (Ackermann, 2001, p. 8).

Applying the ideas of constructionism, we discovered different learning dimensions were not explicit in constructionist theory. Learning also includes specific disciplinary know-how; goal-setting and execution; technique and motor control; innovation and the abilities to see the big picture and break challenges into chunks, test for consistency and coherence, and develop habits and skills that foster being part of a team and a community. The framework systematises these important learning dimensions, allowing them to be observed and identified, and guides the facilitation of activities to encourage and assess the full potential of learning.

CONSTRUCTIONISM WITH "OBJECTS-TO-THINK-WITH"

Materials, contexts and embedded ideas produce learning (Papert, 1980). Since differently situated objects facilitate the assimilation of knowledge differently, constructionist environments must be designed and equipped with particular materials to allow children to construct meaning using "Objects-to-think-with".

"Objects-to-think-with" possess three main characteristics: (1) they are part of children's socio-material environment, (2) they are used in disciplinary domains and (3) they allow children to explore complex ideas through bodily engagement (Papert, 1980). In making, learners master more complex, abstract concepts. These objects allow students to internalise more formal thinking routines as they search for a desired solution to a question or problem they find significant.

Papert believed that education institutions emphasise didactics, or the art of teaching, at the cost of *mathetics* (Papert, 1993). Children are taught what to learn, rather than how to learn, never mastering strategies such as how to analyse real-life situations, how to connect new learning to what is already known, how to manage time and how to break problems into parts in order to deal with them one by one—in short, how to problem solve.

Learning by doing requires some agency on the part of the learner. The learning space must be observed to ensure it is equipped with different examples, technologies and materials which students can use as they work towards a solution. Educators must also make available ideas, thinking strategies and concepts—the fruit of past learning. As students master *mathetics*, they become bricoleurs (Papert, 1993), with the confidence to use the materials and concepts at hand in order to resolve immediate challenges while advancing the project overall. In a spiral of learning, they make, do and reflect, constructing meaning with "objects-to-think-with" which advance the art of learning, or *mathetics*, permitting the mastery of more complex thinking patterns and mental structures.

Papert showed how digital tools can aid children as they learn by making. When problem solving involves coding, learners must put more complex strategies into action, prompting educators to involve learners in "reflecting on more complex aspects of their own thinking" (Papert, 1980, p. 28). This is achieved by placing children in the programmer's position, permitting them to connect coded commands with ideas from science, mathematics and the art of construction. Children naturally learn from their surroundings. Much time is spent learning how to communicate, yet, children learn to do it quickly and well. Programming is communicating with other entities, with computers and microprocessors, in a language common to both humans and machines. The power of learning by doing becomes evident when a child learns to programme, not in the manner of studying an abstract new language theoretically, but as a means to an end inside the context of a problem to be solved. The student is active, autonomous and self-directed, a bricoleur of code.

When appropriate conditions are created to pursue a project, children will develop a wide range of skills, including programming. This occurs in what Papert termed microworlds (Papert, 1980), or spaces where learners can simulate scenarios in order to develop powerful ideas and thought patterns. "Microworld settings provide the possibility of pupils working with concepts that they do not yet understand. Understanding emerges through activity". (Ainley et al., 2006). Microworlds become knowledge incubators, as they feature elements that are part of their real-world counterpart, on a more manageable scale. This can be seen as children learn to create their own video games or animations: the complexity of their thinking increases inside the ever-widening spiral of learning. Children "**imagine** what they want to do, **create** a project based on their ideas, **play** with their creations, **share** their ideas and creations with others, **reflect** on their experiences—all of which leads them to **imagine** new ideas and new projects" (Resnick, 2007, p. 1).

FRAMEWORK DESIGN

The framework is theoretically based on literature that presents how a makerspace should be guided by **constructionism** (Ackermann, 2001; Martinez & Stager, 2013; Papert, 1980, 1993); how **learning** is developed doing things, interacting with the environment, materials and with others (Dewey, 1960; Papert, 1980; Vigotsky, 1979); how **learning in maker-spaces** is provoked and learners are inspired (Ainley et al., 2006; Falloon, 2020; Hsu et al., 2017; Kumpulainen & Kajamaa, 2020; Papert, 1980; Regalla, 2016; Resnick & Robinson, 2017; Stevenson et al., 2019; Tucker-Raymond et al., 2016; Urrea & Bender, 2012; Wardrip & Brahms, 2015); how **the maker movement** can incite educational transformation (Dougherty, 2012; Sheridan et al., 2014); the importance for learners to **develop interpersonal skills and agency** and thus gain confidence (Grover et al., 2015; Pick et al., 2007); how **soft skills and work skills** are vital for young people (Davies et al., 2011); how **creativity** is essential to solve real-life situations (Robinson & Aronica, 2015) and how other existing **frameworks** have been used to analyse similar learning spaces (Bevan et al., 2016; Marshall & Harron, 2018; Petrich et al., 2013; Wilkinson et al., 2016). We added different learning dimensions and indicators (see Table 1) from our practice, following a research method identifying major learning themes through a concurrent, iterative cycle of literature review, data collection and analysis (Cresswell, 2012).

