

Failing Together: Interactive Patterns of Problem-Solving between Youth and Educators in Informal STEM Environments

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Abstract: By incorporating learning-through-failure into facilitation, educators can offer learners the opportunity to promote their creativity and problem-solving skills. However, more research is needed to explore the implementation of this pedagogical approach. In this study, we utilized sequential analysis to examine common failure-based problem-solving patterns between educators and learners during informal STEM-based museum activities. Our data included 38 self-recorded videos of museum educators interacting with a learner or a group of learners in either a camp, drop-in exhibit, or a class setting. Through sequential analysis, the results demonstrate the joint nature of educator-learner interactions, while also emphasizing the educator's crucial role in guiding learners through the problem-solving cycle with pedagogical moves. Specifically, the results of this study highlight the importance of an educator's use of 'prompting' to motivate the learners to engage in the cycle. Simultaneously, we observed how the collaborative nature of interactions, where educators and learners engaged in problem-solving roles, supported the learners in demonstrating creativity and agency. These findings contribute to both theory and practice by reframing failure as a co-constructed learning experience and identifying facilitation strategies that support creativity and problem-solving in informal STEM settings.

Key words: joint activity, failure, problem-solving, STEM-focused activities

1. Introduction

Failure, while touted for its potential to promote learning (Jackson et al., 2022) and problem solving (Tawfik et al., 2015), is also deeply intertwined with supporting creativity; yet their connection is often overlooked in discussions about 21st-century skills, particularly within

educational contexts (Creely et al., 2019; Stretch & Roehrig, 2021). This relationship is particularly evident within the engineering design process, where iterative cycles of prototyping and revision rely on failure as a mechanism for refining and optimizing solutions (Simpson et al., 2024a; Stretch & Roehrig, 2021). In other words, experiencing failure may promote opportunities for creativity, defined as “the sequence of thoughts and actions that leads to a novel adaptive production” (Lubart, 2001, p.295), while engaged in a problem-solving process. By providing opportunities for children to experience failure as part of their learning environments, educators can support the development of students’ creative potential while simultaneously enhancing their problem-solving competencies (Creely et al., 2019; Haavold & Sriraman, 2021; Sirajudin & Suratno, 2021). Yet as noted by researchers, additional research is needed to better understand how expertise interacts with failure (Tawfik et al., 2015) and to support young learners through failure as part of their routine practices (Erol, 2024).

In this study, we took up this call for additional scholarship by considering the interactions between children (as novice learners) and educators (as expert learners) by addressing the following research question: In what ways do young children and educators engage in failure problem-solving patterns when experiencing failure moments during STEM-based activities in museum settings? We deliberately explored the role of failure in STEM-related activities as it is a crucial aspect of STEM learning and engagement (Marks & Chase, 2019) and professional growth in STEM fields (Simpson & Maltese, 2017). Museums provide a distinctive setting for reshaping youths’ often negative perceptions of and feelings around failure in a low-stakes and supportive space (Mortensen & Younas, 2023; Simpson et al., 2024b), as well as support creativity and problem solving through providing room for free play, exploration, and experimentation (Feliu-Torruella et al., 2021; Gong et al., 2020; Gregoriou, 2023).

Subsequently, through this analysis, we further focused on the educator; how their failure problem-solving patterns and instructional moves shaped young children's engagement in failure problem-solving patterns. Museum educators are of particular interest as they are unique in their educational roles and identities within a dynamic, non-formal, and sometimes unpredicted learning environment (Bailey, 2006; McCall & Gray, 2014). For example, Shaby et al. (2018) noted several roles in which museum educators engage with children: a technician that provides instructions on how to operate exhibits, a motivator that offers and harnesses emotional engagement in learning, and a kinesthetic guide that engages their own and children's bodies as part of their instruction. However, their pedagogical moves tend to be grounded and informed by their own experiences of learning in a school-based environment (Lachapelle et al., 2019). In addition, they are not trained as teachers and sometimes lack experience in facilitating learning of young children (Eadie et al., 2022). Their development as educators is often supported through short, top-down provided trainings (Tran et al., 2019). Through the results of this study, we argue that a collaborative learning-through-failure approach, which utilizes educators' guidance as expert learners, can foster the development of creativity and problem-solving skills in youth during STEM-focused activities.

2. Relevant Literature

We situate this study along three lines of research focused on how educators foster children's experiences with failure, creativity, and problem-solving. This scholarship is grounded in both classroom and museum learning environments, with the research in museum settings gaining traction in these three areas.

2.1 *Failure*

Research on educators' responses to learners' moments of failure in STEM contexts is often framed through a failure-positive lens, as it focuses on transforming potentially negative experiences (e.g., frustration, quitting) into positive outcomes and growth (San Juan & Murai, 2022). Effective strategies include normalizing failure as part of the process, celebrating mistakes, asking questions to uncover learners' thinking, encouraging reflection, and offering choices on how to proceed (e.g., Chen, 2021; Gomoll et al., 2018; Maltese et al., 2018; San Juan & Murai, 2022; Tissenbaum, 2020; Warshauer, 2015). Educators can also model their own failures, such as sharing personal challenges or “glorious goofs,” which helps learners view setbacks as temporary obstacles rather than reflections of their abilities (Ryoo et al., 2015). These approaches promote iteration and persistence, and develop learners' capacity to navigate failure moments (Simpson et al., 2024b).

However, educators sometimes adopt less productive responses when supporting children through failure, often driven by the desire to ensure a successful outcome. Stepping in to fix problems, providing direct instructions, or offering a single solution can undermine learners' sense of agency and limit opportunities for problem-solving (Simpson et al., 2019, 2024b; Warshauer, 2015). These tensions may frequently stem from competing priorities, time constraints, or the pressure to achieve visible success (Simpson et al., 2025). While such interventions may offer short-term solutions, they can unintentionally discourage learners from viewing failure as a valuable part of the learning process. Supporting learners through failure requires balancing guidance with opportunities for independence, allowing them to experience the productive struggle necessary for growth.

2.2 *Creativity*

Educators support young children's creativity by creating environments and exhibits that encourage exploration, problem-solving, and self-expression (Kumpulainen et al., 2014; Leggett, 2017). They carefully plan for opportunities that ensure children have access to a variety of familiar and unfamiliar materials, flexible spaces, and open-ended resources (Craft et al., 2014; Davies et al., 2013; Gong et al., 2020). Arnott and Duncan (2018), for example, found that vibrant, well-resourced settings often fostered possibility thinking and asking what if questions; while more challenging spaces supported problem-solving and the development of novel and unique ideas. Educators also design environments that allow children to collaborate with peers, helping them build on each other's ideas and co-construct creative solutions (Davies et al., 2013).

In addition to shaping the environment, educators foster creativity through their interactions with children (Leggett, 2017), and by valuing children as capable and imaginative learners (Craft et al., 2014). Educators often take on flexible roles—such as onlooker, stage manager, or co-player—adapting their involvement based on the needs of the child and the context (Tok, 2022). They balance “standing back” to give children freedom with “stepping in” to offer support, guidance, or thought-provoking questions (Craft et al., 2012; Gregoriou, 2023). This balance allows young learners engagement in STEM activities to remain child-centered while also ensuring children receive encouragement and challenge when needed.

