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# The effects of problem-based learning scaffolds on cognitive load, problem-solving, and student performance within a multimedia-enhanced learning environment

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# The effects of problem-based learning scaffolds on cognitive load, problem-solving, and student performance within a multimedia-enhanced learning environment

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## Dissertation

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# Dedication

*For Paxton*

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**The effects of problem-based learning scaffolds on cognitive load, problem-solving, and student performance within a multimedia-enhanced learning environment**

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Abstract: Learners who are novice problem solvers often encounter difficulty when solving complex problems. One explanation for this difficulty is that the cognitive requirements of problem-solving are sufficiently high that learners easily become overwhelmed and frustrated, leading to a state known as cognitive overload in which learning is obstructed. Cognitive Load Theory is concerned with the design of instructional approaches intended to manage the cognitive load required for thinking and problem-solving tasks. Scaffolds are any kind of support that facilitates the accomplishment of a difficult task that a learner would not be able to accomplish on their own. They are potential mechanisms to support students in negotiating the potentially high cognitive load required by complex problem-solving. The purpose of this study was to examine the effects of technology-based scaffolds within a problem-based learning environment known as *Alien Rescue*. The study investigated the impact of scaffolds on cognitive load, problem-solving behaviors, science knowledge, and student perceptions of the learning environment. Participants for this study included sixth grade students from a suburban middle school in the southwestern United States. Student classes were assigned to one of three treatment conditions: (a) a problem constraint condition in which students were guided through a problem-solving process similar to that of an expert, (b) a prompt condition in which students were provided with guiding messages during problem-solving, and (c) a control condition with no scaffolding. All conditions participated in the use of *Alien Rescue* for three weeks. Measures including a self-report measure of mental effort, calculated instructional efficiency scores, problem solution scores, student activity logs, and science knowledge test performance were used to evaluate students' cognitive load, problem-solving performance, problem-solving strategies, and learning gains. An open-ended questionnaire and student interviews were used to gather data on students' perceptions of the program. Results of the study indicate statistically significant differences between treatment conditions with respect to problem-solving efficiency, student problem-solving behaviors, and scientific knowledge gain. Additionally, qualitative findings highlight problematic aspects of the highly structured condition as implemented within the classroom context while also identifying components of the learning environment that were perceived as helpful and useful to participants. Teacher interviews also provided insight into classroom implementation of the program and opportunities to further enhance scaffolds to support student learning. Implications of the study from research, instructional design, and technology perspectives are discussed along with a treatment of study limitations and opportunities for further research in this area.

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# CHAPTER 1: INTRODUCTION

## Significance of the Study

Technological tools continue to grow in complexity and sophistication and are increasingly harnessed by teachers, instructional designers, and innovators to transform teaching and learning. Technology-based learning environments, in particular, hold great promise for delivering virtual, yet authentic, contexts within classroom settings that engage students in inquiry, problem-solving, and knowledge construction. The emergence of these learning environments corresponds with fundamental shifts in our views of learning that emphasize learner-centeredness. Learners who participate in these new learning environments do so with an increased sense of agency, taking responsibility for planning and executing their own learning activities, collaborating alongside other learners, engaging with problems and situations that reflect the messy, complex nature of real-world contexts, and, consequently, developing, evaluating, and refining their own knowledge.

Novice learners, however, often lack preparedness and skill to interact productively within open-ended learning environments (Krajcik et al., 1998). Across the literature, three issues continue to emerge that underlie the challenges that students face in these environments. First, the diversity and number of components within open-ended learning environments can overload students' thinking processes, leading them to become overwhelmed, frustrated, and confused. Second, students often lack experience and knowledge of problem-solving and learning strategies that allow them to make best use of the learning space. Finally, in many instances, students lack the domain knowledge to which they can refer to form initial understandings of the problem and consider possible steps to be taken towards a solution.

There are a number of potential explanations for student difficulty in open-ended problem-solving. One such explanation is found within Cognitive Load Theory. Cognitive Load Theory is concerned with the role of working memory in learning. Because working memory has an extremely limited capacity, it can easily become overloaded. Cognitive load theorists are concerned with the design of instructional experiences that prevent cognitive overload and allow learners to direct cognitive capacity towards creating and refining their knowledge. A significant number of research studies have identified the role of cognitive load in learning and various strategies for managing it.

