Chapter 10
Science Teachers' Construction of Knowledge About Simulations and Population Size Via Performing Inquiry with Simulations of Growing Vs. Descending Levels of Complexity

Billie Eilam and Seena Yaseen Omar

10.1 Introduction

The biology domain is all about complex systems, from the cell organelles to the biosphere different ecosystems. Understanding complex systems requires high-order system thinking relating to systems' multilevel structure cause and effect of components' interactions, system emergent behaviors, dynamicity or equilibrium (Eilam, 2012). Simulations were found to be effective tools for developing understanding of such multifaceted phenomena, as well as to facilitate users' scientific mode of thinking and inquiry (e.g., Charles & d'Apollonia, 2004; Greca et al., 2014; Hinton & Nakhleh, 1999; Jacobson et al., 2011; Resnick & Wilensky, 1998). Hence, simulations use in science teaching is highly recommended (Eilam & Reisfeld, 2017; Merchant, 2019). Yet, students' efficient use of simulations is challenging and little is known about what teachers themselves – who mediate the use of simulations to students – know and understand about simulations, how best to access and select simulations and how to use them effectively for performing an inquiry (Stinken-Rösner, 2020). For example, no study was found regarding the pedagogy of an effective acquisition of this high-order skill, as associated with the order of exposing students to simulations of different complexity (number of variables involved). Thus, an investigation of teachers' interactions with simulations while performing an inquiry in the biology domain, in particular, is called for. Such an investigation would facilitate an improved instruction of biological complex systems and may include, among other issues, the examination of the preferred order of using simulations of different complexity for instruction. It would provide pre- and in-service

B. Eilam (✉) · S. Y. Omar
Faculty of Education, University of Haifa, Haifa, Israel
e-mail: beilam@edu.haifa.ac.il

O. Ben Zvi Assaraf, M.-C. P. J. Knippels (eds.), *Fostering Understanding of Complex Systems in Biology Education*, Contributions from Biology Education Research, https://doi.org/10.1007/978-3-030-98144-0_10

teachers' education programs with timely and relevant information for developing an effective pedagogical mode of instruction, as well as possibly facilitate the optimization of simulations pedagogical design for classroom use.

The use of simulations requires not only the understanding of how simulations function and their potential but also the application of many related cognitive and metacognitive skills. Skill acquisition requires learners to engage with problem solving and experience skill applications in many diverse situations (Anderson, 1981). Namely, to use simulations effectively, teachers have to experience inquiries with diverse simulations. The question asked is: While experimenting with different simulations, what should be the effective order of teachers' exposure to the different levels of simulation complexity? Complexity is defined here as the number of variables available for manipulation. The present chapter describes an investigation of Arab science teachers' engagement with three Simulation-Based Scientific Inquiries (SBSI) of ascending or descending levels of complexity, involving two, four and six variables. We focused on teachers' construction of knowledge about simulations' function and effective use, their affordances in teaching and learning, as well as on teachers' simulations- related beliefs. Most research focus on students' learning with simulations (van der Meij & de Jong, 2006), leaving a lacuna regarding teachers' experiences with simulations. No study was found regarding the influence of the order of using simulations of different complexities on teachers' successful learning processes and products but no information was given on how literature search was made such that we judge the reliability of the claim.

10.1.1 Simulations

Computerized simulations are defined as interactive dynamic models representing certain qualitative or quantitative components of any referent (e.g., a phenomenon, idea, process, system), enabling its abstraction, simplification, and explanation, as well as making predictions about its behavior (Khan, 2011; Landriscina, 2013; Stern et al., 2008). Simulation tools claim fidelity, accuracy and validity (Sauve et al., 2007). The core of simulation models is the ability to manipulate and control the variables composing the referent phenomenon in order to reveal their interrelations. Simulation models afford an immediate feedback regarding the manipulation effect, which expose the phenomenon recurring patterns of behaviors and its related principles. Simulation-related predictions improve students' epistemological beliefs about phenomenon, supporting the enhancement of relevant theories and the updating of knowledge about different referents (Lamb et al., 2018; Tasquier et al., 2016). Hence, experiencing problem solving and inquiry via the effective manipulations of simulation variables may facilitate high-order "systems thinking" (Gerard et al., 2011). Simulation's design and structure may promote and alleviate learning by enabling learners to control the speed of information presentation; to view the referent from different perspectives; to direct learners' attention toward core characteristics of the phenomenon; to simplify the referent complexity; to emphasize implicit borders between different events; or to use visual and dynamic illustrations of the referent (Hegarty, 2004).

10.1.2 Performing a Simulation-Based Scientific Inquiry

Simulations create a scenario-based learning environment, where students are engaged in problem-solving processes of real-world authentic problems, by interacting with the simulation components, applying their relevant prior knowledge and practical skills, and enacting a self-driven acquisition of knowledge. Depending on factors such as the content represented, the simulation design, or teachers' role, studying with simulations frequently shows positive effect on knowledge and skill/meta skills construction (e.g., complex concepts, deep learning, higher-order thinking, problem solving, inquiry, reflection). Moreover, simulations facilitate learners' ability to connect theoretical issues to real-world situations (Lamb et al., 2018; Vlachopoulos & Makri, 2017). However, in spite of these affordances, performing a SBSI (Simulation-Based Scientific Inquiry) is challenging due to both simulations' features and learners' characteristics (Eilam & Reisfeld, 2017). Simulations may cause a high cognitive load due to the large amount of representations and information presented simultaneously on the computer screen, impeding their processing (Watson et al., 2010). Performing a SBSI requires relevant prior domain knowledge as well as cognitive and metacognitive high order inquiry skills such as raising hypotheses, collecting or processing data (Gerard et al., 2011; Hmelo-Silver & Azevedo, 2006; Kornhauser et al., 2007).

Teachers' knowledge about simulations their understanding of its function as models of referents, and their beliefs about simulation classroom use, changes and develops along their professional lives while accumulating formal and informal experiences. Teachers' development may be influenced by factors such as their personal characteristics, modes of training, their interaction with their environment, the context in which they have constructed their knowledge, or their teaching practices (Scardamalia & Bereiter, 2006; Shulman, 1986; Tondeur et al., 2017). Research about teachers' visual and technological pedagogical content knowledge about simulation and their use is limited, but simulation prominence in science education requires teachers' high exposure to SBSI and many experiences with it (Greca et al., 2014).

