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Learning within fiber-crafted algorithms: Posthumanist perspectives for capturing human-material collaboration

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Abstract

A key commitment of computer-supported collaborative learning research is to study how people learn in collaborative settings to guide development of methods for capture and design for learning. Computer-supported collaborative learning research has a tradition of studying how the physical world plays a part in collaborative learning. Within the field, a material turn is emerging that considers how digital and tangible technologies actively contribute to collaborative learning processes. Studying how tangible materials produce collaborative learning visibly and algorithmically is particularly important at a time when advanced algorithms are integrated into educational contexts in ways that are not always transparent. However, the needed methodologies for capturing how non-human agents take part in collaborative learning remains underdeveloped. The present study builds on current CSCL research that investigates materials in collaborative learning and introduces posthumanist perspectives with the aim to decenter humans methodologically and to probe empirically whether and how these perspectives contribute to empirical understanding of collaborative learning processes. Taking fiber crafts (e.g., weaving and fabric manipulation) as a context for computational learning, the present study conducted a posthumanist *analysis of differences* among human and non-human participants in collaboration using video data to investigate how middle school youths and fiber craft components performed algorithms over time. The findings show how both youths and craft materials actively contributed to the performance of algorithms. In weaving, algorithms became repeated youth-material movements one dimension at a time. In fabric manipulation, algorithms became a repeated confluence of component parts. Decentering humans through an analysis of differences among human and non-human introduced human-material collaboration as a productive unit of analysis for understanding how materials and people together contribute to producing what can be recognized as computational performance. The findings of this research contribute to ongoing conversations in CSCL research on how computational materials can be considered in collaborative learning and present a new approach to capture collaborative learning as physical expansion over time. The study has implications for future research on capturing collaborative computational learning and designing physical computational learning opportunities that show technology as evolving.

Keywords Human-material collaboration · Posthumanist perspective · Analysis of differences · Computational learning · Fiber crafts

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Introduction

Improving theory and knowledge about collaborative learning is crucial to better understand how to design high-quality approaches to capturing and facilitating learning (e.g., Kolodner, 2004; Lee, 2018). A prerequisite for that is the study of the material world where learning takes place (Kolodner, 2004). Computer-supported collaborative learning (CSCL) research has a strong tradition of considering how digital and tangible materials contribute to collaborative learning and collaborative learning processes. Studying the use and movement of digital and tangible materials that learning is contingent on provided evidence of collaborative learning and collaborative learning processes, extending the unit of analyses to include environmental and contextual factors, such as material and body movements (e.g., Arnseth & Krange, 2016; Davidsen & Ryberg, 2017). Especially in CSCL research on design and craftsmanship, there is a growing trend that emphasizes the active involvement of materials in collaborative learning (e.g., Kumpulainen & Kajamaa, 2019; Mehto et al., 2020a, b).

Collectively, the focus on better understanding the role of materials in the empirical study of collaborative learning resonates with posthumanist perspectives. Within the field of education, a range of posthumanist perspectives have been spearheaded by literacy studies (e.g., Kuby & Rowsell, 2017; Sheridan et al., 2020; Taylor & Ivinson, 2013; Wohlwend & Thiel, 2019) that built on animal studies, new materialism, material feminism, and decolonial and indigenous theories (Rosiek et al., 2020). Like other posthumanist perspectives, the Barad (2003) approach that this paper takes on does not look past the human and highlights the importance of analyzing differences between the physical and non-physical form of a phenomenon over time (see also Lenz Taguchi, 2010). This resonates with CSCL research because it contextualizes possible computational learning (e.g., computational concepts like algorithms, troubleshooting, and control structures) within the physical learning environment. The posthumanist analysis of differences between states of a physical phenomenon over time is relevant for the study of collaborative learning because it connects to recent CSCL conversations about how to include and account for the doing of (computational) materials in collaborative learning (e.g., Kumpulainen & Kajamaa, 2019; Mehto et al., 2020a). Expanding this work is particularly timely as advanced technological algorithms that are not always obvious become embedded within educational settings.

However, it remains understudied whether and how an investigation based on posthumanist perspectives can productively contribute to an empirical understanding of collaborative learning and what implications this shift could have for capturing and designing for collaborative learning. Yet, empirically testing a posthumanist analysis of differences is distinctly useful for contexts that grapple with biases (Kuby, 2017), such as computer science, with its continued lopsided gender rpresentation (e.g., Sax et al. 2016). Taking an additional perspective on collaborative learning promises to show real learning processes that are going on but that were not possible to capture without a shift in what collaborative learning is and can be. Further, taking an additional theoretical orientation can show whether and how the introduction of materials that are non-dominant or underrepresented in computing, such as fiber crafts, transforms learning.

Fiber crafts, such as weaving and manipulating fabric, are compelling contexts for investigating the insights we can gain into collaborative computational learning from a posthumanist analysis of differences. The dominant reasons for that are that weaving and fabric manipulation are connected to computing (e.g., Fernaeus et al., 2012; Plant, 1995) and require people and materials to move in routine ways to perform algorithms (Keune, 2022). The present study stands in the context of recent research that showed how fiber crafts are a context for computer science and mathematics learning (e.g., Peppler et al., 2020b; Keune, 2022; Thompson, 2022; Saxena et al., 2023). Taking two fiber crafts (e.g., weaving and fabric manipulation) as contexts for computational learning, the present study probes beyond the prior work. For instance, the prior work found that weaving and fabric manipulation are contexts for performing computational concepts (e.g., loops, variables, conditionals) and for directing computational learning (i.e., weaving focuses on computing as automation and fabric manipulation focuses on computing as 3d modeling; Keune, 2022). These findings derived from taking on a dual theoretical approach that included investigating domain learning and the doing of materials from a posthumanist lens (e.g., Peppler et al., 2020b). The present study focuses on the insights we can gain when taking only a posthumanist perspective and framing tangible craft materials along with people as co-actants in a computational collaborative learning production. The research questions are:

1. How do the component parts of weaving and fabric manipulation collaborate to produce a computational algorithm and a reliable output?
2. How does the craft-specific collaborative computational algorithm change over time and what does this mean for capturing collaborative learning in computational contexts?

To answer the research questions, this qualitative study performed a posthumanist analysis of differences using video data from a craft course with middle school students to identify: (1) Differences in the patterns of how people and craft materials came together to produce what can be considered an algorithm and (2) variations in these patterns that advanced algorithms and fiber outputs in weaving and fabric manipulation over time. The findings show that the computational algorithms developed while people and materials collaborated in craft-specific ways. Youth and craft materials were unequivocal collaborators in the production of performed algorithms. Additionally, findings show that algorithms developed over time through changes in youth-material collaborations. Learning became possible to define in terms of the way in which algorithm and fabric outputs were established in performance by the youth and the materials as well as how the algorithmic performance changed and physically expanded over time. The empirical analysis points to a definition of collaborative learning as a process of a physical and tangible becoming of an algorithmic production.

The work contributes *human-material collaboration* as a unit of analysis in collaborative learning and the analysis of differences as a productive way to capture collaborative learning as a physical expansion over time. The study empirically showed that an analysis of differences that takes human-material collaboration as a unit of analysis can show how tangible and digital technologies become active contributors to conceptual development and conceptual learning possibilities. As such, the work adds to the emerging material turn in CSCL research (e.g., Arnseth & Krange, 2016; Davidsen & Ryberg, 2017; Kumpulainen & Kajamaa, 2019; Mehto et al., 2020a, b). For instance, the study provides a way to include and account for computational materials and technologies' active contributions to collaborative learning. The present study has implications for designing and capturing collaborative computational learning. For example, it can inform design decisions toward integrating a wider range of practices for learning about algorithms, such as valuing seeming mistakes as a possibility for expanding conceptual productions within the learning environment. It guides design toward facilitating student awareness about how materials contribute to computational and technological design and to study what youth are learning when they identify materials as collaborators. Further, the findings hold relevance as we begin to see semi-autonomous computational algorithms and robotics being introduced to educational settings. These new technologies present opportunities to change learning processes and collaboration (e.g., roles, definitions, social norms). To meaningfully leverage their capacities, human-material collaboration promises to be one way to study how relations with novel technologies form and how relevant computational ideas develop and get enacted.

Background

Human learning is contingent on the material world. A key tenet of the study of learning is that enduring educational challenges can be addressed through design that is grounded in theoretical perspectives of learning as it unfolds in situ (Kolodner, 2004; Lee, 2018). Learning theory can guide what can be identified as learning, how learning can be captured, and how it can be enhanced through design (Kolodner, 2004). Similarly, computer-supported collaborative learning is principally committed to the advancement of people's lives, and the field studies the material world where learning takes place as an indispensable contributor to a nuanced understanding of what learning is and how to support it (Kolodner, 2004).