2.3 *Problem solving*

Lastly, educators play a crucial role in supporting young children's problem-solving skills and encourage failure analysis (Brenneman et al., 2019; Erol, 2024). Two approaches to promoting problem-solving skills is to activate learners' prior knowledge and pose questions that promote discovery and exploration of ideas (Olsson & Granberg, 2024). Educators can also

model problem-solving behaviors and use language to promote children's autonomy and self-efficacy (Kelley, 2018). As examined by Kelley (2018), educators demonstrated how to approach obstacles calmly, reason through failures, and identify possible solutions through “thinking aloud.” This visible modeling not only provided children with a problem-solving framework, but also helped them develop emotional regulation and confidence in their abilities (Kelley, 2018; Pekrun, 2006).

2.4 *Summary*

Collectively, this literature base emphasizes the important role educators play in shaping how young children navigate failures, approach creativity, and develop problem-solving skills in STEM contexts. Educator actions can empower learners to persist, explore, and navigate failures—or they can inadvertently diminish these capacities if they over-direct or prioritize immediate success. Less attention has been given to how these capacities develop within *shared* pedagogical relationships. Our framework responds to this gap by centering joint activity as a lens for understanding how learners and educators co-construct STEM-centered learning through mutual engagement, negotiation, and responsiveness (Vossoughi et al., 2021).

3. **Theoretical Grounding**

STEM-centered learning is an educational approach that highlights active, hands-on participation in designing and producing physical or digital creations. This method encourages deep understanding through experiential, iterative processes (Clapp et al., 2016). It also fosters learner agency by empowering individuals to take ownership of their projects, make meaningful choices, and navigate open-ended challenges. Effective teaching within STEM-centered environments, however, requires moving beyond simplistic dichotomies, such as educator-led versus child-led practices (Vossoughi et al., 2021) or the separation of academic knowledge from

everyday experiences (Gutiérrez, 2008). Vossoughi and colleagues (2021) advocate for pedagogical strategies that emphasize collaboration between educators and learners. Through what they term “joint activity,” both adults and children engage in shared, dynamic learning processes that unfold through intergenerational collaboration (Wertsch, 1998; Rogoff, 2003). This model positions children and adults as co-participants in carrying out tasks and solving problems (Vossoughi et al., 2021).

Research has demonstrated that such collaborative interactions between adults—such as parents or teachers—and young learners can yield valuable outcomes, including the development of transdisciplinary knowledge (Gravel et al., 2022) and enhanced problem-solving skills (Baker et al., 2022). However, shifting the adult role from authoritative expert to facilitator and partner in learning poses challenges. This transformation is shaped by factors such as the educator's view of knowledge, their personal experiences, and their ability to respond flexibly to learners' needs in the moment (Hladik et al., 2023). As Ramey and Stevens (2023) note, this adjustment requires a nuanced understanding of collaboration and adaptability within the learning process.

As such, this framework provides a lens for analyzing how children and educators navigate failure not as isolated actors, but as co-participants whose shared problem-solving efforts reflect dynamic, relational learning processes. In doing so, it enables us to address our research question - In what ways do young children and educators engage in failure problem-solving patterns when experiencing failure moments during STEM-based activities in museum settings? - by identifying the collective patterns that emerge during failure moments in STEM-based museum activities.

4. Methods

4.1 *Organization and participant information*

This study involved ten museums from various locations across the United States that varied in size and focus (see Figure 1). The number of informal educators involved in the project for each partnering organization ranged from one to four. Across these museums, consent was obtained from 31 informal educators. Of the participants that self-reported ($n = 25$, 80.6%), the majority of the educators identified as White ($n = 18$, 72%), six (24%) as Asian/Pacific Islander, two (8%) as Hispanic/LatinX, two (8%) as more than one Race, and one (4%) as African American. Additionally, the majority of educators that reported their gender identity ($n = 24$, 77.4%), identified as female ($n = 15$, 62.5%), seven as male (29.1%), and two as non-binary (8.3%). The educators had a range of experience as a museum educator with the majority having less than 4 years of experience ($n = 13$, 52%), five (20%) having between 5-7 years of experience, three (12%) having between 8-10 years of experience, and four (16%) having more than 10 years of experience.

Figure 1. *Map of Partnering Organizations*



Note. Size was self-reported or matched with similar museums using IMLS data (Frehill & Pelczar, 2018).

4.2 Data source

We collected 38 self-recorded videos of educators interacting with a learner or a group of learners (e.g., class, family) during a STEM-making activity. The use of self-recorded video data was intentional as it captured natural interactions between educators and learners, as well as provided museums with autonomy regarding where to place the video recording device, when to record, and what videos to share with the research team. This decision further supported dynamic consent and assent of visitors as they chose to engage in an exhibit in which video data was being collected.

The context of these activities included either a camp, drop-in exhibit, or a class developed for and implemented with children between 6-12 years of age. There was a total of 20 drop-in exhibit videos (52.6%), 14 class videos (36.8%), and four camp videos (10.5%). The length of the videos ranged from 00:02:40 (hh:mm:ss) to 1:35:28 (hh:mm:ss). The average length of less videos was 00:50:26, and the average length of more videos was 00:43:19. In general, the

STEM activities across the museums fell into two categories – tinkering and creative construction (Bevan, 2017). The majority of activities were tinkering, which encompassed student-centered tasks that offered minimal instruction and few constraints, giving youth the freedom to explore and engage in iterative problem solving. For instance, Children’s Learning Museum (pseudonym) offered a drop-in exhibit where learners were tasked with creating an object using a range of materials (e.g., washers, pencils) that would balance on a cork. Failure was experienced during testing when the object fell from the cork. As another example, City Science Museum featured a drop-in exhibit where learners were instructed to independently create a rocket using limited materials, such as pipe cleaners, at a workstation. After they were finished, the learner approached the educator at a new station, where the learner would attempt to launch their rocket into a certain zone. The learner experienced failure when the rocket fell apart or the learner did not reach their specific goal of landing in a zone based on the height and width of their rocket.

