Interactive Constructionist Scaffolds for Agent-based Modeling and Programming in NetLogo

John Chen
Northwestern University
civitas@u.northwestern.edu

Michael Horn
Northwestern University
michael-horn@northwestern.edu

Uri Wilensky
Northwestern University
uri@northwestern.edu

ABSTRACT

This paper explores the benefits of interactive scaffolds in constructionist learning experiences with Agent-based Modeling and Programming (ABM & P). While many previous studies have supported ABM & P learning, they often lack embedded interactive scaffolds. In a recent study, we introduced the Tortuga Interactive Scaffolding system for designers to build interactive scaffolds for ABM & P with simple commands that can react to learners' emergent interactions and a model's emergent behaviors. To explore the design affordances of this system, we implemented scaffolds for eight agent-based models with three design paradigms: content-agnostic, exploration-oriented, and programming-oriented. With log data collected from out-of-school, online learning contexts, our quantitative analysis shows that exploration-oriented and programming-oriented scaffolds did better to engage learners in constructionist ABM & P activities. We discuss implications for other constructionist learning designers.

CCS CONCEPTS

• Human-centered computing - Human computer interaction (HCI) - Interactive systems and tools; **• Applied computing – Education - Interactive learning environments**;

KEYWORDS

Interactive Scaffolds, Constructionist Learning, Agent-based Modeling, NetLogo

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1 INTRODUCTION

Agent-based Modeling (ABM) has become a powerful tool for scientists to understand natural and social phenomena [4]. Building on constructionist traditions, [26] argues for a new representational infrastructure that shifts the focus of learning. For them, ABM is among the most important examples of this restructuration. By using individual autonomous computational agents instead of equations in scientific modeling, ABM enables learners of younger ages to understand complex phenomena that were previously inaccessible to them [30]. As such, agent-based restructurations can be used in learning contexts in which scientific phenomena can be computationally represented as simple rulesets for agents [26].

Building agent-based models necessitates the learning of agent-based programming (ABP), wherein learners need to program rules for individual agents. ABP is used in scientific modeling while also supporting a wider array of computational activities, ranging from creative art, games, to expressive programming [8]. By reinforcing decentralized, probabilistic mindsets [30], ABP is poised to promote epistemological changes to learners' scientific thinking [8].

While many previous studies of ABM & P have been conducted in classroom environments, less work has examined learners' engagement with ABM & P in informal contexts. Recent advances in technology have brought NetLogo [27], a widely used platform for ABM & P, to mobile devices in the form of Turtle Universe (TU) [7]. By engaging learners in online, informal contexts, TU creates opportunities to engage learners from diverse socio-economic-cultural backgrounds. However, opportunities for engagement do not equate to learning or engagement [20]. On the contrary, the absence of teachers and structured curricula creates new challenges for supporting learners and building interest over time. The online, out-of-school informal learning contexts necessitate the introduction of technology-enabled learning scaffolds, which few previous studies have touched on.

We recently introduced the Tortuga Interactive Scaffolding system [9] that responds to these challenges. Our system can react to both learners' interactions with an agent-based model and the dynamics of the model itself. Tortuga Interactive Scaffolding naturally invites both learner-adaptable and learner-adaptive scaffolds and flexibly supports multiple paradigms of design that could cater to diverse learning needs. However, our preliminary exploration of the design affordances of Tortuga Interactive Scaffolding was insufficient.

How could we design better interactive scaffolds that support learners' constructionist engagement with ABM & P? In this paper, we present a detailed analysis of scaffolds designed with three paradigms: **content-agnostic**; **exploration-oriented**; and **programming-oriented**. We present a detailed account of our learning design and embedded design hypotheses. In 2021-2022, we collected log data from 7,256 learners who used at least one of the eight scaffolds and quantitatively analyzed their engagement metrics to understand their learning interests. Building on our recent studies [8][9], we seek to answer the two research questions:

- How did our interactive scaffolds support learners' engagement and interests with ABM or P?