In research on computer-supported collaborative learning, collaborative learning often refers to the way in which two or more people, in pairs, small groups, or large groups, learn together toward a shared goal (e.g., Stahl, 2015) and multiple goals (Tissenbaum et al., 2017). Most recently, Järvelä et al. (2023) advanced human-AI collaboration to add a conceptualization of the interactions between humans and artificial intelligence systems with the aim of leveraging the strengths and capacities of both humans (e.g., creativity) and AI (e.g., automation) to achieve a shared purpose. This work shows that there is an interest in the CSCL community to deeply consider how agents, whether human or not, come together to productively improve learning. In this process, digital and tangible materials serve different functions in the collaborative learning process.

In the following, I present how materials have been considered in CSCL research with a particular focus on research related to collaborative learning in collaborative design activities. Then, I discuss how the growing empirical evidence within CSCL about the distributed contextual aspect of learning, including the tangible and material world, factored into collaborative learning and called for innovative methodological approaches and units of analyses. I will close the background section with posthumanist perspectives and how they promise to add to ongoing CSCL conversations about how materials need to be part of the unit of analysis to develop knowledge about collaborative learning processes.

The role of materials in collaborative learning through design

Materials–whether digital or physical–are often considered mediators of human actions, including creative expressions like design practices (e.g., Carvalho et al., 2019; Davidsen & Ryberg, 2017; Ritella & Hakkarainen, 2012). To name a few, in CSCL research, materials have been discussed as serving the learning of a particular subject matter (Wake et al., 2018; Arnseth & Krange, 2016), creating improved artifactual solutions (Yrjönsuuri et al., 2019), constraining or inspiring design solutions (Lahti et al., 2016; Sinervo et al., 2020), and facilitating collaborative processes in exploratory learning tasks (Hod & Twersky, 2020). Especially relevant to the present study are works that relate collaborative processes to the creation and use of tangible and physical materials. Indeed, designing personal projects in collaboration with others has been a focus of CSCL research to improve understanding about collaborative learning processes, including those that lead to convergence in understanding across more than one person.

One example of researching materials as part of collaborative learning in a design process is Carvalho et al. (2019) who investigated collaborative design activities through the lens of instrumental genesis. Instrumental genesis relates to the mutual shaping of a product and how it is used over time (see also Ritella & Hakkarainen, 2012). Instrumental genesis can support seeing how people adapt artifacts and use them to get things done. This mediational role of materials within collaborative learning includes the idea of affordances. Affordances imply two processes that merge through a dialectical relationship between humans and human-made physical and digital objects, where humans learn how to use artifacts for a purpose and further elaborate them (Overdijk et al., 2012). For example, designers create affordances while developing artifacts for a particular purpose and communicate these purposes through social engagement and routine processes. Whether intentionally created by a person or during use, affordances are related to what an artifact can do for people.

Stemming from a longer tradition inquiring into design and craft practices across settings, a turn toward an active role of materials within collaborative learning settings is emerging (e.g., Peppler et al., 2020b; Keune et al., 2021; Kumpulainen & Kajamaa, 2019; Mehto et al., 2020a, b). One such move builds on positioning the collaboration and the setting where collaboration takes place as multimodal (i.e., talk, gestures, body, and materials) from which an ecology of technologies can emerge, which prompts to analyze the roles that component parts of a larger collaborative unit take on (Kumpulainen & Kajamaa, 2019). Kumpulainen and Kajamaa (2019) show that in collaborative settings, a material object becomes a social object by means of joint attention. Joint attention is coordinated across interacting parties with respect to the corresponding material object. Within Kumpulainen and Kajamaa's (2019) research, material objects become social objects when joint attention is coordinated about the objects, around the objects, and with the objects. The multimodal analysis of collaborative processes that led to social objects presents inroads for studying multiple levels of active material doing.

Materials as part of the unit of analysis in CSCL

Advancing knowledge about collaborative learning with computational technologies requires looking at how learning is distributed across context and anchored in the material world (Enyedy et al., 2015). Thus, research in CSCL has considered digital and tangible materials as resources for extending language to show how other mediational means (e.g., embodied, spatial, and physical evidence) can serve meaning making and productive collaborative learning processes (e.g., Arnseth & Krange, 2016; Danish et al., 2020; Davidsen & Ryberg, 2017, 2019; Shapiro et al., 2017).

For instance, Arnseth and Krange (2016) emphasized the importance of digital and tangible tools as mediational means that support the process of collaborative inquiry and students' conceptual development. Using these tools, students and teachers jointly engaged in processes that helped develop their understanding of science concepts. Arnseth and Krange (2016) introduced the functional system as a unit of analysis for making sense of how elements of an interconnected dynamic system, such as tangible and digital materials, concepts, and social interactions work together to support science learning. This finding extended CSCL research by showing how "learning in the computational age is the result of complex interconnections between the human and non-human" (p. 22). Within the tradition of integrating evidence in addition to language for capturing collaborative learning processes, the unit of analysis for Carvalho et al. (2019) included the artifacts that groups of educators produced as analyzed through spoken exchanges, actions, object manipulations, and interaction with the artifacts.

With a stronger focus on the human body in combination with tangible materials in collaborative learning, Davidsen and Ryberg (2017, 2019) empirically showed how individuals use physical materials together with their bodies as resources to interact and collaborate with others. The authors call this body-material collaboration, which moves the analysis of collaborative learning toward nonverbal cues and highlights the physical environment as an important aspect of meaning-making practices and collaborative interactions. For Davidsen and Ryberg (2017), the unit of analysis becomes short video-recorded moments of youth sketching their room and then transferring the sketch to a touchscreen device with the help of a partner to analyze how bodily-material actions mediate collaborative learning processes. The work highlights bodily-material resources as a vehicle for learning in collaborative settings that complement language. Davidsen and Ryberg (2019) build on the idea that CSCL should hold space for a broad sense of technology beyond digital technologies, empirically showing how the body of people surrounded by and moving together with materials in the production of tangible architectural design influences collaborative learning and should be part of the analysis.

In the turn toward materials as active contributors to learning, one particularly relevant body of work for the present study reimagines the role of materials, including prototypes of designs in collaborative learning (Mehto et al., 2020a, b; Vega et al., 2021; Yrjönsuuri et al., 2019). One example of this larger body of work is an innovative methodological approach for tracking the activeness of materials in collaborative maker-centered learning among people by drawing on sociomaterial perspectives, which emphasizes the importance of capturing not only what people are doing but also how materials contribute to what constitutes technology and collaboration (Mehto et al., 2020a; see also Seitamaa-Hakkarainen et al., 2022).

Sociomaterial approaches, as taken on by Mehto et al., (2020a, b), intertwine social and material aspects in the analysis of an interactive design process, in which materials become co-inventors in the design process. This adds to findings from Lahti et al. (2016) and Tan et al. (2017) that illustrate the contributions of materials to design outcomes and knowledge creation through design (see also Vega et al., 2023). Mehto et al. (2020a, b) add to the prior work insights into how collaborative design and the production of shared projects emanates from the active coming together of human and material actors in the context of shared maker-centered activities. The work is relevant to the present study also because it shows that possibilities for collaborative learning get produced in the intersecting and merging process of humans and materials in a collaborative setting.

Collectively, the prior work presents CSCL as a methodologically heterogeneous space with different units of analysis that make it possible to consider collaborative learning as a process that is shaped by active people and active materials. Thus, CSCL research presents inroads for framing collaboration as more than a process among people. The present study builds on the multimodal and material-relational threads within computer-supported collaborative learning by extending prior work that began to study material collaboration as another form of collaborative learning and casting materials as active participants (Keune et al., 2021).

Promise of posthumanist perspectives for studying collaborative learning

Prior work that investigated fiber crafts (i.e., weaving and fabric manipulation) as a context of computational learning took a dual theoretical approach that combined constructionist approaches to learning with posthumanist perspectives to understand how computational concepts (i.e., loops, variables, and conditionals) developed and how the craft materials actively drove learning. The present paper builds on the position of fiber crafts as a computational context and materials as drivers of computational learning. It advances the prior work by empirically investigating what insights posthumanist perspectives can provide for computational collaborative learning by analyzing how fiber crafts and youth produce processes that can be recognized as algorithmic and how these processes change over time.