While other frameworks (Bevan et al., 2016; Petrich et al., 2013; Wilkinson et al., 2016) identify 23 indicators inside six learning dimensions of engagement, initiative and intentionality, social scaffolding, developing of understanding, innovation and solidarity, our framework addresses eight learning dimensions with 65 indicators. This permits a thorough analysis of learning. As facilitators and investigators, we developed our framework working with the same learners on projects over several weeks, while those we used as reference were designed by researchers who analysed data obtained from photos, videos, interviews and visits.

The framework guides the facilitation, observation and reflection in constructionist educational spaces, provoking learning and making it visible.

Eight dimensions of learning

To make visible the learning that is experienced in the Creative Garage, we created a framework with eight dimensions and 65 indicators that help tag important aspects of learning. We believe learning includes those skills which permit a participant to develop holistically as a person inside a community, able to be alone and with others.

1. *Cognitive domain*: refers to the learning related to the specific expertise of different disciplines. As learners advance on projects, they acquire greater skills, knowledge and understanding specific to the discipline (Falloon, 2020; Marshall & Harron, 2018), addressing specific phenomena from a fresh perspective, gaining an expert's range of vision through ongoing investigation.
2. *Problem solving*: requires having an overall view of a situation that permits breaking it down into smaller, more manageable parts (Resnick, 2017). Projects begin with problems that can only be resolved with practical skills, strategy and a high level of organisation for handling emergent issues. Learners must determine whether the project satisfies the demands of the problem that created it (Hsu et al., 2017).
3. *Critical thinking*: tests assumptions and theories for consistency and coherence over the course of a project. Potential decisions must be placed in doubt, as alternatives are contrasted in the search of the best outcome. The project's process and final result must be observed with a critical eye (Bevan et al., 2016), becoming a subject for reflection.
4. *Use of tools and materials*: focuses on the selection and application of the right tools and materials for the project. Tools may be digital or analogue, while materials may be anything that is at hand. This dimension requires prior knowledge concerning tools (Wilkinson et al., 2016), and the ability to test their functionality and use safely.

TABLE 1 Learning dimension framework

Learning dimension	Learning indicators
1. Cognitive domain • Learning related to the specific know-how of different disciplines	• Understanding of concepts • Systematisation of information • Use of specific vocabulary • Search for information • Implementation of procedures • Understanding complexity • Developing and using models • Analysing and interpreting data • Connecting concepts across different contexts • Application of knowledge in the execution of projects • Abstraction of concepts • Transdisciplinarity understanding • Learning from mistakes • New-media literacy • Computational literacy • Technological literacy • Computational thinking • Enquiry
2. Problem solving • Ability to see the big picture and break challenges into smaller chunks	• Definition of problems • Analysis of problems • Strategies for approaching problems • Strategic planning for alternative solutions • Analysis of alternative solutions • Phase design to reach solution • Observation of similar situations • Ability to remix projects • Evidence-based decision making • Drawing conclusions from trial and error • Prototyping and testing • Handling uncertainty • Time management • Best practices in investigation • Communication about tools, materials and phenomena • Replication and iteration

TABLE 1 (Continued)

Learning dimension	Learning indicators
3. Critical thinking • Evaluating the consistency and coherence of the assertions	• Composition of explanations • Evidence-based argumentation • Development of a line of thought
4. Use of tools and materials • Discovering functionality and techniques	• Determining possible uses of tools and materials • Potential combinations of tools, materials • Identification of potential hazards • Safe handling of digital and manufacturing tools • Identification of available resources • Repurposing of different components • Tinkering skills • Progressive skill-building in use of tools • Incorporation of safety protocols
5. Psychomotor development • Development of fine and gross motor control	• Hand strength • Precision in the use of tools and manipulation of objects • Hand–eye coordination • Spatial awareness • Proprioception
6. Creativity • The creative process used to respond to situations in an original manner	• Creation of original ideas • Discovery of innovative solutions in unexpected situations • Ability to imagine alternatives, new ideas and projects • Creation of projects based on ideas • Playing with creations • Sharing creations • Reflection on the experiences • Evaluation of design complexity • Different forms of expression • Enjoyment of unique insights • Developing novel and adaptive thinking • Taking intellectual and creative risks and persevere • Reconciliation between ideas and realistic possibilities • Sense of aesthetics

TABLE 1 (Continued)

Learning dimension	Learning indicators
7. Intrapersonal domain • Skills for defining personal goals and acting upon them	• Self-confidence • Determination and intentionality • Personal Competence • Goal-setting • Motivation • Purpose • Responsibility • Decisiveness • Commitment • Curiosity • Persistence • Self-efficacy • Initiative • Control over what is learned • Self-reliance • Agency • Self-awareness • Self-management • Management of frustration • Self-control • Self-regulation
8. Interpersonal domain • Habits and skills that foster being part of a community and allow teamwork and creation with others.	• Collaborative teamwork • Socialisation • Effective communication • Empathy • Leadership • Purpose-driven mutuality • Persuasiveness • Intercultural skills • Peer learning • Negotiation • Ability to request or offer help • Ability to inspire new ideas or approaches • Dialogue

5. *Psychomotor development*: promotes specific motor skills, from the muscles of the hand, wrist and forearm to the entire nervous system, supporting optimal psychomotricity and developing proprioception, as participants learn to make automatic micro adjustments. These movements are the product of the interplay between tonic activity and kinetic activity, between the expression itself and its adjustment to the external world in a specific moment (Sassano, 2020).
6. *Creativity*: relates to an individual, personal and original response to a situation (Robinson & Aronica, 2015), where alternatives are freely imagined and limits are tested.
7. *Intrapersonal domain*: involves those abilities at play in goal-setting and pursuit (Pick et al., 2007), where participants learn to propose alternative ideas with security and respect, persistently advancing the objectives of the project (Ainley et al., 2006).
8. *Interpersonal domain*: centres on the habits and skills required to create with others and be part of a community. Projects are the work of teams, and require participants to reach agreements, listen and negotiate (Stevenson et al., 2019). Frustration is shared among team members, as is the search for solutions. Projects foster a sense of shared responsibility, with a balanced share of the work, and promote a sense of belonging to a whole that is greater than the sum of its parts.

