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Makerspace activities in a school setting: Top-down and bottom-up approaches for teachers to leverage pupils' making in science education

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ABSTRACT

This article addresses the opportunities and challenges of turning a science, technology, engineering, and mathematics (STEM) classroom into a makerspace for hands-on experimentation with digital tools and materials in science education. In this qualitative case study, over a period of 16 weeks, video data were collected during making activities in an advanced placement science course with 19 pupils aged 12–16 years, and interviews were conducted. We combined thematic and interaction analyses of empirical data and identified three themes: 1) engagement and spontaneous concepts, 2) programming and making physical objects, and 3) subject integration. Our conceptual framework for the analyses integrated two features of the Vygotskian sociocultural theory of learning: concept development as a dialectical process of scientific and everyday concepts and the "tool and symbol" duality. Our findings show that both top-down and bottom-up approaches to integrating school subjects into a makerspace were effective but underused. We illustrate this by mapping pupils' shared understanding in a sociotechnical space, visualized as a process of "rising to the concrete", which may require teacher's scaffolding at different levels of abstraction and use of instructional materials in different modalities.

1. Introduction

The aim of our research was to understand the opportunities and challenges of using makerspaces for hands-on experimentation with physical and digital materials and tools in science learning. We hypothesized that these educational makerspaces provide a fertile ground for studying "talking science," or doing science through the medium of language, which combines communication, scientific, and technical education (Lemke, 1990). At the conceptual level, our approach integrates learning topics in science, technology, engineering, and mathematics (STEM) and the development of more general skills such as collaboration, communication, creativity, critical thinking, and computational thinking, which are often referred to as 21st century or generic skills (Voogt et al., 2013). At the technical level, our approach builds on integrated learning environments as platforms where domain-specific knowledge and generic skills are interwoven and practiced together in the same digital environment (Mørch et al., 2019). Critics have argued that a future-focused education should do more than gradually adopt 21st century skills and digital literacies; it should also be disruptive to cope

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with the rapid growth of knowledge (Gilbert, 2017), modernize education (e.g., disciplinary renewal), leverage computational representations and literacy (diSessa, 2018), and connect education to its broader social or political context (Gilbert, 2017). However, research literature and policy documents show that no consensus has been reached on whether the current trend of computational thinking (e.g., programming with or without using makerspaces) should be considered a 21st century or domain-specific skill and, consequently, whether programming should be used as a method across subjects or taught on its own. Although both approaches have been investigated in previous research (e.g., Blikstein, 2018; Grover et al., 2015; Sheffield et al., 2017; Torralba, 2019), in Norway's national curriculum, which is shared with other Nordic countries, programming is not taught as a separate subject but is integrated into STEM subjects (Bocconi et al., 2018). We address related works in the following thematic areas: makerspace in educational contexts, makerspace pedagogy, and collaborative knowledge creation (CKC).

The article is organized as follows: Section 1 presents previous studies and links them to the present study by our research questions (RQs), and Section 2 presents the theoretical framework, followed by our research setting and aims (Section 3). Our research methods are presented in Section 4; and our findings, in Section 5. In Section 6, we discuss our findings and compare them with those of the surveyed related work. Lastly, we identify the limitations of our study and suggest directions for further work.

1.1. *Makerspace in educational contexts*

Given the broad field of makerspaces, we narrowed the scope of our investigation by focusing on makerspaces in education, the roles of the teacher and pedagogy, and CKC in makerspace research.

Most makerspace research has traditionally been performed in non-school settings such as after-school clubs, libraries, museums, and science centers (e.g., Calabrese Barton et al., 2021; Skåland et al., 2020). Recently, more research has focused on K-12 school settings (Schad & Jones, 2020), increasing the focus on the inclusion of subject curricula in making activities.

The potential for the integration of makerspace activities into STEM subjects has been investigated (Calabrese Barton et al., 2021; Sheffield et al., 2017). Several studies have found that students struggle to connect makerspace activities and STEM learning (e.g., Sheffield et al., 2017). Few studies have identified STEM content learning, although two studies with an e-textile intervention found learning gains regarding electrical circuits (Litts et al., 2017; Peppler & Glosson, 2013). Moreover, a qualitative study showed that students applied STEM knowledge in relevant ways (Mørch et al., 2019). Thus, further research is needed to improve the connections between STEM curricula and the domain-specific artifacts that students create in makerspace activities, for which purpose this study was conducted.

The relationship of making and understanding has been studied in previous works, and researchers have developed and applied innovative methods for analyzing interdependencies. For example, Jeong (2013) distinguished group domain understanding and intersubjectivity in pupils learning electric circuits, which involved sketches of circuits and physical circuits. The two types of understanding could explain why domain understanding was not achieved despite the groups' circuits working correctly (intersubjectivity reached at a suboptimal level). Another innovative approach to capture the interdependency of making and understanding is the Making-Process-Rug video analysis method (Riikonen et al., 2020). The authors used the method to visualize the entanglement of selected makerspace activities in developing innovative artifacts from gadgets to clothing. The authors referred to the activities as collaborative making and reported on the complexity of the unfolding sociomaterial entanglement (Riikonen et al., 2020). The collaborative making process was driven by shared epistemic objects and an open-ended learning assignment, but curricular learning goals were not part of these objects. Our work foregrounds curricular (domain-specific) goals to drive the process.

1.1.1. *Maker pedagogy*

Maker pedagogy derives from the making movement where people engage to design, create, and develop things that are useful to them personally or their community (Bullock & Sator, 2015). When focusing on the teacher's role, viewing the teacher as facilitator in makerspace research is a tradition much due to the most widely applied constructionist focus (Schad & Jones, 2020). Here, the focal point is mainly on the students constructing physical and digital artifacts while constructing knowledge, where the teachers are considered to play a supporting role in this process rather than the role of an authoritative instructor or where the aim of knowledge is rather unclear (Jeong, 2013; Riikonen et al., 2020; Schad & Jones, 2020).

Makerspaces can be disruptive in conventional (teacher-centered, authoritative) classroom practices and tension laden when pupils know more than their teachers (Kajamaa et al., 2020). Researchers have found that teacher participation could be conceptualized along a scale ranging from authoritative to enabling student-driven activities and that successful teachers draw on the flexibility afforded by makerspaces. Makerspace activities tend to be complex and may require cultural change from both teachers and pupils and moving from an authoritative to a collaborative interaction (Kajamaa et al., 2020).

This calls for an understanding of how teachers can be supported in taking on and bridging these new and flexible roles. One way of achieving this is to provide teachers with support in designing learning opportunities that integrate top-down learning goals with bottom-up learning activities (Toikkanen et al., 2015). Another way is to focus on the sociomaterial process in the makerspace. Sociomaterial approaches are defined as the constitutive entanglement of the social and the material in everyday life (Orlikowski, 2007). Although not the focus of this article, related research has adopted the perspective. Researchers have focused not only on relationships between students and teachers but also on the material forces at play in the learning space (Kumpulainen & Kajamaa, 2020), as materials in this perspective are viewed as agents (Sheridan et al., 2020).

Our research continues this line of integrative work from a different perspective, encouraging student-teacher collaboration by studying how teachers intervene in a makerspace classroom to connect pupils' prior knowledge of a topic and their everyday experiences of making and programming with scientific concepts.

1.2. Collaborative knowledge creation

An important feature of makerspaces is the organization of learning in group work and collaborating to succeed in joint artifact creation. CKC means two or more individuals developing shared artifacts using tools to mediate the activities (Moen et al., 2012) and developing shared understanding in the form of knowledge or ideas through a process of intersubjectivity (Stahl, 2006, 2015). The activities range from writing a paper to learning science in small groups. One theoretical premise of CKC is the notion of a shared object adopted from activity theory. This is the object aimed at in the joint work, such as an article written for a specific journal or an understanding of photosynthesis in a biology classroom. CKC models provide steps toward the shared object as a guide (e.g., Moen et al., 2012; Chan et al., 2012).

Pupils reuse everyday experiences and ideas from out-of-school experiences when they engage in classroom conversation in science education (Furberg & Silseth, 2021). According to Silseth (2018), teachers must not only refer to these experiences in classroom conversations but also know that these experiences are shared. Teaching models to facilitate contextualized instruction such as project-based science (Rivet & Krajcik, 2008) have been proposed. Other models to engage pupils in an inquiry process toward scientific understanding by starting from a real-world (or hypothetical) situation triggered by questions are knowledge building (Chan et al., 2012) and knowledge integration (Linn & Eylon, 2011). Our work was aimed at contextualizing conceptual science learning through hands-on (physical and digital) activities.