Several studies examined the effect of different factors on students' performance in SBSI. For example, a study examined the effect of the types of relations between the values of physics variables on students' performance (i.e., unrelated, simple relation - a change in one variable value results in a change of another value, and complex relations – where a change in one variable value results in changes in some variables values). Findings showed that differences among groups were more salient while using simulations of high complexity, and best performance was evidenced in the most complex simulation (van der Meij & de Jong, 2006). Another study compared between students' performance along two consecutive SBSIs involving similar surface simulation elements (e.g., agents' color) and two different simulations. They have found that performance with the different simulations was higher than that with the similar simulations, and in particular in high achievers. They concluded that the latter were able to ignore superficial similarity and focus on the abstract characteristic of the biological phenomenon studied (Goldstone & Sakamoto, 2003). Other researchers examined differences in performance of students who were engaged in problem solving of three ill-structured and well-structured problems provided to them in different order. The two groups received well-structured problems as the second trial and ill-structured problems at the third trial. However, one group began the series with ill-structured and one with well-structured problem. Although the performance of those who experienced solving the ill-structured problem first, was lower than those experiencing the well-structured problem first, the students exhibited better performance while solving the third ill-structured one. The researcher concluded that a learning sequence that begins with ill-structured problems enables students to construct flexible knowledge and understanding and to adapt their use for application in future new situations. He termed the phenomenon "Productive failure" (Kapur, 2008, 2015). Pathak et al. (2008) examined students' performance while being engaged in a series of three SBSIs – complemented by guidance or lacking it. They found that students that have started the series without guidance exhibited a productive failure and were cognitively primed to better succeed in the third task. As presented here, there is still debate regarding the conflict between the productive failure phenomenon and the cognitive load notion. Findings regarding students with low domain knowledge did not support the productive failure notion (Toh & Kapur, 2017). These different studies call for more research on factors affecting SBSI performance.

In the present study we explored Junior high school teachers' SBSI performance using three agent-based simulation modeling adapted from the NetLogo computer language (Wilensky & Rand, 2015). All three simulations were in the domain of science, modeling the ecological complex system of population size, but involving two, four or six variables – defined as the simulation level of complexity. In addition to examining teachers' SBSI behaviors as well as their knowledge and beliefs about simulations, we focused on the effect of a descending or ascending order of simulation levels of complexity on teachers' performance – from two variables to six variables simulation and vice versa. We asked:

How does the order of performing three simulations of different complexity levels influence teachers'-

1. knowledge about simulations inherent characteristics?
2. knowledge and beliefs about an effective classroom SBSI?
3. domain and relevant representational knowledge?
4. SBSI performance?

10.2 The Study and Its Context

A mix method paradigm was applied, utilizing both the qualitative and quantitative methods' affordances (Johnson et al., 2007; Mayoh & Onwuegbuzie, 2015).

10.2.1 Participants

Thirty Arab teachers volunteered to participate in the study. They were mostly females with BA and MA degrees, who teach science in few Arab sector junior-high schools in the north of Israel. The group was highly heterogenous in their demographic characteristics, ranging from 1 to over 15 years of teaching experiences, mostly with four to ten previous SBSIs experiences but some with none, and more than half of them never receiving an explicit, well-planned program of theoretical and practical learning about simulations. The teachers were divided into two similar groups ($n_1 = n_2 = 15$). The first - Group A (GA) experienced the three provided simulations in an ascending order of complexity whereas the second – Group B (GB) experienced the same three simulations but in a descending order of complexity. All simulations represented in a similar manner the dynamic phenomenon of changes in population size, using different components of the complex ecosystem (e.g., grass, deer, growing rates) (Fig. 10.1).

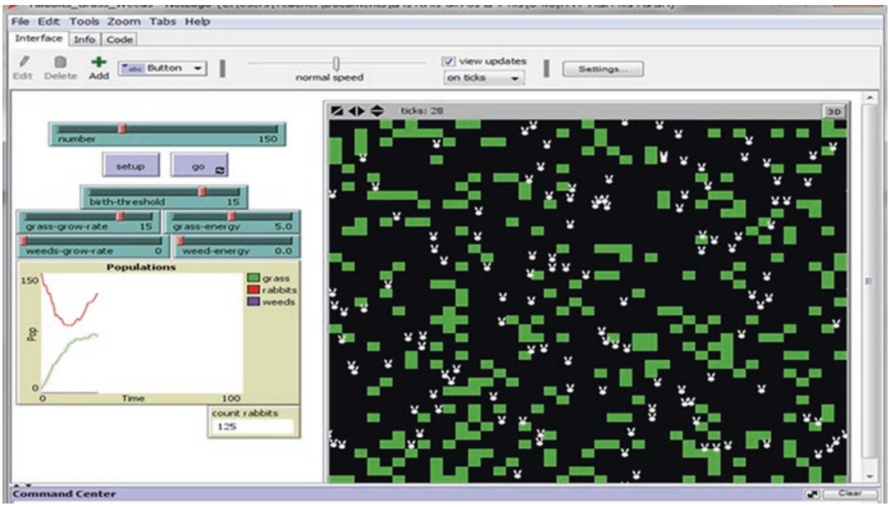

Fig. 10.1 A Photograph capturing a screen view of the six-variable simulation, including The number of rabbits (range of 0–500); rabbits birth-threshold (range of 0–20); Grass growing-rates (range of 0–20); Grass energy (range of 0–10 energy units); Weeds growing-rates (range of 0–20); and Weeds energy (range of 0–10 energy units)

10.2.2 Data Collection

Data about the teachers' inquiry process and knowledge construction were collected using four main tools: (a) identical pre- and post-SBSI questionnaires for assessing teachers' theoretical knowledge about simulation and their characteristics, including 20 statements about simulations and 34 about simulation potential for classroom use and their selection. The duration of time between the pre- and post questionnaires and the high number of questions of the type used decreased the test effect, especially following the number of simulations performed (examples and experimental). Teachers were asked to indicate their extent of agreement with the different statements on a 1 to 3 range scale (e.g., "The simulation enables to predict relations between different represented variables"; "The use of simulations is appropriate for students having reading difficulties only"; "I search in the internet simulations for my teaching"). The 3 range scale was chosen due to the more general type of statement; (b) identical pre- and post-domain knowledge questionnaires for assessing teachers' knowledge of the topic of population dynamics and related visual representations. It was composed of five open tasks and one multiple choice task (e.g., "interpret the two presented graphs, explain each of them and compare between the meaning of their representations"); (c) observations, video-recordings of each teachers' computer screen and audio-recordings of teachers' think aloud while performing SBSI; and (d) post-inquiry semi-structured deep individual interviews with five teachers of each group (n = 10). The interview was conducted as an open dialogue between the teacher and researcher and has been audio-recorded. It was based on pre-prepared questions or issues that the researcher raised for discussion while often presenting a short video clip of interviewee's interactions with the simulation, for activating their memory. Our aim was to expose the interviewee's hidden considerations and the meaning of the specific phrasing they used for describing their ideas and explanations for different activities enacted during the inquiry (Beggrow et al., 2014). The tools were validated for their content by two disciplinary and simulation experts.

10.2.3 Data Analysis

Data analysis included the use of predetermined criteria for performing content analysis on teachers' responses to the open questions of the content knowledge questionnaires. Criteria were based on relevant canonic knowledge about ecosystems, food webs, food chains and population dynamics in particular. These criteria were applied for analyzing the open questions in the questionnaires. The grounded theory approach was applied for analyzing teachers' verbal and non-verbal SBSI performance as recorded by the video camera, and for the individual interviews recorded data. Scoring indicators lists were developed for various data features. Qualitative and quantitative (MANOVA and t-tests) comparisons were carried out between the scores gained in each of the three SBSIs and between the frequencies of teachers' verbal and non-verbal behaviors in each group, for assessing the extent of teachers' constructed knowledge and understanding along their experiences with the three SBSIs and to evaluate the effect of the order of exposure to a certain level of complexity on this constructed knowledge. The analysis of teachers' interviews yielded a deeper understanding of teachers' different moves along the inquiry and the considerations behind them.

