Unpacking Students' Epistemic Cognition in a Physics Problem-Solving Environment

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Abstract

It is a widely held view that students' epistemic beliefs influence the way they think and learn in a given context, however, in the science learning context, the relationship between sophisticated epistemic beliefs and success in scientific practice is sometimes ambiguous. Taking this inconsistency as a point of departure, we examined the relationship between students' scientific epistemic beliefs (SEB), their epistemic practices, and their epistemic cognition in a computer simulation in classical mechanics. Tenth grade students' manipulations of the simulation, spoken comments, and behavior were screen and video-recorded and subsequently transcribed and coded. In addition, a stimulated recall interview was undertaken to access students' thinking and reflections on their practice, in order to understand their practice and make inferences about their process of epistemic cognition. The paper reports on the detailed analysis of the data sets for three students of widely different SEB and performance levels. Comparing the SEB, problem solutions and epistemic practices of the three students has enabled us to examine the interplay between SEB, problem-solving strategies (PS), conceptual understanding (CU), and metacognitive reflection (MCR), to see how these operate together to facilitate problem solutions. From the analysis, we can better understand how different students' epistemic cognition is adaptive to the context. The findings have implications for teaching science and further research into epistemic cognition.

Keywords: epistemic beliefs, problem solving, physics simulation

Introduction

An oft-stated goal of science education is to support students' understanding of the nature of science (Deng, Chen, Tsai, & Chai, 2011), so that they leave school knowing what makes science 'science'. Understanding the epistemological basis of science enhances the relevance of science to students in their everyday lives, and, as members of society, enables them to evaluate and draw informed conclusions regarding science-related issues (Sinatra, Kienhues, & Hofer, 2014). Moreover, there is a growing body of theoretical and empirical research which contends that there is a close connection between students' *scientific epistemic beliefs* (SEB) and various facets of their science learning, such as problem solving and learning strategies (e.g., Bodin, 2012; Elby, Macrander, & Hammer, 2016; Kittleson, 2011; Liang & Tsai, 2010).

As yet, the vast majority of research on epistemic beliefs has used self-reporting surveys to examine the individual differences in students' perceptions of knowledge and knowing (Greene & Yu, 2014). Unfortunately, inconsistencies and mixed results have cast doubt upon the findings. There have been several criticisms and discussions about the challenges of this research approach, since it has been shown to be particularly hard to measure epistemic beliefs in a valid and reliable way. Samarapungavan, Westby, and Bodner (2006) claim that items in surveys are often too decontextualized and abstract, which suggests that there is a lack of consideration in terms of contextual and situational factors (Bromme, Pieschl, & Stahl, 2010; Muis, 2008). Despite these measurement issues, some insights can still be gained in terms of establishing epistemic patterns if the sample size is large (Greene, Azevedo, & Torney-Purta, 2008) and surveys can be combined with observations and interviews to confirm interpretations (Sandoval, 2005; Schommer-Aikins, 2004).

Sandoval (2005) has suggested a distinction between formal and practical epistemology in order to overcome some of the theoretical and methodological problems that have plagued

the field. He considers students to hold 'formal epistemologies' based on their conception of professional science and 'practical epistemologies' developed from their own experiences of scientific practice. Moreover, Sinatra and Chinn (2011) argue that one's formal epistemology (commonly measured by self-report surveys) may be poorly related to one's practical epistemology. In this study, we aim to unpack the processes that drive an individual's behavioral response in relation to a specific science context, a problem-solving situation in physics, where knowledge and knowing are in play. We conceptualize these processes as comprising aspects of students' *epistemic cognition*, and refer to their associated behaviors as their *epistemic practice*. We have chosen to use the term epistemic cognition in line with Sinatra (2016) as being dynamic and changing according to context, in contrast to more stable epistemic beliefs that are consistently expressed across different contexts. We suggest that students in a particular learning context have a set of epistemic beliefs that they bring to bear, either tacitly or explicitly, in the learning context that result in their epistemic practice (Chinn, Buckland, & Samarapungavan, 2011; Sinatra et al., 2014).

Therefore, and in response to Sinatra's (2016) call for further research that captures the process of epistemic cognition in action, the aim of this study is to describe students' epistemic practices during a particular problem-solving situation in physics and their sense making in the moment in order to deepen our understanding of the process of their epistemic cognition. The following research questions guided the phase of the study presented in this paper:

1. What epistemic practices do students express during the science problem-solving task?
2. How can processes of epistemic cognition be understood from three students' epistemic practices in this specific context?

Theoretical Framework

In order to understand how students' behavior and actions in the problem-solving situation (epistemic practice) can help us to characterize their epistemic cognition, we need to establish a framework that can be used for analysis of the information obtained from the students. After outlining the problem-solving context, we define epistemic beliefs more specifically, in particular scientific epistemic beliefs (SEB) and how these are identified. This is followed by what we understand by epistemic cognition, and finally, features of epistemic practice.

Problem solving

Problem solving in physics education is the subject of numerous research studies (Hsu, Brewe, Foster, & Harper, 2004). A problem-solving situation can vary in many ways depending on the context and the problem to be solved. Problem-solving exercises that are provided in traditional textbooks are in many cases based on idealized contexts and encourage a means-end strategy (Sweller, 1988), i.e. solving problems by working backwards rather than forwards, which could lead to box-checking rather than meaning-making. However, problems that lack a well-defined structure and provide for an open approach might require other strategies, such as trial-and-error or a more systematic approach to changing variables, to establish different possible solutions (Milbourne & Wiebe, 2017). In recent years, digital environments and tools for simulation, visualization and modeling have increasingly been used for problem solving, particularly in physics education. These tools can offer contexts that have a more open and real world character, and require different approaches to problem solving by enabling the user to manipulate variables systematically.

Previous research shows that different behaviors of students with varying epistemic profiles will emerge from different problem-solving situations. For instance, Muis (2008)

examined the relationships between epistemic profiles, self-regulation and problem solving. The results revealed that students' approaches to problem solving were consistent with their epistemic profiles. Thus, a person's epistemic stance might influence their selection of problem-solving strategies while coping with complex questions in 'ill-structured' problems (Jonassen, 1997), i.e. those which possess multiple solutions, solution paths and uncertainty regarding the concepts, rules and principles required.

Epistemic beliefs

Epistemic beliefs refer to an individual's assumptions about the nature of knowledge and knowing (Hofer & Pintrich, 2004). Students' epistemic beliefs have received considerable attention over recent decades in educational research. Nevertheless, this field of research may in some respects be perceived as both vast and muddled (R.F. Kitchener, 2011). A wide range of terminology has emerged regarding individuals' epistemic understanding and thinking: epistemological beliefs (Schommer, 1990), epistemic beliefs (Muis & Franco, 2009), epistemological resources (Louca, Elby, Hammer, & Kagey, 2004), epistemic cognition (Chinn et al., 2011; Sinatra, 2016) and so forth, are examples based on different theoretical standpoints. Different lines of research have addressed the process by which people come to know, the beliefs they hold about knowing, and the manner in which they utilize these conceptions to understand their surroundings (e.g., Hammer & Elby, 2002; Perry Jr, 1968; Schommer-Aikins, 2004). In science education, research indicates that students' epistemic beliefs can have a positive influence on conceptual learning and science inquiry (e.g., Ding, 2014; Murphy & Mason, 2006; Tsai, 1999). Furthermore, studies show that students' epistemic beliefs may also affect their conceptual understanding and the way they evaluate their learning (Mason, 2010; May & Etkina, 2002). For example, Stathopoulou and Vosniadou (2007) studied the relation between tenth-graders' physics-related epistemic beliefs and their physics conceptual understanding. They concluded that sophisticated

epistemic beliefs were a predictor of conceptual understanding in physics. Students who held a more sophisticated stance towards physics demonstrated a deeper conceptual understanding. In a recent intervention study, Yerdelen-Damar and Eryılmaz (2019) investigated the effect of metacognitive instruction on tenth-grade students' understandings about the nature of physics knowledge (epistemic beliefs) and their conceptual understanding regarding force and motion in an inquiry-based learning environment. Results revealed that teaching in the context of inquiry was more effective in terms of improved conceptual understanding for those with more sophisticated views about the nature of knowledge in physics.

Despite strong evidence that epistemic beliefs matter and play a crucial role in learning (Greene, Sandoval, & Bråten, 2016), a number of researchers in this field have taken a more critical stance towards the commonly used notion of epistemic beliefs as either 'naïve' or 'sophisticated', since this leads to dichotomized interpretations of knowledge (Sinatra, 2016). Research has shown that the characteristics of the learning situation may largely determine which epistemic beliefs are most conducive to science learning (Bråten, Strømsø, & Samuelstuen, 2008). In other words, what is theoretically assumed to constitute sophisticated epistemic beliefs may not necessarily be associated with a productive approach to science learning and must therefore be accounted for by its appropriateness in the particular context (Elby & Hammer, 2001). Thus, epistemic beliefs that are conceived as conducive to certain situations are then also considered as productive epistemic beliefs (Elby et al., 2016). In Lindfors, Winberg, and Bodin (2019) naïve Source and Authority beliefs (authority dependence) were associated with a high degree of adherence to instructions, these naïve beliefs were thus productive regarding following instructions. It may be that in the commonly authoritarian science classroom, naïve SEB (e.g., viewing the teacher as the source of knowledge) can sometimes be seen as directly productive for science learning (i.e., generating

successful outcomes). It is with this connection in mind that we explore now the concept of epistemic cognition, as being the process that connects epistemic beliefs to practice.