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- How were the impacts on learners different for the three paradigms of interactive scaffolds?

2 RELATED WORKS

2.1 Broadening Access to ABM & P

ABM & P has been widely used and known to be successful in promoting systems thinking and computational thinking in formal and informal learning contexts (e.g., [15] in museums; [19] in K12 classrooms; [12] in professional education). The "low threshold, high ceiling" design of NetLogo helps educators and learners without a CS background better understand the powerful ideas of complex systems, such as feedback, emergence, critical parameters, and sensitive dependence through building and exploring models [26] [21]. One of the main goals of the NetLogo ecology is bringing ABM & P to a broader audience. Hence, NetLogo Web [29] was introduced for classrooms and students without access to full computers and has been embedded by many ABM-based curricula (e.g., [12] [5]). [7] brings opportunities for engaging young learners in out-of-school, informal learning contexts.

While those efforts aim to leverage novel technologies to promote constructionist learning experiences of ABM & P in diverse learning landscapes, more opportunity for learners to engage does not lead to more engagement or learning [20]. Bringing ABM & P to informal, online learning contexts creates urgent needs for designing technology-enabled scaffolds, as learners' time could be more fragmented, their engagement could be more interest-driven, and instructors could be less available. However, this realm is not only understudied, but also challenging to measure and interpret design outcomes. As TU [7] relies on online learners' voluntary engagement, many rigid assessment approaches in classrooms become much less viable. In this paper, we draw on [20] framework and interpret short-term and long-term engagement as a manifestation of learners' situational and individual learning interests.

2.2 Technology-enabled Scaffolding

Scaffolding was first used to describe the support from interpersonal tutoring (Wood et al, 1976), and later expanded to include learning support from software [14]. In this paper, we adopt [10]'s definition of scaffolding which stems from experts' support for novices to carry out tasks. Here, the ultimate goal of the cognitive apprenticeship is to enable learners to carry out similar tasks without scaffolds, thus allowing scaffolds to fade. [16] categorized scaffolding into three types: supportive, where the support aims to help learners with the task; reflective, where the support aims to help learners think about the task; and intrinsic, where the task structure is changed to reduce the complexity.

Extending the notion of scaffolding to support from software, Jackson et al. (1998) also discussed two design strategies of technology-enabled scaffolds in computer-based environments: learner-adaptive, where the technical design responds to learners' needs and fades when no longer in need; and learner-adaptable, where the technical design enables learners to initiate the fading of scaffolds. To better understand the learning impacts of scaffolds, the scaffolding analysis framework [24] stresses the necessity to compare learning performance between unscaffolded and scaffolded situations, and that scaffolds are layered. For example, while textbooks could be seen as scaffolds for domain knowledge, in classrooms, teachers' instruction could be seen as scaffolds for textbooks. As such, ABM & P could be scaffolds for complex systems thinking [3] while being a target for scaffolds as well (e.g. [23] [13]).

2.3 Scaffolding Efforts for ABM & P

Among many previous studies around ABM & P, we focus on cases where scaffolding is (partially) provided by technology-enabled design. The first type of scaffolding leverages interface widgets. For example, the Bird Breeder [21] used buttons and text boxes to provide supportive and reflective scaffolding. It also results in more complicated code, limiting learners' capability to understand or build on that model. Next, many scaffolds aim at supporting the learning of NetLogo, as it could take several sessions to begin with. For example, BIND [1] enables learners to try out each primitive in a simple model. Other studies introduced block-based interfaces for ABM & P. Frog Pond [15], CTSiM [23], NetTango Web [16], StarLogo Nova [25], and DMSE [13] were launched to provide a "code-first" or "quickstart" environment for young or novice learners. Through intrinsic scaffolding, they hide the complexity of text-based coding for ABMs. However, those scaffolds require technical expertise to build. As the complexity of such interfaces increases, they may need another layer of scaffolding (e.g. [25]).