10.2.4 Procedure

Three individual meetings have been conducted with each participant: (a) providing a full explanation about the study and teachers' tasks and filling up the pre-inquiry simulation and domain knowledge questionnaires; (b) explaining the NetLogo simulations and demonstrating the use of three simulations that were not used in the study itself. Teachers performing of the SBSI according to the group assigned order of complexity; (c) teachers filling up the post-inquiry simulation and domain knowledge questionnaires and 10 teachers being interviewed.

10.3 What Did we Learn About Teachers' Knowledge and SBSI?

A comparison between the different demographic characteristics of both groups revealed no significant difference, except for a small difference in the number of previous experiences with simulation reported. At least half of GB teachers (descending complexity) reported 4 to 10 prior experiences, whereas GA teachers (ascending complexity) reported only 1–3 ones. GA and GB knowledge of simulations and of the related domain was found to be similar as well. The similarity between the groups suggests that these factors did not intervene in performance or that if they intervene one can assume the intervention was roughly similar across groups.

10.3.1 Teachers' Knowledge About Simulations and their Function

Many diverse factors may influence teachers' knowledge, as it develops and changes alongside their life experiences, formal learning (e.g., teachers' in-service programs), classroom practical experiences, and/or informal and incidental experiences with simulations (Sevinc & Lesh, 2018). The pre- and post simulation knowledge questionnaires' scores calculated for teachers in both groups were found to be in the range defined here as having average knowledge about simulations (5 to 15 points out of possible 20 points). As expected, a significant growth in knowledge about simulations and their function was found for both GA and GB teachers, after experiencing the SBSI (GA – $Z = -2.307$, $p \leq 0.05$; GB - $Z = -2.419$, $p \leq 0.05$). However, this growth was similar in both groups, showing no order effect. Moreover, both groups teachers' responses exhibited similar difficulties. In particular, errors evolving from teachers' lack of understanding that simulations are models of a phenomenon were identified. Prior to the inquiry, teachers' knowledge about simulation and their function was characterized as at the lower part of the range defined as average level. Based on research about skills acquisition and in particular about the ability to perform an inquiry through simulation use, experiences with simulations alone usually contribute to learners' understanding of scientific models (Ruebush et al., 2009). Hence, we expected teachers' knowledge about simulations and their function as a model of phenomenon to grow after performing three simulation inquiries. However, in spite of the revealed increase in both groups teachers' knowledge after completing the inquiries, it still remained in the average level range only, as defined in this study. It seems that involvement in a short experience having little knowledge to begin with is not enough for acquiring this high-order skill. Researchers also suggested that teachers understand models as efficient tools for teaching scientific content rather than as tools for performing scientific inquiry (Henze et al., 2007). Teachers' responses were partial, general, and used the names of the different components of the simulation they experienced – stating facts, rather than principles of function (metacognitive knowledge) and ignoring the possibilities provided by the simulation for investigating the phenomenon it models. Teachers in both groups agreed with erroneous statements in the pre- and post-inquiry questionnaires, suggesting low understanding of the simulation features and function and a difficulty to construct a comprehensive mental model of it. For example, in spite of teachers' experiences with three simulations, they failed to perceive the simulation as representing only certain selected aspects of the referent rather than being identical to it and that one can control this interactive tool (e.g., stopping it or controlling its running speed).

10.3.2 Teachers' Pedagogical Knowledge and Beliefs About Teaching with Simulations

Teachers' pedagogical knowledge regarding simulation use in teaching, as expressed in the post-inquiry questionnaire (extent of agreement with presented statements) was similar between groups, did not change significantly and did not exhibit an order effect. GB teachers scored higher (although not significant), which may suggest the productive failure effect. It was not surprising to find that teachers' self-report about their own ability to locate a relevant simulation in different sources and use it for teaching, was not significantly different in the two groups. These teachers reported minimal experiences with simulations before the study and did not have the chance to experience classroom teaching after the study, and as is well-established, the construction of practical knowledge requires practice. Our finding corroborates reports (Donnelly et al., 2014; Opfer & Pedder, 2011) claiming that limited inquiry experiences that lacked explicit guided classroom experience are not sufficient for changing deep and entrenched beliefs. Changing deep beliefs requires an investment of time and efforts for performing a qualitative change and a reorganization of one's body of knowledge, but both possibilities were not available for teachers in this study. Teachers' responses suggest they mostly did not consider simulations affordances for teaching science but were predominantly influenced by superficial instructional pedagogies such as: simulations increase interest, facilitate misconceptions, hinder motivation, or that drawing information from text is easier than from simulations.

10.3.3 Teachers' Knowledge and Understanding of Population Dynamics and Related Representations

A comparison between GA and GB regarding teachers' domain and related visual representations knowledge before their SBSI experiences yielded no significant differences, ruling out prior knowledge as an intervening factor. However, a significant difference ($F_{(1,28)} = 8.893$, $p < 0.01$) was found while comparing the magnitude of the change ensuing in teachers' knowledge from the pre- to the post domain knowledge questionnaire in each group using MANOVA. Experiencing the simulations in an ascending order of complexity, GA teachers were able to construct more domain knowledge than GB teachers, who experienced the simulation in a descending order. An examination of the pre-post changes ensuing in scores for each of the six tasks separately showed that on most tasks scores of GA teachers improved more than those of GB. Hence, GA teachers were better able to construct some theoretical knowledge and understanding of the complex construct of population dynamics and to interpret more accurately the meaning of the related graphs. For example, before the SBSI most teachers described the graphs in a general manner ("At first there was a sharp rise in the number of individuals"). In teachers' post responses – more in GA responses – a shift was revealed toward more accurate and detailed interpretation including indication of units ("At first we see a sharp rise till the third generation from the value of 25 to 100 thousand"). Another example showed – again more representative of GA teachers – that teachers in the pre- simply described what they saw in the graph. This single graph presented a continuing increase in the rabbits population over time and a parallel increase in the fox population but only to a certain point in time, from which the population remained of constant size. The graph was interpreted by a GA teacher as "The number of rabbits is rising all the time and the number of foxes is rising over time, so there is a relation between the rabbit and the fox populations" - ignoring the change ensuing in the fox population. In the post this teacher wrote: "There is a constant increase in the number of rabbits, as compared with the fox population that first increases, but then their number remain constant. One cannot infer the kind of relation existing between the size of the two populations, because there is not enough data to identify it". Some even used the concept of "arriving at an ecological equilibrium". These representative examples suggest that many teachers in the post-inquiry questionnaires, but more the GA teachers, related to the tasks, and the graphs data in particular, more precisely than in the pre-inquiry questionnaires and their inferences improved. They examined the variables and the units on the graphs' axes more carefully, responded more accurately and in a focused manner, and raised broader inferences than in their pre-responses. Because the topic of ecology, including population dynamics, gained considerable importance in the Israeli curriculum in the last few decades, it is safe to assume that most teachers' prior knowledge on the topic has been activated by their engagement with the simulations, promoting their ability to grant meaning to the different simulation results. Moving from the easy simulation (2 variables) to the complex one (six variables) enabled GA teachers to better understand the growing complexity of the ecosystem inquired, whereas GB teachers exhibited some confusions and diffused responses that were too general to explain their arguments regarding the targeted issue. Indeed, personal experiences led to an improved domain understanding (Goldman et al., 2019).