Epistemic cognition

The recently published *Handbook of Epistemic Cognition* (Greene et al., 2016) makes an important contribution to our understanding of epistemic cognition. In this volume, Sinatra (2016) defines *epistemic cognition* as a process, which “invokes or draws upon learners’ beliefs, schemas, mental models, resources, frameworks, or other contents of their cognition” (p.480). Other research on epistemic cognition processes deals with how individuals think in terms of what knowledge is, how knowledge can be used, how they can determine what they know, and how they know that they know (Greene et al., 2016; K. S. Kitchener, 1983). However, it is still unclear whether the term “epistemic cognition” denotes cognition, metacognition, or a mix of both. Indeed, scholars have emphasized the importance of including the reflective aspect of epistemic cognition to increase the understanding of epistemic development as well as epistemic practices (Barzilai & Zohar, 2016; Hofer & Sinatra, 2010; Sinatra, 2016). Alexander (2016) in her commentary of the role of reflection in practice highlights the distinction between orientations to learning when students are confronted with information - information management and knowledge building. The former can be characterized as a process that is generally undertaken fast and automatically, when the need for a deeper engagement is not recognized, and can be associated with non-epistemic aims. More cognitively demanding practice occurs when the perceived need is to handle information in a way that results in productive learning and knowledge construction (for example for a test), which is more epistemic in nature.

In line with Sinatra (2016), we use epistemic cognition (i.e., cognition related to epistemic matters) as the dynamic process that drives an individual’s epistemic practices, that

is, their behavioral response in a particular situation. Thus, we are going to use epistemic practices to infer epistemic cognition. What comprises the 'contents of cognition' referred to by Sinatra is central to the analysis undertaken in this study. In the problem-solving context we provide, we will be able to investigate students' problem-solving strategies through observation. The context will also provide an opportunity to explore their conceptual understanding and explore the role of metacognitive reflection. We will undertake an analysis that attempts to link these components with students' previously measured SEB to make inferences about epistemic cognition. Making inferences about this process from student behaviors will involve an interpretation of the possible interplay between these components: scientific epistemic beliefs (SEB), problem-solving strategies (PS), conceptual understanding (CU), and metacognitive reflection (MCR) as expressed through self-evaluation.

Chinn et al. (2011) proposed an epistemic cognition framework that characterizes epistemic cognition in terms of aims, standards and criteria (ideals), and reliable processes for attaining epistemic achievements. In this framework, epistemic aims are defined as a subset of cognitive goals associated with finding things out, understanding them, forming true beliefs and engaging in inquiry (i.e., the inquiry-related goals students adopt in learning contexts to which all other epistemic beliefs and activities are directed). Furthermore, this framework takes the situation-specific nature of epistemic cognition into account and allows for a more fine-grained investigation on how students conceptualize knowledge. We argue that the epistemic practices that students express are dependent upon their epistemic aims (Chinn & Sandoval, 2018). Chinn et al. (2011) claim that epistemic aims are essential for interpreting students' behavior, since different epistemic aims may influence the degree of engagement in activities and the way students use knowledge to achieve them. Scholars have also distinguished between epistemic and non-epistemic aims, such as competition, improvement of human welfare, practical achievements, task completion etc. (e.g., Buehl & Fives, 2016;

Chinn, Rinehart, & Buckland, 2014). It has been proposed in the context of science education, that helping students to set up high-level (sophisticated) epistemic aims during knowledge acquisition and construction can have a positive impact on their epistemic beliefs development (Ge, Ifenthaler, & Spector, 2015). High-level (sophisticated) epistemic aims will probably motivate students to perceive the complex nature of scientific knowledge. For example, in school science a high-level epistemic aim would be to develop an explanatory model of how and why mechanical equilibrium can be achieved, in contrast to an attempt simply to describe in detail what can happen. In a learning situation, it is likely that a student's behavior is guided by a mix of epistemic and non-epistemic aims (Alexander, 2017) that coexist and intermingle. For instance, a student might want to be able to understand and explain scientific concepts in a test (epistemic aim) whilst also be the one to finish the test first (non-epistemic aim).

According to Sandoval (2014), it is currently possible to determine a research shift away from mainly characterizing epistemic beliefs towards a more situated perspective on the processes of epistemic cognition. It has been suggested that a greater focus on different contexts and situations where the cognitive processes operate and where the epistemic thinking and understanding are involved will enhance our understanding of the dynamic process of epistemic cognition, which Likert scales are unlikely to capture (Lising & Elby, 2005; Sinatra et al., 2014). Muis and Gierus (2014) also support this view, and conclude that context and content influence which epistemic beliefs are activated. They recommend more attention to behavioral indicators of students' epistemic cognition for future research. Similarly, Bråten (2016) stated that there is a need for more suitable measures and therefore suggested a greater focus on behaviors that show what he refers to as adaptive epistemic cognition. Having an adaptive epistemic cognition is considered as being able to adapt one's epistemic cognition to match the norms in the particular situation where one's epistemic

cognition is enacted (Greene et al., 2016). Hammer and Elby (2002) espoused the important role different contexts and situations play in shaping the structure of an individual's epistemic cognition. They concluded that an activation of certain epistemic resources enables individuals to make sense of knowledge and interpret what is most appropriate in the current setting (Berland & Hammer, 2012).

Epistemic practice

From the arguments we have put forward regarding the process of epistemic cognition, we suggest that a possible way to understand and capture the process is to explore what is *in situ* observable (Chinn et al, 2011; Russ, 2014), that is, how students' behave when they engage in a specific context such as a problem-solving situation in science. In line with Kelly (2008), we define *epistemic practices* in science as the specific ways a person approaches, justifies, and evaluates scientific knowledge within a given context. The epistemic practices are considered to unfold because of the dynamic process of epistemic cognition and can thus be observed as behavioral responses. Moreover, epistemic practices are suggested to be contextual in nature and should therefore be studied *in situ* as "these practices are situated in time, space, social practices, and cultural norms" (Kelly, 2016, p. 397). In a recent study, Zhu, Liu, Liu, Zheng, and Zhang (2019) investigated university students' behavioral patterns in a project-based learning activity that somehow demonstrated their epistemic thinking. In the same vein, the results of a study by Christodoulou & Osborne (2014) revealed that students' epistemic thinking, as reflected in their engagement and behavior, was influenced by guidance from an instructor and collaboration with their peers.

According to Abd-El-Khalick et al. (2004), there is an increasing emphasis on inquiry in the science classroom involving a practice-based approach to science education. A more practice-based approach may help students to overcome rote performance and support their

epistemic understanding of how to engage meaningfully in scientific knowledge construction and evaluation (Berland et al., 2016). As Sandoval (2012) notes; “One important way to understand the epistemic ideas that people bring to bear is to examine their participation in practices of knowledge evaluation and construction. Sinatra (2016) and colleagues have recently suggested a greater focus on defining epistemic practices by exploring the use of epistemic beliefs and conceptions of knowledge in settings where problem solving, decision making, and reasoning are in focus. Although some research has been carried out on capturing “epistemic beliefs in action” (Mason, 2016), there are still too few empirical investigations.

In keeping with Sandoval, Greene, and Bråten (2016) and others, we claim that revealing students' thinking and behavior while engaging in specific contexts may provide important insights about the productiveness of epistemic beliefs and what constitutes successful epistemic practices. Importantly, these insights may also deepen our understanding of the way students are adaptive to the requirements in a specific context. Arguably, being adaptive to a certain context also implies productive epistemic beliefs and successful epistemic practices. This can be inferred, for example, in a task with a high degree of freedom, where the student shows an ability to produce several very complex solutions (successful epistemic practices) based on the given conditions in the specific context. Documenting epistemic practices in order to understand the richness of the tacit epistemic cognition is a challenging task. Nevertheless, we argue that it is the next step to take if we want to improve and truly understand how individuals engage their epistemic cognition. Methods such as observation and think-aloud have been suggested as beneficial since they can be implemented in contexts where students are prompted to think and reflect upon issues pertaining to knowledge and knowing (Knight & Mercer, 2016; Mason, 2016). Furthermore, the suggested methods facilitate exploration of epistemic cognition as it occurs since it might be hard to verbally reconstruct one's enacted epistemic cognition in a specific situation in a correct way.