While existing technology systems sometimes provide a low-threshold pathway to create scaffolds for ABM & P, they often reflect the design patterns of paper-based handouts [1]. The technical design of such web portals parallelly displays the model and the scaffolds with fewer options for interactive design. To address this challenge, we recently introduced Tortuga Interactive Scaffolding, the first technical system that enables designers to create interactive scaffolds with the NetLogo language itself [9]. It intentionally leaves a large possible space for learning designers: an interactive scaffold could be as simple as a two-screen prompt, or as complicated as a network of pathways and triggers. The deep integration between NetLogo and Tortuga Interactive Scaffolding enables adaptive and adaptable scaffolds based on learner interactions [9].

3 SAMPLE LEARNING DESIGN

To understand the design and learning affordances of the Tortuga Interactive Scaffolding system, we designed and implemented 9 sets of sample design following 3 paradigms. First, the **content-agnostic** paradigm is designed as a baseline: while scaffolds are designed to be interactive, with general prompts (e.g. "Here you can change the parameters of the models", or "Do you want to make changes to the model"), they are not directly related to specific agent-based models (e.g. Fig 1, left). Next, we seek to understand if turning existing verified non-interactive learning materials (Info Tab) that accompany NetLogo models could be beneficial. We introduce the **exploration-oriented** paradigm, where 8 classical agent-based models from NetLogo's Models Library are transformed. Finally, we hope to explore if interactive scaffolds could support more open-ended creative expression of agent-based programming and create the **programming-oriented** paradigm. A dedicated model, the Pocketworld Playground [8] was created specifically as an agent-based block-based programming space to be scaffolded by this

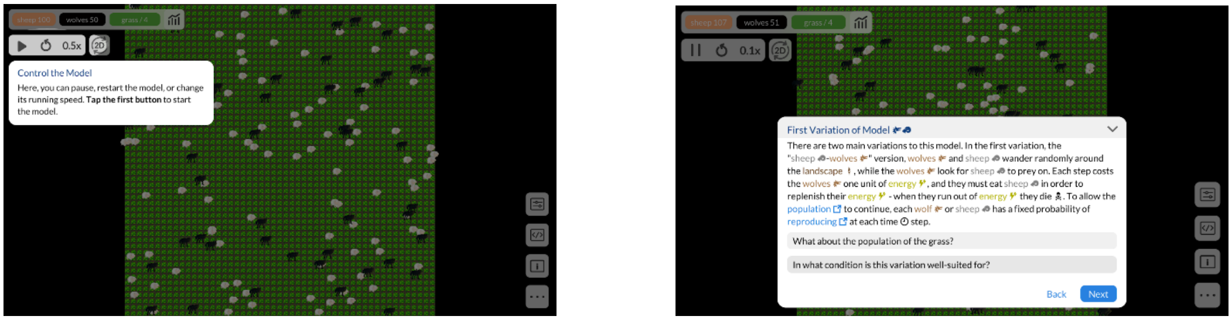

Figure 1: Screenshot of the content-agnostic tutorial; of an exploration-oriented tutorial.

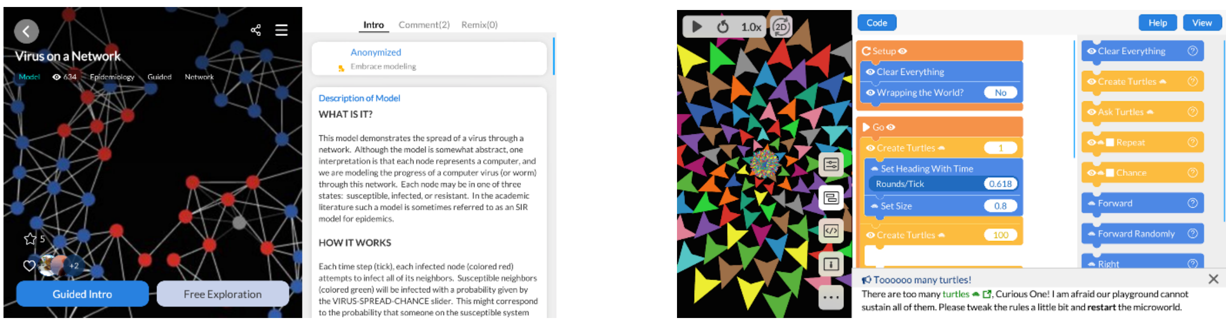

Figure 2: Screenshot of the Info Tab in TU; of the programming-oriented tutorial.

design paradigm. Below, we introduce the three paradigms that are used in our empirical study in more detail.