METHOD

This study was directed by the facilitators of Creative Garage and originated from a previous work (Morado et al., 2020) which detailed how a real-world problem was solved by two children programming Micro:bit microprocessors (www.microbit.org) in a constructionist makerspace. However, it did not explain in detail the specific learning experienced by the project participants, and did not provide a framework for facilitation, observation and reflection.

We chose this case because the development of the project was well documented with photographs, videos and field notes, and allowed a full-scale application of the framework's learning dimensions, which were developed iteratively with repeated revision of the bibliography and further analysis of the case. As Papert affirms (1980), “the best way to understand learning is to understand specific, well-chosen cases and then to worry afterward about how to generalize from this understanding” (p. 10). As part of case study research (Bassey, 1999), we revisited the original case, analysing both process and results in an effort to make the learning experienced by the participants visible for educators seeking open-ended learning inside a constructionist setting.

Guided by the fundamental ideas behind constructionism, we looked specifically for evidence that learning is the intersection of ideas, materials and environment; is created with technological tools; flows from concrete to abstract through making; is incremental; takes place in situ and invokes the initiative of the learner. Our initial dimensions included strategies for approaching problems, computational thinking, learning from mistakes and computational literacy. However, as the research progressed, new learning dimensions and indicators appeared. For example, when the students had to modify the cables to fit the design, indicators related to psychomotor development emerged, while their project presentation in front of a real audience revealed indicators related to the interpersonal domain. As we detected more learning dimensions and indicators, a rigorous reading of new literature was required in order to explain what our research case was revealing.

This framework was required for two reasons: first, to make the participants' learning visible through the creation of projects in a constructionist educational makerspace; second, to provide a framework to analyse existing practice for future improvement, given our double role as both investigators and facilitators. The framework allows us to visualise the flow of multiple informal interactions and activities that make up the schema of learning at Creative Garage.

Articulating elements of practice and investigation is necessary for progress, as it allows reflection from pedagogical and epistemological points of view of what worked, and what did not, permitting students' learning and holistic development to be analysed and highlighted (Cain et al., 2019). Reflection-in-action (Schöon, 1987) encourages us to study a particular aspect of our knowledge at work, and to experiment as we engage in activities. The framework could guide other educational makerspaces and even formal academic institutions towards a more critical view of their practices.

This case study was developed following the logic of jointly negotiated research (Bevan et al., 2015), which aims to produce results which are useful in practice. To address the practical concerns which arise in our double role as researchers and practitioners, we design collaboratively as we explore new approaches, advancing in theory as well as practice in order to create a foundation for progress that goes beyond the project at hand. We apply the different aspects included in the framework to integrate evidence gathered from the case study, create plausible interpretations of what is found, test for the trustworthiness of these interpretations, construct a worthwhile argument and relate the argument to relevant research.

Setting and context

The study took place in the Creative Garage, which is an educational makerspace that has held after-school workshops for children 3 years of age and older since 2017. Children participate in "creative technology" in weekly 1-hour workshops called Electro Kids (3–5 years), Little Inventors (6–11 years) and Creative Makers (12–16 years). They create fun projects which are significant in terms of their personal interests, using diverse materials and skills such as coding, circuits, 3D printing, markers, paints, motors, LED lights and more.

Working inside the theoretical framework of constructionism, we pay close attention to the conditions that best promote learning. As children enter the makerspace, they explore the available materials to see what they can make. We propose project ideas and accompany learners as they develop their chosen project, acquainting them with the potential uses of the technology. Learners will use this knowledge later, with more complex projects.

Participants

Sixty children participate regularly in the Creative Garage workshops. In this paper, we share a case involving two 11-year-old boys, who decided to enter the Micro:bit Challenge 2018[1] and spent 5 weeks from brainstorming to completion. Their case demonstrates a learning path to greater complexity and authorship, to solve a problem selected by the learners themselves. They began playing with different technologies and programming games, then applied these skills to find a solution, thus displaying two of the fundamental principles of *mathetics*: learners must connect something new to something already known; learners take ownership of new knowledge by playing or constructing with it.

DATA SOURCE AND ANALYSIS

We used an interpretivist approach in the analysis of our case study, collecting data through participatory observation. We recorded ethnographic field notes as the students produced the 'Cubik Shaker' over five classes and presented it at the Maker Day Fest in 2019. We photographed and filmed segments of each class and obtained a summary written by the participants that explained their different decisions and how they reached their solution. We observed body language for emotions such as enthusiasm, uncertainty or frustration and recorded verbal expressions that supported indicators in the framework, such as "identification of problem" or "defending points of view". This allowed us to create case summary sheets and identify the progressive development of learning related to the interplay of materials and psychomotor abilities. This decoding process allowed us to organise the information thematically, examine overlaps and eliminate redundant information. In this way, we documented the process of constructing an "object-to-think-with" as well as the learning achieved.