In the ongoing effort to clearly articulate the usefulness of posthumanist perspectives in the study of learning (Keune et al., 2022; Peppler et al., 2020a), scholars have analyzed data from a range of theoretical perspectives and to articulate new methods that align with posthumanist perspectives (e.g., Jackson & Mazzei, 2012; Keune et al., 2022; Kuby & Rowsell, 2017). Such inquiries connect to recent CSCL discussions that consider how computational materials can be accounted for. This work also connects to ongoing discussions about how semi-autonomous robots begin to challenge notions of collaboration within architecture, computer science, and construction (e.g., Treusch, 2020).

The material turn in educational research adds to the understanding about the relationships among humans and materials without forsaking the commitments of educational research to human development (e.g., Taylor, 2016). The turn is grounded in posthumanist perspectives that are emerging across a range of fields, including political ecology (Bennett, 2016), material feminism (Alaimo & Hekman, 2008; Barad, 2003), new materialism (Coole & Frost, 2010; Grosz, 2010), indigenous ways of knowing (Tuck, 2009), and posthumanist humanities (Braidotti, 2013; see also Taylor, 2016). The word *posthumanist* may suggest that these approaches seek to move past the human; however, many posthumanist perspectives, including Baradian's (2003) posthumanist approach, which is the one taken on in the present study, only decenter humans to make it possible to see how knowledge production is bound to material being and doing (Kuby, 2017; Taylor et al., 2012).

The approach highlights the importance of analyzing differences between the physical form of a phenomenon over time (Barad, 2003; Lenz Taguchi, 2010). This *de*centers cognitive processes that are systematically facilitated across an environment by focusing on the contextual production of a phenomenon by people and materials. As humans and materials come together over time, they form a continuity of parts in which none is superior (Barad, 2003; Hultman & Lenz Taguchi, 2010; Taylor, 2016). Thus, the researcher's focus and the unit of analysis shifts to how components come together and collaborate to produce something new together. This perspective carries forward the historical emphasis on the collaborative process in CSCL research and brings into view a new possibility of a shape-shifting unit of analysis, namely that of physical form as it changes over time, which constitutes a phenomenon under investigation.

The posthumanist idea of intra-actions promises clarity. While the idea of *interaction* sets a focus on the relationship between two discrete entities, the idea of *intra-action* places a focus on the relationships among parts and the phenomenon that materializes through the jointness of parts (Barad, 2003). Intra-actions imply response-ability of physical components (including people) that are able to respond to one another as they mutually shape each other. The ability to respond does not rest solely with humans but comes about through intra-action among unspecified, changing, and entangled components (Barad, 2003). It is through intra-active repetitions in the way people and materials come together, touch one another, and move one another by applying force that a phenomenon emerges (Barad, 2003; Taylor, 2013; Taylor & Ivinson, 2013).

For example, in the context of a nature-based learning environment, Harwood and Collier (2017) analyzed video data of how children and sticks become entangled during literacy learning. As sticks and children formed a unit and intra-acted, new imaginings were produced that were in constant motion and that challenged human centricity and the linear flow of common lock-step literacy learning. Correa et al. (2023) also observed the powerful entanglement of a range of matter in the context of STEM learning within research on intraspecies creativity in the learning sciences. Productive transformation can emerge from changes within routine patterns as people and materials form a unit (Kuby, 2017; Wohlwend et al., 2019). This calls to focus on what alters the ongoing change, what halts it, and what redirects it (Lenz Taguchi, 2010; Wohlwend & Thiel, 2019). Therefore, capturing a collaborative learning phenomenon from a posthumanist point of view requires analyzing intra-active responsibility, which can be interpreted as an analysis of differences, which focuses on the jointness of parts, their movements, and their varying and changing physical shapes. The analysis of differences makes it possible to view humans and materials on an equal plane.

The perspective of materials as something other than a resource that becomes purposeful through human intentional actions is productive for the study of collaborative learning. It suggests that the extent to which something can be learned depends on what becomes possible through human-material relations and how these relations can change over time. Therefore, framing CSCL research from a posthumanist perspective led this research (a) to consider both humans and materials as actors in collaborative learning that produce something together (e.g., a fabric output based on a process of repeating numbers of steps performed by youth and craft materials) and (b) to compare and contrast what is produced jointly by humans and craft parts over a period of time (e.g., looking at the evolution of the fabric artifacts that are produced). Thinking from a posthumanist perspective suggests, in theory, that computational collaborative learning becomes the shared production and subsequently changing production of a physical and traceable computational process and product. Change over time would be ongoing through the repetitive and changing collaborative performance of people and materials. This understanding forms the basis of the present study and resonates with threads in CSCL research that call for a historical analysis of how humans and materials play a part in the shared production of a construct that is developing in productive directions over time (e.g., Davidsen & Ryberg, 2019).

Methods

This study investigated the potential of posthumanist perspectives for adding to the understanding of the role materials play in collaborative learning through an empirical investigation of fiber crafts as computational learning. Qualitative methods of video data collection and analysis were selected and innovated by thinking with theory (Jackson & Mazzei, 2012). Thinking with posthumanist theoretical perspectives includes considering how the camera angle becomes an instrument of distortion and how to think about the distortion to reveal new perspectives on the collected data. The process of thinking with theory also guides the use of analytical techniques to reveal patterns in material-youth collaborations as well as changes in what those collaborative patterns mean for learning.

The *setting* of the present study was a 6-session long craft course that the author facilitated twice in a K-8 charter school located in a Midwestern college town. The school served 300 students, of which the majority (77%) were white (McCormick, 2018). In the 2012–2013 school year, the school started maker-centered learning. In weekly sessions, seventh- and eighth-grade students were given the opportunity to engage with open-ended and personally chosen projects, including woodworking mobile phone stands, crafting gemstone jewelry, and knitting scarves. Many of the materials that the students used for their projects were donated by students' family members. During the time set aside for maker-centered learning, the research team facilitated a fiber crafts course that was part of the school's larger effort to offer guided modules taught by community experts to broaden student access to a diverse range of materials and activities. The author facilitated each session together with a team of three additional researchers, one of whom joined each session. The teacher facilitated maker-centered learning activities for other students in the same room while the data collection was ongoing. Occasionally, the teacher visited the craft table to ask the participating students what they were working on. The students who joined other activities did not join the craft table.

The *fiber crafts course* consisted of six 70-min-long sessions and was facilitated twice. The course covered weaving, fabric manipulation, and animation of fiber-craft projects through soft robotic actuators. For the article, the author analyzed the data that was collected during the weaving and fabric manipulation units. Weaving and manipulating fabric were selected because they are both matrix-based fiber crafts that allowed youth to perform computational concepts. The animation of the projects through soft robotic actuators was excluded from this analysis because the focus of this study was to look at how the components of traditional crafts drive processes that can shape learning.

The weaving session included backstrap looms, rigid heddle looms, and educational tabletop looms. The mechanics of the looms could be engaged through the design of personal projects, including patterns that were open for personal adjustment. All looms were warped before the course started. They were ready to go with thread to weave into. Apart from the warp threads, each loom included a heddle, a flat laser-cut rectangular piece of acrylic with alternating short and long openings. The heddle guided the warp threads on the loom and made it possible to lift and lower every other thread on the loom through up-and-down motions. A fabric was woven by guiding a shuttle, a holder and carrier of yarn, through the warp threads on the loom.

The fabric manipulation unit included cotton fabric in a range of colors, different colored thread, needles, needle cushions, scissors, grid paper, pencils, and a laser-cut matric template, which was an acrylic sheet with holes arranged in a square grid pattern. Students could place the template on top of a piece of fabric to trace a matrix of dots onto the fabric before sewing dots together into a design. The first design was a twisted square pattern, which required that students anchor a thread on one dot on the fabric, pick up the remaining dots of a square shape with running stitches, pull all four stitches together, and secure the stitches with a knot. Throughout the course, the facilitators made sure that the students knew about the purpose of the study (i.e., connections between computing and crafting [see Keune, 2022]). The facilitators did not ask students to recognize the crafting tools and materials as co-actors.

The participants of the course were 16 middle school students between 11 and 14 years old, a crucial age at which students decide whether to pursue STEM or not (Sadler et al., 2000). While materials changed, the youth remained the same across the weaving and fabric manipulation units. A majority of female participants (i.e., six female and two male participants) joined the first course iteration. This gender representation was flipped in the second iteration (i.e., six male and two female participants). Overall, two of the craft course participants were Latine. Of all participants, 12 were white, three had more than one racial background, and one participant was Black. Some participants had prior experiences with fiber crafts, including weaving and sewing, and all the participants had at least some computing experiences (e.g., a block-based programming language). Participants self-selected to join the course and could choose which iteration to join. To enable the self-selection, the classroom teacher circulated a survey for youths to rate their interest in the craft course and other facilitated activities during the same school year (e.g., illustrating graphic novels). The classroom teacher helped arrange the groups based on the participants' preferences.