Fig 1 (left) demonstrates the first paradigm, the **content-agnostic interface tutorial** of Turtle Universe. Here, the learner is supposed to change the model's speed and running status through the highlighted interface, while other parts are temporarily masked. This stencil-based design is conceptually similar to [18], serving as a control group in our empirical study. While learners cannot leave this stage of the scaffold, they are free to opt-out at many other stages, including at the beginning. This scaffold brings the learner through the main parts of TU's interface and cognitive features: inspecting individual agents; monitoring the macro-level emergent pattern through graphs; changing the model's parameters through numerical inputs; and expanding or modifying the model through text-based and block-based programming. The linear pathway in this scaffold would stay mostly the same for each individual model, although it may hide some portions if they do not exist in the model (e.g. if a model does not have graphs, it will skip the section).

For the **exploration-oriented paradigm**, we designed individual scaffolds for several classic ABMs. They cover a diverse range of topics: biology (Wolf Sheep Predation); physics and chemistry (GasLab Gas in a Box); earth science (Climate Change); computer science and mathematics (Virus on a Network; 3D Surface); social science (Traffic Basic); and generative art (Sunflower). Those tutorials differ slightly from each other, but the principle is the same: providing first-time learners with adaptable scaffolds to support their exploration of the model at their own pace. To design them, we mainly used existing learning materials accompanying the models (the "Info Tab" of each model, Fig 2, left). While we still designed each scaffold with a linear pathway, the original texts are separated into dialogs (e.g. Fig 1, right). By introducing options for learners to choose from, the "must-read" text is significantly shortened. Now, learners can choose to "learn more" of concepts by clicking on links; can choose to "ask questions" by clicking on options; and can choose to interact with the world by minimizing the Dialog. They can also find information about the meaning of each interface widget by clicking a question mark next to the widget. In addition, each interface widget receives a question mark that will trigger more information about its meaning. As the "Info Tab" was originally written for an audience at (at least) high school level, we added small portions of dialogs that explain concepts that might be new for a younger audience.

The **programming-oriented paradigm** was built on the **exploration-oriented** one with differences coming from different learning goals. While classic ABMs come with a recommended set of "what to do" or "how to explore", as the introductory model for ABP, the Pocketworld Playground (POP) is designed for learners to explore the space of creative expression through agent-based programming [8]. This prompts us to develop its design paradigm further. Some of the highlighted differences between the two paradigms: 1) instead of a mostly linear structure, the scaffold for AM was designed as a network, with 5 major pathways and branches that fit into different levels of prior knowledge and types of personal interests; 2) A "Help" button was introduced to provide flexible support for learners (to get more programming blocks, to re-affirm the current task goal, to switch between pathways, etc);

Table 1: *In-study learners in each condition & group*

Type of Scaffolds	1. Content-Agnostic	2. Exploration-oriented	3. Programming
Usage of Scaffolds	Seven classic ABMs	Seven classic ABMs	POP
Engaged with Scaffolds	2,478 (87.8%)	1,712 (86.3%)	1,903 (78.0%)
Opted out of Scaffolds	343 (12.2%)	273 (13.7%)	537 (22.0%)

3) learner-adaptive scaffolds was introduced to react to learners' modeling decisions. For example, if a learner creates too many turtles in the modeling world - which often come from an initial "misunderstanding" of ABP - the model would automatically pause, and a Dialog will pop out (Fig 2, right). This design would both prevent the learning environment from crashing and turn a "moment of failure or frustration" into a moment that encourages learners' further exploration.