Nonetheless, semi-structured interviews have been proposed as a useful complement to triangulate and strengthen interpretations from observations (Sandoval et al., 2016)

Research Design

The analysis reported in this paper is the third phase of a mixed-methods research design. The first phase included a survey on science epistemic beliefs (SEB) undertaken with a large cohort of students aged 15 to 16 years in Sweden; statistical analysis of quantitative data was used to map students' epistemic beliefs. The second phase involved 19 selected participants from the survey (having a range of SEB) who subsequently completed a science problem-solving task; their epistemic practice and problem-solving solutions were studied whilst performing the task and qualitative data were collected and analyzed in this phase. The methodology and main outcomes of these first two phases have been reported elsewhere (Lindfors et al., 2019) but details of these phases that are pertinent to this paper are included below. From the analyses of these phases, and from our reading of the literature cited above, we believed that emergent understandings of epistemic practice and how it relates to epistemic cognition in problem solving could be obtained from closer analysis of individual SEB and problem-solving activity on the task. In particular, we devised an analytical procedure that would enable us to determine problem-solving strategies, conceptual understanding and metacognitive reflection. Such analysis would provide insights into the process of epistemic cognition in this context, through comparing the SEB profiles, detailed actions, problem solutions and verbal contributions of students who demonstrated contrasting performance. To this end, we selected three students for detailed analysis who engaged in and reflected on the task in very different ways. The analytical methods used to provide these insights and the outcomes of that analysis are the focus of this paper.

The SEB questionnaire

A Swedish adaptation of the epistemic beliefs questionnaires by Wood and Kardash (2002) and Hofer (2000) was used for assessing upper secondary school students' SEB. The full instrument for measuring epistemic beliefs, including its development, validation and analysis, is described and published elsewhere (Lindfors et al., 2019). Items relevant to the analysis of the data relating to the participants in phase 3 are presented in Appendix A. The questionnaire was distributed to all classes in two public upper secondary schools in a small municipality in Sweden. In total, 1060 students participated (52% females and 48% males). As described by Lindfors et al., (2019) a hierarchical Principal Component Analysis (PCA) was calculated for all constructs to establish the variation in students' SEB and to identify representative students (Abdi and Williams 2010). Two significant SEB components were produced ($R^2=.60$; $Q^2=.29$) and validity checked by an exploratory PCA ($R^2=.35$; $Q^2=.23$). These two SEB components were: component 1) acknowledgment of their own responsibility in learning and a focus on principles for learning, and component 2) a belief that learning is quick and that knowledge is fragmented and certain. The combined rating on these two components represented the range between sophisticated and naïve aspects of SEB. Students aged 15 to 16 years who represented this variation of SEB were asked to participate further in the study (phase 2). In all, 19 students agreed to participate (12 females and 7 males) and these were distributed across the two components. The component dimensions and the 19 students' positions on the dimensions are described in detail and illustrated by Lindfors et al., (2019) (Figure 1, page 5).

The problem-solving task

The 19 students performed the computer-simulated problem-solving exercise using the physics sandbox tool Algodoo (2009-2017), which is a simulation toolbox that allows the user

to produce real-time simulations of physical phenomena and processes. With this tool, it is possible to investigate students' problem solving in a way that would be difficult using standard laboratory equipment. An important feature is that Algodoo allows for continuous feedback that sustains momentum in the process of problem solving and make parts of the process visible to an observer. Algodoo covers mainly the physics content of classical mechanics. The user interface of the environment allows the user to visually build and explore simulations and easily adjust a range of properties, for example, mass, shape, material, coefficient of friction and restitution, and to change environment variables such as air resistance and gravity. The visual scenes that are built are continuously open for real-time interactions, modifications and exploration. A screenshot of the interface is shown in Figure 1.

Figure 1. Screenshot of the Algodoo interface and the problem-solving scene used in this study.

The task chosen for the study was to bring a plain seesaw into balance, as this allows for solving problems that can have a diverse set of solutions in order to make possible a wide

range of epistemic practices (Lindfors et al., 2019). The task would enable the students to bring their own experiences and intuitive knowledge of how the seesaw was expected to behave, but would not require formal physics knowledge to achieve problem solutions. The seesaw was presented as an Algodoo scene and included a number of objects of different shapes, sizes, and masses. By organizing the objects on the seesaw, it could be brought into balance. The task was to find at least four different solutions as to how the objects could be organized to achieve balance. In order to help students become familiar with Algodoo, one of the authors briefly introduced it to the students. Students were then seated in separate rooms, each with a computer and a headset. Students were provided with a written tutorial with guided instructions called “Getting to know Algodoo”, which enabled them to identify all the features of the simulation, for example, how to start and stop the simulation, how to move and rotate objects and use specific features such as the scale and knife tools. As students became acquainted with Algodoo, they had an opportunity to raise questions if something seemed unclear. Students were asked to think aloud during the task in order to capture further insights into their behavior. The instructions included 1) where to open the starting scene in Algodoo, 2) how to combine the red objects into a seesaw, 3) encouragement to use the available blocks to create equilibrium on the seesaw and to freely change the block properties, and 4) how to save the solutions in numerical order on the computer. Distinctions between different solutions could depend on how many and what type of objects could be used, whether an obvious symmetry solution was reached, or whether different positions of the objects as well as the position of the pivot point were explored.

Participants

The 19 participants who undertook the problem-solving task in the second phase were all white Europeans living in a suburban setting and following a range of different educational programs in the Swedish upper secondary system. For participating in the study, each of the 19 students was paid 200 SEK. From these 19, three students aged 16 years (2 males, Julian and Alex and 1 female, Nelly, all pseudonyms) were selected for detailed analysis in this paper, due to their different SEB, behaviors and outcomes in the computer-simulated problem-solving situation. The new analysis depended on comparing epistemic aims and practices of students who performed the problem in different ways. We have chosen not to consider gender differences in epistemic beliefs after reviewing previous studies, since those have shown mixed results (e.g., Bendixen, Schraw, & Dunkle, 1998; Conley, Pintrich, Vekiri, & Harrison, 2004; Kessels, 2013). The aim was to provide an in-depth analysis of their problem solving to gain more insights into their different epistemic practices. The three were selected based on the number, variation and complexity of solutions found in their problem solving, as defined in Lindfors et al., (2019). Though one student (Nelly) exhibited many non-epistemic behaviors (see below), her different approach and behavior was of interest to see whether her epistemic practices provided contrasting insights to those of the other two selected students. Complexity of solution is a combination of whether the beam is balanced, the situation of the pivot point, and symmetry of the block position and manipulation of the block. Table 1 shows how these three students vary in their problem-solving solutions.

Table 1. *Selection of three students based on problem-solving outcomes*

	Nelly	Julian	Alex
Number of solutions	12	6	7
Number of unique solutions	2	3	5
Median complexity level	1	2	7

Data sources and collection

The data sources included in this paper are 1) the three student SEB profiles provided by the questionnaire, 2) Video and screen recordings capturing students' behavior during the computer-simulated problem solving, and 3) Audio recordings from semi-structured interviews with the students. Video and screen recording methods allow the researcher to observe students' behavior in real-time without participating (see, Hennink, Hutter, & Bailey, 2010). They can be used to great advantage in conjunction with other methods like stimulated recall in order to provide a broader understanding of what is investigated (Cotton, Stokes, & Cotton, 2010). The computer was used as the recording unit using a screen and video recording software, Camtasia (1995-2017) that captured students' facial expressions, their talk, and every action they performed in the simulation environment. Thus, while the students' were performing the simulation and generating solutions to the problem-solving task, their manipulations within the environment and all their spoken comments during the simulation were video and screen recorded. These were fully transcribed to produce a transcript for coding that included observational notes from watching the screen recordings and verbatim student comments, in chronological order.

Stimulated recall interviews were conducted after the students' participation in the computer simulation (Appendix B). During these interviews, the student and the researcher reviewed the screen recordings from each solution to stimulate discussions about the student's behavior and the outcome. In this respect, interviews were used to probe what the students understood from the problem-solving activity. Hence, to gain in-depth understanding and access to what they were thinking, the students were asked to verbalize their thoughts while looking at their solutions as well as their thought processes whilst engaged in problem solving. In addition, the researchers raised questions where the students had to clarify and justify why certain strategies had been chosen, evaluate each solution, compare these with each other, and

describe their experiences from the simulation (e.g., satisfaction, level of complexity of their solutions etc.). Questions that were more general were raised at the end of each interview to infer how the students felt whilst participating in the simulation, how they understood the exercise, and how they were able to judge their own performance. Student responses were also transcribed and included chronologically in the main transcript for each student.

Data analysis

The items of the questionnaire in phase 1 were rated on a 5-point Likert scale (1=strongly disagree; 5=strongly agree). As mentioned above, the statistical analysis, involved Principle Component Analysis, and is described in detail in Lindfors et al., (2019) (p. 128-132). The analysis revealed that different sets of the students' SEB were conducive to different parts of their problem-solving process and outcomes. For example, the SEB dimension Source/Authority showed a positive relationship with high proportions of unique solutions. Furthermore, no universal relationship between theoretical sophistication of SEB and quality of problem-solving outcomes could be found. The conclusion was therefore, that the relationship should be interpreted in the light of the actions SEB induce, and what these actions could lead to in the longer term. The analysis in phase 2 therefore focused on the relationship between epistemic beliefs, problem solving and the number and complexity of solutions produced by the 19 students participating in the simulation. In order to better understand the interplay between epistemic practices and epistemic cognition for phase 3, we needed a more detailed description of students' SEB profiles, analysis of their talk and actions in the problem-solving situation, and their reflections on actions. The process of data analysis involved three stages: 1) analyzing the three students' SEB profiles in more detail, 2) merging all the transcribed data from the multiple data sources, including video and interview data, in chronological order, and coding these transcripts (see below), then 3) constructing and analyzing individual narratives based on the merged and coded data, and the SEB profiles.