For the first research question: What are the characteristics of a constructionist educational makerspace? Our analysis identified the following features: (1) construction of "objects-to-think-with"; (2) advancement of the participants' *mathetics*; (3) tinkering as a form of solving real-life problems using digital and manual tools; (4) development of microworlds in order to simulate scenarios akin to real-life situations.

For the second research question: What is learned in a constructionist educational makerspace? Our analysis broke the learning experienced into eight dimension: (1) Cognitive domain; (2) Problem solving; (3) Critical thinking; (4) Use of tools and materials; (5) Psychomotor development; (6) Creativity; (7) Intrapersonal domain and (8) Interpersonal domain (see Table 1).

For the third research question: How is learning made visible in a constructionist educational makerspace? We created a framework and analysed a case where we had defined and displayed the participants' learning. Our work was based on the theoretical concepts of learning through making, and the facilitation of learning through a careful curation of learning conditions.

Analytical techniques

First, we analysed the data collected, to obtain a general sense of the material, then, we coded it to identify themes and patterns while simultaneously reviewing our bibliography, enriching our framework and updating our case report.

We wanted to understand a specific case in its social context, so we employed the interpretivist paradigm to analyse our data, "accepting and seeking multiple perspectives, being open to change, practicing iterative and emergent data collection techniques, promoting participatory and holistic research, and going beyond the inductive and deductive approach" (Willis, 2007, p. 583). We used personal assessment to choose the description that best fit "the situation or themes that capture the major categories of information" (Cresswell, 2012, p. 260). The iterative feedback from the bibliography, our case analysis and a continual reflection upon our practices helped us create the learning dimensions that make up the framework, and analyse our case.

FINDINGS: EVIDENCE OF LEARNING IN A CASE

We analysed a project developed in 2018 under our mentorship at the Creative Garage. Using our framework, we aimed to make visible the learning of the participants who carried it out.

The case study consists of a project which aimed to find a technological solution to a problem related to health and well-being. Its result: the creation of a wearable device called the 'Cubik Shaker', which activated different alarms for sedentary behaviour of more than 20 minutes. Two 11-year-old boys decided to develop a device for video-gamers. As fans of Fortnite[2], both spent hours sitting in front of screens. Through investigation, they learned that sedentary people can develop heart problems and obesity. They proposed the Cubik Shaker as their solution; this device would be worn next to the body, in a pocket as shown in Figure 1. Sitting still for more than 20 minutes would trigger an alarm, making the Cubik Shaker vibrate, play an annoying tune and display the message “Move!” until the wearer moved energetically for a specific period of time, causing the Cubik Shaker to reset its timer.

Cognitive domain

The learning began with **research** in order to **understand the concepts** related to the health effects of sedentarism and obesity. The students developed **new-media literacy** and enquiry skills as they searched the internet, learning how the cardiovascular system functions in good health and how it could be affected by prolonged inactivity. They **analysed, interpreted and systematised the data they found using specific vocabulary**. Next, they came up with possible technological solutions that could prevent users from being sedentary for too long, demonstrating they **understood the complexity** of the problem and **were able to develop models** to solve the problem. To create an electronic device, they learned more about microprocessors, focusing specifically on the Micro:bit because of its wide range of features, acquiring more knowledge about technology and computers as well as health and wellness and **connecting concepts across different contexts**. Through play, they discovered that a Micro:bit has inputs, such as sensors and accelerometers, and outputs, like screens, motors and speakers. They developed **computational thinking as they** learned that microprocessors must be programmed to function, and began to code, empirically learning about algorithms, events, conditionals, loops and variables (Figure 2).

They discovered electronic circuits the same way. While connecting the vibrator and speaker to the Micro:bit, they observed how a flow of electricity transmitted information;

FIGURE 1 The ‘Cubik Shaker’ in a t-shirt pocket. Photo by María Florencia Morado [Colour figure can be viewed at wileyonlinelibrary.com]