Studies that explored the interdependencies of making and CKC included high school students' interactions with technology-mediated plant growth observations in a biology class and found that students' hypothesis generation during group work ("theoretical mode") often led them to switch to a "practical mode" of experimentation and vice versa, gradually leading to a better argumentation for understanding the phenomena of photosynthesis (Mørch et al., 2019). In another study on making and CKC referred to as collaborative making, Riikonen et al. (2020) analyzed weekly craft lessons with school activities at the seventh grade. The authors used the Making-Process-Rug method to capture patterns of sociomaterial intertwining of discursive and hands-on activities with shared epistemic objects to anchor the process.

The productivity of student collaborative learning is shaped by different activities (i.e., project planning, physical making, and programming) and how students view each other in socio-emotional terms (i.e., their degree of support or restiveness to collaboration) (Lui et al., 2020). Lui et al. found that pupils collaborated in the initial phase but worked in a more siloed-off manner during the making phase, with great variation in their communication levels during this period. Collaborative productivity is affected by students' social interactions during physical computing workshops. We used a similar method in our study but with an orientation toward understanding STEM topics. Specifically, we used the Vygotskian distinction of spontaneous/everyday and scientific concepts.

Based on our literature survey, we found that further research is needed to improve the connections between STEM subjects and making in terms of concretization. Furthermore, the teacher's role in student concept development has been investigated mainly using a constructionist or constructivist framework. Our study aimed to fill this gap and apply a broad range of sociocultural perspectives in our analysis, which we will address with the following research questions:

RQ1. : How can we understand pupils' collaborative science learning in a makerspace from the perspective of the dialectic of everyday and scientific concepts?

RQ2. : What are the opportunities and challenges of using a makerspace in science education? Drawing on the Vygotskian notion of the duality of physical and conceptual tools.

The rationale for the RQs is to map out a sociocultural space bounded by two types of concepts (everyday and scientific) and two types of tools (physical and conceptual). We employed two additional elements in our analysis: digital tools and theoretical concepts. The relationship between concepts and concrete tools are visualized in Section 2.3.

2. A sociocultural perspective

2.1. The dialectic of everyday and scientific concepts

Research on makerspaces has been mainly constructivist or constructionist (Schad & Jones, 2020), with its theoretical underpinnings affecting the focal points in this field. Meanwhile, sociocultural perspectives are emerging (e.g., Furberg & Silseth, 2021; Kajamaa & Kumpulainen, 2019; Skåland et al., 2020), and their increased use may pave the way for less researched areas such as the dynamics of science concept learning according to the Vygotskian framework, which was investigated in this study.

In analyzing children's conversation in play and interaction with adults, Vygotsky (1986) distinguished between scientific and everyday (spontaneous) concepts. We use the two terms (*everyday* and *spontaneous*) interchangeably in this article, emphasizing the common sense (everyday) vocabulary that children form, sometimes incorrectly, without any formal education, such as "Heavier objects fall faster." When acquiring knowledge from interactions with others, the collaborative learning process involving instructional scaffolding can be defined by two processes moving in different directions: upward toward generalization from spontaneous concepts and downward from scientific concepts initiated by an instructor or a more knowledgeable peer, which we refer to as bottom-up and top-down pedagogical approaches, respectively. Vygotsky suggested that the development of scientific concepts benefits from the systematicity of instruction and cooperation (Vygotsky, 1986) to speed up children's natural (i.e., bottom up) learning, noting that the two processes "are related and constantly influence each other" (Vygotsky, 1986, p. 157). For example, he used "exploitation" and "brother" as examples, the latter being a concept infused with meaning from early childhood (i.e., emergent from action and interaction, and “self-taught”), whereas the former appeared, perhaps for the first time, in a social studies class introduced by a teacher (i.e., taught top-down and concepts first).

Vygotsky argued that the two processes of concept development are unique because they move in different directions, but they may connect by sharing referents (common objects) in the social world (Vygotsky, 1986, p. 172–192). Vygotsky's work on the relations of scientific and everyday concepts has inspired later researchers to develop methods and techniques for teaching and learning. For example, Davydov introduced an intermediate level between everyday and scientific concepts, which he referred to as “theoretical concepts” (Davydov, 1990) (see Section 2.2). Contemporary work includes going back and forth between the concrete and abstract representations of the targeted concepts (Howe, 1996), and studying the dialectic interplay of everyday and scientific concepts in young children's play-based encounters (Fleer, 2009). Fleer showed that the two sets of concepts can meet when children's day-to-day life experiences provide the potential for scientific concepts and are realized by transforming everyday practices, which can occur when the teacher or facilitator integrates both types of concepts (Fleer, 2009). Another technique for connecting the concepts is visualization and elicitation of prior knowledge to support the process of knowledge integration (Linn & Eylon, 2011). A recent application of the “top-down” method and sociocultural theory to understand teachers' facilitation of online collaborative learning is presented by Engeness (2021). The author studied interactions in a massive open online course in a teacher education program and found that learners moved from interacting with digital tools to developing an understanding of how to engage in online learning.

2.2. *The duality of physical and conceptual tools*

According to Vygotsky (1978), learning occurs first in social situations, and mediation is a central activity in education and a steppingstone to learning. Vygotsky distinguished two types of mediation: tools (physical) and signs (language), which are complementary, leading to a “tool and symbol” duality (Vygotsky & Luria, 1994). The duality suggests that human development, on the one hand, is carried out through practical work by using tools and actions and, on the other hand, involves (intellectual) concepts or verbal means (symbols and signs) to make sense of the actions without using physical tools (Vygotsky & Luria, 1994). With digital tools, new opportunities arise for tool mediation that goes beyond physical tools in terms of malleability and adaptability, supported by end-user development (EUD). As the opposite of technical development by trained programmers and software engineers, EUD refers to a set of methods and techniques that allow nonprofessional software developers to create or modify a software artifact (e.g., Andersen et al., 2021; Fischer et al., 2004).

Davydov (1990), a junior of Luria, developed a method of instruction using a dialectic process he referred to as “theoretical thinking,” or “rising to the concrete” (Chaiklin & Hedegaard, 2013), arguing that theoretical knowledge should develop by clarifying concreteness while remaining abstract in the core (Davydov, 1990). Thereby, he refined Vygotsky's notion of scientific concepts with a more flexible interpretation, less tied to a fixed system of scientific concepts. The theoretical concepts taught in school can help students establish and maintain local grounding (Chaiklin & Hedegaard, 2013) and enable future applications (Engeström, 2020). Following Vygotsky (1986), Davydov developed a method that combines two complementary learning paths involving abstract and concrete activities that are intertwined during development. The “essence of a concept” is a key notion in Davydov's theory and is the feature common to all instances: concrete and abstract parts that are subject to development by the dialectic approach (Davydov, 1990). It is metaphorically described as a “germ cell” (Engeström, 2020; Hedegaard, 2020) with a potential for development driven by internal contradictions among the parts or as a set of internal relations of sub-concepts (Chaiklin & Hedegaard, 2013). The essence of a concept is both sensory (concrete) and verbal (abstract), and visuality is the central sensory aspect (Davydov, 1990).

Davydov developed a three-step process for supporting concept formation for application in classroom teaching by combining visual and discursive activities, referred to as “rising to the concrete”: 1) perception, 2) visual conception, and 3) theoretical conception (Davydov, 1990), or 1) initial problem situation or task (diffuse sensory concreteness), 2) visual modeling, and 3) conceptually mastered systemic concreteness (Engeström, 2020). These activities are compatible with learning in a makerspace, which consists of tangible objects and physical events to be connected by pupils in meaningful ways in educational tasks such as visualizing the relationships of objects and events before running an experiment or a computer program and before learning concepts and formulas. According to Davydov, the switch from verbal behavior to physical action is driven by a need for visuality, the visual expression of the emerging concept (Davydov, 1990). We interpret this to mean that an inherent tension exists between visual and verbal expressions, which can be resolved by switching to the complementary mode of expression for clarification or concretization. In addition, we add digital tools and programming concepts as new types of physical tools and theoretical concepts, which is new from this perspective.