Problem-based learning environments represent an approach that engages learners in solving messy, realistic problems. Students engaged in problem-based learning are presented with a problem, generate an initial understanding or representation of the problem, conduct research to better understand the problem and generate potential solutions, undertake processes for evaluating and selecting viable solutions, and articulate and justify the reasons for their choices. Viewed through the lens of cognitive load theory, many researchers believe that open-ended problem-solving can generate unproductively high levels of cognitive load. For novice learners to be productive, they require access to support, guidance, and tools that can reduce the complexity of the problem-solving environment, offload complex tasks, and provide direction and feedback on problem-solving approaches.

Combining technology tools and skilled teachers holds significant potential for providing the types of support that allow students to build expertise within these environments and become independent learners. Problem-based learning researchers, in particular, consider the role that scaffolding and cognitive tools can play in the process of complex problem-solving, particularly among novices who lack the necessary knowledge and skill to be productive. Scaffolds are supports that can facilitate the accomplishment of a task that a learner would otherwise be unable to accomplish on his or her own. Scaffolds can be implemented in the form of teacher-driven guidance and feedback and through technology-based tools. Cognitive tools are technology-based supports that extend and enhance the cognitive abilities of learners during thinking and problem-solving.

There is a lack of research investigating the role of problem-based scaffolds and cognitive tools in managing the cognitive load of novice problem solvers. Likewise, clearer understandings of how various forms of scaffolding influence problem-solving behaviors and learning outcomes within student-centered learning environments are also needed.

## Purpose of the Study

The purpose of this study was to investigate the role of various forms and levels of technology-based scaffolds as students engage with a multimedia-enhanced, problem-based learning environment known as *Alien Rescue*. *Alien Rescue* engages students in finding homes in our solar system for six alien species that have been displaced from their home planets. Each alien species has specific habitat requirements. To be successful within the environment, students must carefully consider the needs of the aliens, identify potential planets and moons that correspond to those requirements, generate and test hypotheses, and articulate well-justified solutions. *Alien Rescue* provides a number of cognitive tools that support various aspects of problem-solving. However, as currently implemented, the program provides very few scaffolds that guide students in applying an effective problem-solving strategy. This study implemented two different forms of scaffolding and a minimal scaffold control treatment within *Alien*

*Rescue* to better understand the role of technology based scaffolds in managing cognitive load, promoting the acquisition of scientific knowledge, and fostering effective problem-solving practices.

## Research Questions

Specifically, the study sought to investigate:

1) How do varying levels of scaffolding affect students' cognitive load, as measured by instructional efficiency?
2) What are the characteristics of problem-solving behavior among students who receive different forms of guidance?
3) How do different forms of guidance effect students' content knowledge and performance within the problem-solving scenario?
4) What are student and teacher perceptions of *Alien Rescue* and the different treatment conditions?

## Definitions

**Cognitive Load.** The cognitive burden placed on working memory due to the complexity of materials, the design of instruction, or processes of knowledge building

**Cognitive Tools.** Technology-based tools that extend the cognitive ability of learners

**Problem-based learning.** An instructional approach in which students solve ill-structured problems in a self-directed manner

**Scaffolding.** Supports that enable learners to accomplish tasks that they would be unable to complete independently

**Instructional efficiency.** A measure that relates the cognitive effort required to complete a task to a learner's performance on the task. Highly efficient instruction requires a low amount of cognitive load to achieve a high level of performance.

# CHAPTER 2: REVIEW OF LITERATURE

The following sections summarize the predominant learning theories of the past century, specific elements of learning theory that influence the design of student centered learning environments, and the role of scaffolding and cognitive tools in supporting learning. In addition, I discuss the foundational characteristics of problem-based learning and consider the ways in which technology-based learning environments can be used to support the implementation of PBL.