Data sources

The research data was video data: (1) Eye-level video of the craft table, (2) bird's-eye-view video of the craft table, and (3) close-up videos of youth projects. The camera is a necessary but distorting component in video-based educational research (Derry et al., 2010). The position and angle of the camera as well as the frame always already include or exclude certain analytical aspects. For example, prior research on youth's use of craft materials showed that data that centers predominantly on human actions impacts possibilities for theorizing materially driven phenomena (Wohlwend et al., 2019). Thus, to explore the active contribution of craft materials in the collaborative computational learning process of this research, the visual centrality of humans was disrupted by capturing a range of angles that showed how materials and people came together at the craft table from multiple perspectives.

Eye-level videos of the craft course (approximately 13.5 h) were captured by a camera that was positioned as if taking a seat at the table. The eye-level position of the camera produced video that focused on the movements that took place at the table on the y-axis and z-axis. The view centered on the actions of the youth while they handled soft materials. Directional microphones attached to the camera and external wireless microphones at the center of the table were both used to capture youths' verbal utterances. Verbal utterances included responses to semi-structured interview questions that asked youth about their design process, including the decisions they made to produce a project and whether they saw connections between crafting and computing. The analysis of the semi-structured interviews showed the computational concepts that youth performed in weaving and fabric manipulation, which is discussed elsewhere (Keune, 2022). It is important to mention the interview here because the verbal utterances from the interview were also captured on the video that the present paper analyzes, although they were not the analytical focus.

The *bird's-eye-view videos of the craft course* (approximately 13.5 h) were filmed with a 360° camera that was attached to the ceiling above the craft table with a custom-designed rig constructed from a 1.5-inch (3,81 cm) PVC pipe. The camera filmed the craft course from directly above the craft table and, thus, focused the researchers' gaze on movements that took place across the table on the x- and z-axis. The 360° camera produced a circular image with some additional distortion, which made it possible for all youth to be part of the frame at once. The camera's inbuilt microphone captured verbal expressions of the participating youth.

Close-up video of youth projects captured project dimensionality and showed the complexity of the youth's projects using an electric rotating turntable and an iPhone camera (435 in total; five per youth project on average). One complete rotation of the turntable took approximately 20 s. This approach was inspired by the Spin turntable for capturing animated GIFs of youth projects (Tseng, 2015). The project videos were appropriate for this research because capturing fiber-crafts projects without controlled movement of student projects can result in blurred images that prevent the retracing of production processes. The video showed more detail of the projects and their construction than the bird's-eye-view and the eye-level videos (e.g., it showed the exact warp threads that the youths skipped over with their shuttle). Further, the close-up videos showed the crafts from different angles and it was possible to pause them to investigate the craft projects in-depth. To maximize crafting time on site, the author documented the youths' projects by creating the close-up videos at the university research laboratory. After each craft session, youth placed their projects into personal resealable storage bags that I returned to them at the start of the next session after documenting the projects.

Analytical techniques

The analysis of the eye-level and bird's-eye-view videos took place interactively to identify (a) how components of both fiber crafts (i.e., weaving and fabric manipulation) came together in routine ways to produce computing (research question 1) and (b) how the routine changed over time (research question 2). As a step toward reducing the data to cases that could show collaborative processes with people and materials, I synced the timestamps of the videos manually and then viewed the video by starting and stopping them nearly simultaneously. Once I identified moments of repeated coming together of materials and people (repetitions) as well as moments of when these repetitions varied (variations), I conducted a fine-grained iterative analysis of the repetitions and variations using a digital tool for qualitative data analysis (i.e., MAXQDA). Viewing the data from different angles simultaneously afforded verification what had been seen from a different angle through visual evidence.

With MAXQDA, the author analyzed the video data to identify patterns of child-material relations during computationally dense moments. These moments were the routines that established a baseline of what could be considered as an algorithm in the context of the craft. Specifically, the author analyzed the videos for repetitions of how youth and materials came together (i.e., youth-material combinations). The analysis included movements of the crafting materials in three-dimensional space and how combinations of youth with specific craft materials repeated over time during computationally relevant moments. Prior work that aligned matrix-based fiber crafts with computational concepts (e.g., Jefferies et al., 2017; Keune, 2022) informed the identification of these moments. It included the coding for craft specific parts of the process that are detailed in Table 1. Aligned with posthumanist perspectives, the analysis informed the understanding of how the routine movements of the component parts of weaving and fabric manipulation produced what can be perceived as an algorithmic and computational phenomenon in the crafts (research question 1). This showed the roles of the youth and materials in the production of computation through regular repetition of youth-material engagement.

The second iteration of coding focused on answering research question 2, about how the craft-specific algorithmic computation changed over time and what this meant for

Table 1 Codes used to trace routine coming together of youth and craft materials

	Code	Definition
Weaving	Heddle up	The hand of the youth and the heddle of the loom *pull up* the warp threads
	Heddle center	The hand of the youth and the heddle of the loom *center* the warp threads
	Heddle down	The hand of the youth and the heddle of the loom *draw down* the warp threads
	Shuttle left	The hand of the youth and the shuttle with yarn move from the right *to the left* through the warp threads
	Shuttle right	The hand of the youth and the shuttle with yarn move from the left *to the right* through the warp threads
	Heddle to youth	The hand of the youth and the heddle *move to* the youth's torso
	Heddle away from youth	The hand of the youth and the heddle *move away from* the youth's torso
Fabric manipulation	Youth-fabric-grid	The youth's hands lay on top of the fabric that is on top of the matrix grid
	Youth-fabric-thread-needle	The youth's hand holds the fabric while the other hand is sewing into the fabric with a threaded needle
	Youth-fabric-thread	The youth's hand and the thread pull the fabric together
	Youth-fabric	The youth's hand and the fabric shift the sewn shape into place

collaborative computational learning. To answer this question, I analyzed variations of the established computational repetitions. The variations physically increased the number of routines that were possible because they added new routines. This process of doing and undoing revealed intra-actions of materials and humans: Moments when material pushed back on and ruptured human intentions as well as how the relational dependencies of craft components and youth negotiated and produced algorithmic movements. The analysis showed how computational phenomena changed over time and how these changes did something to human learning. I coded each craft on the video perspective that best showed the production based on prior understanding of the crafts. For weaving, the eye-level view became the primary source because it showed the multidimensional movements of the parts of the loom well. The eye-level video captured movement on the z-axis of the traditional cartesian plane. For fabric manipulation, the primary video source was the bird's-eye-view videos because stitches on the fabric produced layers of fabric that folded down on the y-axis of the traditional cartesian plane, which the eye-level videos captured well.

The analysis of the close-up project videos verified the repetitions and variations in relation to specific projects by reverse-engineering the production process. I viewed the videos repeatedly and took screenshots of angles that exposed wefts and stitches to produce graphic representations of patterns of youth-material collaborations.

Throughout the analysis, I shared data excerpts and discussed data analysis with a research team of learning scientists who were familiar with weaving and fabric manipulation as well as with posthumanist perspectives. The shared data perusal and analysis made it possible to cross-check the author's reading and sensemaking of the data and what it meant for the research questions. Additionally, the author showed data excerpts and discussed data analysis with two scholars with interdisciplinary backgrounds. One was an anthropologist and material culture studies scholar whose familiarity with the craft processes helped clarify the particular movements needed for each craft and how to point to them in the data. The second was a scholar in public management and public administration who conducts research from different theoretical perspectives and methodological approaches. The conversations with the scholars supported me throughout the analytical process in bringing clarity to the discussion of the theoretical ideas and how they informed the analysis and pointed to the findings.

Findings

The aim of this study was to investigate the insights that can be gained about collaboration in computational learning when taking a posthumanist perspective. To illustrate the findings in response to the research questions, this section includes four parts. In response to research question 1, the first two parts present, respectively, how youth and weaving craft materials as well as youth and fabric manipulation craft materials collaborate to produce craft-specific algorithms and reliable outcomes by drawing on representative excerpts from the video data of the facilitated fiber crafts courses. In response to research question 2, parts three and four show evidence of how the material algorithm changed over time, first in weaving and then in fabric manipulation, and what this meant for capturing computational collaboration.