Davydov (1990) explained (visual) conception using an example of learning elementary physics, describing a situation of pulling a rope connected with a suspended weight and saying that children single out and use prefixes (precursors) to refer to the objects in the situation. The verbalization of the situation serves as the preliminary understanding of Newton's third law. This understanding is associated with certain invariants of the situation, a stable repetitive element such as a set of relationships among concepts, representing a set of concrete tools and actions that may vary. We refer to the unfolding process as a trajectory of collaborative knowledge creation (a group of pupils developing a common understanding) in a sociotechnical space, which we illustrate with an example in Section 2.3. Furthermore, we understand precursors to be words such as *this* and *that* (i.e., deictic references) that indirectly refer to scientific concepts (e.g., “force,” “mass,” and “acceleration”) that are not yet mastered but perhaps partially understood in terms of other names and relating them by causal relations indicated by gesturing.

Chaiklin and Hedegaard (2005, 2013), following Vygotsky (1978, 1986) and Davydov's (1990) theory of rising to the concrete, developed the notion of radical-local teaching that explicitly uses subject matter teaching to encourage children's development in relation to their social conditions. By acquiring basic academic skills in a theoretical framework, children learn how to analyze their own local situation, according to a Davydovian perspective. One instructional method based on radical local teaching is the "double move" approach (Chaiklin & Hedegaard, 2005, 2013; Hedegaard, 2020), which was inspired by Vygotsky's (1986) analysis of everyday and scientific concepts, and Davydov's (1990) account of theoretical thinking. With the double-move approach, each teaching session is planned according to theoretical thinking (rising to the concrete), combining children's experiences, imaginations, and motives with the theoretical (subject matter) concepts, thus the movement in two directions. The starting point is a germ cell model of the knowledge to be taught (Hedegaard, 2020). Hedegaard and Chaiklin presented an elaborate case study on how they developed concrete lesson plans for teaching immigrant children in an underprivileged New York City neighborhood using the double-move approach and enumerated their accomplishments and the difficulties they encountered in implementing the approach (Chaiklin & Hedegaard, 2005).

We have similar aims but with a different starting point, combining the two activities (schoolwork and local practice) from two ends (top-down and bottom up) in the same physical location, a makerspace inside upper secondary schools. We take advantage of a rich set of instructional materials and teachers' scaffolding in a common learning environment, drawing on pupils' out-of-school making experiences.

2.3. *A model to visualize "rising to the concrete"*

We were inspired by Lewin (1951), Lemke (1990), and Stahl (2006, 2015) to provide a method to visualize the collaborative process of establishing and maintaining a common referent (shared object of understanding). According to Chaiklin (2011), Lewin and Vygotsky similarly adopted ideas from other disciplines for use in psychological research. Lewin adopted concepts from mathematics and physics to develop a theory of social-psychological spaces (life space) based on field theory (topological and vector psychology) and the dynamic concepts of tension, force, and resistance (Lewin, 1951). He developed a method to graphically depict the process of building scientific concepts and formulas and to analyze causal relations (Lewin, 1951). On the other hand, in science education research, Lemke (1990) developed a notion he called "thematic patterns," which are subject-specific thematic content areas, organized as a network of semantic relations among sub-concepts in terms of how language is used in the field (Lemke, 1990). In this study, we focused on pupils' use of language in a makerspace classroom in group work and trace the development of their common understanding as it develops over time, which Stahl (2006) refers to as group cognition and the process intersubjective shared understanding (Stahl, 2015). The notation we use to model development of shared understanding is shown in Fig. 1.

Lewin and Lemke's methods for representing scientific knowledge involves establishing relations between concepts and sub-concepts (a conceptual representation) to describe a dynamic process of group behavior in a life space by using tools of various kinds in a bottom-up manner (Lewin, 1951), and filling in the missing parts of a teacher's thematic pattern of a scientific concept (Lemke, 1990). More specifically, our model (Fig. 1) was developed to address the research questions by mapping out a sociotechnical space within which a trajectory of collaborative knowledge creation is projected, allowing researchers to analyze pupils' evolving shared understanding in terms of rising to the concrete and scaffolding. We argue that by shortening the path to solving the learning task, important learning opportunities may be missed out because physical actions on concrete things enable pupils to develop experiential knowledge (diSessa, 1996) and making the task harder may increase learning opportunities (Reiser, 2002), suggesting curvy group knowledge trajectories (Fig. 1).

In our research, we investigated how pupils demonstrate theoretical thinking by combining abstract (conceptual) and concrete (making) activities. This can occur as pupils make artifacts with concrete materials connected to certain STEM concepts, which pupils may initially refer to by other names. This can also occur the other way through instruction as teachers introduce scientific concepts

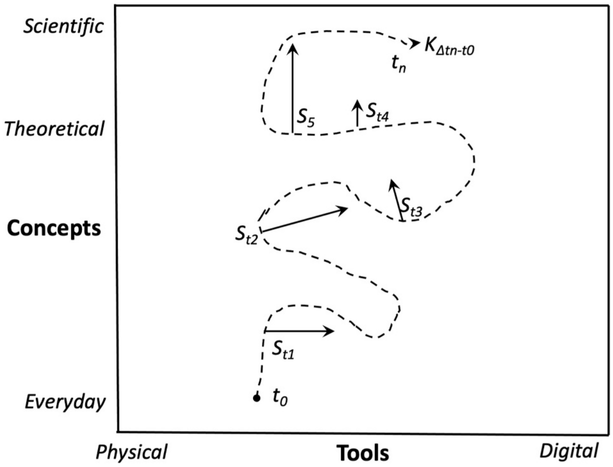

Fig. 1. Tracing pupils' shared understanding (*K*) about a scientific topic in a sociotechnical space of tools and concepts. This trajectory is idealized and scaffolded (arrows, *S*, at different time points, *t*). Scaffolding contributes to changing *K* in vertical (abstraction) and horizontal (concretization) directions.

that refer to aspects of pupils' domain-oriented artifacts. Teachers' top-down and bottom-up scaffolding can facilitate or hinder conceptual understanding. As researchers, we need a data collection method that can capture verbal and non-verbal behaviors in a makerspace. We used multiple video cameras for this purpose (see Sections 3 and 4). In Section 5 (Findings), we used Davydov's framework to organize, analyze, and visualize our results.

3. Research setting and aims

For 4 h every second week for 16 weeks, a group of pupils were taken out of lower secondary school to participate in the makerspace intervention at a nearby upper secondary school. The pupils (N = 19) were in grades 7 to 10 (12–15 years old) (Table 1). The students were selected based on two self-report forms indicating their interest in science and mathematics and a parent form indicating the adoption of scientific thinking and experimenting, such as performing their own science experiments and making their own hypotheses. Furthermore, after parental consent, the pedagogical psychological service in the municipality was consulted as to which students had been reported for needing extra resources in cases of dyslexia, school refusal, and general dissatisfaction with school. These students were prioritized and composed mostly (approximately 50 % of the participants) of underachieving gifted students. To confirm that the selected participants were gifted, they were tested with the Wechsler intelligence test organized by certified psychologists.

The makerspace workshops were taught by two teachers who were both makerspace enthusiasts, having taught students in makerspaces at numerous previous occasions. The main teacher had an information technology degree, while the assistant teacher had both physics and pedagogical degrees. They received no training before the intervention and planned the learning goals and lessons themselves, refining their materials based on their experience during the previous workshops. The learning objectives were to acquaint students with computer programming, electronics, and other makerspace equipment (e.g., laser cutter, microcontrollers, and Inkscape design software), and provide gifted students (both high achieving and underachieving) with opportunities to meet other students like themselves (i.e., gifted), which do not often happen during regular class attendance. Students were provided with oral explanations and brief instructions from the main teacher at the beginning of the workshops and written material (digital or analog) to guide them through the making activities.

3.1. Materials and activities

The learning activities of the children involved assembling different types of physical material and software programs. Following Sheffield et al. (2017), who argued for a strong connection between the physical artifacts and the STEM content, our workshops included the making of the following artifacts: 1) circuits with LEDs, buzzers, and microcontrollers (micro:bit/Arduino; Fig. 2, right); 2) a robot car with different sensors controlled by a micro:bit (Fig. 2, left); 3) a chain reaction including at least one servo motor controlled by a micro:bit; 4) gear trains from plywood with servos controlled by Arduino; and 5) devices for protecting an egg from cracking when falling 4 m and measuring its acceleration with a micro:bit (Fig. 2, middle). The egg drop activity was used in the analysis for illustration.