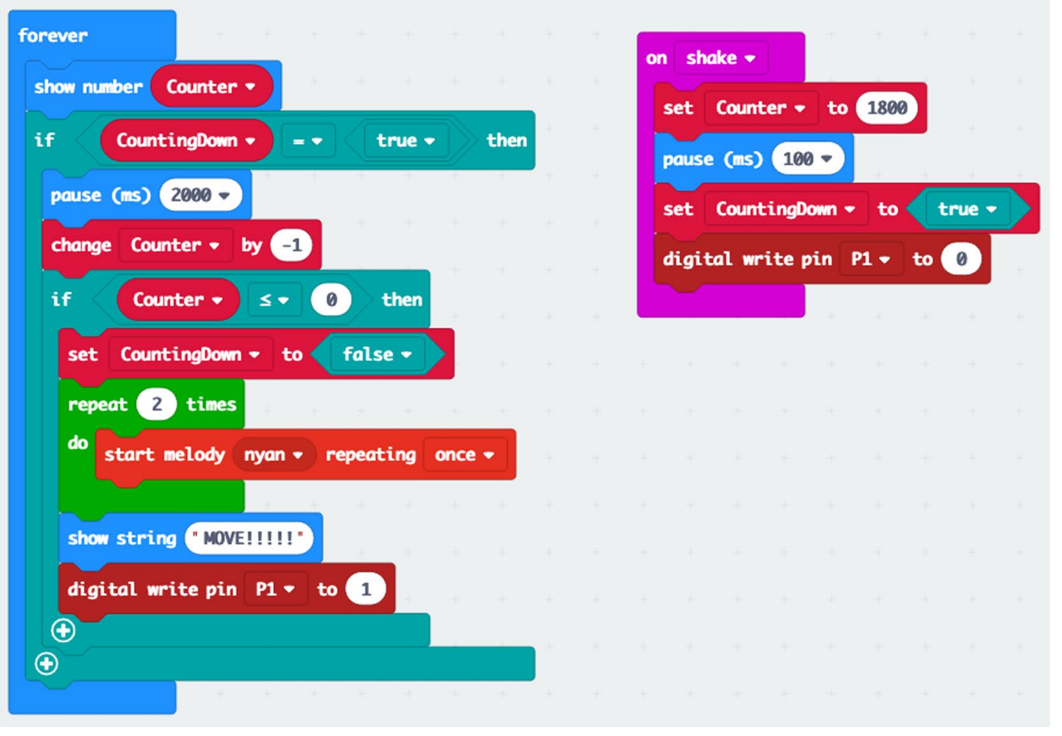

FIGURE 2 The code of 'Cubik Shaker'. Screenshot by María Florencia Morado [Colour figure can be viewed at wileyonlinelibrary.com]

when troubleshooting a faulty circuit, they assimilated concepts like voltage, resistance and ground, **applying knowledge on the execution of projects**. To create a case for the 'Cubik Shaker', they learned principles of design and prototyping. As they played with different designs for this case, they learned 3D modelling and mastered commands such as grouping, duplicating, aligning, combining solids and holes and rotating. Abstract notions taught in math became concrete during this process as they worked with measurements, conversions, proportion, ratios, area and volume. To create different prototypes of the case, they learned how to operate a 3D printer. They learned how to communicate about their project, shown in the explanation they sent to Micro:bit Challenge (see Figure 3).

Their work became **transdisciplinary** during the design process, as concepts from anatomy, physiology, psychology and programming were expressed in the learners' own words. **Abstract concepts** were grasped in the making of the project, through learning by doing.

Problem solving

Underpinning the project was the concept of a *microworld*, which was present in a real-life problem that needed to be solved: people who spend long periods seated in front of screens can develop cardiovascular disease and obesity. This is how the **problem** to be solved was **defined**. Stimulating movement that could prevent health problems was the **strategy to solve** it. Having **defined and analysed the problem**, the students proposed and **analysed alternative solutions**. The first was a device which showed an onscreen command, Move! However, they determined more stimulation would be required to shift the user into activity.

Team: Los Tucanes Pura Vida

The solution for a ND disease is a device called "Cubic Shaker" designed to vibrate, emit a sound and show a text instruction ("Move!!") if a person has remained immobile or nearly immobile for 30 minutes. When the 30 minutes have passed, and if the person has not moved a muscle it will keep vibrating, making sound and instructing movement until the person moves enough to activate the device's sensors with the shake input. The Cubic Shaker's design allows the person to wear it in his or her pocket or hanging from his or her neck, both very close to the body. After it has been shaken, the device will reset the counter every time it senses the person movements. Should the person, again, remain static for 30 minutes, it will vibrate, emit a sound, and text. The Cubic Shaker never stops functioning (and counting) as long as the battery is working (3 AAA are needed to make it work).

We invented this device because there are people who suffer from sedentary issues, for example: obesity, high cholesterol, cardiac problems as well as diabetic issues. These illnesses are mostly present in people who are required to stay in one position for long periods of time, for example: cases such as abuse of technology like binge watching TV, gaming, shopping online or, working and studying while seated for many consecutive hours. That is why we created this device, to remind people to move vigorously every certain amount of time (30 minutes in this case).

This will help our community because people will stay healthier and do more exercise. This idea also came to us because we ourselves are gamers, and wanted to find a solution to what could be our own problem in the future.

FIGURE 3 Explanation about the project

The second device featured shrill music and vibration. In another early version, the device reset the regressive counter with minimal movement that never stimulated the cardiovascular system. This was modified so that the alarm would be deactivated only after sustained energetic movement, which inspired the name "Shaker". As a strategy to approach the problem and **plan for alternative solutions,** they **prototyped and tested** three times. Figure 4 shows the testing process: writing code, downloading to the device and checking if external devices work. The problem solving was **iterative**, as students created prototypes, tested them, identified problems and made changes until reaching a satisfactory solution, along the way discovering **best practices in investigation**.

Critical thinking

As students advanced different designs, they tested and analysed each prototype in light of the objective. They defended their theories with evidence-based arguments as to what would make the most successful design, **developing a line of thought**. Writing about the project allowed them to reflect on the process through **compositions and explanations**, refining their **evidence-based argumentation**, as can be seen in Figure 5.