Weaving: Algorithmic production through human-material collaboration

To weave fabric, it was the way youth and the materials of the loom came together and actively collaborated that produced an algorithmic performance and reliable fabric output. With the loom strapped to their bodies, youth could sit down, stand up, lean into, and lean away from the warp threads to tighten and loosen the warp threads that stretched horizontally across the table. The active parts of the collaboration included similar parts for all looms included in the research: (1) The youth who held the loom, (2) the plastic or wooden shuttle that compactly held yarn for creating fabric patterns by passing it through (3) the threads on the loom (warp threads) into which the yarn on the shuttle (weft threads) were woven, and (4) the heddle that the individual warp threads on the loom passed through and that made it possible to move the warp threads up and down (Fig. 1).

To weave fabric, participants and the components of the looms came together in a collaboration of consistent and rhythmic motion. A movement pattern that could be recognized as a computational and machine-readable algorithm and that produced reliable outputs transformed irregularly shaped yarn balls into flat fabric. The process involved a repeating intra-active sequence of youth-material collaborative movements that was established over multiple repetitions.

One example of this collaborative pattern was Mia's process, pictured in the top row of Fig. 2. Mia was one of the youths who participated in the craft course. She began her plain weave by moving the rigid heddle (i.e., the craft component that the individual warp threads on the loom pass through) up and then drawing the shuttle that the yarn was wound up on from the left to the right. Mia tightly packed the row that this motion wove to the already woven fabric by drawing the heddle toward her body. To weave another row, she drew the heddle away from her body, then pulled the heddle down, and then moved the shuttle from the right to the left, in the opposite direction as the row before. To complete the process, she packed the second row onto the existing fabric and set it up for the next row by drawing the heddle away from her body. Such a sequence happened for all youth in the craft course because all started out with a plain weave pattern.

The sequence can be described by projecting the movements that happened in the classroom onto a traditional Cartesian plane with x, y, and z axes (Fig. 2 bottom). Put simply, the sequence can be described as moving up, right, toward, away, down, left, toward, away (see blue arrows in Fig. 2) or as moving on the following Cartesian coordinates "y, x, z, z, y, x, z, z" (see axes in Fig. 2). The youth-material collaborative intra-actions that became

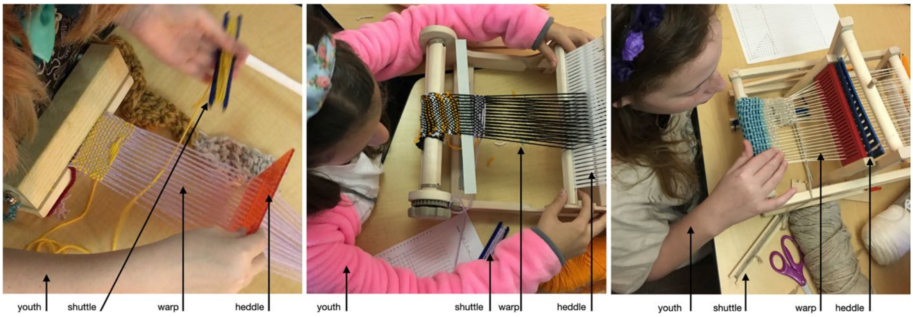

Fig. 1 Component parts of weaving with three types of looms

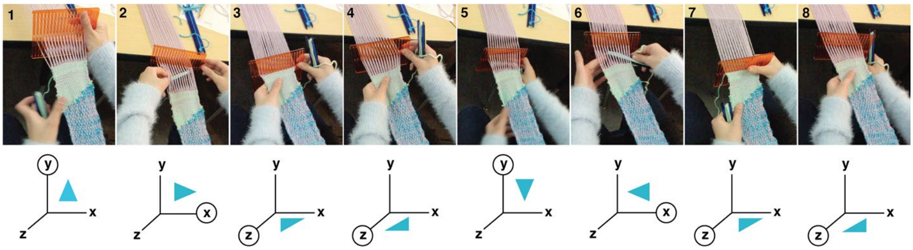

Fig. 2 Repeating sequence of youth-material collaborative intra-actions that produced both a performed algorithm and a reliable fabric output in weaving

visible through this analysis happened in one dimension at a time (Fig. 2). As youth lowered and lifted the heddle (i.e., the craft component with the slots that the warp threads on the loom pass through) to change warp thread positions (i.e., threads on the loom), movements were produced on the y-axis (Fig. 2, panel 1 and 5). When shuttles maneuvered from left to right or right to left across the warp threads, it produced a movement on the x-axis, parallel to the front side of the participants' bodies (Fig. 2, panels 2 and 6). When heddles moved toward and away from a youth's body, it created movement on the z-axis (Fig. 2, panels 3, 4, 7, and 8). Each youth-material collaborative intra-action was paired with one movement in one predominant dimension. The repetition of youth-material movements produced a baseline algorithm of a reliable process (i.e., heddle up, shuttle from left to right, heddle toward youth, heddle away from youth, heddle down, shuttle from right to left, heddle toward youth, heddle away from youth etc.; see Fig. 2). This performed algorithm provided the same expected output every time and could be translated into machine-readable language and graphic patterns.

Yet, evidently, the performed algorithm is different from a computer program. For example, when the youths came together with the parts of the loom–the warp threads, the heddle, and the shuttle with yarn–computational loops and conditional statements were initiated and defined with the first woven row. Youth could either draw the heddle up or down. Then, they could either draw the shuttle from the left to the right (like in Mia's case) or from the right to the left. These two movements established a pairing of directions in the dimensional sequence that could be translated into machine-readable language (e.g., if heddle up, move shuttle from left to right; if heddle down, move shuttle from right to left; see also Keune, 2022). This algorithmic pairing was produced in action and was enacted repeatedly while the production of the plain weave was going on. Another example of how this algorithmic performance differed from computing code was the emergence of the pattern duration. While computing code would typically demand the number of threads used in a pattern at once, during the craft course, the number of rows that were part of the loop emerged in real time. In fiber crafts youth-material collaborative intra-actions produced fabric continuously, a running code that prepared the youth and the loom for more complex implementations. The algorithm became a performance of a three-dimensional artifact transformation over time.

The performed algorithm as shown in Fig. 2 begins to illustrate how youth and materials collaborated to produce the very same algorithm and fabric output repeatedly. Next, I draw on data to show in more detail how youth and materials collaborated at the example of Boe, a 13-year-old male participant, and his loom producing a gap pattern that all other participating youth also implemented and worked through in a similar way. Gap patterns were produced by weaving in opposite directions with two shuttles (i.e., the craft components with yarn wrapped onto), separating the total number of warp threads on the loom into two spaces (see Fig. 3, center). Midway through, Boe explained his process:

> *I'm basically just doing what I was before but stopping halfway and going back to make it help the side and then this will be on the other.*

At first, Boe-loom collaboration worked to produce one side of the fabric, the right side (Fig. 3, left), following the plain weave algorithm presented in Fig. 2. When it was time to produce the second side of the gap pattern, the z-axis movement of the heddle, which packed wefts (i.e., woven rows) tightly together into the fabric mesh, could not reach the weft of the left side of the fabric (Fig. 3, center). The heddle movement was obstructed from reaching the weft rows located lower on the warp thread because the heddle stopped at the longer side of the fabric (the blue side). In Boe's words: "Since you pulled [the heddle] back to tighten it, I had to go on this [yellow side] and on this [blue side]." The working of the loom demanded the simultaneous building of both sides of the gap, the yellow side, and the blue side. Thus, Boe-loom collaborative intra-actions reversed, undid a few wefts (i.e., woven rows), and then proceeded to weave both sides of the gap pattern at once (Fig. 3, right).

The data excerpt shows that the algorithm in weaving (i.e., one dimension at a time) materialized through the arrangement of weft threads on warp threads that the loom's material parts–as much as the youth themselves–produced. It materialized in the impossibility of weaving the second side of the gap as tightly as the first side. The production of the performed algorithm and the fabric output was neither driven by the youth nor the loom on their own. The loom did nothing without the youth acting on it, and the youth did not perform algorithms without the loom acting on the youth. The youth could not choose the path of the pattern. The loom could not demand the flow of the pattern. Both youth and the loom actively drove the production of the algorithmic performance (i.e., arrangement of movements) and output (i.e., fabric). The algorithm and the fabric output came about in the repeatitive youth-material collaborative intra-actions.