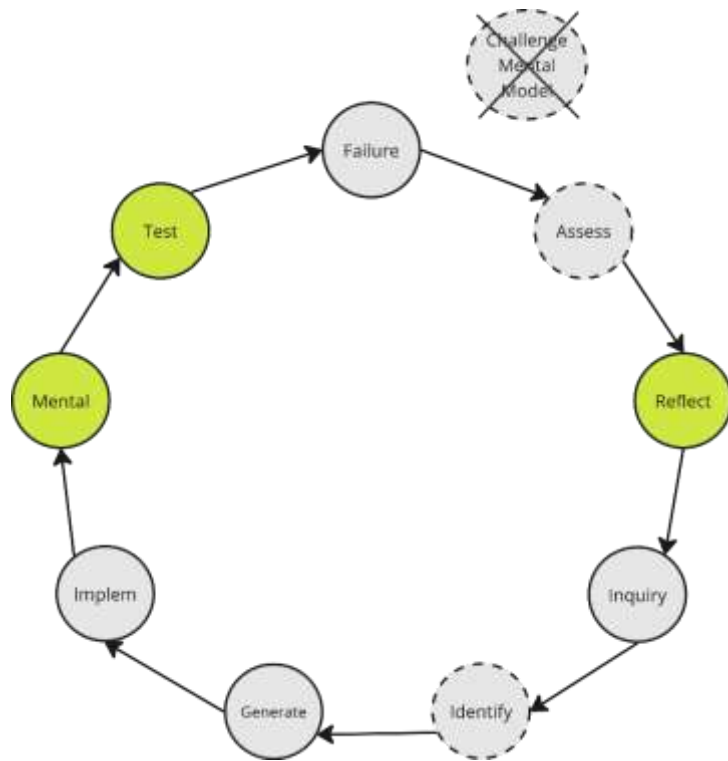
Creative construction, on the other hand, involved tasks that included some structured procedures while still offering youth choices and opportunities for exploration. As an example, in a class setting, the Museum of Science Creativity tasked learners with creating a bridge that only touched two foam blocks and could bear the weight of a toy car in the center. However, the material provided limited the possible design options and the learners’ ability to iterate. While failure was often externally imposed by the nature of the tasks (e.g., object must hover in the middle of the wind tube), the tasks also allowed for self-imposed goals that the learner may or may not meet (e.g., landing in Zone 4 as opposed to Zone 1 or including a loop as part of a paper roller coaster).

4.3 *Data analysis*

Author A and Author J watched each video to identify episodes in which failure(s) by the learner(s) or educator occurred. Failure within the activities was defined as when something did not go as expected, and was observed more often during the testing phase (i.e., externally imposed), but also included moments in which the learner indicated not meeting a self-imposed goal. For example, after successfully launching a ball into the first or lowest platform of a mountain range, one learner continued to change their prototype as they were aiming for the ball to land into the last or highest platform. As stated by the learner, “We got several in already, but we’re aiming for the highest one.” Once episodes were identified, Author J transcribed the entire interaction verbatim. Next, Author A and Author K coded the episodes line-by-line, providing codes for both learners and educators based on the nine elements within the failure-based problem-solving cycle by Tawfik et al. (2015). Developed using frameworks, theories, and associated research relevant to the concept of learning from failure, this cycle is composed of nine elements such as experienced failure, challenge existing mental models, new solution generation, and assess viability of outcomes. It further illustrates a continuous cycle (i.e., no end point) that begins with experiencing failure and moves circularly through each subsequent element. Throughout the coding process, Author A and Author K met every 1-2 weeks to discuss lines of transcript that did not align well with the original nine elements, as well as build consensus in our understanding of the codes within the context of STEM activities within a museum setting through our disagreements and agreements (Ariel Cascio et al., 2019). Any changes to our understanding of the codes resulted in Author A and Author K re-analyzing previous videos and coding with the new understanding in mind.

It was through this process that we adapted Tawfik et al.'s (2015) original model in four ways (see Figure 2). First, we combined three of the original elements into one, Identify reasons, causes, and/or evidence, as regardless of whether participants were identifying potential reasons, root causes, or evidence to validate reasons, we observed them occurring simultaneously as participants were in search of why the failure occurred. Second, we omitted an element, Challenge existing mental model, as this element was not observed or perhaps unobservable as such actions and behaviors would be identified through indirect indicators and be grounded in what we might infer regarding pre-instructional understandings that learners and educators possess prior to their interactions. Third, we developed three new codes based on our line-by-line analysis: (a) test, (b) reflection, and (c) mental foreshadowing. For example, within the context of our study, youth and educators were physically testing their design, which was not accounted for in the original model in which failure was framed more broadly as an element within instructional designs of problem-solving tasks. As another example, mental foreshadowing represented moments when learners were thinking about how the solution might work out without actually engaging in a physical test of the design; thus, it more often occurred after implementing a proposed solution. Fourth, we developed codes to capture the instructional moves that educators utilized to support learners through the failure problem-solving cycle. These codes included the following: (a) prompt, (b) confirm/revoice, (c) praise, (d) clarify, and (e) encourage. While some of the instructional moves we identified align with the design principles outlined by Tawfik et al. (2015) (e.g., prompting), their framework did not explicitly situate these moves within the real-time dynamics of the problem-solving cycle as it unfolds during social, interactive moments. See Online Resource 1 for a codebook that defines and provides examples for each code.

Figure 2. *Failure-based problem-solving cycle codes (adapted from Tawfik et al., 2015)*



Notes. Gray color identifies codes from Tawfik’s original model. Dashed outline identifies codes that we modified (e.g., moved or combined). Green color identifies codes we added. Codes for instructional moves are not included.

We used the Generalized Sequential Querier (GSEQ 5.1) software to analyze the interaction between the educators and the learners in each video. The main function of GSEQ is to perform sequential analysis, a method used to study the sequence of interactions (Bakeman, 1995; Bakeman & Quera, 2011). Multiple studies have conducted sequential analysis through GSEQ to analyze interactions in an educational setting (e.g., Hu et al., 2022; Sung & Kelley, 2019). In this study, we incorporated lag sequential analysis to determine how the dialogue and actions of one participant affected the immediate response of another participant (lag 1): how does behavior A affect behavior B? We analyzed the entire data set, but interpreted the results through four relationships: (a) learners as the given and the target ($L \rightarrow L$); (b) educators as the given and the target ($E \rightarrow E$); (c) learners as the given and educators as the target ($L \rightarrow E$); and (d)

educators as the given and the learners as the target ($E \rightarrow L$). For example, a learner to learner ($L \rightarrow L$) interaction demonstrates a learner executing two failure-based problem-solving moves in a row.

Using GSEQ, we first calculated simple statistics to determine the frequency of each failure-based problem-solving code spoken by the learners and educators. Second, we computed adjusted residuals to identify which given and target codes were strongly associated with one another. A large adjusted residual, either positive or negative, indicated that the observed frequency for a given code was different from what would be expected if the variables were independent, suggesting a strong influence on the association. For example, a large positive adjusted residual between an educator's 'prompt' and a learner's 'generate' response indicates that the educator is having a greater-than-expected positive effect on the learner's response – effectively influencing the learner to exceed expectations in finding solutions. To determine significance, we calculated the corresponding z -scores and the subsequent p -values with a significance level set at $p < 0.05$.

In addition, we calculated Yule's Q , which is an index that conveys the strength of association between two behaviors and provides a comprehensive measure of association ranging from -1 to +1. For example, a Yule's Q closer to -1 would indicate a negative association between behavior A and behavior B, a Yule's Q closer to +1 would indicate a positive association, and a Yule's Q close to 0 would indicate no association. Additionally, according to Bakeman and Quera (2011), values of around (+/-) 0.11, (+/-) 0.33, and (+/-) 0.50 for Yule's Q correspond to weak, moderate, and strong associations, respectively.