In what follows, we outline the different stages of our data analysis in order to explain how our data contributed to the construction and analysis of narratives. Constructing narratives helped us to derive meaning, by identifying and comparing epistemic practices that involved different components. Our aim was to infer each student's unique epistemic cognition process and through comparison of the three students, gain more insights into the process of epistemic cognition.

Stage 1: Analyzing SEB profiles. The first stage in the analysis was based on the three students' written responses to the SEB questionnaire from phase 1. This analysis paid more attention to how the students had scored on each dimension and on the specific items within the different dimensions in the SEB questionnaire (Appendix A). If a student had high scores on traditionally labeled naïve dimensions (e.g., Certainty and Truth) and low scores on traditionally labeled sophisticated dimensions (e.g., Construction and Modification), the individual SEB profile was considered to indicate a more naïve SEB and vice versa. Moreover, it was also possible to achieve a mix of naïve and sophisticated SEB. The interpretations of the scores for the three students are outlined in the results below.

Stage 2: Analysis of video and interview recordings. The second stage in the analysis process was to organize and structure the data from recordings in a coherent way that allowed us to explore students' behavior and actions in chronological order. The students' behavioral responses to the computer simulation could be observed/heard in terms of their various actions, strategies and verbally expressed decisions. Their speech during the computer simulation was transcribed verbatim and their actions seen on the video described in detail. The interview transcripts were then merged in chronological order with the transcriptions from the behavioral response for each student. For example, an interview statement regarding a particular action and the description of the action were placed successively in the merged transcripts. Interview statements that were more general were placed at the end of the merged

transcripts. To facilitate the reading and coding of the transcripts, actions, student talk during problem solving, interview responses and solution complexity were highlighted in different colors.

The processes involved in our video analysis are reflected in many of the studies of video research in the learning sciences documented by Goldman, Pea et al. (2007). In the preface to this volume, Goldman et al. (2007) point out that the use of video in qualitative research can support the construction of compelling narratives, establish coding schemes and develop meaning making. The video is the basis (along with interview) of a primary source of data that can then be used to develop or apply a coding scheme specific to problem solving (see below), and construct a narrative incorporating other data sources (SEB profiles and problem-solving solutions). The chronological account produced by combining interconnected transcript of student and adult voices, observation and post-task interview could be seen as similar to Bakhtin's (1981) notion of 'chronotype', a pattern of timings and paces of action interconnected with movements in and among particular settings (Lemke, 2007, p. 49).

As pointed out by Miller and Zhou (2007) observation of video and coding schemes can be different for different viewers, also the complexity of video data can be challenging (Ash 2007). To establish robustness of interpretation of the observed behaviors two of the authors viewed and described the observations to establish a common interpretation of events. The video record allowed for several iterations of evaluation to establish robustness of interpretation (Engle et al. 2007).

As mentioned previously, taking Sinatra's position on epistemic cognition, we decided to focus on identifiable behaviors as indicators of epistemic practice that included problem-solving strategies (PS) and conceptual understanding (CU), and to explore the role of metacognitive reflection (MCR) as expressed through self-evaluation. To code the transcripts in this stage we drew on Polya's (1945) framework as a basis for coding. This framework has

been the inspiration for numerous studies in problem solving (Jonassen, 1997; Kim & Hannafin, 2011; Schoenfeld, 1992). In the framework, the following central steps in mathematical problem solving are identified (which are similar to those in physics problem solving): 1) Understand the problem, 2) Make a plan, 3) Carry out the plan, and 4) Look back. In the first step the problem is framed and activates a conceptual understanding (CU) of the context. This is indicated by concepts students use and how they use them during the task. The second and third steps reveal problem-solving strategies (PS). The fourth step includes an evaluation aspect and can reveal metacognitive information of students' own progress (self-evaluation, SE). Polya (1945) suggests two main approaches that can be adopted when carrying out a problem-solving plan: *Guess* or *Think*. The guessing approach reveals typically no systematic features and involves trial-and-error and "acting it out" using whatever equipment and tools are available. The thinking approach contains several strategies showing a certain amount of systematic behavior that will keep the focus on the problem, such as looking for patterns, using symmetry, working backwards from the answer, using formula, or using known skills from other problems.

Polya's four steps were identified in the chronologically sequenced data, which was thereby coded according to Conceptual Understanding (CU), Problem-solving Strategy (PS), or Self-Evaluation (SE) (as indicated above). The codes for problem-solving strategies (PS) were divided into Guess and Think, in line with Polya's two approaches. Each action, student comment (during action or in response to the researcher), was considered and coded where one of these steps in problem solving was identified. In addition, further codes were derived from the data that would represent more specific aspects. For example, a 'guessing' strategy could be seen as 'Trial and error' or 'Acting out' (according to the combination of action and talk) during problem solving. An example of coded transcript is provided in Appendix C. The Tables in the results section include extracts of coded data using this framework.

Stage 3: Construction of narratives. In order to achieve an understanding of each of the three students' outcomes, we needed an analytical process that would draw together the SEB profiles, number and complexity of solutions, and the outcomes of coding the actions and talk (comments in action and reflections). Constructing a narrative for each student that took into consideration all these analyses was perceived as a useful way to explore meaning, compare students and make inferences about epistemic cognition. This process can be compared to the use of 'storylike' frames to aid understanding of events (Erickson 2007). The approach to narrative construction and its analytical purpose in this study also has parallels with analytical procedures documented by Miles and Huberman (2000) in their account of the use of vignettes in case study research and illustrated narratives in sequential analysis. Each has a chronological element but also draws together data sources to explicate meaning within the chronology. Vignettes bring together 'pockets of especially representative, meaningful data.... that can be pulled together in a focused way for interim understanding.....they are also helpful in formulating core issues – your theory of what is happening.' (p. 81). Similarly, in our study we saw the process of constructing narratives as a means of drawing together the SEB profiles, problem-solving solutions and all the coded talk and actions in our chronological sequences to help us understand and characterize these three students' epistemic cognition.

Three narratives were therefore constructed based on all the data sources and analyses. Each began with a description of solution complexity and the SEB profile, then consideration of the coded transcript. The narratives took the form of extended text that therefore included reference to all the coded data from video and interview transcripts, SEB profiles and problem-solving solutions (including screen-shots) to draw out explanatory accounts that would culminate in a characterization and understanding of epistemic cognition. All the data sources were referred to constantly throughout the construction of the narratives, in order to

draw together actions, decisions, and rationales that could be associated with students' epistemic beliefs and cognition in the problem-solving situation. For example, these included manipulations of the various features in the simulation and verbal expressions of their sense making in the moment that indicated certain problem-solving strategies, such as guessing or thinking, or conceptual understanding, such as expressing scientific concepts relevant for the context, as well as self-evaluations, such as showing confidence or drawing on previous experience. As each narrative was constructed by one researcher, the research team read and reflected on the interpretations of all the data upon which it was based in order to apply our combined theoretical understanding of epistemic cognition to learn more about how it is characterized in the situation of the problem-solving task. Once all three narratives were constructed, these were analyzed by reading and comparing all three. This 'analysis of narratives' was undertaken by appraisal of their meaning as they related to all aspects of the data (by reading through and discussing the narratives alongside the data sources) and making inferences about epistemic cognition. Including all the narratives with their reference to data sources would be too lengthy; therefore, the results section includes the findings that emerged as we compared all the data for each student.

Results

To convey the outcomes of this complex analytical process, in this section we present the SEB profiles of the three students and then the findings on epistemic practice derived from comparing the three students' data, using the framework of PS, CU and MCR. We then provide a short account of each student that originates in their narrative, to interpret each of the three students' epistemic practices and outline their unique epistemic cognition features. In order to capture the nature of their epistemic cognition, we have chosen to acknowledge the voice of each student by using direct quotes from the coded data.

SEB profiles and problem-solving solutions of Nelly, Julian and Alex

From their scores on the SEB questionnaire (Appendix A) the three students differed in how they perceived knowledge and knowing in science. Nelly presented a theoretically very naïve stance towards scientific knowledge and knowing and her SEB profile was therefore categorized as naïve. She *strongly agreed* that learning occurs quickly, believing that if she is to understand something in science, it must make sense to her the first time she is confronted with the information. Furthermore, her beliefs about what constituted a successful student were linked to an ability to memorize many facts. According to Nelly, a successful student is a person that has an innate ability to learn. She had a great faith in authorities, such as teachers and scientific researchers, and believed that certainties in science are likely not to change over time. More specifically, she believed authorities have or are able to find answers to every question. Nelly produced 12 solutions that were classified as two types of unique solutions, although 8 solutions out of 12 were categorized as a non-approved solution (Table 1).