As some of the programming tasks were complex, the pupils were encouraged to reuse and modify examples, and the teachers scaffolded the pupils after the tasks had been introduced. Block-based programming languages were used to control the physical devices, but Python (a text-based language) was used for the falling egg activity.

4. Methods

4.1. Case study and data collection

This research was an exploratory case study that employed qualitative methods for data collection and analysis (Silverman, 2005). A case study is a particular instance of something used or analyzed to illustrate a thesis or principle (Yin, 2003). We used observation and interviews as our main methods for data collection. We interviewed 17 pupils during the sessions using a semi-structured interview guide (a total of 4 h 6 min, or 246 min). We observed seven makerspace sessions where two of the authors and one assistant were present and recorded extensive field notes using a pen and paper. Two of these sessions were video recorded (8 h 55 min of video data). In this study, we present data from one of these sessions (4 h 20 min of video data) and extracts from the videos of two groups of pupils (one group of four and another group of two) as they worked on their makerspace projects. We chose the groups for observation based on their previous high verbal activity. The video recordings were organized based on the principles of the video research suggested by Derry et al. (2010). At the beginning of the learning activities in class, we placed one camera facing the materials table where students from all the groups gathered and found materials. After this initial phase, we faced the cameras toward the main workspaces of the two selected groups. The dynamic nature of makerspaces meant that the students moved around in the room, and the students' focus moved

Table 1
Student sample according to gender and grade.

Number of participants	Male	Female	Grade 7	Grade 8	Grade 9	Grade 10
19	15	4	3	9	5	2

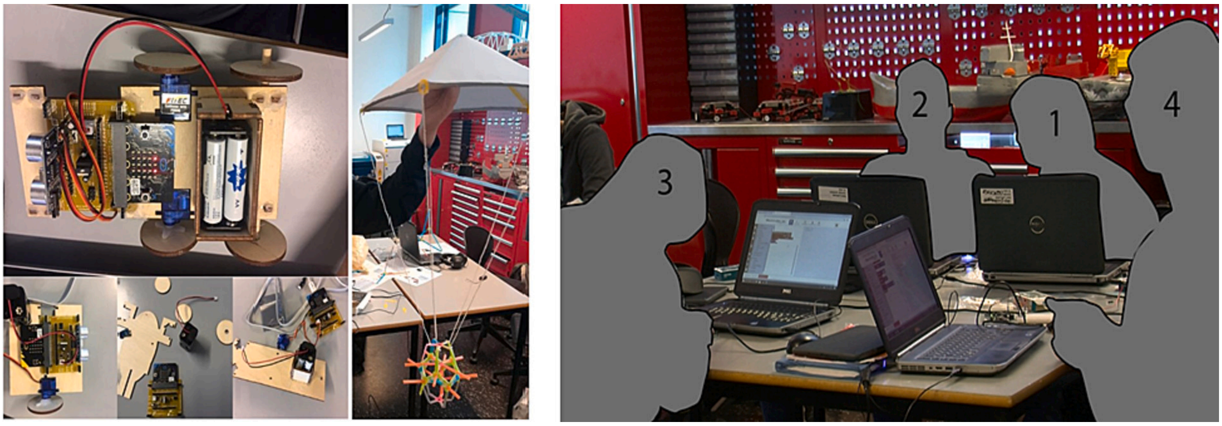

Fig. 2. Examples of artifacts made by the pupils. On the left is a robot car in various stages of assembly; in the middle is an artifact to save a falling egg from breaking; and on the right is the typical arrangement of the pupils during group work.

between digital devices, physical objects, and social spaces, which were also dynamic. In addition, the students were free to leave the room at any time to test their egg-saving devices. While we adjusted the cameras when the groups' workspaces moved or the focus moved between bigger (zooming out) and smaller artifacts (zooming in) and between individual actions and group interactions, we did not conduct video recordings outside the classroom for privacy reasons. In addition to the video transcripts, we selected one extract from our interview data, and we drew on our larger set of field notes, although these were not explicitly reproduced in the paper.

4.2. Data analysis techniques

To analyze the data, we used both thematic (Clarke & Braun, 2014) and interaction analyses (Jordan & Henderson, 1995). The thematic analysis was based on a combination of inductive (bottom-up, open-ended) and deductive (top-down) coding strategies (Clarke & Braun, 2014). The process involved four researchers (one was a PhD student) and two master students who discussed and coded all transcribed video extracts and interview data in collaboration. For the categories deemed to be of most relevance to this article, all extracts were analyzed, and those that provided the highest information content were chosen. Furthermore, we used the theoretical framework presented in the previous section to help us focus (top-down) on the final selection of themes to bring into the article.

Coded extracts of video and interview data were further analyzed using an interaction analysis (Jordan & Henderson, 1995), basing further claims on the participants' utterances, group interactions, turn-taking, tone of voice, and body language (e.g., gesturing).

We identified the following three general themes of learning activities based on our data organization (inductive and deductive coding): 1) engagement and spontaneous concepts, 2) programming and making physical objects, and 3) subject integration. In Section 5, we present data extracts for each theme, within which we provide examples of challenges and opportunities of top-down and bottom-up pedagogical approaches to developing scientific understanding in a makerspace.

5. Findings and analysis

We present and analyze four illustrative extracts (labeled Extracts 1–4 below) based on their information content regarding the identified relevant themes from the video data and interviews, which contained data from two female and five male participants and one teacher. All extracts were from (or related to the topic of) one workshop in which the pupils were given an open-ended assignment to save a falling egg by constructing some sort of damping device. Extract 1 focuses on engagement and spontaneous concepts, Extract 2 discusses programming and making physical objects, and Extracts 3 and 4 provide two perspectives on subject integration: a) the integration of a makerspace with school subjects and b) the gap between scientific concepts and previous knowledge. The workshop was conducted for 4 h in 1 day. We selected this workshop as a focal point because it covered all factors of our interest: it involved programming and making, which is a complicated task, and it was relevant to teaching and learning a STEM topic. The task included measuring the acceleration of the falling egg using a micro:bit circuit board attached to the egg to gather acceleration data, which were sent by the radio function of the micro:bit to another micro:bit connected to a computer that logged the data with Python. The assignment included programming these two micro:bits. During this assignment, the pupils were exposed to scientific concepts, including velocity and acceleration. All pupil names in the data extracts were rendered as pseudonyms. The following concepts obtained from our theoretical framework were used in the analysis: 1) Davydov's three-step process of concept development, which helped organize the data presentation (understanding the task, conceptualizing the solution, and developing theoretical concepts), and 2) our sociotechnical space model, which is used to visualize rising to the concrete, making it easier to compare pupils' activities. The four extracts are preceded with a summary of the findings.

5.1. Understanding the task

At the beginning of the workshop, we observed a series of hands-on activities in the makerspace depicted by the three snapshots in Fig. 3, which took place for approximately 20–30 min after the start of the workshop, in the middle of a brainstorming session, near the materials table.

In Fig. 3a, one pupil demonstrated how he wanted to use a piece of string to lower the egg, while the other pupil looked on with interest. In Fig. 3b, the rest of the group joined the pair from Fig. 3a, and two of them demonstrated a possible solution to the egg assignment by combining a string and a small programmable motor while the other pupils held pieces of a string connected to it. The pupils did not talk much, but they were very hands-on with the material and used body language in their explanations to each other. In Fig. 3c, we observed a pair of students who appeared in extracts 2 and 4, standing by the materials table, individually searching for suitable materials (e.g., straws to create a frame for the falling egg) without communicating with each other.

Everyday concepts and physical actions were elicited in conjunction with talking while making low-tech prototypes at the beginning of the workshops and sometimes deep into the activities (e.g., the pupil's hat serving as a container for the egg in Extract 1 that we reproduce below). The engagement observed was primarily determined by elements of enthusiasm (verbal or bodily), mainly in collaborative settings, as indicated by the extract and later supported by interview data in which the pupils identified what they liked or disliked in the interventions. Testing low-tech prototypes helped the pupils to understand the task, which we illustrate below.

5.1.1. Data Extract 1: engagement and spontaneous concepts

The following 30-s dialogue (Table 2) took place in one of the four-pupil groups. Prior to the first turn, two group members, Lars and Filip, indicated uncertainty about how to proceed with the task.