10.3.4 Science Teachers' Inquiry Performance

The qualitative analysis of the transcripts of teachers' audio and captured screens videos, including teachers' behaviors, explanations and considerations, yielded three major themes, each with several subthemes (Fig. 10.2). The analysis of the transcripts of teachers' interviews yielded five major themes, somewhat overlapping with the themes revealed in their performance (Fig. 10.3).

In the next sections we describe our main findings concerning some of these issues as revealed in teachers' behaviors, considerations and notions.

10.3.5 SBSI Time Duration

Although the total time invested by teachers and the time invested in each simulation may attest to various explanations (e.g., teachers' motivation, interest, difficulties encounters, persistence, fatigue), it may still give us a clue regarding teachers' performance. Unsurprisingly, the time invested in the SBSI in both groups was significantly and positively related to the simulation complexity level, namely, the

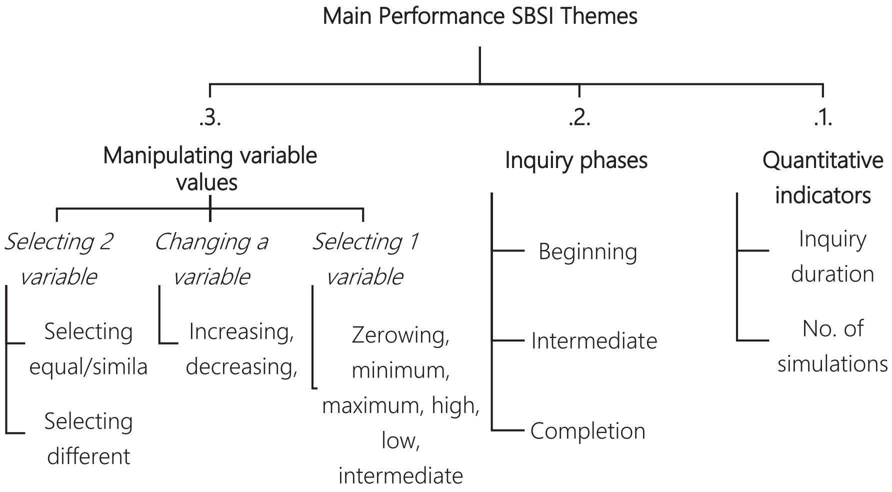

Fig. 10.2 Teachers varied verbal and non-verbal behaviors while performing an inquiry using simulations

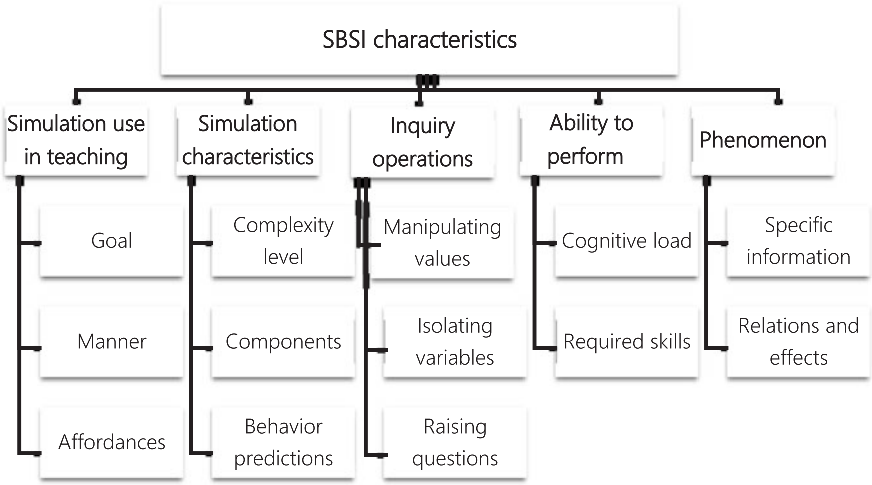

Fig. 10.3 Themes identified in teachers' interviews about their use of simulations for performing an inquiry regarding the "population size" complex system

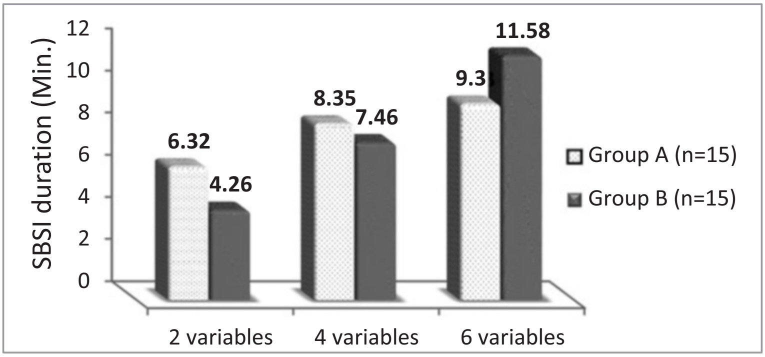

Fig. 10.4 The SBSI time (in minutes) consumed by each group teachers, for each of the simulations

more variables to manipulate – the higher the number of runnings performed, and more time consumed (Fig. 10.4). The total time invested in the SBSIs by both group teachers was similar. A significant difference between the two groups in the time consumed was found only for the 2 variables simulation – that was performed by GA as the first in the three simulations series, hence required significantly more time than in GB – that performed it as the third one, after "training" on two other more complex simulations ($t_{(28)=}3.186$, $p < 0.01$). Surprisingly, the time invested in the 6 variables simulation, by both group teachers, was not sig. Different, although this high-complexity simulation was performed as the first one by GB teachers. Probably, they abandoned this difficult task after a while, due to the high difficulty encountered.

As expected, a significant positive relation has been found between the simulation complexity level and the number of runnings enacted by teachers, with GA teachers enacting significantly more runnings than GB teachers, thus being engaged longer with the simulation and promoting their understanding of its function and of the phenomenon represented. It seems that the gradual increase in the simulation's complexity enabled GA teachers to first grasp the principle of manipulating a single variable value while keeping the other constant (low cognitive load) to reveal the potential relations among them, and that further manipulation of additional variables deepens the comprehensive understanding and enables the prediction of the phenomenon behavior. Beginning the inquiry with a large number of variables promoted GB teachers' trial and error moves that lack the consistency that usually enables the studying of the phenomenon.

10.3.6 Inquiry Phases

Teachers' performance may be described as including three phases for each simulation: (a) the initial phase defined as teachers' total moves from the moment they press the simulation button of "go" after setting the variable values, till they press the "setup" button – composing a single simulation running in each of the three simulations; (b) the intermediate phase defined as the "go" of the second running till the "stop" of the running performed before the last runnings of the final phase, including different number of running depending on the performer; and (c) the final phase defined as the last single simulation running from "go" to "stop" in each simulation. As mentioned above teachers performed different number of runnings in the second phase, which increased with the growing level of complexity. However, the main differences were found regarding teachers' manipulation choices of variables values, which influenced their ability to acquire the effective mode of SBSI and impeded knowledge construction.