Julian's SEB profile was somewhat similar to Nelly's, although he also showed some sophisticated SEB. Since his scores on the SEB questionnaire indicated both naïve and sophisticated stances towards scientific knowledge and knowing, his SEB profile was categorized as mixed. Julian opined that he gets confused if he tries to integrate new ideas in a science textbook with knowledge that he already has. Like Nelly, he demonstrated an authority dependence and indicated that he sometimes just accepts an answer from an authority like the teacher, even though he does not understand it. Furthermore, he agreed to some extent that what is true in science will most likely not change in the future. He took a more sophisticated stance when it came to the importance of how a prolonged effort and engagement in learning will lead to a greater understanding. When he encounters a difficult concept in his textbook, he makes an effort to work it out on his own instead of asking his

teacher. When learning science, Julian stated that it is important to think creatively. He thought that it is fun to reflect on scientific questions that even experts fail to agree upon. Julian produced six solutions and three of these were classified as the same type of solution with a low complexity, which signified symmetry solutions (Table 1).

Alex demonstrated an overall sophisticated SEB profile. His scores on the SEB questionnaire revealed that he enjoys reflecting on scientific issues and firmly believes that creativity and effort are very crucial when learning science, but he questioned authorities and strives to be as independent as possible. According to Alex the learning process does not occur quickly *per se* as soon as one is confronted with new information. Instead, one might need to re-read and process, for example a new concept or content in a science textbook, before learning occurs, which also applies to the really smart students. Alex managed to produce five unique solutions out of his seven solutions and reached a high complexity level, even though he did not use all the available time (Table 1).

Epistemic practices

Analysis of the narratives against all data sources (coded transcripts, SEB profiles and problem-solving solutions) enabled us to identify students' epistemic practices using the framework of problem-solving strategies (PS), conceptual understanding (CU) and metacognitive reflection (MCR), from which we were then able to infer each student's epistemic cognition. In the next three sections, we compare the students according to these epistemic practices, with examples from the coded transcripts.

Problem-solving strategies. Students could be seen using strategies that were more or less goal-oriented and required different levels of cognitive effort. A student can be very consistent with non-systematic strategies (e.g. guessing) even if these do not lead to any progress in solving the task. A more systematic approach (thinking) was very evident for

Alex, who stated that he used his previous experiences to be able to solve this type of task.

Table 2 shows examples of how the different epistemic practices in problem solving are revealed in talk and actions for each student.

The guessing approaches were characterized as “trial-and-error” and “acting out and testing the environment”. The trial-and-error approach was most often recognized as attempts to add, remove, or move blocks on the seesaw without any apparent systematic approach, or randomly turning on and off the simulation, meaning that for each failing attempt the student had to start from the beginning again. Typically, the acting-out approach was to test different features of the simulation environment, a behavior associated with trying to understand the limitations and possibilities of a particular context. In some cases, this approach could lead to successful outcomes, for example, when Alex checked on different materials and changed the material on another small block to stone, then moved it to the other stone block at the far left and the other standard blocks to the right (Table 2).

The thinking approaches involved more systematic strategies. The strategy of using symmetry was most prominent and usually successful. By making sure that the weights on each side of the seesaw were equal, and at the same distance from the pivot, many attempts led to solutions. However, in order to find unique solutions other strategies had to be considered, such as looking for patterns and using experiences from similar tasks. Only one student, Alex, managed to look beyond the symmetry approach at an early stage and find new strategies in order to produce more unique solutions. His observed behavior provides evidence of a thinking approach when looking for patterns. The video where he produced his seventh solution showed that he started from the standard scene. He then looked at the speed of the blocks and he tried to freeze the speed. He entered the material, and checked the information about the properties of the blocks (Table 2).

Table 2. *Example of students' problem-solving strategies as epistemic practices*

Problem-solving strategies				
	Guess		Think	
	Code	Example	Code	Example
Nelly	Trial-and-error.	Adjusts the positions of the blocks, restarts the simulation and moves the standard block to the right. Turns the simulation off and moves the yellow block to the left. Restarts the simulation. (video, solution 4)	Using symmetry	"I probably use the rest of the figures and put them the furthest out on the narrow red pin and I'll try to get it as even as possible so that it weighs the same on both sides." (video, solution 1)
	Acting out.	"And I was supposed to use four different methods and I have really tried that every time, ... to replace the figures. You cannot really replace the board." (video, solution 9)		
Julian	Trial-and-error.	<p>"As a way for me to see what and how I can do this. I don't know why I did that, but. Never mind." (video, solution 1)</p> <p>"Yes, so. If I hypothetically try to just pile on (blocks). If I try to rotate it here. If I try to rotate this one. There! And I will then pull you up. Not yet (equilibrium) I'm trying to get equilibrium by simply using weights on one side and none on this side. We'll see how it goes. By randomly put them on the seesaw." (video, solution 4)</p>	Using symmetry	<p>"I am thinking that if I simply split them, I will have one on each side. I will then have achieved equilibrium already, but what if I put them here. And now see if it will tilt. There you go."</p> <p>He puts a large green and purple standard block on each side of the board, and then two small standard blocks on top of each large block. (video, solution 3)</p>
			Looking for patterns	"Check Properties, materials, hm., standards, hm .. the same. Yup. Both of them seem to be standard and they have the same characteristics. This also applies to these." (video, solution 3)
Alex	Trial-and-error.	He changes the material on another small block to stone and moves it to the other stone block at the far left and the other standard blocks to the right. He restarts the simulation and the attempt fails. The simulation is turned off. He moves the standard blocks from the right side further toward the breaking point. The board tilts when the simulation is running again. (video, solution 2)	Using symmetry	<p>"This is fairly even now, now I'm doing like this." (video, solution 2)</p> <p>He assembles the seesaw, starts the simulation. Adjusts the board. Turns off the simulation, adjusts the board. Restarts the simulation. Stops the simulation. Changes the material to helium in two small blocks and puts them under the seesaw on each side. Restarts the simulation. The attempt succeeds. (video, solution 4)</p>

	Acting out.	He checks on different materials in the scrolling list. Then he changes a little standard block into helium, and then changes it again to steel. The simulation is turned off. He puts on a wooden block and a steel block. The steel block is placed on the pivot point and wood block to the far right. (video, solution 3)	Inquiry	Checking around among the tools. Reads the instructions. "Now, I got an idea! " (video, solution 6)
			Looking for patterns	He starts from the standard scene. He looks at the speed of the blocks, he tries to freeze the speed. He enters the material, and also checks the information about the blocks properties. (video, solution 7)
			Using known skills	<i>I: "Do you think you understand what equilibrium is all about?"</i> <i>A: "Yes, I understood it also before, but for those who don't understand is this [exercise] good." (interview)</i>

Conceptual understanding. Students showed conceptual understanding in how they carried out the task and in what they said about their actions while they were working with the task, as well as retrospectively. The way they used concepts was a strong indicator of whether they had internalized the concepts and their meanings and were thus available for cognitive processing (epistemic cognition).

What became evident when comparing all the data was that the students' behavior and talk displayed different conceptual understanding according to how they used scientific concepts in their explanations and in the extent to which they explored those concepts in practice (Table 3). More specifically, their behavior indicated different levels of being able to carry out the simulation procedures flexibly, accurately, and appropriately. For example, Nelly's behavior demonstrated an inability to accurately interpret on which side of the seesaw's pivot point to put the blocks. When working on solution one, she stated, "I'll start by

moving the different rectangular and square figures and the red long stick. I'll move the red triangle to the middle and put the red stick on top of it". Thus, the students' talk, triggered by their own actions, revealed whether they had the ability to logically reason, explain, and reflect upon the responses from the simulation. For example, Julian reasoned with himself and pointed with the mouse to how he would possibly load the blocks and which way the board would tilt. He checked information about different materials and the block features. He changed the standard material into helium. He zoomed in and looked at the block information. He changed the material back to standard again before re-started the simulation (Table 3). Students' reasoning indicated whether they had the capability to compare, contrast, and integrate concepts and principles as well as use the vocabulary that was associated with the context. The observations of Julian and Alex showed differences in this regard (Table 3). Alex shows that each step he moves forward, he does not have to keep checking like Julian. Verbally demonstrating conceptual understanding does not mean that one has the capacity to transfer that to practice. This was characteristic for Julian, who most of the time showed conceptual understanding in his explanations of the relationships between concepts but he was not able to transfer this kind of understanding into practice.

Table 3. *Example of students' conceptual understanding as epistemic practices*

Conceptual understanding		
	Code	Example
Nelly	Limited knowledge of concepts.	"I'll start by moving the different rectangular and square figures and the red long stick. I'll move the red triangle to the middle and put the red stick on top of it" (video, solution 1)
Julian	Good knowledge of concepts but limited transfer to problem solving.	<p>"I need to get some more weight on that side. Ok, I can try to add the second polygon. The second polygon on the corresponding side just to see what happens... I take these three on one side and these on the other side. These four have the same mass and the same area" (video, solution 4)</p> <p>Julian reasons with himself and points with the mouse to how he would possibly load the blocks and which way the board would tilt. He checks information about different materials and the block features. He changes the standard material into helium. He zooms in and looks at the block information. He changes the material back to standard again before re-starting the simulation. (video, solution 6)</p>
	Reflects productively.	<p>I: "In what ways are your suggestions for equilibrium different?"</p> <p>J: "This is slightly different. I began to check the mass on this[one block], it was... well 0.188 and then I compared it with the mass if I changed the material on a smaller block. Then I got a mass that was relatively close to 0.15... Actually, it is not so much that distinguishes them [the solutions] from one another... so it is just that it is different masses. Thus, it is the same mass on both sides. It has nothing to do with the positioning at all. It is only the 6th [solution] that differs from the others. I came up with the 6th because... I thought that the former [solution] was a bit boring" (interview, solution 6)</p>
Alex	Effectively interprets, applies and integrates.	Alex checks for different materials in the scrolling list. Then he changes a little standard block into helium, and then changes it again to steel. The simulation is turned off. He puts on a wooden block and a steel block. The steel block is placed on the pivot point and wood block to the far right. He adjusts the position of the blocks while the simulation is running. The wood block falls off... He puts on a small block of wood on the right, removes it. He presses the undo button several times... The simulation is running. The block's positions are adjusted when the simulation is turned on. (video, solution 2)

Self-evaluation. Students' self-evaluation demonstrated their metacognitive reflection (MCR) while processing feedback from the simulation environment. Self-evaluation provided crucial information about what students had understood and how their learning had developed during the specific situation. Their self-evaluation provided information about how they monitored their own performance and, if they were able, to identify gaps between what they intended to achieve and what they actually achieved in the specific learning situation.