In this section, we introduced the three paradigms of interactive scaffolds that are designed for the same purpose: to engage online, out-of-school young learners with ABM & P through developing their learning interests. Next, we present an empirical study that compares their effectiveness.

4 EMPIRICAL STUDY

4.1 Data Collection

All sample learning designs have been implemented in Turtle Universe since early 2021. In this study, we collected and analyzed anonymized log data from 34,647 learners during a 14-month period. Per our IRB protocol, we only included learners who agreed on the anonymous data collection during their initial launch of the software and they could opt out at any point. As we did not collect personally identifiable data from learners, we have to speculate the user identity through: 1) the timing of user interaction: most users used TU in school holidays, lunch breaks, or early nights; 2) our informal conversations with learners on TU's online discussion groups. Our impression is that most were K-12 aged youth with little knowledge of ABM & P. As such, we are interested to understand if our design could support their short-term and long-term learning interest. To compare the impacts between different design paradigms, we only look at learners' interaction with the 8 models for which we designed an **exploration-oriented** or **programming-oriented** tutorial. By filtering the dataset to only include first-time TU users' first visit to any project, we excluded the effect of learners' prior exposure to (the beta versions of) TU and focused on the "authentic" newcomers.

Sample learning designs are implemented in a way that creates three quasi-experimental conditions through TU's design, each with two groups (Table 1). Whenever a learner visits any of the eight models, two options will be available: "Guided Intro" and "Free Exploration". Here, we only discuss the situation for the first-time learners. For the seven ABMs, the "Guided Intro" button would lead to the **exploration-oriented** scaffolds, while "Free Exploration" would lead to the **content-agnostic** scaffolds, as we believed learners would still need some guidance over the interface during their first contact with the software. For the Pocketworld Playground, we only consider the "Guided Intro" group, as the "Free Exploration" does not provide direct scaffolds due to its simpler interface design. In all three groups, features like "question mark" or "help button" would stay as-is, but they must be intentionally called by the learner.

While interactive scaffolds created by Tortuga Interactive Scaffolding were initially displayed to all learners, they were free to decide whether and when to stop using the scaffolds. Depending on learners' reaction to the scaffolds, two groups are naturally created for each condition: learners who engaged with the scaffolds ("Engaged with", or the quasi-experimental group); learners who opted out of them ("Opted out", or the quasi-control group). Since each set of interactive scaffolds comes with an introduction and/or learning goal section, we define "Engaged with" as learners who finished this portion and "Opted outs" as learners who did not finish. The non-interactive scaffolds, the "*Info Tab*" of each model, were always available for conditions 1 & 2. To exclude learners who accidentally got into the models or dropped out due to technical reasons, sessions shorter than 10 seconds in any model are also excluded. A total of 7,256 learners were left in our study.

4.2 Data Analysis

Different from our preliminary study, to consider the non-Gaussian distribution of engagement data, we used nonparametric series regressions to compare the effectiveness of design paradigms on learners' short-term and long-term engagement with ABM or P. We also used logistic regressions to measure the design's impact on the probability of re-engagement. When there are multiple models present in the same condition, we used fixed effects to control the inherent differences between individual models. Following our design goal to support learners' online and informal engagement with ABM & ABP learning activities, we re-iterate our research questions here: 1) *How did our interactive scaffolds support learners' engagement and interests with ABM or P?* 2) *How were the impacts on learners different for the three paradigms of interactive scaffolds?*

Building on an existing study [11], we leveraged the following metrics from the log data to measure learning engagement. The learning engagement is then interpreted with a framework of interest development in computer science [20] as either situational interests that correspond with short-term engagement, or individual interests that correspond with long-term engagement.