Lastly, we examined the significant patterns among the four relationships (i.e., $E \rightarrow L$, $L \rightarrow E$, $L \rightarrow L$, and $E \rightarrow E$) to determine ways that young children and educators engaged in failure

problem-solving patterns when experiencing failure moments during STEM-based activities, specifically through the lens of joint activity (Vossoughi et al., 2021). Our analysis further centered on the educator, specifically investigating how their approaches within the failure-based problem-solving cycle shaped young children's engagement in analogous failure-related problem-solving processes. Once significant patterns were identified, we returned to our transcript and coding sheet to make sense of the failure-based moment. For example, the sequential analysis revealed a significant pattern of Generate (E)→Implement (L), indicating that the educator generated a new solution that the learner would then implement. On the surface, it would appear that the educator removed the opportunity to generate their own solutions. However, revisiting the transcript revealed nuances, which are discussed below.

5. Results

In general, engagement in one element did not necessarily lead to a clear transition or pathway to another element as illustrated in Figure 3. For example, one may expect that determining the reasoning of the failure (i.e., Inquiry (L)) would lead to a learner generating a new solution (i.e., Generate (L)), yet our results showed this to be a non-significant pattern. Rather, we found connections between non-adjacent steps in the cycle (e.g., Fail (L)→Inquiry (L)) and iterative loops to previous steps in the cycle (e.g., Test (E)↔ Fail (E)).

Figure 3. *Learner-to-Learner and Educator-to-Educator Interactions Within the Failure-Based Problem-Solving Cycle*