The initial phase. Generally, starting with simulation 1 (2 variables) most GA teachers (73%) set equal/similar values, and more of them did so in simulation 2 (4 variables), with a bit more teachers setting different values in simulation 3 of the highest complexity. This behavior suggests teachers' gradual construction, organization and generalization of knowledge. Most GB teachers behaved similarly to GA teachers, but exhibited greater "boldness" (60%) in setting two different values in simulation 1 (2 variables) probably feeling more assured following their prior experiences with the simulations of higher complexity. Moreover, in simulation 2 (4 variables) all GA teachers chose to set one of the variables to zero while manipulating the other, attempting to reduce the number of variables and thus – the complexity of data, differently from GB teachers who mostly did not use the zero option. Hence, exposure to descending complexity level order affected variables' values setting, and in turn was expressed in the construction of a partly fragmented knowledge that hindered the ability to infer about the studied phenomenon characteristics and its involved relations.

The intermediate phase. In this phase, all teachers performed several runnings and value manipulations after the initial phase and till the final one. The first indicator for comparing SBSI performance between the two groups and across the three simulations is the average number of runnings carried out by each group teachers and the percentage of each group teachers who carried out a small number of runnings or a large one (Table 10.1).

Generally, all teachers' average number of runnings in simulation 1 and 2 (of lower complexity) was similar but increased in simulation 3 – of the highest complexity (six variables). However, this average was higher for GA teachers in simulation 1 and 2 and lower in the third simulation than the average number of runnings performed by GB teachers. This finding suggests an order effect. Whereas GA

Table 10.1 Average number of runnings performed by group A and group B teachers in each of the three simulations and the percentage of each group teachers who performed small/large number of runnings

Sim. No.	1			2			3		
No. Run.	Ave.	1–4	5–8	Ave.	1–4	5–8	Ave.	1–4	5–17
GA (%)	~4	60	40	~4	67	33	~6	46	54
GB (%)	~2	93	07	~2	93	07	~8	33	67

teachers experienced a gradual ascending complexity, which prepared them for dealing with the highest complexity of simulation 3, GB teachers encountered the high complexity first, which required many runnings for making sense of the phenomenon behavior, after which a small number of runnings was required in simulations 2 and 1. Similar effects have been revealed for the percentage of teachers performing a small number of runnings, which consistently grew from simulation 1 to 2, but in simulation 3 a higher percentage of teachers performed a large number of runnings, differently from GB teachers, whose percentage performing a large number of running was the highest, dropping to almost all teachers performing 1 to 4 runnings in sim 1 and 2. Hence, the order effect was revealed in teachers' performance of the intermediate phase of the three SBSIs. GA teachers' performance fit the gradual ascending difficulty they encountered from simulation 1 to simulation 3, expressed in the duration of the time devoted to the experience, as well as the number of runnings performed in each SBSI. GB teachers exhibited a reduction in duration of time and number of runnings from the first simulation they experienced, which was the most complex one, to the second and third less complex simulations. Both group teachers exhibited high variability in their value manipulation behavior. The general view of each group performance over the three simulations is presented in Fig. 10.5 (a–f) below.

The final phase. No significant difference was found between the two group teachers' choices of variable manipulation. Generally, after several runnings (in each simulation initial and intermediate phases) more teachers "dared" to set different variables values. Mostly, GA teachers who experienced the ascending order of complexity set in this final phase of simulation 1 (two variables) different values (60%), in simulation 2 about 50% of them set similar values, and about 60% set in simulation 3 partly equal/similar and partly different variable values. GB teachers, who experienced the descending order of complexity, set in this final phase of simulation 1 (their third SBSI) different values (80%), in simulation 2 – partly equal/similar and partly different values (60%), and in simulation 3 - all similar values (60%). Hence, no order effect was revealed. It seems that all teachers required time for understanding how an effective SBSI function as a tool for inquiry and a model.

10.3.7 Teachers' Talk About Population Dynamics and SBSI Experiences

Almost all the two groups' teachers concluded a negative relation between the no. of deer and no. of tigers in simulation 1. However only about half of GB teachers, but most of GA teachers noticed the equilibrium existing regarding the populations size, and the tigers' death in extreme situations. In simulation 2, both group teachers' conclusions were similar. However, surprisingly, once again only half of the teachers could indicate equilibrium states of the populations as presented clearly in the graphs. This, in spite of their many correct theoretical explanations of the