- **Total time spent in the activity**, to measure learners' first-time short-term engagement.
- **Time spent in the model (excluding time spent on scaffolds)**, to understand if learners' engagement did increase with the model other than simply reading the prompts.
- **% engaged with exploration or tinkering events** (e.g. changed the value of a widget in ABM; added, changed, or removed programming blocks in ABP; or change the NetLogo code), to measure learners' meaningful engagement with

Table 2: ***Effects on Engagement (Left: Duration & Right: Duration excl. Reading Prompts, in Seconds)***

Condition	Agnostic	Exploration	Programming	Condition	Agnostic	Exploration	Programming
Engaged w/Scaffolds	**158.383	***150.06	***234.17	Engaged w/Scaffolds	***118.82	***99.53	***124.87
	(2.77)	(4.02)	(6.74)		(2.56)	(3.33)	(5.04)
Opt-out of Scaffolds	**123.33	***97.521	***72.43	Opt-out of Scaffolds	***118.00	***82.25	***34.89
	(8.33)	(11.09)	(4.62)		(8.30)	(8.19)	(4.31)
Observed Effect	***35.05 (8.12)	***52.54 (11.07)	***161.74 (9.59)	*Observed Effect*	0.81 (9.36)	*17.28 (7.78)	***89.99 (5.91)

Table 3: (Left) ***Effects on Engagement, Exploring/Tinkering Events, among Learners Who Engaged*** **(Right)** ***Effects on 14-month Engagement in 8 Scaffolded Models (in Seconds), among Learners Re-Engaged***

Condition	Agnostic	Exploration	Programming	Condition	Agnostic	Exploration	Programming
Engaged w/Scaffolds	***6.14	***6.91	***13.97	Engaged w/Scaffolds	***564.20	***883.48	***822.04
	(0.19)	(0.34)	(0.67)		(30.19)	(114.13)	(44.88)
Opt-out of Scaffolds	***8.09	***6.53	***10.8	Opt-out of Scaffolds	***686.08	***787.88	***754.79
	(0.86)	(0.91)	(4.53)		(141.42)	(162.47)	(119.03)
Observed Effect	*-1.94 (1.00)	0.37 (0.67)	3.14 (4.21)	*Observed Effect*	-121.89 (172.68)	95.6 (179.10)	67.25 (107.30)

*For all tables: * p<0.05, ** p<0.01, *** p<0.001*

ABM & P; for those who engaged, **number of events**. We view those metrics as "meaningful interaction" because constructing is inherently desirable in a constructionist learning environment.

- **% of re-engagement**, to measure learners' long-term voluntary re-engagement; for those who re-engaged, **total time spent in the scaffolded models (after the first visit)**.

For each condition, we compared the engagement metrics between learners who engaged with scaffolds and opted out of scaffolds. Then, we compared the effect sizes of the 3 conditions to understand the different impacts of different types of design. A robust variance estimator was used to account for heteroskedasticity. In the following section, we report empirical evidence of our sample learning design's impact.

5 FINDINGS

Table 2, Table 3 demonstrate different paradigms of scaffolds' impacts on learning engagement.

While all types of scaffolds improved learners' total time spent in the model during the first session (Table 2, left), the effect sizes were different. The programming-oriented condition performed the best (+223%), followed by exploration-oriented (+54%) and content-agnostic (+22%). But a closer look at **how** they increased the short-term engagement would reveal more information. Content-agnostic scaffolds increased engagement almost entirely because of the presence of scaffolds: learners spend more time only to read the additional prompts (Table 2, right). As a result, no more learners were found to have meaningful interactions (the difference in % is insignificant), and learners who had them saw a decrease in events (Table 3, left).

While there might be inherent differences between the learner population between the two conditions, which is a limitation in this quasi-experimental study, we find that exploration-oriented scaffolds did better than their content-agnostic counterparts. Around 33% of increased short-term engagement was due to interactions outside the provided learning materials (Table 2). Learners are 46% more likely (p<0.01) to engage in meaningful events in this condition, although, for learners who had them, the effect was still insignificant.