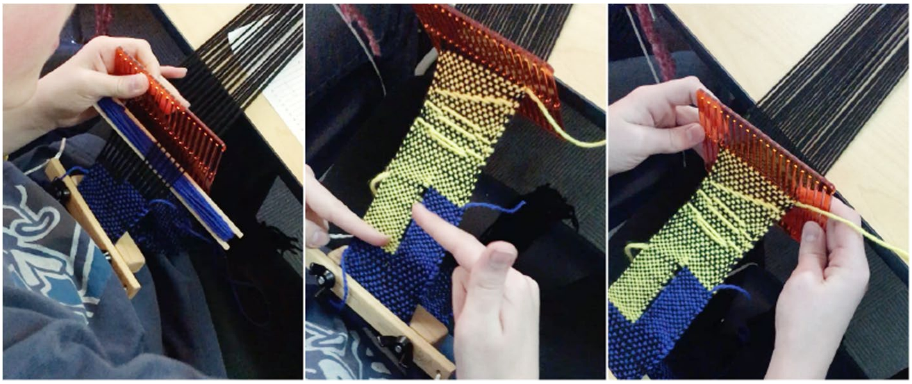

Fig. 3 Boe-loom collaboration produced a gap pattern: Right side of gap pattern (left); Boe's explanation of the heddle (center); final gap pattern (right)

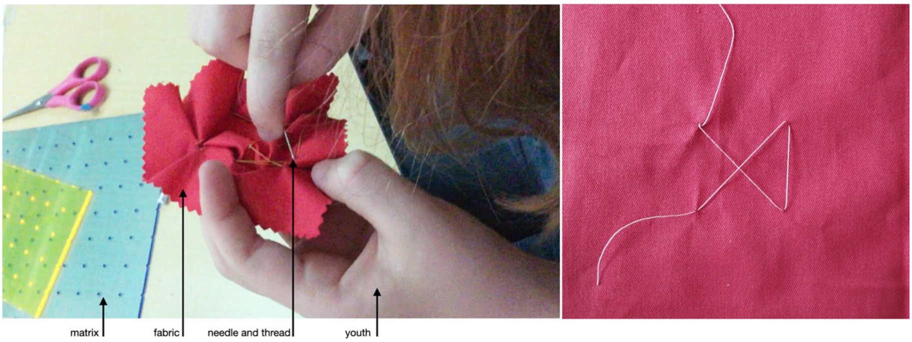

Fig. 4 Components of fabric manipulation (left), stitch pattern (right)

Fabric manipulation: Algorithmic production through human-material collaboration

In fabric manipulation, just like in weaving, youth and the craft materials also came together to produce an algorithmic performance and a reliable fabric output. Yet, fabric manipulation involved a very different set of components. The components of this craft were (1) a laser-cut grid with holes to trace a matrix of dots onto fabric, (2) fabric to sew stitches into, (3) thread to connect matrix dots on the fabric, (4) a needle to pierce the fabric and to sew thread into fabric, and (5) the youth who handled, twisted, and turned the other components in repeating arrangements (Fig. 4).

As the components came together, a pattern of youth-material collaboration emerged that produced an algorithmic performance that differed from the one-dimension-at-a-time performance of weaving. The transformation of flat fabric squares into three-dimensional twisted squares also involved youth-material movements on the y-, x-, and z-axis. However, the movements brought multiple dimensions together at once. More dominantly, the algorithmic performance in fabric manipulation and the fabric output of the craft were contingent on a repeating series of different combinations of components paired with the steps of the craft.

Savanna-fabric-matrix transposed a matrix onto the fabric and produced the algorithmic space.

Savanna-fabric-thread-needle created sewer's knots and running stitches that produced computational loops.

Savanna-fabric-thread pulled sewn units together and processed input variables.

Savanna-fabric unfolded the fabric output of the algorithm.

Fig. 5 Repeating sequence of youth-material collaborative intra-actions that produced a performed algorithm and a reliable fabric output in fabric manipulation

One example of the algorithmic pairing of youth-material combinations is shown in the photograph of Fig. 5. The process shows Savanna, a 12-year-old youth participant, and fabric manipulation craft materials coming together over time. This is how all youth participated with fabric manipulation. First, Savanna-fabric-grid intra-actions transposed a matrix of dots onto the fabric, which produced the algorithmic space (Fig. 5, panel 1). Then, Savanna-fabric-thread-needle intra-actions created sewing knots and running stitches that produced computational loops as the youth brought the fabric closer to their eyes and isolated particular matrix dots (Fig. 5, panel 2). This was followed by Savanna-fabric-thread intra-actions that pulled sewn units together and processed the stitch pattern that can be recognized as input variables (Fig. 5, panel 3). Lastly, Savanna-fabric intra-actions unfolded the results of the fabric algorithm into user-readable output, the final project (Fig. 5, panel 4).

Together, the repeated occurrences of the combination of youth and materials produced what can be recognized as an algorithm in the context of fabric manipulation. Just like in weaving, the performed algorithm was different from a computer program. For example, when youth-fabric-matrix came together, they produced the algorithmic space that loops and conditional statements could be sewn into (e.g., for items in the matrix of dots, if the item is unused, assign a stitch, see Keune, 2022 for details). Stitches picked up four dots that were arranged in a square (see Fig. 4, right) before pulling the stitches together and assigning a knot to fix the matrix dots together at the center where all dots met. This shrank and rotated the square into a twisted square once the fabric was unfolded. The pattern of stitches was repeated several times by ensuring that at least the same amount of space was between squares as there was between the matrix dots that were used to sew a square. Leaving space between sewn squares ensured that all squares could fold flat when unfolded into a pattern of many interconnected twisted squares (i.e., a tessellation of geometric shapes without overlaps and gaps). Where it is possible to implement the algorithm in collaborative performance among youth and material, due to the bending of the fabric, it has not been translated into computing code.

The analysis of fabric manipulation shows the role of the youth and that of the material in the production of an algorithmic performance and an algorithmic output. Next, I show in detail how youth and craft components played an active part and collaborated in this production. The youth-material collaboration that produced the algorithm and fabric output became salient when youth and fabric unfolded the input stitches into perceivable

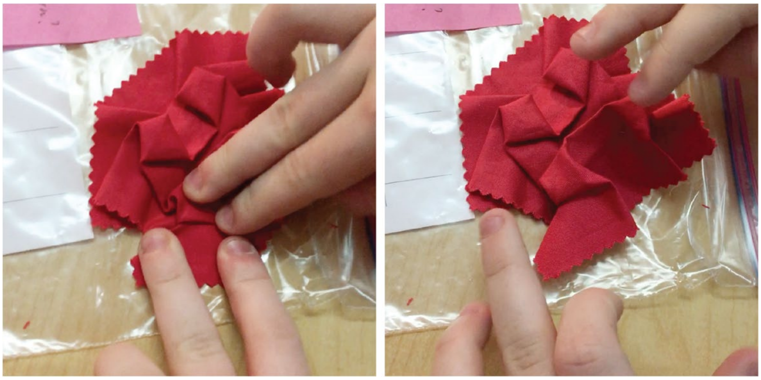

Fig. 6 Photographs of Savanna attempting to will the fabric into its place

output (e.g., twisted square design). For example, zooming in on the intra-action in Fig. 5 panel 4, Savanna worked on unfolding a twisted square design. Savanna tried to produce the flat folds by pulling the square shape vertically up and then pressing down on its center (Fig. 6). This produced folds next to the squares that prevented the square from evenly lying flat on the fabric.

Next, Savanna slammed her hand on the fabric, then continued to push and pull the fabric. She explained: "*I am trying to force it to be like these ones because I think these ones are good…push it into position like folding and bending it.*" Savanna noticed that there was something pushing back against her actions on the fabric. This was similar to other youth in the course who initially tried to force the material to bend to their will. In doing so, Savanna pushed against the twists that the sewing pattern had programmed into the fabric. As the fabric pushed back and did not fold the way Savanna wanted it to, the jointness of youth and fabric created friction that could be felt. Once Savanna and the other youths followed the lead of the fabric, arranged the folds, and twisted the fabric in the way stitches directed it to fold, the twisted square pattern appeared and folded flat into a tessellation.

This data excerpt shows that youths were one but not the only acting component in the craft. In fact, the craft materials were lying motionless on the table when the youth did not act on them, and the youth did not progress in the craft without the materials. The youth could not will the folds into place. Rather, the algorithm and the fabric output were driven by the way the youth and the materials collaborated throughout the repeating sequence of components coming together.