This example of a “bottom-up” situation where the pupils' understanding originates in a conversation involving everyday experiences was initiated by Filip asking who had used his hat as a container for the egg, and William hesitantly stated that it was him. What William had done prior to the situation was to tie the egg inside Filip's hat, perhaps as an act of creative appropriation that he was unable (or too ashamed) to articulate in words. Filip had a hunch that this was a solution to their problem, which, at that time, was a vague understanding (Turns 1.1–2) and turned around to inform all the group members about his “Aha!” moment (Turns 1.3 and 1.4). Then, through a clarifying conversation and a repetition of how William had tied Filip's hat around the egg, Filip and William reached an initial common understanding about the hat as a possible egg-saving contraption (Turns 1.5–10). The episode ended when William recreated the device, and all four pupils left the laboratory to test their tentative solution by dropping Filip's hat from a 4-meter height with the egg inside.

The group's conversation was not about science but about understanding the task and gathering materials for assembling them into a physical artifact to partly achieve the assigned task. Two pupils reached an understanding on what to do, but the other two did not yet engage in the discussion. The vocabulary is informal at this stage, with deictic references to physical objects and involving physical action to simulate the concrete part of a scientific process.

5.2. Conceptualizing the solution

When the task was understood, more advanced physical artifacts were built and programmed to control or measure aspects connected to the artifacts. The pupils eventually created the program code but struggled with understanding some of the programming tasks. When the pupils started to ask questions relating to scientific concepts in the assignment or the learning activity more generally, they used the physical artifact as a shared referent. When the pupils were stuck with conceptual problems or had questions they could not answer, they switched to making and testing things. The learner behavior we observed at this level was mainly conceptualizing (Davydov, 1990), that is, to understand the path to a solution. In some cases, this became two distinct activities (physical construction of prototype and programming circuit boards using the Python programming language).

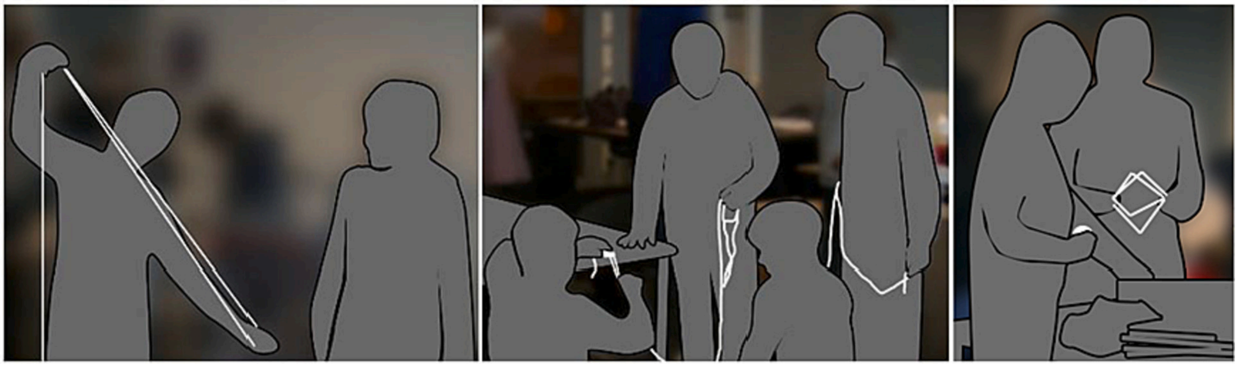

Fig. 3. Pictures (a–c, left to right) of pupils' different situations in a makerspace while standing around the materials table, where they tested string materials and discussed possible solutions for the assignment.

Table 2
Engagement and spontaneous concepts (Extract 1).

Turn	Actor	Interaction	Action/comment
1.1	Filip	Need to tie it	Seems to reach an “Aha!” based on tone of voice
1.2	Filip	Need to tie it to my hat	Walks around the table and carries a micro:bit in one hand and lifts hat with other hand, which is tied up with the egg inside
1.3	Filip	Need to tie it to my hat	Repeats the statement and turns to the other members, who were uncertain about what was happening; Filip inspects the hat
1.4	Filip	Who tied it to my hat? Was it you who tied it to my hat?	Turns to William; the two other pupils talk in low voices
1.5	William	You mean that one?	Pointing to Filip's hat
1.6	Filip	Yes!	Shaking his left hand, which might indicate anger
1.7	William	Your hat was lying around there	As if it was an object to be used
1.8	Filip	Yes, but who did it?	
1.9	William	It was me!	A bit hesitant as he thinks Filip is angry
1.10	Filip	Do it one more time?	William understands Filip is not angry but has an “Aha!” moment; William repeats the procedure, and they start to cooperate
1.11	William	Okay	Responsive tone of voice; Filip smiles; both work with their hands and take the physical objects out of the room to test them

In the next extract, we followed a group of two students, Henrik and Ella, who created a prototype of their egg-saving contraption. Ella took the lead in programming, and Henrik made the prototype. Before we entered the situation shown in Table 3, Henrik tested the functionality of his physical prototype by standing on a chair and dropping the device from his hands. The device functioned as a parachute with the aid of a plastic bag tied outside a plastic straw egg-holding device (see Fig. 2, middle image, for a final version and Fig. 3c for an early version).

5.2.1. Data Extract 2: programming and making physical objects

After testing the preliminary device several times, Henrik moved to sit with Ella by the same desk. She had been thinking about the conceptual part of the solution for a while, that is, programming two micro:bit circuit boards to measure and log the acceleration of the device in free fall.

Data Extract 2 is an example of an incomplete attempt at either the top-down or bottom-up approach to conceptual modeling. Ella took the lead in programming, and Henrik made the prototype, but they did not communicate much. The challenges caused by technical vocabulary belonging to programming interfered with the pupils' practical understanding of the task, as demonstrated by their different activities and incomplete common understanding: Henrik's testing of the device in free fall from his chair (thus avoiding the conceptual task) and Ella's programming of the first micro:bit to obtain the data from the falling object but reaching an impasse. In the beginning, the pupils were not bothered by this; they were deeply engaged in their own work and gave the impression that they were going to solve the task. When Henrik sat down, Ella coded, and Henrik began to comment (Turns 2.1–2.2). However, it turned out to be difficult for them (Turns 2.3–2.5), starting with Ella's utterances in Turn 2.3, “I am starting with this one now” and “I am trying to understand how the code works.” Ella was referring to the sample code from the instruction sheet and gradually became frustrated, as she could not get the code to work. She tried to understand how the two circuit boards communicate. However, she persisted and tried to figure out how to put the lines in the correct sequence; they were given the code in a scrambled sequence for them to sort out as part of their learning. However, Henrik resigned himself to not knowing. He disconnected from the programming session and started to play a video game on his PC. After some time, Ella also bailed out, exclaiming that she did not know what to do. She looked around and raised her hand to call for help.

The two pupils worked on different parts of the task but did not achieve a shared understanding. They created their own understanding of what they were doing (two different conceptualizations) but were not able to tie the physical parts (egg-saving prototype) and conceptual parts (programming and understanding the physics) together. A teacher or a more competent third person could have put them on track. The programming involved a low-level code to read signals from a sensor attached to the egg-saving prototype, but the instruction sheet did not help. The group was perhaps too small, or the programming for reading the physics properties of the

Table 3
Programming and making physical objects (Extract 2).

Turn	Actor	Interaction	Action/comment
2.1	Ella	There, yes, micro:bit. Wait… Can it be “from micro:bit import radio”?	She starts to explore the instruction sheet, which includes scrambled code statements
2.2	Henrik	Do you start with this one or that?	Points at the instruction sheet
2.3	Ella	I am starting with this one now because I am trying to understand how the code works… import radio from…	Points first at the instruction sheet; Henrik is thinking
2.4	Henrik	Shall we…	Starts playing a video game on his computer
2.5	Ella	Import radio from x… for or… for radio x it is the same as bytes… So, from micro:bit in a way… It is… I think I'll go and… Maybe I should ask (for help). Oh! What (coding statements) belong together in a way. Okay. Maybe from import while true… Oh? I don't know!	She takes the instruction sheet in her hands and reads and looks at Henrik, who does not follow. She looks for a teacher and starts to copy some text

device might have been too complex.