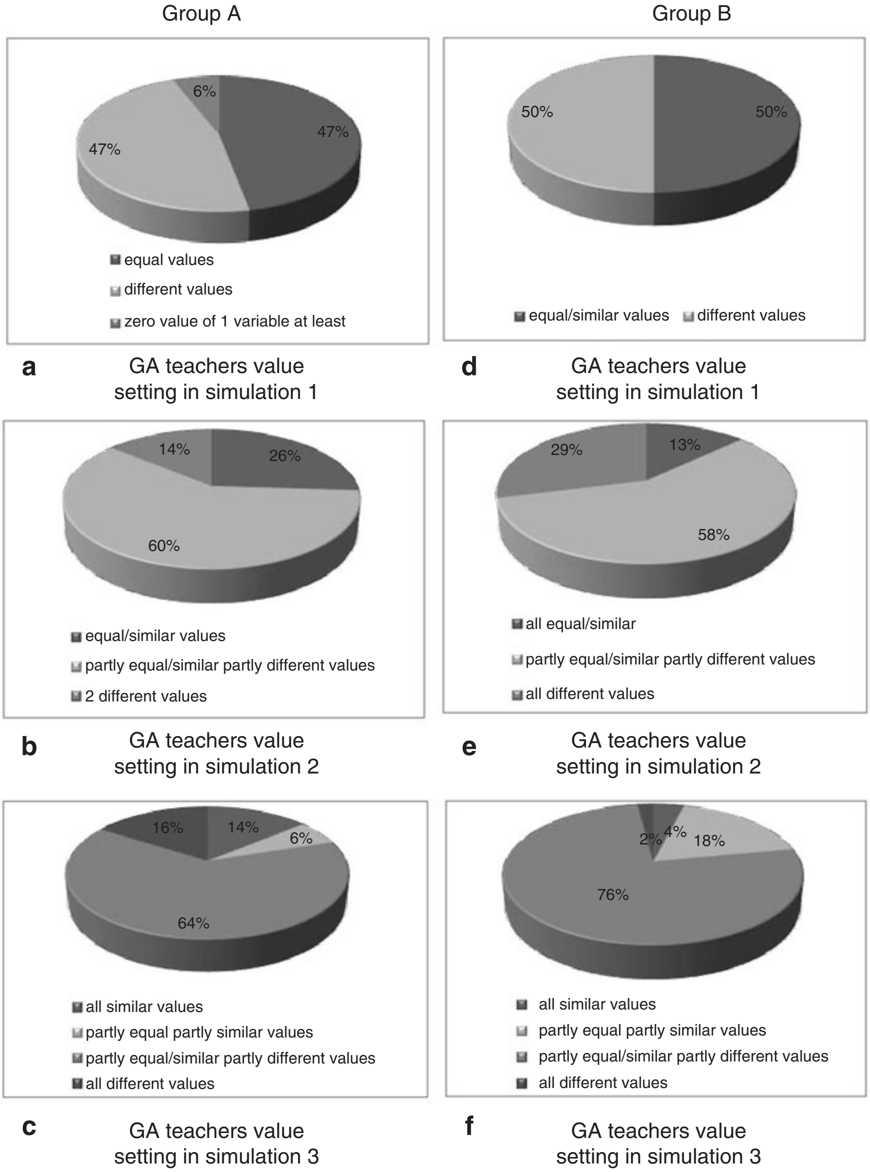

Fig. 10.5 (**a**–**f**) Teachers' values setting while performing the inquiry

concept of equilibrium provided in the knowledge questionnaire and interview. This finding suggests that ecology teachers could gain a lot from SBSI experiences, transforming theoretical knowledge into practical one, identifying states in presented data. A smaller number of GB teachers concluded that the sheep fertility affects the number of wolfs as well, and the wolf's fertility affects the sheep number. This implicit relation requires some thinking and can't be inferred directly from observing the graphs simulations. Results for simulation 3 were somewhat different than those for the other less complex simulations. The difference between GA and GB teachers was expressed in the different conclusions they have arrived at, rather than in the number of teachers reaching a certain conclusion, suggesting confusion and an inconsistent mode of manipulation and thinking when the number of variables is high. This happened even when experiencing an ascending order of complexity. It seems that for the acquisition of the SBSI high-order skills, more practice with simulations is required that would allow for a deep understanding and appreciation of the simulations as inquiry tools and models of phenomena.

Some representative example of teachers' domain knowledge after their SBSI experiences are described next. A GA teacher explained: "an ecological equilibrium is required among populations. A state where the number of one population individuals rise too much, if the carnivores will multiply much more than the that of the devoured population, the latter would parish and the former would parish right after it and the equilibrium will be affected". Another GA teacher said: "now I understand that both populations influence the equilibrium". And yet another said: "In simulation 3 I thought that there is a relation, and that the reduction of the rabbits was related to competition and the two types of food available. But this was not so. As one food type contained more energy – the number of rabbits increased. A smaller number of GB teachers exhibited domain understanding. Both group teachers identified explicit relations between variables and the possibility to manipulate the simulation variables for revealing this relation characteristics: "I have discovered the answer by my own manipulations and repeated trials" or "you have to observe every piece of data you get and try to understand its meaning". Teachers noticed the difficulty encountered with the increased number of variables: GA teacher: "the last simulation was the most difficult – what should be changed? and what should be left constant? To change one variable or both". (GB teacher) "at first it was difficult, and I had to understand what it is and how does it work. But in the rest of the simulations it became easier." Many teachers of both groups recited the need for variables isolation, probably known from science experiments they carried out in their classrooms. Yet, although they indicated that only one variable should be manipulated while the other stay constant, many did not apply this principle in their SBSI, and in particular in the highly complex simulation 3, where they changed the values of few variables at the same time. Another related point is that teachers did not apply a metacognitive thinking regarding the performance of inquiry itself and the research question examined. Again, this may suggest some automatic application of an inquiry recipe, as is frequently reported regarding science classroom instruction, which seldom enacts an open inquiry. Teachers' relation to a simulation (the tool) was highly simplistic (e.g., "I change factors and observe the graph on the screen – all this together is the simulation"; "we exhibit reality through the simulation"; "You may repeat many times and it helps to understand the topic"). Such responses suggest superficial understanding based on explicit external characteristics and elements, rather than reflection and metacognitive considerations. An understanding of simulation as a model, affords the making of predictions regarding the represented phenomenon behavior. Only few teachers from the whole sample mentioned predictions ("I saw the relations to the prey, if the number of the carnivores goes up – the number of the prey decreases. I could also change – if the number of carnivores raises – and see what would happen in the future").

Some teachers characterized the simulation with properties that may be relevant to any learning aid such as the need to fit it to students' characteristics, it enables an easier understanding, etc. without indicating what in this tool enables these affordances. Many stated that before using it in the classroom, this tool, its function and use should be explained to students. A GB teacher indicated that students should be introduced first to two variables and only then complexity should be gradually increased.

To sum, it seems that most of the teachers' talk was situated in specific instances. In spite of their prior knowledge about ecosystems, they did not generalize the specific experiences gained into a thorough description of the ecosystem represented and its function - describing the "big picture". They were satisfied with indicating partial inferences regarding a specific relation or situation in a particular population. For example, none of the teachers mentioned food webs (vs food chains) as nature "means" for maintaining equilibrium among different population sizes. Granting a broad meaning to the fragmented knowledge they constructed required the investment of efforts while reflecting on their experiences and integrating these experiences' products. At a first glance it seems teachers did not have the motivation or the time to invest in metacognitive thinking and go beyond the direct inferences. However, it is also plausible that the task was quite challenging for them. Teachers reported almost no prior experiences with simulation inquiry or with teaching with simulations and no formal explicit learning of its principles and function. The analysis of teachers' actions suggested that teachers enacted frequently trial and error moves, which somewhat improved over the three SBSIs. Many findings were not significant, which probably resulted from the small sample, as expressed in their revealed consistent trend. This trend was almost always in favor of GA teachers (ascending order of complexity), whose knowledge and understanding of both the simulation and the phenomenon of size population improved more than that of GB teachers (descending order of complexity). The former mostly manipulated a single variable while keeping the other variables constant, enabling the examination of this variable' effect on other variables and the raising of inferences regarding the phenomenon inquired. Differently, the latter, who were challenged initially with six variables, applied mostly intuitive trial and error manipulation moves, changed few variables at the same time, and exhibited confusion.

Our findings suggest that a gradual increase in the number of the simulation variables enabled teachers to be more systematic in their approach and construct a more detailed and accurate mental model of both the simulations and the domain knowledge as expressed in their verbal and non-verbal responses, supporting relevant literature (Wen et al., 2018). Repeated experiences through the three simulations inquiring the same phenomena, strengthen this model and sharpened its conditional knowledge for an effective future use (Brucker et al., 2014; Bryce et al., 2016; Greca et al., 2014).

Interestingly, most teachers exhibited a correct knowledge about scientific inquiry, including the need for isolation of variables. This knowledge probably evolved from their formal and informal science education and their classroom practices with short-term, mostly two variables “recipe” experiments. However, they confronted real difficulty in transforming this knowledge into the practice of an open-ended dynamic simulation inquiry. Open-ended inquiries are rare in school context. Dealing with several variables in the more complex simulation was found to be a real challenge (Scanlon et al., 2011). Additionally, most teachers experienced difficulties to process the dynamic information involved in the simulation inquiry probably due to high cognitive load, which may have impeded their learning (Hegarty, 2004; Mayer, 2009; Scheiter et al., 2009).