Weaving: Variations of youth-material collaboration and algorithms over time

Frequently, the rhythmic flow of computation in weaving trailed off into different directions when variations of the one-dimension-at-a-time pattern occurred (i.e., heddle up, shuttle from left to right, heddle toward youth, heddle away from youth, heddle down, shuttle from right to left, heddle toward youth, heddle away from youth etc.; see Fig. 2). Variations were composed of subtle differences in how youth and materials came together compared to the baseline of paired movements of youth-material and dimensions. One type of variation that occurred frequently across youth projects was the reversal of shuttle directions (e.g., passing the shuttle with yarn for weaving rows from the left to the right [→] of the warp threads on the loom and then from the right to the left [←]) without changing the position of the heddle with the slots that yarn passed through (e.g., not lifting the heddle both times the shuttle passed through to part warp threads in opposing ways and, therefore, not accommodating the interlocking that was needed to produce another row of fabric). This movement was similar to the regular repeating pattern, but it lacked the crucial step of changing heddle positions (i.e., one y-axis movement) that resulted in unweaving the previous weft instead of adding a new row to the fabric production. Youth noticed their role in the emergence of these variations, and Lisa, a 14-year-old participant who had a range of craft experiences and little programming experience prior to joining the craft course, stated:

> *I am more in control, which means that I am more prone to make mistakes… every little thing, I have to choose and sometimes when I forget to do something it will be more of a problem.*

Lisa conceived of her own movements as faulty compared to the smooth, rhythmic, and forward-progressing computation of paired y-axis, x-axis, and z-axis movements. This assumed computation to be a progression toward a foreseeable outcome as well as a stable process in which the youth had a scripted part to play. Variations from the script became mistakes, which, in turn, assumed a deficit on the part of the youths, who did not play the part that was scripted by the material repetitions. With this framing, it would follow that the youth needs to change to meet the demands of the baseline computation.

However, when youths persisted, variations propelled projects in a different direction and became part of the algorithmic collaboration of youth and loom. For example, in Boe's project, the irregular pairing of heddle positions and shuttle directions produced new fabric patterns and computational loops. This became apparent in Boe's explanation: "*I am trying to make it so that…where the yarn goes over [so that] it's like all in a line. I don't know if it'll, like, become unwoven or something.*" Boe built on the experienced variation of the regular pairing of heddle-positions and shuttle-direction that initially led to unweaving wefts but eventually created a new pattern. This was possible by combining the variation with a skip pattern that ensured that the second woven row was not unwoven. The pattern included two woven rows. First, the heddle lowered, and the shuttle moved from right to left, while skipping over every other thread on the top layer of threads on the loom (Fig. 7, top). Second, the heddle with the slots that threads passed through continued low but the shuttle with yarn moved from left to right, the opposite direction, while skipping over every other warp thread on the loom (Fig. 7, bottom). Figure 7 shows two rows of fabric being produced in the form of (a) photographs, (b) the one-dimension-at-a-time algorithmic movement, (c) the abstracted graphic illustration of the project, and (d) the final project output.

The variation from the baseline (as established in 4.1) produced an algorithmic pattern (i.e., heddle down, shuttle right, shuttle left) that was different from the baseline pattern (i.e., heddle down, shuttle right, heddle to youth, heddle away from youth, heddle up). This made it possible for the weft thread to wrap around the warp thread without coming undone. The change produced a new function that built on the variation of the rhythmic youth-material movement that initially led to unweaving a weft.

Skipping three steps physically altered the algorithmic performance and the fabric output. The integration of the variation in a way that built up rows of wefts rather than removing them physically expanded what could be considered an algorithmic performance. A larger range of movements became possible. The analysis of differences highlighted the

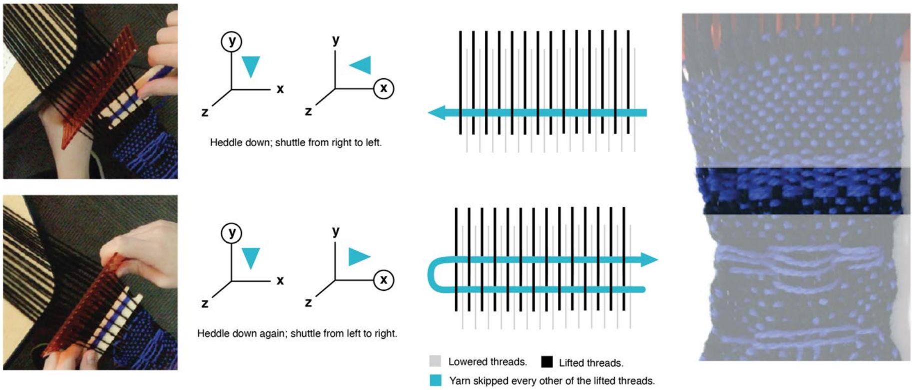

Fig. 7 Variation in youth-loom algorithm that produced a new pattern

potential of capturing variations in the youth-material collaborations to show changes in the algorithmic performance. It showed that algorithms were an emergent performance and it was possible to physically expand them. For the youth, variations in youth-material movements became opportunities for increasing loop-making possibilities.

Fabric manipulation: Variations of youth-material collaboration and algorithms over time

As with weaving, in fabric manipulation, variations are differences in the patterned ways components move compared to the baseline repetition. Variations made it possible for algorithms to expand. Compared to weaving, the variations in fabric manipulation physically manifested differently. A frequently recurring variation in the data that was analyzed was breaking out of the provided dot matrix to sew illustrative shapes into the fabric, including Warrior Cats characters and geometric forms. Although this change was still the production of a computational playing field, the variation introduced a crucial difference from youth-material collaboration: Youth-fabric-grid (i.e., Fig. 5, panel 1) changed to youth-fabric-paper. About half of the youth participants tried that.

An example of this variation was Savanna's second fabric manipulation project. Savanna decided to sew a star into her fabric that did not fit into the provided grid-based matrix (Fig. 8, left). The matrix on the fabric was the basis for processing loops as knot-stitch combinations on the fabric. Once a matrix was selected, a range of algorithms could be performed that produced fabric outputs, such as the twisted square. To trace the vertices of the star onto the fabric, Savanna placed a paper drawing of the star on top of the fabric and then frequently lifted parts of the paper to mark vertices on the fabric. The production of the personal matrix with locational variables that were different from the provided grids was time-consuming and resulted in skepticism from neighbors who showed their seemingly advanced project progress to Savanna while she continued to trace the star vertices onto the fabric.

Like weaving, these comparative acts assumed that algorithmic performances were materially stable and bound to the square matrix. Thus, variations from the script became mistakes. In turn, this assumed that the youth who were part of the variation have to change to perpetuate stability (i.e., the baseline algorithmic performance). However, persisting with such variations in the matrix grid produced a new computational matrix with a new range of possible sewing patterns and computational loops. Savanna said, "*I would just go on these outer rims and then scrunch it together and maybe it would make a star.*" Savanna

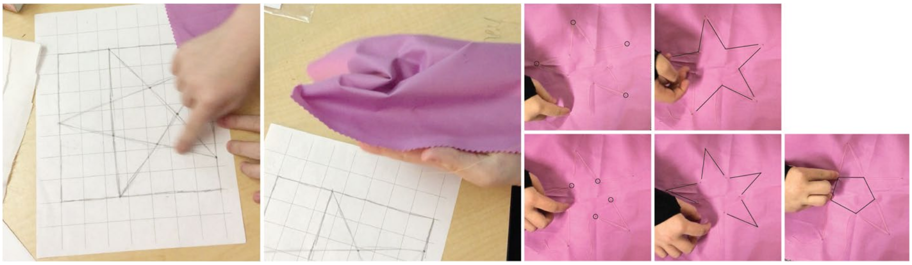

Fig. 8 Savanna's paper plan for the star (left), first sewn implementation (center), and algorithmic possibilities of the matrix as star (right)

expected that pulling together all ten vertices of the star shape would produce a flat folded star like the twisted square fold. She proceeded to implement this plan and embroidered the outline of a star onto her fabric by sewing a knot into the first vertex and then picking up the remaining vertices with the same thread.

Once the fabric was pulled together (Fig. 8, center), Savanna noticed ruffles that looked nothing like the expected star. Savanna wondered about alternative possibilities:

> *If all the outer edges would have [sewing] knots, then you scrunch them up as you go along. These ones would be scrunched up and these ones would be scrunched up. If these ones were, this whole thing would be scrunched up. And this whole thing would be scrunched up.*

Savanna considered how the use of similar steps with variations in the location and the amount of the sewing knot or running stitches would produce a range of different fabric transformations (see also Fig. 8, right). Savanna's play with the placement of sewing knots on the star turned the shape into its own matrix grid. The personalized variation changed how the computational components of fabric manipulation physically came together (i.e., youth-fabric-paper vs. youth-fabric-grid) and produced a physical expansion of algorithms collaboration. Variations of the matrix grid became opportunities for increasing loop-making.