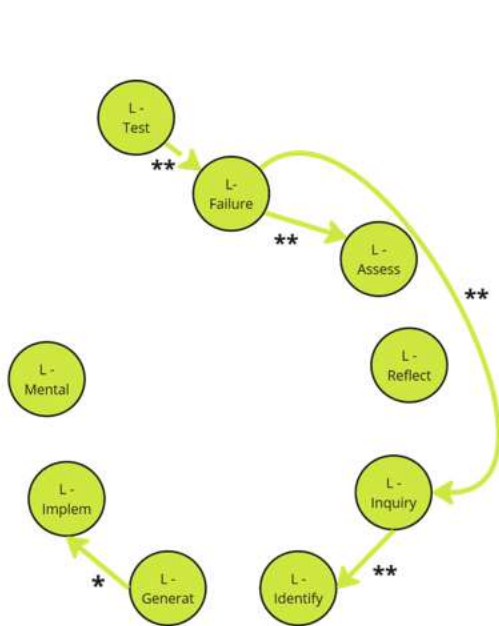


Figure 3A

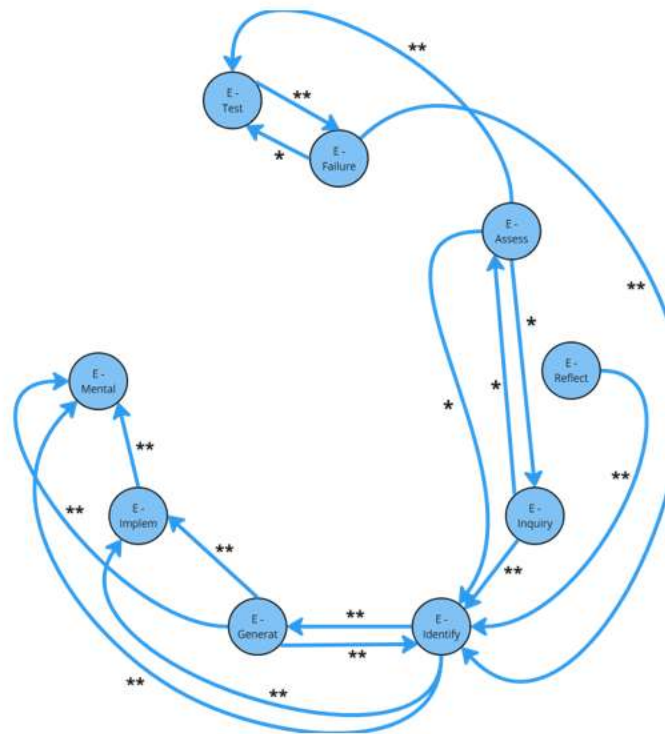


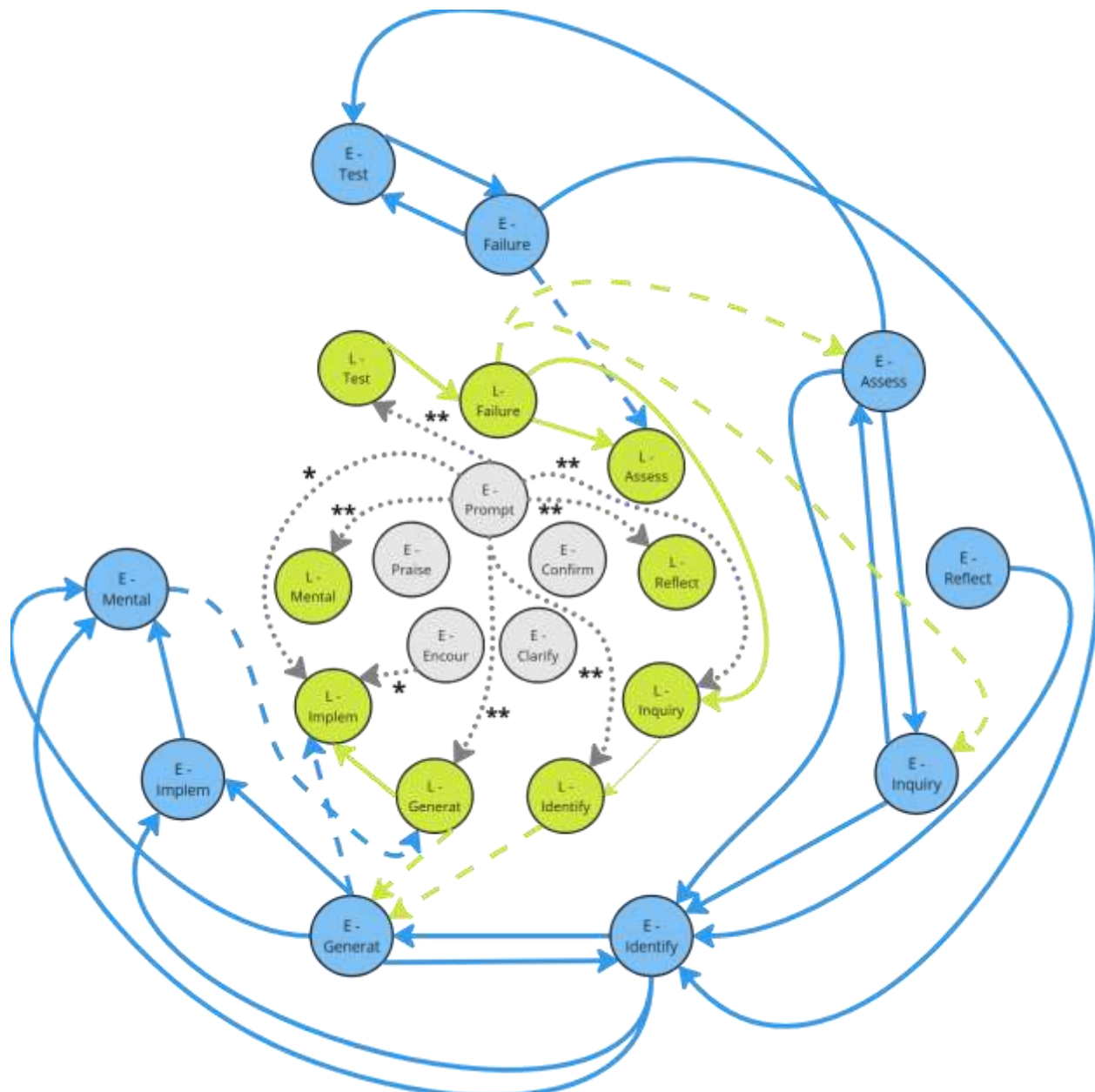
Figure 3B

Note: $*p < .05$. $**p < .01$. The figure only includes positive significant results as indicated through the use of colored lines. The arrow shows the direction of the significant results. All figures in the result can also be found in Online Supplementary 3.

This suggests that knowledge-building does not occur in sequential, ordered steps but skips, jumps and returns to steps as needed to build on and from what is known and/or learned through the process. This is even more evident in Figure 4, as we observed significant patterns between learner and educator's actions and behaviors within the failure-based problem-solving process. This is not to imply that learners and educators did not engage in each component of the problem-solving cycle (see Online Resource 2 for descriptive statistics). For example, descriptive statistics reveal that learners engaged in reflection (7%) through their interaction within the failure-based problem-solving cycle. However, as indicated in Figure 4, this component was not significantly associated with any other component of the cycle other than through prompting from an educator. In what follows, we highlight significant patterns as

informed by the concept of *joint activity* (Vossoughi et al., 2021; Rogoff, 2003). All significant results can be found in Online Resource 2 with additional figures provided in Online Resource 3, which displays the results as a layered set of relationships.

Figure 4. *Interactions between Educators and Learners Within the Failure-Based Problem-Solving Cycle*



Note. * $p < .05$. ** $p < .01$. Blue indicates educators. Green indicates learners. Dotted lines indicate E->L or L->E. Solid lines indicate E->E or L->L, which are the same from Figure 3 with learners nested inside educators as we would expect educators to guide/facilitate learners problem-solving failure process as opposed to vice-versa.

5.1 Problem solving as a collaborative process

Through our analysis, problem-solving unfolded as a collaborative process, with educators and learners working through failure moments together; initiating and responding to each other at various stages of the process. To illustrate, we expand upon two significant patterns. First, as observed in Figure 4, educators seemed to take an active role in generating new solutions either in addition to learners' own solutions (Generate (L)→Generate (E); $z = 2.40, p < .05$) or in place of learners (Identify (L)→Generate (E); $z = 3.71, p < .01$). This may be perceived as co-constructing a shared understanding (Simpson et al., 2024b). Let's consider two examples from an activity in which learners were to create devices (e.g., catapults, slingshots) that would launch a ball into a platform.

Learner: (*Experienced failure*) Oh, too much power. (*Identify*)

Educator: I think, I think what you need to do is go down a little bit so you're arcing it.

(*Generate*)

In this instance, the educator did not provide the learner with an opportunity to generate a solution based on identifying the reason for the failure being "too much power," but provided a solution to the learner on how to launch the ball. Conversely, in the next example, the learner proposed a solution that would change the angle of the catapult while the educator suggested an alternative solution, to make the catapult stable - framing it tentatively ("maybe") and inviting the learner's perspective ("What do you think?").

Learner: (*Experienced failure*) So I think we need to tighten these, so it's at the exact angle we want it. (*Generate*)

Educator: So maybe you can adjust your design to make it a little more stable on that side.

What do you think? (*Generate*)

In this example, the problem space is being actively negotiated as responsibility for solution generation is distributed and the problem-solving process is characterized by shared sensemaking rather than direct instruction.

Second, both learners and educators described the outcome of the test (i.e., Assess) or noted where the failure occurred (i.e., Inquiry) in response to learners' failures (see Figure 4), which reflects co-constructing an initial understanding of the failure moment. Consider the following example from the same activity as above.

Learner: (*Experienced failure*) The bucket, the bucket was (inaudible). Look at the bucket.

(*Inquiry*)

Educator: Alright, give a go. I want to be able to look too. (*Prompt*)

Learner: (*Test, Experienced failure*)

Educator: Alright, tell you what. Whether we think it's the bucket, what I want you to do...I want you to pull down to about right here and just let it go. (*Prompt*)

Learner: [Tested the design without a ball]

Educator: Do it one more time and I want you to look closely at the bucket. (*Prompt*)

Because I think you are on the right track. (*Encourage*)

Learner: [Tested the design without a ball] It's [bucket] turning back down. (*Inquiry*)\

In this particular example, the learner's initial inquiry regarding the bucket (i.e., Fail (L) → Inquiry (L); $z = 2.85, p < .01$) was taken up by the educator through prompts, as opposed to telling the learner what they were noticing and/or how to proceed. This encouraged the learner to not only test their design without a ball, but to focus their attention on the bucket. This intergenerational exchange led to the conclusion that the bucket was turning down. As such, both the learner and the educator were actively involved in determining the issue; they were

positioned as co-investigators, each contributing to a developing narrative of the failure moment. Yet, this moment was an extension of the significant pattern Fail (L) → Inquiry (L).

5.2 *Effective educator moves*

Our analysis revealed particular actions and behaviors from educators that supported learner's engagement in the failure-based problem solving process. First, learners utilized actions and thinking skills to overcome a failure (i.e., solve a problem) creatively as they produced a novel approach or idea not yet put forth. This was particularly evident for two components of the cycle: new solution generation and mental foreshadowing. As illustrated in Figure 4, learners did not engage in these two components on their own (refer to dotted gray and blue lines), but through their interactions with educators, learners proposed new solutions or made a prediction to improve upon the failed design. We highlight this through the following example in which learners were tasked with creating a design that will hover in the middle of a wind tube and not hit the side of the wind tube. While the learner experienced success, they wanted to continue changing their design, a penguin.

Learner: You know what? I covered this end so that the air can't go through.

Educator: Alright, so what are you trying to do? (*Prompt*) You trying to make it so the air goes up, and then it won't get- what will that do? (*Prompt*)

Learner: It will help the penguin fly. (*Mental foreshadowing*)

Educator: Do you think it'll catch enough air to hold the penguin though? (*Prompt*)

Learner: I think so. (*Mental foreshadowing*)

Educator: Yeah, and if it doesn't what are you gonna do? (*Prompt*)

Learner: See if I can add a bit less weight. (*Mental foreshadowing*)

Although the learner had achieved a functioning design, their desire to continue improving it created an opening for deeper engagement in the problem-solving cycle. The educator's layered prompts scaffolded the learner's mental foreshadowing, encouraging them to articulate not only *what* they were trying to do but also *why* and *how* it might work. This is especially evident in the sequence of questions that help the learner simulate future outcomes ("what will that do?"; "if it doesn't what are you gonna do?"), prompting them to reason about airflow and weight in relation to the penguin's flight.