Study limitations. Our relatively small and highly heterogeneous sample limited our ability to more clearly and significantly show the differences ensuing between the two study groups by applying more fundamental quantitative methods. However, the trends of the different aspects of the teachers’ inquiry behaviors were consistent all through the study, supporting our inferences. This small heterogeneous sample also showed that in spite of the increase in their knowledge of the relevant biology, this knowledge still remained within the average range as defined in our study. It is possible that our range definition was too general to capture limited constructions of knowledge. However, this finding may also show the limited effect that a single experience with simulation inquiry, while having a deficient prior knowledge, may have.

10.4 Promoting System Thinking through the Use of Simulations – Few Recommendations for a Pedagogy and a Learning Environment As Well As Implications for Instruction and Learning

Several recommendations regarding simulations’ potential to promote teachers’ system thinking emerged from our study: (a) experiences with simulations should result in the construction of a broad mental representation and deep understanding of the multifaceted complex systems these simulations modelled. Such desired outcomes require time - time for processing and reflection after each simulation experience, time for being able to experience many diverse simulations about different aspects of the same/similar/other systems, and time for completing deficiencies in teachers' knowledge of the examined phenomenon; (b) multiple experiences with diverse simulations of different systems should promote teachers' deep understanding of the concept of modeling as simplistic static or dynamic representations of system-related phenomena. This goal may be achieved by applying to each simulation experience an explicit and directional guidance that elicit students' awareness of the affordances and weaknesses of each manipulation performed during an inquiry, and of its links to the inquiry outcomes. They should involve practical processes of well-structured problem solving, as required for high-order skill acquisition (Hmelo-Silver & Azevedo, 2006). Teachers should be engaged in a discussion that would lead them from the understanding of specific instances toward a generalization and a deep understanding the phenomenon as a whole. Such an explicit and directional guidance should also encourage teachers to examine the different alternatives available for performing an inquiry using simulations; (c) the described notions suggest teachers should apply self-regulation of their inquiry process. They should clearly define their goal and examine the contribution of each performed inquiry step to this goal achievement or its hindering effect; and (d), our study showed that teachers should be exposed to simulations in an order that consider these simulations' (phenomena's) complexity (number of variables involved), beginning with the less complex simulation of two variables and ascending to simulations of greater complexity. This principle enables teachers to independently learn some important aspects of the simulation functioning while dealing with the lower complexity, aspects which may be applied latter on for performing the more complex inquiry.

Even though simulations seem to be already an integral part of today's science education, teachers need to increase their knowledge of the nature of simulations, their affordances for teaching science, their ability to access and select appropriate simulations, and their effective use in classroom teaching. We should also consider teachers' needs by providing them more opportunities to experience relevant simulations in teacher education programs. Our findings showed that many teachers perceive simulation in a simplistic superficial manner, disregarding these representations' dynamic nature and its being a simplistic model of a phenomenon and its function, having a prediction power (Vo et al., 2015). In short, teachers have to develop simulations-related Visual-Technological and Pedagogical Content Knowledge. Special professional development courses that take in consideration the recommendations discussed above need to be designed to ensure such development. This is true in particular for promoting the understanding of ecological complex systems of these teachers' students and for the development of their high-order thinking in the course of constructivist learning (Basu et al., 2013; Jimoyiannis, 2010; Lee et al., 2016). Simulations can enable participation of all students, but may also create certain barriers for achieving success (Stinken-Rösner, 2020). Further research about the effective implementation, especially in science education, is called for.

References

Anderson, J. R. (Ed.). (1981). *Cognitive skills and their acquisition* (2011th ed.). Routledge.

Basu, S., Dickes, A., Kinnebrew, J. S., Sengupta, P., & Biswas, G. (2013). CTSiM: A computational thinking environment for learning science through simulation and modeling. In *Proceedings of the 5th international conference on computer supported education* (pp. 369–378). Aachen.

Beggrow, E. P., Ha, M., Nehm, R. H., Pearl, D., & Boone, W. J. (2014). Assessing scientific practices using machine-learning methods: How closely do they match clinical interview performance? *Journal of Science Education and Technology, 23*(1), 160–182.

Brucker, B., Scheiter, K., & Gerjets, P. (2014). Learning with dynamic and static visualizations: Realistic details only benefit learners with high visuospatial abilities. *Computers in Human Behavior, 36*, 330–339.

Bryce, C. M., Baliga, V. B., De Nesnera, K. L., Fiack, D., Goetz, K., Tarjan, L. M., & Ash, D. (2016). Exploring models in the biology classroom. *The American Biology Teacher, 78*(1), 35–42.

Charles, E. S., & d'Apollonia, S. (2004). Developing a conceptual framework to explain emergent causality: Overcoming ontological beliefs to achieve conceptual change. In K. Forbus, D. Gentner, & T. Reiger (Eds.), *Proceedings of the 26th annual cognitive science society*. Lawrence Erlbaum Associates.

Donnelly, D. F., Linn, M. C., & Ludvigsen, S. (2014). Impacts and characteristics of computer-based science inquiry learning environments for precollege students. *Review of Educational Research, 84*(4), 572–608.

Eilam, B. (2012). System thinking and feeding relations: Learning with a live ecosystem model. *Instructional Science, 40*(2), 213–239.

Eilam, B., & Reisfeld, D. (2017). A curriculum unit for promoting complex system thinking: The case of combined system dynamics and agent-based models for population growth. *Journal of Advances in Education Research, 2*(2), 39–60. https://doi.org/10.22606/jaer,2017.22001

Gerard, L. F., Varma, K., Corliss, S. B., & Linn, M. C. (2011). Professional development for technology-enhanced inquiry science. *Review of Educational Research, 81*(3), 408–448.

Goldman, S. R., Greenleaf, C., Yukhymenko-Lescroart, M., Brown, W., Ko, M. L. M., Emig, J. M., Wallace, P., Blaum, D., & Britt, M. A. (2019). Explanatory modeling in science through text-based investigation: Testing the efficacy of the project READI intervention approach. *American Educational Research Journal, 56*(4), 1148–1216.

Goldstone, R. L., & Sakamoto, Y. (2003). The transfer of abstract principles governing complex adaptive systems. *Cognitive Psychology, 46*(4), 414–466.

Greca, I. M., Seoane, E., & Arriassecq, I. (2014). Epistemological issues concerning computer simulations in science and their implications for science education. *Science & Education, 23*(4), 897–921.

Hegarty, M. (2004). Dynamic visualization and learning: Getting to the difficult questions. *Learning and Instruction, 14*, 343–351.

Henze, I., van Driel, J., & Verloop, N. (2007). Science teachers' knowledge about teaching models and modeling in the context of a new syllabus on public understanding of science. *Research in Science Education, 37*(2), 99–122.

Hinton, M. E., & Nakhleh, M. (1999). Students' microscopic, macroscopic, and symbolic representations of chemical reactions. *The Chemical Educator, 4*(4), 1–29.

Hmelo-Silver, C. E., & Azevedo, R. (2006). Understanding complex systems: Some core challenges. *The Journal of the Learning Sciences, 15*(1), 53–61.