The three students in this study revealed a variety of reactions to their performance in relation to the well-defined criteria for the problem-solving task (Table 4). This was evident not only in how they evaluated their performance and made adjustments while the simulation was running, but also in how they were able to track their own progress retrospectively. For example, students differed when and how they were expressing confidence. On the question of whether the task was easy or difficult to solve, Alex said; "It was not that hard but I had to have a steady hand and reflect about where to put it [the blocks], so it weighs up [evenly]" (Table 4). Nelly tended to believe that she had performed well when in fact some of her solutions were not stable, thus her self-evaluation was less accurate. How students critically analyzed their own assumptions and causes of the setbacks in the computer simulation demonstrated whether they were able to estimate their own performance accurately. All students were very confident with what they had accomplished despite the obvious difference in their ability to properly evaluate and assess their performance.

Table 4. *Example of students' self-evaluations as epistemic practices*

Self-evaluation		
	Code	Example
Nelly	Confident	"A bit hard! But I will most likely manage this after a while! ...There it is, now I have made my second solution. I think I nailed it!" (video, solution 2)
	Motivated	"And like I said, I think I am improving each time! Oki doki, only one figure remains!" (video, solution 4)
	Proud of attempts	"Now I am happy with the setup... I think that I have made a good one ([to the seesaw] The stick is somewhat straight" (video, solution 1)
Julian	Confident	"Check Properties, materials, hm., standards, hm.. the same. Yup. Both of them seem to be standard and they have the same characteristics... I think something like this will be good!" (video, solution 1)
	Proud of attempts	"Yup, this looks really good! ... I'm almost there now. I need to get some more weight on that side... The second polygon on the corresponding side just to see what happens" (video, solution 3)
Alex	Confident	I: "Was it easy or difficult to solve the task?" A: "It was not that hard but I had to have a steady hand and reflect about where to put it [the blocks], so it weighs up [evenly]. (interview)
	Draws on previous experience	I: "How do you know about equilibrium?" A: "... It's like I just know. I know how much one need roughly [referring to weights and distances]. I can see it... I've seen how it sways when I have produced the other solutions [referring to the seesaw] (interview)

Describing the students' epistemic cognition

From the analysis of all the data, we sought to understand ways in which each student's epistemic cognition could be inferred, according to their epistemic practices and beliefs in this problem-solving context.

Nelly. Nelly's reflections during the simulation indicated a limited conceptual understanding and a mix of both non-epistemic and epistemic practice. In some cases, Nelly

made relevant reflections while the simulation was running. However, what she said did not always match her actions. For example, she talked about bringing the seesaw into balance and what that required—but repeatedly put only one block on one side of the midpoint and, when the solution failed, moved the block to the other side instead. In addition, she usually saved her solutions without knowing if the seesaw was in equilibrium by just stopping the simulation when the beam was straight. Her behavior resulted in some simple symmetry solutions but three quarters of these were eventually classified as non-approved when the simulation was running again (i.e., not in equilibrium) and coded as ‘acting out’ (Table 2). Figure 2 shows four of Nelly’s twelve solutions, where two solutions (no. 1 and 5) were not in equilibrium. However, solution 8 and 12 are in equilibrium, which shows slight progress, but with low complexity.

When analyzing her talk it became clear that she did understand what equilibrium is and the importance of letting the seesaw swing freely to start with (epistemic aim). Nevertheless, she stated that she wanted to improve her time (non-epistemic aim) and tended to use simplistic wording for the features of the simulation.

“I will start by moving the different rectangular and square figures and the red long stick. I will then move the red triangle to the middle and put the red stick on top of it. And it is supposed to be able to swing freely. By doing this, I will try to get it as even as possible” (video, solution 1)

Nelly's naive SEB profile, limited conceptual understanding, and difficulty with cognitively engaging in finding more productive problem-solving strategies, indicate that her process of epistemic cognition did not result in a productive engagement in the task. It was difficult for Nelly to process the feedback from the simulation environment, which made it tricky for her to navigate in the context. That is, her epistemic cognition process was not fully adaptive in this context. She could not realize from her self-evaluation what she needed to do

in order to find solutions that would be more efficient and thus make progress through the task. It became obvious that Nelly often monitored the responses from the simulation environment, but could not cognitively process the information in an accurate way. This was evident even when she was given guidance, in terms of hints about what would happen if a block had another position etc., in the interview afterwards. She still expressed confidence about her efforts even though it was obvious that most of her solutions were not in equilibrium. When asked to evaluate her problem-solving process and solutions at the end of the interview, she stated:

“It became easier and easier when one already had produced some [seesaws] in equilibrium.” (interview)

Our interpretation is that the interplay between Nelly's scientific epistemic beliefs (SEB), conceptual understanding (CU), problem-solving strategies (PS), and metacognitive reflection (MCR) limited her effort in this context. She encouraged and boosted herself several times with positive feedback throughout the problem-solving process, but her limited reflective analysis and mix of epistemic and non-epistemic aims hampered her progress.

This type of problem solving seems to have been a major challenge for Nelly based on the limited ways she produced solutions. Her epistemic practices indicate that she was not adaptive to the surrounding context and therefore did not have the ability to be flexible and take advantage of feedback given by the simulation environment, such as setbacks.

Figure 2. Nelly's solutions, from top to right, number 1, 5, 8, and 12 (no 1 and 5 non-approved).

Julian. Julian appeared to enjoy the challenge of working with Algodoo, which was evident by his smiles, whistles, and verbal comments about his actions and solutions. Julian expressed good conceptual understanding (CU) when checking and comparing the block properties. Nevertheless, his epistemic practices revealed that his efforts with finding efficient strategies for solving the problem were not very successful. The low interplay between scientific epistemic beliefs (SEB), conceptual understanding (CU), problem-solving strategies (PS), and metacognitive reflection (MCR) made the epistemic cognition process unstable, explaining why Julian was stuck in his attempts to find new solutions to the task. Figure 3 shows four of Julian's six solutions, all in equilibrium and mostly symmetry solutions. The four solutions were categorized at three different complexity levels, where solutions 1 and 3 displayed the same complexity level. Moreover, it became very clear to Julian when he was tracking his progression, that all of his solutions were very simple and similar. When he was prompted to reflect upon his solutions in the interview, he was no longer static in the

epistemic cognition process and was able to move forward in the dynamic process of his epistemic cognition.

“Actually it is not so much that distinguishes them from one another, at least not the first three or four ones [solutions]. It is just that they [the solutions] have different masses. Thus, it is the same mass on both sides. It has nothing to do with the positioning at all. Actually, it is only the sixth [solution] that differs from the others.”
(interview)

Julian was not able to adjust to the situation and perform what was applicable in this particular situation as it occurred, that is, as it happened. Initially, he was so committed to a particular strategy that he did not consider whether some other strategies would have been a better option. Despite expressing clearly how he was planning, he was not able to explore and transform those plans into practice. That is, he did not adapt his knowledge to fit the requirements of the context. On some occasions, his talk revealed preconceptions about a very simplistic and naive view of how one should accomplish good solutions. This was sometimes totally contradictory with what he previously expressed. Once Julian was confronted with his solutions a second time, he immediately evaluated and demonstrated an understanding of his shortcomings, thus he became adaptive to the situation.

“I don’t know if it was a bit too easy or similar [...] Solution four, it is also quite simple. I took a smaller block, divided it in the middle, and put those on each side. Because then I got two equal pieces that had the same mass, and if I put them on the end of this seesaw, I should be able to reach equilibrium. [...] Actually, it is not so much that distinguishes them from each other, at least not the first three or four. It is just that it is different mass.” (interview, solution 2)

By being prompted to reflect, Julian started to reveal several innovative ways of solving the task as well as how one could have conceptualized this simulation task differently.

Figure 3. Julian's solutions, from top to right, number 1, 3, 4, and 6.