5.3. Theoretical concepts

Using and understanding scientific concepts (e.g., physics concepts relevant for falling bodies) in a bottom-up manner are extremely demanding tasks in a makerspace with a diverse group of pupils, given the limited time we had (classroom constraints). However, the payoff is that the physical grounding of the embedded knowledge may lead to theoretical thinking. We do not have video data to demonstrate the pupils' mastery of scientific concepts, but our interview data showed that the pupils found the activities memorable and used scientific concepts in some conversations when prompted in interviews afterward.

In the interviews, we asked whether the pupils found the workshop topics relevant and whether they could see connections of the subject matter with programming and making. We provide an example of one pupil's answer in the next data extract, which was chosen because of its large information content. Most students did not provide answers at this level of specificity.

5.3.1. Data Extract 3: integration of a makerspace with school subjects

Table 4 reproduces an extract from one of the interviews. We asked the pupil, Hannah, what she did not like about the makerspace and whether she had any suggestions on how teaching could be done differently.

This is an example where the informant (Hannah) proposes a solution to the problem brought up in Extract 2, a lack of integration of separate activities. Hannah was one of the three pupils who explicitly suggested that traditional school subjects should be better integrated with the activities in the makerspace. She identified that the makerspace activities were related to “sciences in general” and saw opportunities for learning about specific scientific concepts (e.g., velocity and acceleration in physics) and formulas for computing these values (e.g., for falling objects) while working on creative projects. These concepts could be better integrated, and our data indicated a solution with a bottom-up path with improved scaffolding, as shown in the final extract (Extract 4). The top-down approach is also viable but outside the scope of our empirical data.

This is one of the few episodes where a pupil naturally used scientific vocabulary in a conversation without being prompted. The scientific knowledge would often be implicit in the pupils' activities of making and following the science assignment but understood in scientific terms only when asked by a researcher or teacher.

5.3.2. Data Extract 4: gap between scientific concepts and previous knowledge

Table 5 shows a conversation that started approximately 50 min after Extract 2. Ella and Henrik were about to finish their work on the coding to measure the acceleration of their falling egg contraption.

We observed that as Henrik asked what the micro:bit was measuring (Turn 4.1), the teacher started explaining the unit of measurement of gravitational acceleration (Turn 4.2). During the teacher's explanation, the teacher realized that the pupils did not know several of the prerequisite concepts in physics. The teacher could have established a platform for scaffolding in the shared referent (common understanding) held by the group. For example, Henrik's question in Turn 4.1 indicates that he was aware that a physics concept is relevant in the situation (“distance” but should be “acceleration”), and Ella had completed the program for computing it (the acceleration). However, as no common referent was established, the teacher realized that scaffolding would take time. Taking into consideration that the pupils had already worked with many new materials that day, the teacher decided to cease any further explanation. Then, Ella left her seat (Turn 4.2), indicating less interest in listening to the teacher. After the teacher's aborted explanation, Henrik also left his seat (Turn 4.3) to join Ella in testing their egg device. Here, we observed that scaffolding failed because of the teacher's lack of awareness of the pupils' prior knowledge and attuning to their common understanding to help bridge them upward to solve the task.

In this situation, the discrepancy was addressed by testing the device, as shown by Henrik's utterance and action in Turn 4.3, “But should we go and test it, then?” (see also Extract 1 for a similar behavior in the four-pupil group), which indicates a makerspace mediating everyday and scientific understanding by toggling between complementary (physical and conceptual) learning activities.

5.4. Comparative analysis of rising to the concrete

The four episodes illustrate the three phases of Davydov's concept of rising to the concrete: 1) understanding the task (Extract 1), 2) visualizing the solution (Extract 2), and 3) theoretical concepts (concepts that relate to a concrete action and/or a physical or digital

Table 4
Integration of a makerspace with school subjects (Extract 3).

Turn	Actor	Interaction
3.1	Researcher	Is there anything you don't like in the makerspace?
3.2	Hannah	I am not sure. It could be that we are not learning enough about subjects, in a way. We do not stick to a topic over time. It's like… You know… I know what we do is based on math and natural science or sciences in general [referring to the falling egg assignment], but we have so much freedom to explore…
3.3	Researcher	[Seven minutes later in the transcript]. Can you come up with any suggestions on how teaching could be done differently?
3.4	Hannah	It would be good to have subject-related knowledge better integrated with our exploratory activities. For example, the project we do now, we could also be learning about velocity and acceleration and similar things, how to compute values and set up formulas, or the way micro:bit works out its computations, or whatever is happening with what we are doing.

Table 5
Gap between scientific concepts and previous knowledge (Extract 4).

Turn	Actor	Interaction	Action/comment
4.1	Henrik	Is that there, what does it measure? Kilometers?	Points at Ella's screen
4.2	Teacher	No, it measures thousandths of the gravitational acceleration (*g* value). So, for the unit, it is 0.001 times the gravitational acceleration, and the gravitational acceleration is 9.81 m/s^2. Just to include *even more* new stuff today (chuckles). So, there are quite a few new concepts you haven't been introduced to yet.	Ella leaves her seat
4.3	Henrik	But should we go and test it, then?	Leaves his seat

artifact) (Extracts 3 and 4). The observational data (Extracts 1, 2, and 4) depict what the pupils were doing, whereas in the interview (Extract 3), Hannah suggested a future situation where the teacher scaffolds the pupil's learning activity by integrating domain knowledge into the pupils' conversations and understanding, such as relevant scientific concepts that explain parts of the science task. The different episodes illustrate various attempts at rising to the concrete (see Fig. 4).

According to Davydov, the essence of a concept consists of abstract and concrete parts (Davydov, 1990). During the three phases, the pupils' activities revealed different configurations of the two parts. Fig. 4a illustrates four pupils' understanding of the task, which is mainly concrete without any abstract core relating to a theoretical concept. Wrapping an egg in a hat as a possible egg-saving contraption is an act of creativity. The potential for further development was realized by a combination of (requested) scaffolding and testing the egg-saving device outside the classroom. In the next situation (Fig. 4b), two pupils, Ella and Henrik, worked at a higher level of abstraction than the other group, and their solution in progress had abstract and concrete parts, but these were not connected. Ella was programming to connect two circuit boards, and Henrik was occupied with the physical prototype and a video game. However, he sporadically oversaw Ella's work and indicated a wish to a achieve common understanding, which was not yet realized and led to frustration and further testing.

Fig. 4c illustrates an idealized situation where Hannah describes how scaffolding can help pupils connect scientific concepts with their science projects. Although the pupils in our case did not naturally use scientific concepts in group conversations, many pupils