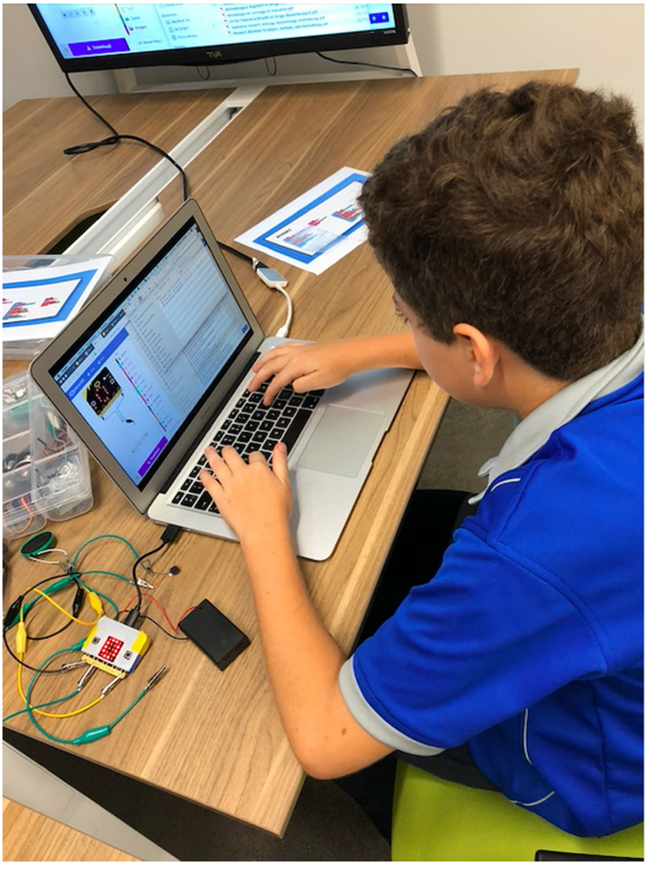

FIGURE 4 Testing the device attached to the computer [Colour figure can be viewed at wileyonlinelibrary.com]

Use of tools and materials

The students **determined possible uses of tools and materials by** selecting the Micro:bit because it could display text on a screen. After exploring the **potential combination of materials,** they decided to add two extensions, a speaker and a vibrator, to allow the device to play sound and vibrate, and adapted cables and alligator clips to fit their design, developing **tinkering skills**. Prior projects had given the students skills in using the tools and materials to reach an objective, and familiarity with the 3D printer, allowing them to **identify available resources**. They designed a case in 3D, so the Cubik Shaker could be worn close to the body, with hidden cables but an exposed screen, vibrator and speakers. In Figure 6, they are organising the different parts of the device in order to make it portable, showing **progressive skill-building in use of tools**.

Psychomotor development

The Cubik Shaker required modified alligator cables, so students cut the cables and peeled back the insulating layer, then used pincers with the precise amount of force to reassemble the clips and close the heads, improving **hand strength** and **precision in the use of tools and manipulation of objects**. This **hand–eye coordination** and **proprioception**

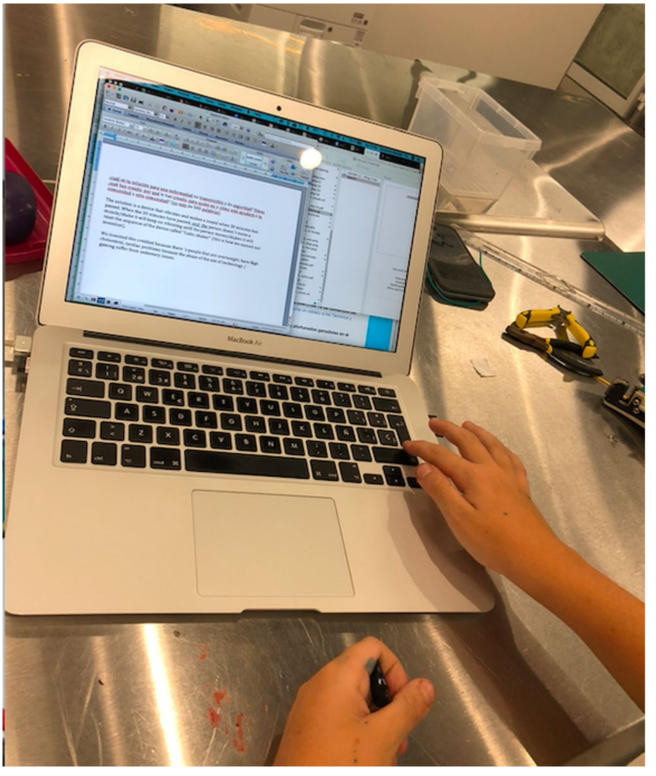

FIGURE 5 Writing down ideas allows reflection [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 6 Attaching the speaker to the battery and Micro:bit [Colour figure can be viewed at wileyonlinelibrary.com]

is shown in Figure 7, as students connect the modified alligator cables to the Micro:bit with precise positioning and the right amount of pressure. They improved their psychomotricity in the constant connecting and disconnecting required in multiple tests of the different prototypes.