The programming-oriented condition saw a more drastic difference between learners who engaged and learners who opted out. Like the exploration-oriented condition, it increased engagement beyond reading prompts: 56% of the increased engagement was due to interactions outside the provided learning materials (Table 2). Learners are 1,360% more likely (p<0.01) to engage in meaningful events in this condition. Although there was still no statistically significant impact on numbers of events for learners who had those events, it was largely because of the high variance in the opted-out group, which is also seen across the entire analysis.

Regarding long-term voluntary re-engagement, we find the trend to be similar. The content-agnostic condition saw no significant difference in % of learners who re-engaged and no significant difference in those learners who re-engaged (Table 3, right). The statistical power for the exploration-oriented condition is also insufficient, but the raw effect size looks better. The only difference lies in the programming-oriented condition, where we saw a 52% increase in likelihood to re-engage, but still, no significant difference if they did re-engage.

6 DISCUSSIONS

All our sample interactive scaffolds helped engage online, out-of-school learners with ABM & P. However, they achieved the goal through different mechanisms. While the content-agnostic scaffold did increase learners' short-term engagement, it only does that by requiring learners to read prompts - we did not even see learners engaged more with meaningful exploration or tinkering events. Being content-agnostic, it could not understand the meaning of widgets and phenomena, making it unable to adaptively support the open-ended and self-driven exploration of learners. On the other hand, by turning existing learning materials into interactive scaffolds, with a grain of story-like framing, the exploration-oriented scaffolds produced significant gains in online, out-of-school learners' short-term engagement in a more meaningful approach. The programming-oriented scaffold saw an even more drastic increase probably by providing personal relevancy to learners [8]. As such, we found that interactive scaffolds for ABM & P should strive to be relevant to the domain knowledge embodied in the model, and be relevant to learners' diverse needs.

While scaffolds of the two paradigms successfully engaged more learners in exploration and tinkering events with the ABM & P learning activities, we did not see a significant increase in learners who engaged with those events. On one hand, the sample size could be insufficient for statistical significance. Or our current ways of scaffold design might be better at encouraging learners to participate than supporting them to explore deeper in a constructionist way. On the other hand, a deeper look into the data could lead to a more interesting observation: across all conditions, opt-out groups have a much higher variance than engaged groups. Two groups of learners could be identified from this observation. It seems that some learners opted out of the scaffolds because they run out of situational interest in the learning activity, yet another group of learners opted out and did not return likely because they are confident enough to explore without the scaffolds. Consequently, we believe that future learning design needs to acknowledge different groups of learners' diverging features and provide more pointed and adaptive support.

Another anomaly from the dataset is between the content-agnostic and exploration-oriented conditions. We noticed that while they are scaffolding the same agent-based models, the performances of different scaffolds at times point in very different directions. We could find the instance in Table 4; both of them refer to more engaged learners. We find engaged learners to do better than opted-out learners in the exploration-oriented condition, yet the contrary is seen for content-agnostic learners. It seems that in the long run, the content-agnostic scaffolds could be doing more harm rather than good for learners. Alternatively, it could be explained as a self-selection process similar to the previous point: learners who chose "Free Exploration" are either experienced learners who need little need (who are more likely to opt-out), or learners in need without realizing it (who are more likely to engage). It would be therefore unfair to simply compare the effect of the two groups, as it could underestimate the effect of the content-agnostic scaffolds. While clarifying this would need a more qualitative study, our study of the Pocketworld Playground did suggest allowing learners to switch between pathways after their first choice, as first-time learners usually lack the necessary information to make an informed decision [8]. Here, we extend the suggestion to interactive scaffolds for ABM learning activities as well.

Lastly, while exploration-oriented and programming-oriented scaffolds supported learners' situational interests, only programming-oriented scaffolds could help their individual interests through increased re-engagement. While our study for Pocketworld Playground [8] did show that re-engaged learners spend more time in the future, it was only for the programming space itself. Here, we show that the transfer to other ABM learning activities was limited. This finding is a confirmation of the interest development framework, where situational interests take time and repeated engagement to transform into individual interests; and a reminder that interest development is a long-term effort that is difficult to develop or transfer in a short session of engagement.

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