Second, educators supported the continued progression of learner's engagement in the failure-based problem-solving cycle by engaging alongside learners during "stuck" moments (e.g., Identify (L)→Generate (E), Generate (E)→Implement (L), Fail (E) →Assess (L)). To illustrate, the following example is from activity in which learners were tasked with constructing a roller coaster for a marble to travel from the beginning to the end with the force of gravity alone. In this example, learners were unsure as to where to place a loop.

Educator: So where do you want the loop to be? Do we want the loop to be up here or down here? Where do you want the loop to be? You can choose for it to be anywhere, can be up here. It could be down here. [Moving loop up and down] Where do you think it should be? (*Prompts*)

Learner: Higher.

Educator: The loop should be higher. (*Confirm*) You want to test it? Yeah. Let's test it.

(*Prompt*)

Learner: (*Test, Experienced failure*)

Educator: So what happened? Do we all see that? What was happening? (*Prompts*)

Learner: Lower. (*Generate*)

Educator: Yeah, let's try lower. (*Prompt*)

Learner: (*Test, Experienced failure*)

Educator: One thing that loop is quite, it's a steep angle. (*Identify*)

Learner: [Shifts position of loop.] (*Implement, Test, Experienced failure*)

Educator: Yeah, so one thing that's happening is actually hitting the tape here. (*Inquiry*)

Yeah, so maybe we could fix that. I would just remove that. (*Generate*)

Learner: [Removes tape.] (*Implement, Test*)

Educator: Alright, so the loop is working. (*Assess*)

In this instance, the educator sustained the learner's engagement in the failure-based problem-solving cycle through active co-participation in the design process, particularly where and how to place the loop. Rather than taking over when failure occurred, the educator used prompts (e.g., "What was happening?") and observations ("...actually hitting the tape here.") to help the learner reflect, reimagine, and re-test their ideas. However, it was through providing the suggestion of removing the tape that led to the learner implementing a design change that led to a successful test. As such, this joint activity allowed the learner to persist through repeated failures—demonstrating how educators can help maintain momentum in the failure-based problem-solving cycle by being attuned, responsive collaborators during "stuck" moments.

Third, Figure 4 illustrates the importance of educators' instructional moves, in particular, prompts (see dotted gray lines). This instructional move alone led to learners' engaging in all but two components of the problem-solving failure cycle – Assess viability of the outcomes or test and Failure – which we would not expect a prompt to lead to a failure void of a test. As the analysis revealed, educators' prompts led to the following problem-solving component for learners: Test ($z = 16.88, p = <.01$), Reflect ($z = 14.22, p = <.01$), Inquiry ($z = 7.77, p = <.01$),

Identify ($z = 7.79, p = <.01$), Generate ($z = 10.88, p = <.01$), Implement ($z = 2.10, p = <.05$), and Mental Foreshadowing ($z = 7.11, p = <.01$).

Educators' prompts were intentional and direct, but also were taken up by learners to meet the goal or outcome of the STEM activity through engaging in the failure-based problem-solving cycle. Consider the following example, which occurred within an activity where the goal was to balance an object(s) (e.g., pencil with small washers as weights) on a cork.

Educator: Alright, let's see what happens. (*Prompt*)

Learner: (Puts design on stand but it immediately falls.) (*Test, Failure*)

Educator: Okay. Why do you think this side is falling down and the other side's not?

(*Prompt*)

Learner: Because this one is farther away from this. (*Identify*)

Educator: Okay, so if this side is lighter, what can you do? (*Prompt*)

Learner: I can make it heavy. (*Generate*)

As this example highlights, each prompt was focused and geared to elicit a component of the problem-solving failure cycle. The second prompt, for instance, probed into *why* the test failed, to which the learner responded accordingly. The third prompt built off this response as the educator asked how the learner might make a change to their design with the learner again responding by generating a possible solution.

The only other instructional move that supported learners' engagement in the problem-solving cycle was Encourage (E) → Implement (L) ($z = 2.04, p = <.05$). Hence, when educators' urged learners to execute their proposed change to their design, learners tended to do so.

5.3 *Ineffective educator moves*

On the other hand, our analysis revealed particular actions and behaviors from educators that were not significantly associated with learner's engagement in the failure-based problem-solving process, nor a collaborative process between learner and educator. Educators were engaged in the problem-solving cycle by themselves, which reflect educator-led behaviors rather than joint activity. First, this was observed when educators unpacked and/or interpreted the failure moment; when describing the outcome of a failure (Assess) or noting what (Inquiry) and why (Identify) the failure occurred. This can be exemplified in Figure 4 by Assess (E): Assess $\rightarrow$ Test ($z = 3.50, p = <.01$), Assess $\rightarrow$ Inquiry ($z = 2.20, p = <.05$), and Assess $\rightarrow$ Identify ($z = 2.07, p = <.05$). Second, as demonstrated in Figure 4, this was also the case when educators implemented a change to the failed design, more often based on their own solution generation (Generate (E) $\rightarrow$ Implement (E); $z = 2.94, p = <.05$) or reasoning as to why the failure occurred (Identify (E) $\rightarrow$ Implement (E); $z = 6.02, p = <.01$).

To summarize our results, we have included a table (see Table 1) to highlight the significant interaction patterns between educators and youth within the failure-based problem-solving cycle based on the sequential analysis.

Table 1

Summary table of pedagogically relevant interaction patterns

Pedagogical Result	Significant Pattern Examples
Problem-solving emerged as a shared, collaborative endeavor with educators and learners jointly working through failure moments.	Generate (L) $\rightarrow$ Generate (E) Fail (L) $\rightarrow$ Assess (E) Fail (E) $\rightarrow$ Assess (L)
Learners engaged in creative problem-solving—particularly through new solution generation and mental foreshadowing—not independently, but in response to interactions with educators.	Mental (E) $\rightarrow$ Generate (L) Prompt (E) $\rightarrow$ Generate (L) Prompt (E) $\rightarrow$ Mental (L)

Educators supported the progression of learner's process in the failure-based problem-solving cycle by engaging alongside learners during "stuck" moments.	Identify (L)→Generate (E) Generate (E)→Implement (L) Fail (L)→Inquiry (E) Fail (L)→Inquiry (L)
Educator prompts was a specific instructional move that supported learners' engagement within the problem-solving process.	Prompt (E)→Test (L) Prompt (E)→Reflect (L) Prompt (E)→Inquiry (L)
Learner engagement was limited when educators worked independently—whether by interpreting the failure moment or implementing design changes based on their own reasoning—highlighting a shift away from joint activity toward more educator-directed problem-solving.	Assess (E)→Identify (E) Identify (E)→Generate (E) Generate (E)→Implement (E)

Note. E = Educator. L = Learner.