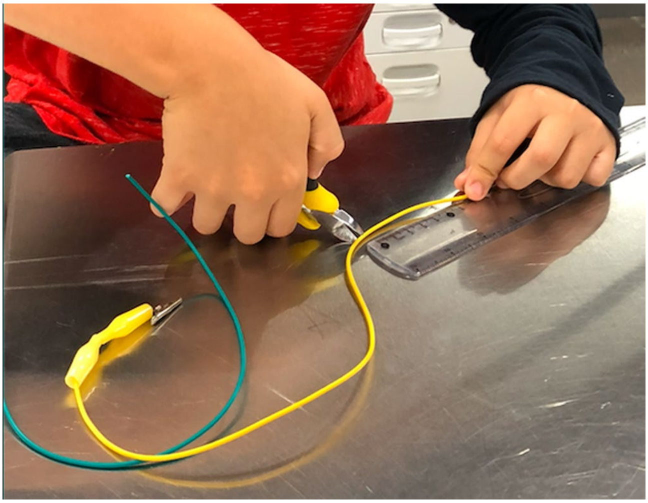

FIGURE 7 Resizing alligators [Colour figure can be viewed at wileyonlinelibrary.com]

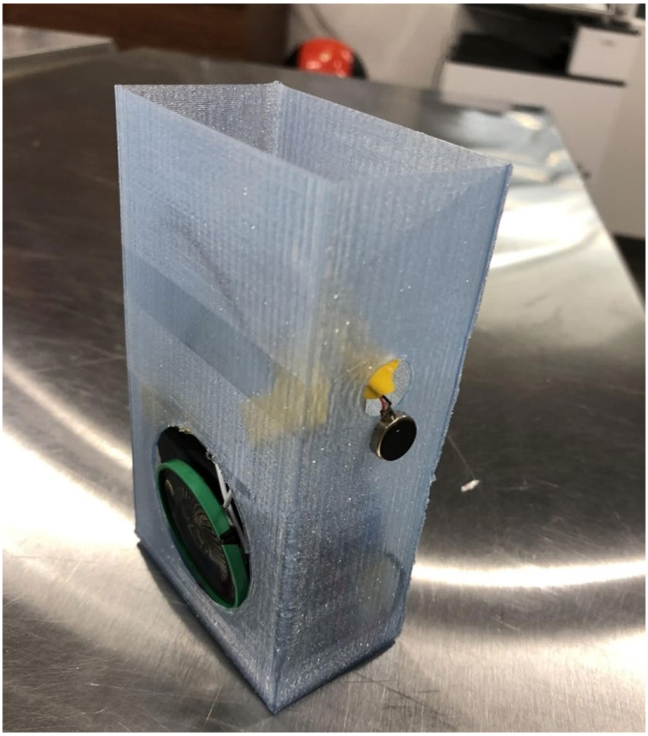

FIGURE 8 Cubic shape of the case [Colour figure can be viewed at wileyonlinelibrary.com]

Creativity

Over the project, there were many opportunities for the students to imagine a wide range of possible solutions without outside restrictions or instructions, allowing them to **create original ideas** and **discover innovative solutions to an unexpected situation**, as well as develop the a**bility to imagine alternatives, new ideas and projects**. Students played with their creations, working out the gaps between what they had envisioned, and the actual reality of the technology they had selected and programmed, and **reflected on the experiences, developing novel and adaptive thinking**. In how they responded to bugs and glitches, they **took intellectual and creative risks** that allowed them to reach their objective, **reconciling** the gap between **ideas and realistic possibilities**. They not only wanted the device to work as designed, but also they wanted it to appear **aesthetically** pleasing (Figure 8).

Intrapersonal domain

The 'Cubik Shaker' was an original project letting them grow in **self-confidence, determination and intentionality, personal competence and motivation**. The students were

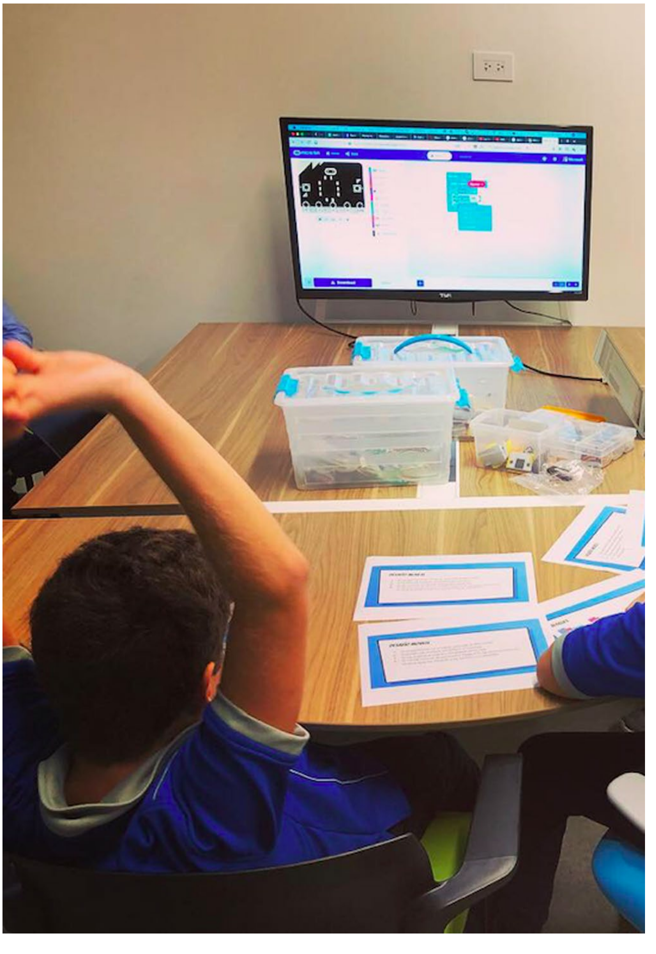

FIGURE 9 Body language showing fatigue [Colour figure can be viewed at wileyonlinelibrary.com]

inspired by the **goal**—to help sedentary people avoid serious health complications—and enabled by an environment that fostered respect, giving them **confidence to follow their ideas**. They showed a high degree of **responsibility** over the intense 5 weeks of work, especially when they found bugs in their programming, **managing frustration** and letting them **develop self-awareness**. They exercised **self-control** and **self-regulation** by resisting the impulse to abandon the project, even when they showed fatigue (Figure 9). They persisted and shared the project with their classmates, families and the Micro:bit community developing **agency**.