For both crafts, weaving and fabric manipulation, the move of decentering the human in the analysis as one active collaborative part of the emergent algorithmic performance and output made it possible to dwell with seeming errors and variations. It was possible to see how these variations changed the algorithmic pattern over time and to see their potential of leading to new algorithms and fabric outputs.

Discussion: Human-material computational collaborative learning

The analysis of the craft course through a posthumanist analysis of differences resulted in two main contributions to the understanding of materiality in computer-supported collaborative learning. First, the work expanded the actors of collaborative learning by developing human-material collaboration as a productive unit of analysis for computational collaborative learning that should be taken into consideration for capturing ongoing learning. Second, the study developed and presented the analysis of differences from a posthumanist perspective as a new and useful methodological approach to capture ongoing collaborative learning by showing how materials contribute to possible learning and framing collaborative learning as physical expansions over time. These issues are discussed in the next section.

Human-material collaboration as a unit of analysis in collaborative learning

The findings show that human-material collaboration is a physical process that involves youth and materials as active collaborators that produce algorithms and outputs together. Both youth and materials were important components that formed routine movements and combinations, which can be considered algorithms. *Youths* were one (not the only) collaborative actor and *materials* were also collaborative actors. Together, youths and materials produced *algorithms* through repetitive youth-material collaborations that resulted in *outputs* in the form of foreseeable fabric artifacts. The analysis of performative and physical differences made it possible to see how people and materials produced algorithms conjointly.

In weaving, youth's hands moved the materials and each material part of the crafts (i.e., shuttle, heddle, yarn) took part in how this process unfolded. This resulted in predictable productions of algorithms through repeated youth-material movements (one dimension at a time) that produced woven fabric with patterns. In fabric manipulation, youth were also part of the pattern in combination with a range of materials and each material part of the craft (i.e., needle, fabric, thread, paper, and grid) provided a range of possibilities to combine with people. The combinations of youth and materials also produced an algorithm that was a repeated pattern of component part combinations, which produced 3-dimensional sewn projects (e.g., twisted square designs).

The contribution of human-material collaboration as a unit of an analysis in collaborative learning connects to CSCL research that considers affordances of digital and tangible materials in collaborative learning (e.g., Carvalho et al., 2019; Overdijk et al., 2012; Ritella & Hakkarainen, 2012). In the present study we can see materials being handled by people in use. However, the present study does not focus on the dialectic relationship of learning about the utility of artifacts and elaborating their purpose (e.g., as presented in Carvalho et al., 2019). Human-material collaboration focuses on what the people are doing as well as how the materials actively push back during moments of collaborative learning, like in the case of Savanna's twisted square.

Additionally, the contribution of human-material collaboration as a unit of analysis aligns with recent work in CSCL that considers an expanded role of materials in collaborative settings and as part of how youth create technological projects (Kumpulainen & Kajamaa, 2019). Further, human-material collaboration contributes to work by Mehto et al. (2020a, b), Vega et al. (2023), and Lahti et al. (2016) that illuminate understanding of materials as co-inventors in design processes through sociomaterial lenses. The present study expands these conversations by empirically tracing the physical character of how an algorithmic production is coming about as youth and materials come together in routine ways. The fine-grained analysis of one person with several materials that are part of a craft is based on prior work that defined such intra-actions as computational learning opportunities (Keune, 2022). The work presented here probes the role that each of the components (youth and otherwise) play in producing this algorithm.

Based on the presented empirical evidence, the study contributes to expanding the actors of collaborative learning and provides human-material collaboration as an additional lens for accounting for materials and technical doing in collaborative learning. This approach is not intended to remain an isolated analysis. It seems possible to integrate this analytical focus with the analysis of other contributing factors that evidence how collaborative learning unfolds and can be supported.

Posthumanist analysis of differences to capture collaborative learning as physical expansion over time

The presented work is in line with recent advances in CSCL that consider the role materials play in maker-educational contexts for the co-construction of technological design projects (e.g., Mehto et al., 2020a, b). The present study adds a novel method to the ongoing CSCL conversation about how the active role of computational materials can be integrated and accounted for in the study of collaborative learning. In doing so, the present study presents the *posthumanist analysis of differences* as a useful empirical approach for capturing ongoing computational collaborative learning over time. The study investigated human-material collaborative learning by (1) first analyzing the baseline of an algorithmic routine of human-material collaboration and then (2) observing any variations from this baseline (e.g., when an algorithm breaks down and this breakdown gets integrated into the algorithm).

For instance, in weaving, variations in the youth-material movement patterns led to a new algorithmic performance and fabric patterns (e.g., Boe's novel weaving), whereas in fabric manipulation, variations in the youth-material combinations led to new algorithmic playing fields and fabric patterns (e.g., Savanna's star). The analysis of human-material collaboration opened possibilities for considering computational collaborative learning as the process that produces craft-specific algorithmic patterns and their development over time (i.e., new algorithms and new outputs). This comparison of performative and physical differences in youth-material collaborations contrasts with comparing youths' abstract and decontextualized knowledge. As youth wove, algorithms physically grew when new human-material collaborations produced new patterns. As youth manipulated fabric, algorithms physically grew when new youth-material collaboration produced matrices that propelled new pattern possibilities into the world. Thus, the present study offers a shift in what counts as and what can be recognized as computational collaborative learning.

The methodological contribution is in line with Arnseth and Krange (2016) call to consider how humans and non-humans are forming relationships that make learning possible. The present study takes a fine-grained look at the process of how an individual person forms relationships with materials to produce algorithmic ideas in the world that can be physically traced through movements and combinations of parts and compares how both may change over time. Like Carvalho et al. (2019), this included a close look at projects (i.e., fabric outputs). Here, the artifacts served less as evidence of cognitive understanding but a verification of the algorithm and youth-material collaborative process that had to have happened to generate such an output.

Furthermore, the analysis of differences over time contributes a way to analyze how the collaborative process of human-material units and the produced algorithmic outcomes of this collaboration change over time. This aligns with Davidsen and Ryberg's (2019) assessment that technology in CSCL needs to be defined as something beyond digital and electronic technology. The present study contributes to this through the empirical study of youth-material collaboration as a unit of analysis through fine-grained video analysis that can identify how technologies and computational techniques are being made and unmade as humans and materials come together in routinized ways. CSCL technologies seem, in fact, constructed and further developed through youth-material intra-action and we can recognize this process of forming and elaborating techniques as collaborative learning.

Implications for capturing and designing for computational collaborative learning

The contributions of this research have implications for capturing and designing for computational collaborative learning. First, the methodological contributions of this study may be applied in future studies to analyze more than one unit of youth-material collaboration at work in the process of forming computational ideas. For example, future work should consider how several youth-material collaborations intersect, such as how algorithms travel across the moving site of several youth-material units. Additionally, it seems productive to consider how the analysis of differences in youth-material collaboration intersects with other factors that have shown to contribute to collaborative learning. This could be particularly interesting when analyzing how advanced digital algorithms and semi-autonomous technological actors enter collaborative computational learning contexts.

Second, the presented findings have implications for designing for collaborative computational learning. Looking at youth as one but not the only actor in a computational collaborative learning context highlights the responsibility of researchers and educators to the learner. The work illuminates the learning potential of variations from set standards that could otherwise be dismissed as off-task or outside of scope. Human-material collaborative learning prompts design of collaborative computational learning opportunities that stay open to what the learners and the materials do together and how this doing may shift into new productive material-specific domain-relevant performances (e.g., working on a twisted square or a star). The study shows that variations from set standards become important to emphasize and a way to value multiple approaches to computational learning. Additionally, seeing algorithms as a physically emerging and changing process highlights that computing can evolve. This is relevant for designing for computational learning because it can provide early experiences of technology and computing as a growing field. One way to approach computing as an evolving field, as implied by the study's contributions, is by designing tangible computational experiences that guide youth to identify the craft materials as active collaborators and to investigate what youth are learning when they see materials as collaborators. The analysis of the processes presented in this study builds momentum for research that investigates how the development of algorithmic and procedural thinking in craft contexts intersects with recognizing materials as collaborative actors in the algorithmic production. An example of this would be illustrating how materials contribute to productions and production processes as a way to shift youth language way from attributing mistakes to themselves like Lisa's explanation. At once, the analysis of the present study also highlights valuing variations from the norm as computationally productive (e.g., Boe's new project that derived from the norm). Youth-material collaboration suggests a need to capture learning as a process of becoming, that is how a domain phenomenon physically establishes and shifts as youth and materials come together.

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