Alex. Alex, who possessed scientific epistemic beliefs (SEB) that are more sophisticated, demonstrated more innovative approaches. His SEB consisted of a flexible set that allowed for more dynamic interaction between his SEB, conceptual understanding (CU), problem-solving strategies (PS), and metacognitive reflection (MCR). By interpreting Alex's behavior and outcomes of the computer simulation, it appears that the interaction between his CU and PS played a prominent role. He generated room to explore different solutions, which could be interpreted as his sophisticated set of SEB allowing him to explore that interaction. Figure 4 shows four of Alex's seven solutions, all in equilibrium and with four different complexity levels. Solutions 1 and 4 corresponded to symmetry solutions and solutions 5 and 6 corresponded to non-symmetry solutions.

In general, Alex had a highly efficient way of working with the task and managed to solve it in a timely fashion even though his attempts sometimes started with a trial-and-error

approach. His actions indicated that he took into account the current context and the feedback provided by the simulation environment and was able to make effective decisions based on this. Though he did not express reflections on his actions orally until asked, Alex's progress could arguably demonstrate metacognitive reflection of simulation feedback through his subsequent actions. Furthermore, he exhibited a flexible manner and presented several innovative solutions (both symmetry and non-symmetry) which all showed equilibrium. Alex had a deep understanding of the aim of the task and what differentiated his solutions from each other. On the question, what differs between your solutions? He answered:

“Different materials, different pivot points on the seesaw, different placements of the blocks on the seesaw. With heavy materials on one side, I will need to move that material closer to the middle in order to weigh up with what is on the other side of the seesaw.” (interview)

His actions, decisions and rationale indicated that he was adaptive to this context. That is, the contents of his epistemic cognition (SEB, CU, PS and MCR) seemed to interplay well in this specific context, which enabled him to approach the problem in a rich variety of ways. Overall, this type of task was not perceived as particularly difficult for Alex as long as he reflected upon what he was doing. His intuition guided him in what to do next in each attempt to achieve equilibrium. When he explained in more detail what his intuition was based on, it became clear that there were strong links to his earlier experiences from school. Alex stated that intuition is something that should be valued as an important resource and should never be neglected.

Figure 4. Alex's solutions, from top to right, number 1, 4, 5, and 6.

Discussion

In this study, we set out to further our understanding of the process of epistemic cognition through eliciting epistemic practices of students whilst they engaged in a science problem-solving task using the physics simulation toolbox Algodoo. Reported in this paper is the final phase of the study, where we chose to extend the analysis by focusing on the data sets of three students who demonstrated contrasting SEB and problem solutions in the earlier phase. Thus, the paper presents a complex analysis of multiple data sets with the aim of providing insights into the process of epistemic cognition. The choice of these three students has been critical as they show contrasting epistemic practices, including differences in problem-solving strategies, conceptual understanding and metacognitive reflection, as evidenced in our results. Our choice of Nelly could have been problematic, as a student whose limitations in using the simulation might not reveal very much about the epistemic cognition process, however focusing on what she was and was not able to do in comparison with Julian and Alex has strengthened our understanding of the epistemic process, as evidenced in the results. Using Polya's (1945) description of problem solving we were able to identify

conceptual understanding, problem-solving strategies, and self-evaluations (metacognitive reflection) that lead to solutions of varying complexity. The analysis of the three students' practices together has enabled us to understand more about the interplay between these elements of our analytical framework. This interplay as demonstrated in the contrasting examples is crucial to our understanding of the epistemic cognition process – the three students' practices show different ways in which this interplay has occurred. The most obvious may be the interplay between conceptual understanding and problem-solving strategies – enhanced understanding might easily be associated with more productive solutions. However, the value of using this simulation has, in particular, allowed us to tap into the role of metacognitive reflection. Such reflection was very limited with Nelly as she switched between epistemic and non-epistemic aims, but productive when Julian was scaffolded to reflect on his results, and demonstrated clearly with Alex through his actions after feedback from the simulation. Building on this result to consider implications for teaching would suggest that encouraging continuous metacognitive reflection, based on observable practices, could enhance epistemic cognition of students.

To appreciate the dynamic process of epistemic cognition (Sinatra, 2016), an important element is to consider how students use the information received in response to the actions they are carrying out. In a paper-and-pen problem-solving situation, this feedback is less transparent than in a computer environment where immediate feedback occurs after different actions performed. In this task, we assumed that the student is continuously receiving feedback from the simulation environment as actions are taking place. The student processes this feedback and takes it into consideration in their subsequent actions, which eventually will lead the student towards a useful solution. Students may, however, be stuck in a feedback loop where the information is not helpful enough to find productive actions or they are not able to process the received feedback information. Their effort does not forward the process,

resulting in poor performance. In this situation, we see their epistemic cognition process becoming static, rather than dynamic.

When students are scaffolded during the problem-solving process, by a teacher or through some other resource, such as instructions or textbooks, the student can be helped through the process. Students' judgment of their own performance is a metacognitive phase that adds to the picture of how well students understand the situation. We can conclude how well students have adapted to the situation in this phase, as they reveal how they understand their limitations and ability to solve the problem. It has been stated that the learning situation determines which epistemic beliefs are most conducive to learning as well as how the epistemic practices are expressed (Bråten et al., 2008; Kelly, 2016). Thus being adaptive to the situation (i.e., adaptive epistemic cognition) is therefore a feature of whether their epistemic beliefs are productive or, in other words, if their epistemic practices are successful in the specific situation (Elby et al., 2016). Our findings regarding the three students are in agreement with those obtained by May and Etkina (2002), whose results revealed a correlation between students' sophisticated epistemic beliefs, deep conceptual understanding, and ability to reflect upon their own learning.

Looking back, we can see that this kind of learning situation might not be productive for all students. On the one hand, one could argue that the situation is not productive for Alex as it may be too easy for him and therefore not challenging his thinking. On the other hand, Nelly does not build on the feedback which results in less successful epistemic practices. In this situation, it is difficult to guide Nelly since she does not appear to process information accurately, meaning that a learning situation like this will be difficult for her unless she finds strategies to understand and make use of scaffolding. Nelly's less successful epistemic practices are in line with previous research that a mismatch between epistemic beliefs and the

epistemic underpinnings of the learning situation result in low achievement (e.g., Dai and Cromley 2014, Barger, Perez et al. 2018).

In the light of Alexander's (2016) distinction between information management and knowledge building when describing how epistemic cognition comes into play, it is possible to speculate whether Nelly's behavior most often indicated information management (i.e., task-driven engagement, automatically and externally motivated) instead of knowledge building. She clearly demonstrated some non-epistemic aims in this situation (for example, achieving a good time), rather than aiming to obtain knowledge about the problem-solving situation or to truly understand (Chinn & Rinehart 2016). According to Alexander (2016), processing of information is not automatically linked to epistemic cognition, which would mean that the expressed practices are not necessarily epistemic in nature. How students perceive, evaluate and adapt to the epistemic underpinnings of the surrounding learning situation can thus influence whether information management or knowledge building takes place. In this situation, Alex, unlike Nelly, demonstrated that he took into account the surrounding context and that he could benefit from the feedback generated by the simulation tool based on his own manipulations. Julian was able to build on feedback from the researcher. These results suggest the importance of helping students to set high-level (sophisticated) epistemic aims, which can help them to better understand what is most conducive in a context and to be able to make most 'use' of such situations (i.e., fostering adaptive epistemic cognition). Students' engagement in epistemic practices can be dependent on how science teachers have designed activities that will ensure a productive participation and how they scaffold their students' learning (Christodoulou & Osborne, 2014).

In accordance with the present results, previous studies by Gu and Belland (2015) have demonstrated that high-level epistemic aims can contribute to both epistemic development and more successful epistemic practices, which in turn will have a positive influence on the

students' learning progression. Based on the above reasoning, it can therefore be seen as important that the students set high-level epistemic aims to promote their learning. An example of a high-level epistemic aim in the context of this study would be to aim to understand explanatory connections between concepts such as the relationship between mass and distance. Teachers therefore need to establish a positive epistemic climate of the classroom where these epistemic aims are made visible. As Feucht (2010) states, an epistemic climate involves a reciprocal relationship between the epistemic beliefs of students and their teachers, as well as the epistemic underpinnings of the instruction and knowledge representations.

Muis et al. (2016) have suggested several important aspects that may play a crucial role for establishing and cultivating a positive epistemic climate as well as fostering adaptive epistemic cognition in students. Teachers should strive to offer opportunities for students to reflect explicitly on their own and others' stances towards knowledge in order to make them more aware of the complexity and tentativeness of knowledge. Similarly, Barzilai and Chinn (2017) argue that it is meaningful to design learning environments where students need to engage in a justification process and take a stance in relation to information that may be contradictory, of different quality and relevance, as well as having different credibility.

Studying these three students in depth has enabled us to gain insights into the interplay between the different contents of their cognition (SEB, PS, CU, and MCR); however, the size of the study limits the claims that can be made in this respect. Moreover, the links between SEB and epistemic practice can only be inferred from questionnaire responses and talk/actions in the situation. Further exploration of these links needs to be undertaken to provide more evidence for such claims. Sinatra's (2016) definition of epistemic cognition as the dynamic process that drives an individual's epistemic practices has been useful for understanding epistemic cognition in this problem-solving situation, through studying in

detail and comparing different students' epistemic practices. In line with Sandoval, Greene, and Bråten (2016) and others, we have found that revealing students' thinking and behavior while engaging in a specific context has enabled us to provide insights not only on what constitutes productive epistemic beliefs and successful epistemic practices but also on how epistemic cognition is adaptive to a specific context. A key finding of our study is that epistemic cognition is meliorated by the content representative in the problem and could be supported by future research in other problem-solving scenarios.