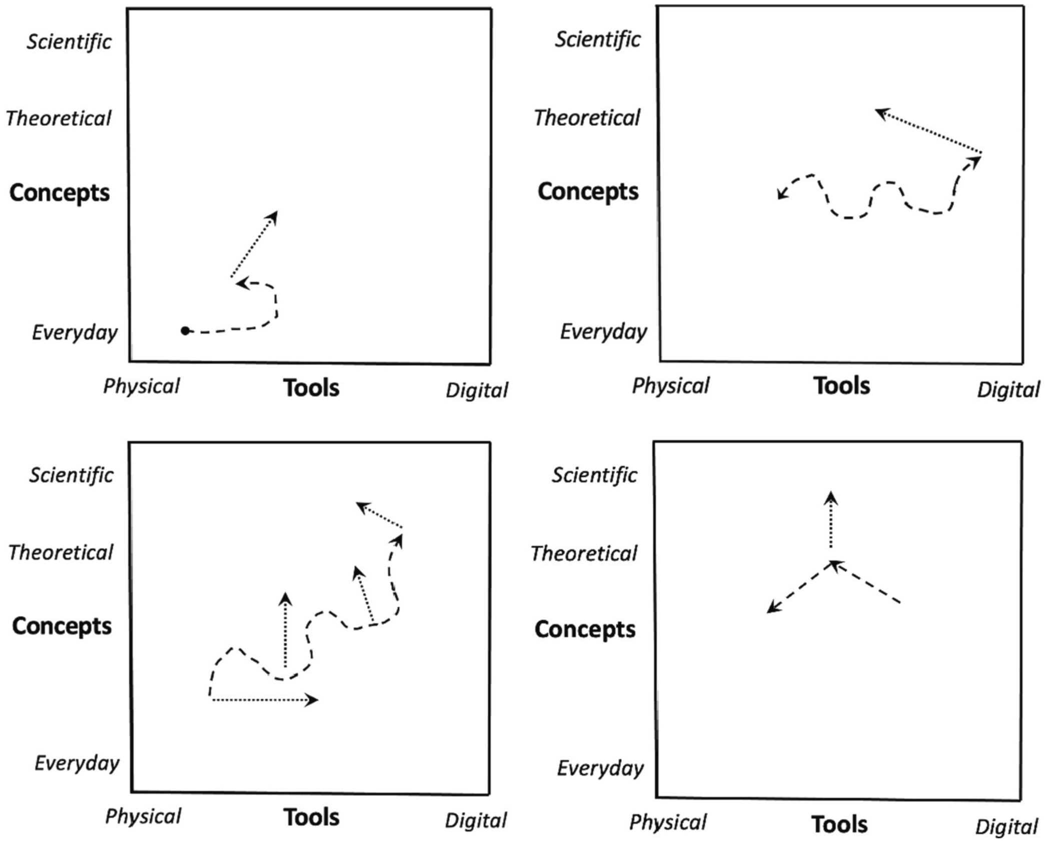

Fig. 4. Pictures (a–d, left to right; top to bottom) visualizing different phases of pupils' shared understanding of science topics in a makerspace, according to the concepts and tools used. The large-dashed arrows depict pupils' shared understanding as it develops over time, and the small-dashed arrows depict teacher's scaffolding effort (anticipated in a–c; actual in d).

displayed theoretical understanding by relating concepts with the science activity. For example, as shown in Fig. 4d, Henrik asked the teacher if the micro:bit measures *kilometers* to capture distance during free fall, indicating an understanding of a physics concept and its relation to a concrete artifact, and involved a unit of measurement. The correct physics concept in the situation is *acceleration*, and the unit of measurement is different. Nevertheless, Henrik was able to connect a theoretical concept with concrete parts, a behavior characteristic of rising to the concrete.

6. General discussion

Here, we discuss the research questions by comparing our findings with the current literature. We highlight the interplay of physical/digital making and conceptual understanding in the pupils' group work and the co-occurring dynamics (dialectics) of spontaneous and scientific concepts in the pupils' and teachers' conversations, which we address in separate subsections.

6.1. How can we understand pupils' collaborative science learning in a makerspace from the perspective of the dialectic of everyday and scientific concepts?

The interpretations of Vygotsky's theory of the relationship between spontaneous and scientific concepts (Vygotsky, 1986) suggest a combination of bottom-up and top-down learning activities, that is, upward toward generalization from the spontaneous concepts and downward toward specific situations or examples of the scientific concepts. According to Vygotsky (1986) and Davydov (1990), both approaches are necessary because they rely on each other and co-occur.

Co-occurrence is exemplified in our case by two sets of concepts (scientific and everyday) with the same referent in the social world or by two parallel channels of information, one for intellectual activity and the other for experiential knowledge based on sensory data. This can be achieved when pupils have prior experience of the school task or have completed some activities before coming to class. Co-occurrence has been studied from the Vygotskian perspective in previous research. It is related to presenting concrete and abstract representations of a concept (Howe, 1996) and studying the dialectic interplay of everyday and scientific concepts in young children's play-based encounters and is scaffolded when the teacher integrates both types of concepts (Fleer, 2009). It has been conceptualized from a Davydovian perspective by a germ-cell, a tension-laden, expansive core domain model referred to as primary substantial abstraction, moving in two directions during teaching, toward pupils' motive orientation and interest, and toward the theoretical domain concepts (Hedegaard, 2020).

Contemporary works include that of Furberg and Silseth (2021), who studied pupils' use of everyday experiences in classroom talk. When teachers take advantage of these experiences (e.g., celebrities and video game characters in their case) and make them relevant in science learning using a bottom-up approach, the experiences become mediational means that may lead to more productive classroom conversations (Furberg & Silseth, 2021). In a makerspace, the teacher spends considerable effort to intervene and adapt to different learner needs (top-down). Kajamaa et al. (2020) suggested that teachers must encourage students to take responsibility for their own learning and share the extra work. Our work addresses teachers' challenges of bridging between everyday and scientific concepts in the classroom, drawing on both conceptual and concrete (hands-on) mediational means, to situate concept development and social organization in a broader sociocultural space (see Section 6.2).

In our makerspace setting, which was organized mainly bottom-up, concept development is a process whereby pupils make artifacts with concrete materials tied to certain STEM and/or programming concepts and formulas. These concepts are introduced to the pupils as necessary to help them gradually see their relevance and adopt the concepts in their conversations, that is, learning to talk science to explain their artifacts to fellow pupils (Mørch et al., 2019; Lemke, 1990). This became a challenge when the teachers did not respond to all pupils' help requests or failed to adapt scientific concepts to the pupils' diverse prior knowledge (ages 12–16 years).

We observed that the pupils preferred to use everyday language when working with their science projects. The hands-on activities and collaborative learning were mediated by the materials available in the makerspace. This was particularly evident in the early phases of the workshops, where most pupils actively used the teacher-provided physical materials to propose (partial) solutions in collaboration with the other pupils in their group, but participation was sometimes uneven, involving both "doers" and "thinkers" (see Fig. 3a). This is consistent with the findings of Riikonen et al. (2020) from the Making-Process-Rug method and shows the complex process the students must navigate, not only between different modes of work across time but also between different modes of work at the same time.

Another observation supporting the prevalence of the use of everyday concepts instead of science talk in pupils' group activities is evident by the high engagement pupils revealed in the activities. The egg-drop workshop findings echo the findings of Lui et al. (2020). An individual primarily initiated the construction of the physical devices (extracts 1 and 2), but during conversation, group members came together (first in pairs and then in a larger group). Most of the time, the pupils seemed to enjoy the making activities, including programming, and constructing physical things, based on their interview answers and positive tone of voice in the video data (e.g., Extract 1). This is consistent with previous research on the programming of physical devices that lead to increased engagement (Austin et al., 2020).

Despite the challenges of talking science, we found that the pupils' conceptual understanding gradually improved in our workshops. For example, when explaining their science project to others in the class, the pupils revealed a level of theoretical understanding. On the other hand, the evolving group knowledge was not a linear trajectory but was curvy and sometimes stopped abruptly (see Fig. 4). Complete conceptual understanding was not reached because the pupils did not use scientific concepts without being prompted. Instead of using the scientific concepts and formulas, the pupils used precursors (Davydov, 1990) or deictic references to objects and events in the makerspace (e.g., "this," "that," and "the other one"), other names (e.g., "kilometers" instead of "acceleration"), and causal relations (data collected by one micro:bit is sent to another micro:bit, acceleration is measured by obtaining information from a series of snapshoots of the movement of the prototype in free fall, etc.).

In an idealized process, the pupils' shared understanding will develop gradually toward science understanding by increasing the use of scientific concepts, which in a good process will lead to "talking science" (Lemke, 1990). This was not achieved in the self-organized small group conversations in our case, but the pupils recalled the scientific concepts when prompted in interviews and by the teacher. We seek further understanding of the observed phenomenon in the next section.

6.2. What are the opportunities and challenges of using a makerspace in science education? Drawing on the Vygotskian notion of duality of physical and conceptual tools

The pupils observed in Extract 1 did not work out a solution together in the beginning. At the outset, multiple alternatives originated from individual group members, one of which was chosen, shared, and continued by the group (e.g., Filip's idea based on William's innovation of an egg in a hat in Extract 1). In Extract 1, a set of independent physical actions were gradually replaced with a conversation that led to an experiment to test a partial solution (dropping the egg wrapped in the hat). We consider this as an example of the beginning of a process of building shared understanding by working upward starting from spontaneous concepts. Jeong (2013) identified two types of shared understanding, intersubjectivity and domain knowledge, and found that pupils completed an assignment without fully understanding the domain knowledge, that is, achieving intersubjectivity and stopping at an intermediate level of understanding (e.g., "The group decides we are doing okay").