6. Discussion

The results from this study highlight the utilization of failure as a pedagogical principle for simultaneously fostering creativity and problem-solving (Creely et al., 2019), both important skills to garner interest in STEM fields (Cooper & Heaverlo, 2013), as well as skills needed to be productive and successful as learners, as citizens, and as part of the future workforce (Battelle for Kids, 2019). This study expands upon the work of Tawfik et al. (2015) by demonstrating that failure-based problem-solving is not simply an individual cognitive process, but a fundamentally relational one. The joint engagement of learners and educators helped shape the trajectory of learners' ideas and actions within the problem-solving cycle, supporting a shift in how failure may be conceptualized—not as a solitary experience, but as a co-constructed opportunity for shared investigation. This expands current empirical and theoretical understandings of failure in STEM education by showing that it may unfold through *joint activity* (Vossoughi et al., 2021; Rogoff, 2003), in which learners and educators actively listen, prompt, respond, and build on one another's thinking and actions. Such a relational approach stands in contrast to adult-centered models of learning, where educators may respond to failure moments by providing solutions or

direct next steps (Simpson et al., 2024b); while these interventions may offer short-term success, they risk limiting learners' opportunities to engage in productive struggle, develop creative responses, and view failure as a meaningful part of the problem-solving process.

To expand, our findings underscored that problem-solving in STEM activities unfolds as a collaborative, relational process, with educators and learners navigating failure moments together (Vossoughi et al., 2021). Similar to Kelley's (2018) work, educators modeled problem-solving behaviors not through direct instruction alone, but by engaging alongside learners in the steps of the failure-based problem-solving cycle. Rather than adhering to rigid roles or stepping in to "fix" the problem, educators supported learners by balancing modeling with strategic prompting—encouraging reflection, generating new ideas, and testing possible solutions. In doing so, educators created opportunities for learners to develop their own problem-solving skills, gradually building fluency with the components of the failure cycle through guided participation. This was exemplified in the roller coaster example above, in which the educator prompted rather than directed a learner through multiple rounds of testing and revision, supporting the learner's growing independence with the problem-solving cycle. This joint engagement positioned educators and learners as intergenerational collaborators engaged in shared inquiry (Baker et al., 2022).

Prompting in particular emerged as a particularly effective instructional move, evident in how it facilitated transitions between various components of the problem-solving cycle. These prompts not only scaffolded learners' reasoning but also created openings for learners to engage in speculative thinking—what we call *mental foreshadowing*—a form of creativity that involved imagining how designs might work before testing them. By showing how specific discourse practices (i.e., prompting) support creative agency during failure moments, our study enriches

existing work on creativity in STEM learning (Lubart, 2001; Stretch & Roehrig, 2021), emphasizing creativity as a sustained and adaptive process, not only a moment of novelty. In contrast, moves such as praise or general approval offered limited support for learners' progress through the cycle. Perhaps prompting is particularly engaging due to its unique nature that suggests to learners that they must respond in some way. This motivates learners to directly exercise their creativity and agency in their response, whereas praise may suggest that further thought or effort is unnecessary, or perhaps lead to negative responses to failure (e.g., perceived performance, persistence; Skipper & Douglas, 2012).

Our results also illustrate that focusing solely on the learners' progression through the failure-based problem-solving cycle only tells part of the story (see Figure 3a); the whole story highlights the importance of educators within the process (Figure 4). Interactions between learners and educators demonstrated role flexibility during problem-solving, with both learners and educators initiating and responding to each other at various stages of the process. For example, as illustrated in Figure 4, we observed several significant interaction patterns between learners and educators that were initiated by learners, highlighting learners' willingness to take initiative and exert control over their learning processes and problem-solving approaches but also highlights educators' uptake or response to learners during the failure-based problem-solving process. This is consistent with research showing the relational nature of supporting children's agency through such interactions. Educators are an intricate part of this process as they hold the power and authority to support or constrain children's agency (Sairanen et al., 2022; Sirkko et al., 2019). Moreover, our findings also draw attention to the flexible roles that educators adopted—sometimes stepping back to allow learners to lead, and other times stepping in to offer guidance. For instance, during the wind tube activity, an educator intentionally stepped back as a

learner independently tested a design, then stepped in with layered prompts at a key moment of refinement—providing timely support while preserving the learner’s ownership of the process. This responsiveness helped balance the distribution of authority and preserved learners’ sense of agency, aligning with Craft et al.’s (2012) notion of standing back/stepping in and with Tok’s (2022) emphasis on fluid educator roles. These relational dynamics reflect not just effective pedagogy, but equitable practice: they invited learners into authentic participation and validated their contributions, particularly when educators took up and built on learners’ ideas (e.g., Vossoughi et al., 2016). These patterns reflect a distributed approach to agency and align with sociocultural perspectives that view learning as co-constructed through interaction (Rogoff, 2003; Sairanen et al., 2022).

In sum, our findings demonstrate that joint activity between learners and educators is critical to navigating failure productively. Prompting emerged as a particularly effective instructional move, enabling transitions across various stages of the problem-solving cycle. Educators supported creativity through scaffolding speculative thinking and sustained engagement, while over-directive moves risked undermining learner agency. These patterns underscore the importance of viewing failure not as an endpoint, but as a generative moment within relational, interactive learning.

6.1 Implications for practice

The findings have implications beyond practice—they offer conceptual tools for rethinking how we frame failure, creativity, and learning. The traditional portrayal of failure as a hurdle to be overcome by an individual learner is insufficient. Instead, our study positions failure as a socially mediated learning event, where creativity is enacted through collaborative iteration and problem-solving unfolds as a collective endeavor. These insights invite a broader

reconceptualization of how we prepare museum educators through professional development (PD) opportunities. Rather than relying solely on brief, isolated trainings, we encourage embedding this work within ongoing professional development, which has been shown to have a greater impact on instructional practice (e.g., Darling-Hammond et al., 2017).

First, our findings underscore the importance of supporting educators in adopting the role of co-learners and collaborators, particularly during moments when learners are “stuck” within the failure-based problem-solving cycle. In these instances, engaging in joint activity allowed educators to break down traditional hierarchies and foster more equitable and participatory learning environments (Vossoughi et al., 2021). We contend that this may require a shift in mindset—from viewing the educator as the primary source of knowledge to embracing a stance of shared inquiry and joint problem-solving (Ramey & Stevens, 2023), and the utilization of reflective video-based professional development opportunities may support this shift (Simpson et al., 2025). In addition, PD may provide opportunities for museum educators to experience “stuck” moments of the STEM-focused task through the perspective of learners (Cohen et al., 2023). Educators can then generate different strategies for how to attend and respond in-the-moment such as testing the learners’ prototype to promote inquiry, generating solutions with the learners, and engaging in mental foreshadowing for learners to consider within their design.

Second, while parents or other adults (e.g., teachers) may be with learners as they engage in the STEM-focused tasks and/or encounter these failure moments, they may be less familiar with pedagogical approaches that best support learners through failure, rather than simply taking over the activity and doing it for the learner. Museum educators should be available/present at these activities but also need to receive PD and/or training about best practices in supporting learners of all ages in such a way that they are jointly engaging in problem-solving and creativity

through experiences with failure; distorting the binary boundary between adult-centered and student-centered models of learning (Simpson et al., 2024b).