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Appendix A

SEB questionnaire

Dimensions	Item	Nelly	Julian	Alex
Speed of knowledge acquisition	1. Usually, if you are ever going to understand something in science, it will make sense to you the first time.	5	2	1
(Quick learning)	2. Working hard on a difficult scientific problem for an extended period only pays off for really smart students.	5	2	1
	3. If I try to integrate new ideas in a science textbook with knowledge that I already have about a topic, I will just get confused.	5	4	1
	4. Almost all the information I can understand from a scientific/science textbook, I get during the first reading.	4	2	1
	5. Learning science is a slow process of building up knowledge.	3	5	3
Speed of knowledge acquisition	6. Re-reading a difficult chapter in a scientific/science textbook does not necessarily mean that I will understand it better.	3	5	5
(Effort)	7. Most scientific concepts have a clear meaning.	1	4	4
	8. I get a better understanding if I re-read a chapter from a scientific textbook several times.	3	2	1
	9. If there is something I don't understand right away in science, I continue to try hard to understand.	5	5	5
Successful students	10. Successful students in science understand things quickly.	3	2	1
	11. Some people are born to be good learners in science, others are stuck with a limited ability.	5	4	4
	12. Being able to memorize a lot of facts in science makes you a good student.	5	2	1
	13. When failing a test in science, it is usually because I did not study hard enough.	3	5	1
Certainty and Truth	14. If scientists try hard enough, they can find the answer to almost every question.	4	4	1

	15. Science is based on certainties that will most likely not change over time.	4	5	1
	16. I believe most things I read in the papers about the greenhouse effect.	4	3	1
Construction and Modification	17. When I encounter a difficult scientific concept in a textbook, I make efforts to work it out on my own.	5	5	5
	18. It's fun to think and reflect on questions in science that even experts fail to agree upon.	2	5	5
	19. Wisdom is not necessarily knowing the answers, but knowing how to find the answers in science.	5	5	5
	20. When learning science, the most important thing is to think creatively.	3	5	5
	21. I always try to assess the trustworthiness in what people, even experts, say about science.	3	4	5
Source/ Authority	22. Sometimes I accept an answer from a teacher, even though I may not understand it.	1	5	1
	23. I find students that challenge the knowledge of teachers a bit full of themselves.	4	3	1
	24. When I encounter a difficult scientific concept in a textbook, I ask my teacher right away.	1	1	2

Appendix B

Interview guide

The student and the researcher reviewed the screen recordings from each saved solution while the student answered the following interview questions.

1. What were your thoughts and expectations about coming and take part in the computer simulation task?
2. How were you thinking when producing your solutions? Any specific aims and goals?
3. In what ways are your suggestions for equilibrium different?
4. Are any of the solutions more advance/complex? Why?
5. Was it easy or difficult to come up with the different solutions? Why?
6. Is there any rule for predicting when equilibrium can be achieved? If so, which kind?
7. Suppose this activity was a task in a physics lesson in upper secondary school. Do you think that this kind of task could have enabled you to learn more about equilibrium?
Why/why not?
8. What do you perceive as important in this task? Why?

Appendix C

Chronological data for coding

In this framework, the following central steps in mathematical problem solving are identified: 1) Understand the problem, 2) Make a plan, 3) Carry out the plan, and 4) Look back. The first step activates a conceptual understanding of the context indicated by the concepts students use and how they use them. The second and, in particular, the third steps are expected to reveal problem-solving strategies. The fourth step is expected to contain an evaluation aspect and can reveal metacognitive information of students' own progress. Polya suggested two main approaches that can be adopted when carrying out a problem-solving plan: Guess or Think. The guessing approach reveals typically no systematic features and involves trial-and-error and "acting it out" using whatever equipment and tools are available. The thinking approach contains several strategies showing a certain amount of systematic behavior that will keep the focus on the problem, such as looking for patterns, using symmetry, working backwards from the answer, using formulas, or using known skills from other problems.

P1) Understand the problem – shows 'conceptual understanding' through concepts used (CU)

P2) Make a plan, - show 'problem-solving strategies' (PS)

P3) Carry out the plan, - show 'problem-solving strategies' (PS)

P 4) Look back – 'self-evaluation' (SE)

Guess/ Think

Extract: solution 1 for Nelly

Solution 1, complexity level 1, turns simulation off/on 14 times

Talk (audio)	Action (video)	Polya and codes
This is harder than I expected!		
	<p>Starts with assembling the seesaw. Puts on a small pink standard block and then presses play in the simulation, the seesaw tilts. The simulation is off. Changes to a blue small standard block instead, starts the simulation, stops, and then puts on a pink standard block on the other side. Adjusts the positions of the blocks while the simulation is off.</p> <p>Reads the instructions.</p> <p>Starts with the first solution, opens the standard scene in the computer.</p> <p>Reads the instructions again. The simulation is turned off; she removes all the blocks and puts the board on top of the support triangle.</p>	<p>P2 and 3</p> <p>PS Guess: Trial and error strategy</p>
<p>I'll start by moving the different rectangular and square figures and the red long stick. I'll move the red triangle to the middle and put the red stick on top of it. And it is supposed to be able to swing freely. By this, I'll try to get it as even as possible.</p>		<p>P1</p> <p>CU – getting the board straight, limited knowledge of concepts</p>

		P2 PS Guess – trial and error
	She moves the board around in order to get it in the middle on the support triangle	P3 PS Guess – trial and error
The stick is now not completely straight, but I'll try to find some method for getting this as straight as possible.		P1 CU – getting the board straight P2 PS trial and error
	Reads the instructions. The simulation is off, moves away all the blocks and puts board on the support triangle.	P3 PS starts again
I'm starting to move these various rectangular and square figures and the red long stick. Move the red triangle to the middle and put the red pin/stick on top. And it is supposed to be able to swing freely. By help from this, I will try to get it as smooth(/even?) as possible.		P1 CU – to get the board even P2 PS Guess- more trial and error

	She begins to put on a little blue standard block on the far left, then starts the simulation. The attempt fails. The simulation is off. She puts on a big purple standard block on the right which falls off. Turns the simulation off again. She puts on a little pink block to the left, the simulation is off.	P3 PS more trial and error
I probably use the rest of the figures and put them the furthest out on the narrow red pin and I'll try to get it as even as possible so that it weighs the same on both sides.		P1 CU no change P2 PS Think – using symmetry
	She presses play and the simulation is running but the attempt fails.	P3 PS trial and error
This was very tricky!		
	She puts a green big standard block to the right, starts the simulation, the attempt fails. Adjusts the board, the simulation is running. Turns off simulation.	P3 PS – more trial and error
What I am really trying to do, is to get the red pin on the top of the red the triangle. Then start placing blocks on the side that is at the top to get a good [smoothness]		P1 CU – no change P2

		PS – more trial and error
	She starts the simulation	
A bit hard!		SE - same
	Puts a small standard block on the board, the simulation is running. Adjusts the block.	P3 PS – more trial and error
But I will most likely manage this after a while!		P4 SE – believes in her PS of trial and error Confident
	Turns the simulation off, moves the block, restarts the simulation again. Turns off the simulation. Adds a small yellow block to the right	P3 PS more trial and error
Now I am happy with the setup, and have used the pink on the left side of the seesaw and also a similar shaped figure. Thus, a square to get it at an even level.		P4 SE – seems satisfied that she is getting somewhere by trying all the blocks in turn, Confident

		CU no change
	She starts the simulation, the board tilts. Removes the yellow standard block and moves the pink standard block further out on the board to the right. Puts on the yellow block again.	P3 PS – more trial and error
I am fairly pleased now, it is (the seesaw) kind of straight. And to get the seesaw as straight as possible, I need to use a yellow square and put it at the far right side. It won't be as heavy then.		P4 SE – is satisfied that she will get somewhere Proud of attempts
	Restarts the simulation, the board tilts. Turns off the simulation and moves the position of the blocks.	P3 PS fails
I move these squares, depending on how the board swings. If one side is higher, I try to move the square which is on the side further towards the end of the board and the second block closer to the center to get a better balance on the board.		CU is the same, commentary seems contradictory to how the problem can be solved
	Adjusts the blocks while the simulation is running. (On both sides)	P3 PS more trial and error

Now I think that I have made a good one (referring to the seesaw) The stick is somewhat straight.		P4 SE – believes she has a successful result Confident
	Reads the instructions. Saves solution no.1 at the computer. She thinks that she achieved equilibrium but never starts the simulation so she can't really know if she actually achieved it.	CU – satisfied that T and E will enable board to balance? PS – does not go beyond trial and error

Post interview, whilst viewing the solutions

interviewer	response	Comment/Polya code
Have a look at the first solution. How did you reason?		
	Yes, this was the first one... I didn't think that much, only to put it (the board) there: And then pause the simulation when I thought it looked ok.	All 'Guess' no 'Think'