Our findings indicate a reciprocal relationship between making and understanding: a conceptual breakdown or exhaustion in understanding led to new making, including testing and repair. On the other hand, when trying to figure out what to make and what to do when things physically or computationally broke down, the pupils shifted their focus to improving their understanding, starting with understanding the physical artifacts and relationships between the parts. In Extract 2, the pupils shifted from a practical mode (testing the egg-damping device in the classroom) to a theoretical mode (programming micro:bits to collect data to measure acceleration, a physics topic). Later, in Extract 4, the same pupils switched from a theoretical modality of attempting to understand another concept in physics (the unit of measurement for the acceleration sensor of the micro:bit) to a practical mode, where they tested a tentative theory and viewed the task from a different angle. By contrast, Chaiklin and Hedegaard (2013) suggested a double-move approach, whereby teaching sessions combine children's experiences and imaginations with the subject matter concepts. The main idea is to increase the chance of applying academic knowledge in practical activities (Chaiklin & Hedegaard, 2005, 2013). This requires teachers' adaptive scaffolding at different levels of abstraction, which turned out to be a challenge in our case due to the pupils' diverse backgrounds.

The switching from the theoretical to the practical modes of collaborative learning and vice versa can be understood as combining complementary activities. This is in line with the tool-symbol duality (Vygotsky & Luria, 1994). Davydov's (1990) visual principle suggests that conceptual knowledge requires visuality for stimulating learning by seeing the relationships of concepts, objects and events and resolving conceptual problems, including programming puzzles, by testing physical prototypes in our case. In his research, Jeong (2013) showed that pupils shifted focus from group understanding to building circuits when they asked hypothetical (what-if) questions such as "What if we use two batteries?" Riikonen et al. (2020) captured the intertwining of making and verbal activities in makerspace and showed that model making is often followed by ideation (e.g., discussion and evaluation of the model). Furthermore, the verbal activities assisted the participants to identify design problems and propose solutions to the models, thus revealing an interdependent process.

The interdependence of making and understanding the making process and the higher-level, more established context encompassing the activities (i.e., science) varied considerably among the pupils in our study, although these were most clearly articulated by how far into the learning activity the pupils were. In the beginning (e.g., Extract 1), the two activities (making and understanding) were invoked serendipitously, vaguely articulated, and poorly connected to science, or had one part (theoretical understanding in our case) completely missing. Later, the students started to work more systematically, for example, when they were coding and connecting micro:bit circuit boards (Extract 2). However, the two activities (programming and creating the prototype) did not combine, as we showed in Ella and Henrik's divergent foci and lack of convergence, in which Henrik built a version of their egg-saving contraption while Ella wrote the micro:bit code to control it, without much communication.

Nevertheless, our observations and interview data indicate that the pupils enjoyed the activity, were deeply engaged, and achieved a physical grounding of their conceptual understanding in the end. For example, in Extract 4, Henrik understood the connection between a concept and a physical process to be measured with the micro:bit controller (acceleration) but was unable to use the correct name for the physics concept. We suggest that this partial conceptual understanding is an instance of theoretical thinking, following Chaiklin and Hedegaard (2005), Davydov (1990), Engeström (2020), and Hedegaard (2020). This is a level of understanding whereby pupils can make connections between objects and processes, displaying an understanding of causal relationships in a science experiment, even though the pupils did not name the relations, objects, and processes (e.g., acceleration) scientifically. We conjecture that understanding at this level, referred to by diSessa (1996) as sub-conceptual or experiential knowledge, is a step toward a deeper understanding of science. Our understanding was achieved by a sociocultural perspective by bridging everyday and scientific concepts (Vygotsky, 1986) and using theoretical concepts (Davydov, 1990). We visualized concept development from this perspective by tracing the pupils' shared understanding in a sociotechnical space.

7. Summary and conclusions

We report on making and STEM education activities carried out in a makerspace from a sociocultural perspective using qualitative methods. We observed a discontinuous trajectory of collaborative learning in the makerspace. On the one hand, involving making and discursive activities (from talking about solving a problem to talking about the physical/digital artifact under construction to talking science using non-formal vocabulary). Scientific concepts were rarely used, but the students solved the assignment by following instructions with minimal assistance, thus revealing their theoretical understanding at a practical level, which we refer to as rising to the concrete (Davydov, 1990). We suggest an intermediate level of conceptual understanding, which is dynamic and visualized as movement of group understanding in a sociotechnical space of concepts and tools and bridging between the end points of the two-dimensional space defined by our research questions (physical tools vs. conceptual tools; everyday concepts vs. scientific concepts). We added digital tools and theoretical concepts as two new elements along the two dimensions, respectively.

The learning activities we observed in our workshops can be divided into three phases: 1) engagement and spontaneous concepts, 2) programming and making physical objects, and 3) subject integration (obtained from thematic data categorization and interaction analysis). Transitioning from one phase to the other was necessary to advance conceptual understanding beyond spontaneous concepts. Findings from the interviews in general and Extract 3 in particular indicate the importance of focusing on specific STEM topics, introducing them early in explicit form as scientific concepts and formulas and aligned teaching models (top-down and bottom-up), akin to the double-move approach (Chaiklin & Hedegaard, 2013; Hedegaard, 2020), rising to the concrete (Davydov, 1990; Engeström, 2020) and scaffolding (Vygotsky, 1978), using appropriate vocabulary and an appropriate abstraction level (Chaiklin, 2003). Our approach is different from the prior work by relying more on bottom-up scaffolding than explicit instruction. The pupils often identified very low-level concepts in mathematics and science in the learning activities (e.g., Extract 4). First, this could indicate that the pupils had not learned any new STEM content. However, a more detailed analysis revealed that they learned at a sub-conceptual level, which we visualized as a trajectory of shared understanding in a sociotechnical space involving abstract and concrete dimensions in an overall effort to drive the process toward rising to the concrete (combining abstract and concrete elements). Several of our examples show that even small adjustments to the makerspace parameters enabled by flexible tools, materials, and scaffolding may allow pupils to master concepts that, at the outset, are too advanced (i.e., detailed knowledge of sensors and electronics, or formulas in physics such as those shown in Extracts 3 and 4). To identify the necessary adjustments, we need a flexible representation for researchers and teachers to see the pupils' activities (making physical and digital artifacts and understanding science topics) at a more general level. Teachers hold the key to adjusting the parameters of educational makerspaces by balancing instructional material in different tool modalities (physical-digital-conceptual) and scaffolding at different abstraction levels (everyday-theoretical-scientific), combining top-down and bottom-up focused STEM activities and pedagogical approaches. Replacing Python with a block-based programming language designed for our target age group (e.g., Andersen et al., 2021), providing more frequent scaffolding, and recruiting expertise locally from among more-knowledgeable pupils are examples of opportunities within the reach of the present approach. Further work with our ongoing makerspace project involves expanding our case study design with a design-based (iterative) research approach and addressing the challenges by incrementally changing the parameters of the makerspace classroom (e.g., starting each workshop with an introduction to the key science concepts applicable in the project work; ending each workshop with each group giving a scientific walk-through of their project; and assessment based on the quality and originality of the expression of the theoretical knowledge).

7.1. Limitations of the study and directions for further work

One limitation of this study is the possibility of a self-selection bias, as only pupils with a particular interest in science and mathematics were selected, although whether this would influence the study results would depend on the specific finding. Based on the findings of this study, the most likely candidates to be affected are three pupils (of the 17 interviewed pupils) who called for more subject matter in the makerspace workshops. In a cohort with less interest in science and mathematics, this finding might not be replicated. Furthermore, the gender distribution in the overall sample of participants or selected extracts presented (more males than females) was not equal. However, the gender inequality is likely less important than the number of participants ($N = 19$), which is too small to generalize. In this study, we did not attempt to generalize the findings to larger groups but treated them as illustrative examples likely to be found in similar scenarios. To find more general patterns of observations in larger populations, studies with more participants are needed.

The following are some directions for further work:

- Ongoing work to use quantitative methods to analyze pupils' STEM learning based on pretest and posttest surveys.
- Investigate other approaches to visual modeling of rising to the concrete using research methods such as multimodal social network, epistemic network, and topological space analyses.
- Integrate ZPD into our conceptual framework and visual modeling for analyzing teachers' instructional scaffolding in a makerspace, starting with the ideas presented by Chaiklin (2003) and operationalized by concepts from vector psychology such as driving force, resistance, and direction (Lewin, 1951).
- Scaffolding is an essential concept for enabling learning. Learning in the future will increasingly be supported by artificial intelligence (AI) applications. Computer-based scaffolding can take advantage of human-centered AI to scaffold pupils' learning of domain knowledge using technology, including technical knowledge of programming (Andersen et al., 2022).

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