Interpersonal domain

In creating a solution, the students **empathised** with the public, not only because they were potential future users of the device, but also because they could now identify with sedentary teens and adults. They developed their interpersonal skills as they **persuaded**, debated, negotiated, and finally agreed over the methods they would use to solve the problem in a **collaborative** way. **Dialogue** and **negotiation** ranged from minor to major issues using **effective communication** skills: from what problems should be solved and how work should be shared, to where the device should be worn, how the case should appear and what the device should be called. Both participants, with their diverse backgrounds, styles and skills, took the lead at different stages of the project, **learning from each other as peers**. When they found themselves stuck, they displayed determination by looking for ideas on how to

FIGURE 10 Student explaining his project to an audience of different ages [Colour figure can be viewed at wileyonlinelibrary.com]

get unstuck, exhibiting **purpose-driven mutuality**. Resolving problems and successfully completing the project strengthened both participants, as individuals and as a team. They discovered they could create solutions, and have the power to envision and create change in a social context, as shown in Figure 10, where one of the participants displays **leadership** and **intercultural skills** by explaining the project to the public at Maker Day Fest 2019.

Knowing whether a learner is exhibiting one of the **learning indicators** depends on close observation and a determination to iterate throughout the project, constantly alert for the emergence of the different **learning dimensions**, even in its most basic stage. With the full range of indicators in mind, practitioners can set the scene for these skills to emerge, then leave space for the learners to approximate, refine, and finally display their learning.

DISCUSSION AND CONCLUSION

In this paper, we investigated what are the possible learning outcomes for students in a constructionist educational makerspace like Creative Garage, and specifically, what was learned in the case study. This research not only continues the line of enquiry of other frameworks which describe learning dimensions in makerspaces (see e.g., Bevan et al., 2015), but it also adds new dimensions and indicators. Our investigation also reveals constructionist characteristics in the activities developed in Creative Garage, in keeping with its aim to promote learner-led enquiry, creativity and making, among other hallmarks of constructionism. "These include learning by doing, building with technology, hard fun, learning to learn, taking time, failing well, teachers as learners and learning together" (Stevenson et al., 2019, p. 3). Created over the course of our investigation, the framework describes the learning dimensions which become evident when the case study is analysed closely inside the context of research-based evidence. The findings link to theory, to research, and to the design and implementation of future practice. Our students learned in a manner that was complex, transdisciplinary, interactive, social and contextualised, putting into practice multiple capacities and skills.

When students experience the range of learning opportunities offered at Creative Garage, they gain fluency (Urrea & Bender, 2012; Wardrip & Brahms, 2015) in diverse fields and areas of expertise. Students develop intuition and comfort with concepts (Marshall & Harron, 2018), allowing them to produce with ease, security and spontaneity. They connect what is new to what is already known, reaching a deeper understanding of concepts. They use their knowledge to resolve problems using different technologies and materials. They develop psychomotricity as they manipulate tools, and exercise their creativity by proposing original, sometimes even unexpected, alternatives. They form effective, productive teams which are mutually enriching, and thus become stronger as whole individuals who contribute to the community.

The experience shared in this paper shows how a practitioner's approach to facilitation and reflection, when guided by a rigorous framework, can identify learning and make it visible. The framework provides direction for practitioners in educational makerspaces, and guides observation during investigation processes. Papert (1980) states that when a project is started, its final result cannot be totally defined and its process cannot be completely organised and outlined. In a constructionist context, the framework liberates a facilitator to let the project develop "free-flow" while providing a structured basis for analysis. In this way, facilitators explore and discover alongside students, and the framework reveals the learning that is produced.

The findings of this paper will permit a more reflective practice, recognising that "the purpose of teaching is to inspire learning in others: to help students become autonomous and independent; to socialise them into ways of thinking and to enable them to learn subject-specific content" (Cain et al., 2019, p. 6). As limitations, we believe that this framework could be adapted to analyse other educational spaces. We believe the framework provides a basis for the creation of future frameworks which permit analysis and reflection for other learning spaces.

ETHICS STATEMENT

We have received ethical approval to conduct our research studies.

CONFLICT OF INTEREST

There is no conflict of interest.

DATA AVAILABILITY STATEMENT

We have made our data available to others.

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ENDNOTES

[1] https://microbit.org/impact/awards/mit-inclusive-innovation-challenge-2018/

[2] https://www.epicgames.com/fortnite/en-US/ **Fortnite Battle Royale** is a third person shooter survival game where the player has to survive against 99 other players. The player can build forts and collect weapons on the way. The main game also has a mode called Fortnite Save The World, which is also available as a separate game. The game can be played on iOS, Android, Nintendo Switch, Windows, PS4 and Xbox One. (Source Wikipedia)

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How to cite this article: Morado, M. F., Melo, A. E., & Jarman, A. (2021). Learning by making: A framework to revisit practices in a constructionist learning environment. *British Journal of Educational Technology*, 52, 1093–1115. https://doi.org/10.1111/bjet.13083