Third, prompting emerged as a particularly effective instructional move throughout the failure-based problem-solving process. These prompts appeared to help learners' transition between different stages of the problem-solving cycle, aligning with prior research on scaffolding through failure (e.g., Olsson & Granberg, 2024; Warshauer, 2015). PD opportunities could provide opportunities for educators to create a set of prompts that might be useful in promoting problem-solving and creativity when experiencing failures within STEM-focused activities. Moreover, attention may be paid to the type of praise being provided as research suggests that process-oriented praise (e.g., Great job incorporating your idea into the design.) leads to more positive responses from failure moments than person-oriented praise (e.g., You are crafty.) (Skipper & Douglas, 2012). As such, process-oriented praise may support further engagement in the failure-based problem-solving cycle.

Fourth, we caution against educators interpreting failure moments or implementing design changes on behalf of learners, as this seemed to undermine learners' agency and reduce their opportunity to engage meaningfully with the problem-solving cycle. However, we also recognize the importance of explanation as a valuable practice within joint activity. As noted in the prior research by Vossoughi et al. (2021), explanations can serve to make the "hows" and "whys" of processes transparent, fostering shared thinking and deeper understanding (e.g., in joint activity). The key difference is that explanations, when positioned as part of collaborative inquiry, should promote learner participation and encourage problem-solving and creativity. Educators should aim to frame their explanations in ways that invite learners to engage, reflect, and contribute their own insights, preserving the learner's role as an active problem-solver.

Grounded in our study, educators may be encouraged to promote new solution generation and mental foreshadowing—approaches that nurtured creative thinking and sustained engagement.

Lastly, attention should be paid to designing tasks and exhibits that invite failure in generative ways, as these moments appear to catalyze deeper problem-solving and creative exploration when skillfully supported. For instance, open-ended design challenges that intentionally include opportunities for learners to encounter failure or “stuck” moments often allow for multiple attempts and revisions can frame failure as a natural part of the learning process (e.g., tinkering, Bevan, 2017), whereas tightly scripted tasks with single “right” answers often diminish opportunities for problem-solving and creativity when failures occur. Cultivating an awareness around the design of tasks and exhibits may support museum educators in knowing where failure is expected to be used as a springboard for promoting problem-solving and creative processes.

6.2 Limitations and future research

We examined failure moments as experienced by learners during STEM activities in camps, drop-in exhibits, or classes developed and implemented in museum settings. While these activities likely share similarities with others in which learners might encounter failure moments, future research could extend our work by examining common failure problem-solving patterns among learners and within learner-educator interactions when experiencing failure moments during STEM activities in other settings such as schools or community makerspaces or in other more (or less structured) settings.

In addition, our study focused on interactions between a learner and educator within each setting. However, in some settings, more than one adult (e.g., educator) and more than one child (e.g., learner) were present. In our analyses, we did not account for multiple learners in one

session. Rather, if more than one learner was present, we coded them as the same learner. For example, a sequence of EPro $\rightarrow$ LTest $\rightarrow$ LFail would assume that both of the learners were the same learner. We do not expect this to have had a large impact on our results since our primary focus was interaction patterns between learners and educators. But by not differentiating out multiple learners, we are not able to gain as clear of a picture of how museum educators adapt to the needs of different learners in a single interaction. The interaction patterns may look different, especially if educators used different instructional moves with different learners based on learner's needs. Further, we were unable to capture moments in which a learner may enact the role of an educator for a peer. As such, this choice missed the nuances of a group setting, which is common in museum settings that facilitate family and school-based interactions. Therefore, we encourage researchers to examine the interplay among multiple learners and a single educator (e.g., small group or class) engaging in the failure-based problem-solving cycle.

Our analysis only let us capture two sequences (i.e., lag 1). As such, we were unable to make statements regarding educator-learner interactions beyond two elements of the problem-solving cycle; therefore, limiting insights of patterns capture across the entire scope of the interaction. For example, in Figure 4, we cannot state with significance that Failure (L) $\rightarrow$ Inquiry (E) $\rightarrow$ Assess (E), but only that Failure (L) $\rightarrow$ Inquiry (E) was a significant pattern and Inquiry (E) $\rightarrow$ Assess (E) was a significant pattern. In addition, if an educator/learner spoke and no one responded or if an educator/learner spoke multiple times in a row followed by a response, the analyses did not account for that. For example, if the educator did Prompt (E), Mental (E), and Encourage (E), and the learner responded with Test (L), our analyses would have coded that the learner responded only to the educator's encouragement (i.e., Encourage (E)). While utilizing lag 1 simplified our analysis, we were unable to observe more nuanced and complex patterns of

interactions through the cycle that would illustrate ways that collaboration and joint activity occurs between educators and learners. Future research could incorporate analyses that examine lag 2 and lag 3 sequences to explore patterns in longer sequences of interactions.

In addition, we observed the value of joint activity between learners and educators in the failure-based problem-solving cycle. When learners were considered independently, their engagement with the cycle appeared limited (see Figure 3A). In contrast, more complex and sustained engagement emerged when learners participated collaboratively with educators (see Figure 4), highlighting the importance of interacting with a more experienced other. While future research might examine how learners' roles in the problem-solving cycle shift with experience, it is important not to assume that increased independence is the sole indicator of progress. Given that collaboration, active listening, and shared problem-solving are essential skills in the STEM workforce (Battelle for Kids, 2019; Jang, 2016), understanding how learners take on new responsibilities within joint activity—rather than move away from it—may offer a more meaningful lens for examining learning and development over time.

Lastly, we contend that engaging in the failure-based problem-solving may play a role in developing learners' identities as STEM thinkers (e.g., Erol et al., 2024). In particular, through the failure-based problem-solving cycle, learners participated and embodied the actions and behaviors of STEM professionals (Steinberg & Danish, 2024), such as failure, collaboration, and creativity (e.g., English, 2023; Simpson & Maltese, 2017). Future research could investigate this more intently, not only with observational data, but through interviews or simulated-recall interviews with learners. This would build upon our current understanding of STEM identity as informed by recognition, competence, interest, and sense of belonging (e.g., Cribbs et al., 2015; Godwin et al., 2013).

7. Conclusion

While typically depicted as a process in which an individual engages independently, our study explored the patterns of interaction between novice learners and more expert educators during informal STEM-based museum activities where they encountered failure moments. The joint nature of the educator-learner interactions resulted in shared, collaborative problem-solving process that was pushed along (or “prompted”) and supported through educators’ use of pedagogical moves. We argue that embracing failure as a natural and productive part of the learning process—particularly through collaborative contexts in which educators act as expert learners—can foster the development of creativity and problem-solving skills in youth. Rather than designing tasks and learning environments that minimize or avoid failure, we should create opportunities for learners to engage with failure alongside more experienced others. Future work could provide further insights as to what impact being taught the failure problem-solving cycle prior to encountering a failure during a STEM learning activity has on how learners engage in the cycle and whether educators’ instructional moves eventually lead to the same learners performing problem-solving moves on their own in future projects or what impact, if any, knowing the problem-solving cycle.

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