Jacobson, M. J., Kapur, M., So, H.-J., & Lee, J. (2011). The ontologies of complexity and learning about complex systems. *Instructional Science, 39*, 763–783.

Jimoyiannis, A. (2010). Designing and implementing an integrated technological pedagogical science knowledge framework for science teacher's professional development. *Computers & Education, 55*(3), 1259–1269.

Johnson, R. B., Onwuegbuzie, A. J., & Turner, L. A. (2007). Toward a definition of mixed methods research. *Journal of Mixed Methods Research, 1*(2), 112–133.

Kapur, M. (2008). Productive failure. *Cognition and Instruction, 26*(3), 379–424.

Kapur, M. (2015). Learning from productive failure. *Learning Research and Practice, 1*(1), 51–65.

Khan, S. (2011). New pedagogies on teaching science with computer simulations. *Journal of Science Education and Technology, 20*(3), 215–232.

Kornhauser, D., Rand, W., & Wilensky, U. (2007). *Visualization tools for agent-based modeling in NetLogo* (pp. 15–17). *Agent2007*.

Lamb, R. L., Annetta, L., Firestone, J., & Etopio, E. (2018). A meta-analysis with examination of moderators of student cognition, affect, and learning outcomes while using serious educational games, serious games, and simulations. *Computers in Human Behavior, 80*, 158–167. https://doi.org/10.1016/j.chb.2017.10.040

Landriscina, F. (2013). *Simulation and learning: A model-centered approach* (pp. 47–89). Springer.

Lee, Y. S., Dervent, F., Ko, B., Wang, T., & Ward, P. (2016). Measuring pedagogical content knowledge in pre service teachers in physical education. *Research Quarterly for Exercise and Sport, 87*(S2), A115.

Mayer, R. E. (2009). *Multi-Media learning* (2nd ed.). Cambridge University Press.

Mayoh, J., & Onwuegbuzie, A. J. (2015). Toward a conceptualization of mixed methods phenomenological research. *Journal of Mixed Methods Research, 9*(1), 91–107.

Merchant, N. (2019). Virtual experiments and simulations in science classroom. *Williams Honors College, Honors Research Projects., 972*. https://ideaexchange.uakron.edu/honors_research_projects/972

Opfer, V. D., & Pedder, D. (2011). Conceptualizing teacher professional learning. *Review of Educational Research, 81*(3), 376–407.

Pathak, S. A., Jacobson, M. J., Kim, B., Zhang, B. H., & Feng, D. (2008). Learning the physics of electricity with agent-based models: paradox of productive failure. In T. W. Chan, G. Biswas, F.C. Chen, C. Chou, M. Jacobson, Kinshuk, F. Klett, C. K. Looi, T. Mitrovic, R. Mizoguchi, K. Nakabayashi, P. Reimann, D. Suthers, s. Yang & J. C. Yang (Eds.), *International Conference on Computers in Education* (pp. 221–228).

Resnick, M., & Wilensky, U. (1998). Diving into complexity: Developing problematic decentralized thinking through role-playing activities. *The Journal of the Learning Sciences, 7*, 153–172.

Ruebush, L., Sulikowski, M., & North, S. (2009). A simple exercise reveals the way students think about scientific modeling. *Journal of College Science Teaching, 38*(3), 18.

Sauve, L., Renaud, L., Kaufman, D., & Marquis, J. S. (2007). Distinguishing between games and simulation: A systematic review. *Education Technology & Society, 10*(3), 247–256.

Scanlon, E., Anastopoulou, S., Kerawalla, L., & Mulholland, P. (2011). How technology resources can be used to represent personal inquiry and support students' understanding of it across contexts. *Journal of Computer Assisted Learning, 27*(6), 516–529.

Scardamalia, M., & Bereiter, C. (2006). Knowledge building: Theory, pedagogy, and technology. In K. Sawyer (Ed.), *Cambridge handbook of the learning sciences* (pp. 97–118). Cambridge University Press.

Scheiter, K., Gerjets, P., Huk, T., Imhof, B., & Kammerer, Y. (2009). The effects of realism in learning with dynamic visualizations. *Learning and Instruction, 19*(6), 481–494.

Sevinc, S., & Lesh, R. (2018). Training mathematics teachers for realistic math problems: A case of modeling-based teacher education courses. *ZDM Mathematics Education (Zentralblatt für Didaktik der Mathematik), 50*(1–2), 301–314.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Teacher, 15*(2), 4–14.

Stern, L., Barnea, N., & Shauli, S. (2008). The effect of a computerized simulation on middle school students' understanding of the kinetic molecular theory. *Journal of Science Education and Technology, 17*(4), 305–315.

Stinken-Rösner, L. (2020). Simulations in science education. *Progress in Science Education, 3*(1), 26–34. https://doi.org/10.25321/prise.2020.996

Tasquier, G., Levrini, O., & Dillon, J. (2016). Exploring students' epistemological knowledge of models and modeling in science: Result from a teaching/learning experience on climate change. *International Journal of Science Education, 38*(4), 539–563. https://doi.org/10.1080/09500693.2016.1148828

Toh, P. L. L., & Kapur, M. (2017). Is having more prerequisite knowledge better for learning from productive failure? *Instructional Science, 45*(3), 377–394.

Tondeur, J., Van Braak, J., Ertmer, P. A., & Ottenbreit-Leftwich, A. (2017). Understanding the relationship between teachers' pedagogical beliefs and technology use in education: A systematic review of qualitative evidence. *Educational Technology Research and Development, 65*(3), 555–575.

van der Meij, J., & de Jong, T. (2006). Supporting students' learning with multiple representations in a dynamic simulation-based learning environment. *Learning and Instruction, 16*(3), 199–212.

Vlachopoulos, D., & Makri, A. (2017). The effect of games and simulations on higher education: A systematic literature review. *International Journal of Educational Technology in Higher Education, 14*(22), 1–33. https://doi.org/10.1186/s41239-017-0062-1

Vo, T., Forbes, C. T., Zangori, L., & Schwarz, C. V. (2015). *International Journal of Science Education, 37*(15), 2411–2432.

Watson, G., Butterfield, J., Curran, R., & Craig, C. (2010). Do dynamic work instructions provide an advantage over static instructions in a small-scale assembly task? *Learning and Instruction, 20*(1), 84–93.

Wen, C. T., Chang, C. J., Chang, M. H., Chiang, S. H. F., Liu, C. C., Hwang, F. K., & Tsai, C. C. (2018). The learning analytics of model-based learning facilitated by a problem-solving simulation game. *Instructional Science, 46*(6), 847–867.

Wilensky, U., & Rand, W. (2015). *An introduction to agent-based modeling. Modeling natural, social, and engineered complex systems with NetLogo*. MIT press.

Billie Eilam is a professor emerita at the faculty of education, University of Haifa, Israel. Her research focus is visualization in science learning, teaching and curricula, as well as informal education. She has authored a book about this topic (Cambridge, 2012) and co-edited a book on science teachers' visualization with John Gilbert (Springer, 2014).

Seena Yaseen Omar is teaching sciences in a junior high school for 28 years. In addition, she mentors the Bedouin sector in the North of Israel in her capacity as a representative of the Israeli Educational Ministry.