## Theoretical Foundations

### BEHAVIORISM

Behaviorism was the dominant theoretical perspective in instructional technology for over 60 years (Burton, Moore, & Magliaro, 1996). In 1913, John Watson defined behaviorism in his work "Psychology as the Behaviorist Views It." According to Watson, behaviorism is a purely objective branch of science concerned with the prediction of responses to environmental stimuli (Watson, 1913). Watson charged psychologists to eschew terms such as "consciousness, mental states, mind, content, introspectively verifiable, imagery, and the like" (p. 166). Behaviorism, as described by Watson, is unconcerned with internal mental states, focusing instead on the observable relationships between stimuli and subsequent responses (Boghossian, 2006; Burton, Moore, & Magliaro, 1996). This relationship between stimulus and response was largely based on Pavlov's conditioning model and believed by Watson to account for learning and personality development (Burton et al., 1996; Schunk, 1991).

Based on early views of behaviorism, Sidney Pressey developed a series of devices that implemented stimulus and response as an instructional method (Petrina, 2004). The "Automated Teaching Machine" prevented progress from one multiple-choice question to the next until the student provided the correct response. It also delivered repeated practice on those items that students initially missed (McDonald, Yanchar, & Osguthorpe, 2005; Skinner, 1986). Pressey's approach provides an early example of behavioristic programmed instruction, in which patterns of stimulus and response were geared toward shaping a final behavior (Cooper, 1993).

Behaviorism considers how consequences to a given response shape behavior (Burton et al., 1996) and features prominently in the work of B.F. Skinner (Delprato & Midgley, 1992; Schunk, 1991). Given this perspective, behaviorism views learning as occurring through learners' reactions to conditions within the environment and shaped through reinforcement and correction (Ertmer & Newby, 1993; Winn, 1990). Reinforcers enhance the likelihood that a learner will provide a given response when encountering a specific stimulus (Schunk, 1991). Skinner describes both positive and negative forms of reinforcement; positive reinforcements are additional stimuli that can be used to shape a behavior, while negative reinforcers remove undesirable stimuli. The use of conditioning supports processes of successive approximation, wherein reinforcement and punishment are applied to promote a gradual refinement in the learner's behaviors.

Behaviorists make no attempt to ensure the articulation between instruction and students' existing knowledge. Because the act of knowing or, indeed, the existence of the mind is unobservable through objective means, behaviorists are unwilling to acknowledge them. Rather, behaviorists are essentially concerned with investigations of human behavior (Jonassen, 1991). Knowledge, according to behaviorist thought, is manifested only in the observable patterns of stimulus and response. Learning is simply a process of strengthening or weakening those patterns (Collins, Greeno, & Resnick, 1996). This reliance on behavior alone as evidence of knowing and learning is a defining characteristic that differentiates behaviorism from the cognitive perspectives that would emerge in the mid 20th century.

## COGNITIVISM

In the late 1950's, theorists began to challenge the behaviorist assumptions that failed to acknowledge the presence or role of internal mental states. Chomsky (1959), for instance, proposed that behaviorism, and its emphasis on externalized patterns of stimulus and response, was insufficient to explain processes of language learning. Learning theorists began to embrace the cognitive sciences and the role of mental processing and memory in learning (Ertmer & Newby, 1993). I will consider a number of general assumptions commonly found within cognitive perspectives, including the active role of the learner, the manner in which knowledge is organized, learning as a process of change in knowledge structures, and the objective nature of the cognitive perspective.

### Assumptions of Cognitivism

#### *Knowledge structures*

As noted by Ertmer and Newby (1993), "cognitive theories stress the acquisition of knowledge and internal mental structures; they focus on the conceptualization of students' learning processes and address the issue of how information is received, organized, stored, and retrieved by the mind." In this way, cognitive perspectives broadly consider the manner in which knowledge is structured in memory (Schmidt, 1993; Ormrod, 2004). The manner in which learners form knowledge representations is dependent on their existing knowledge structures (Glaser, 1991). These knowledge structures develop and become increasingly well-structured through learning, providing learners with sophisticated mental models that guide problem-solving activities; for this reason, expert and novice problem solvers approach problems in fundamentally different ways (Glaser, 1991; Shuell, 1986).

### ***Learning as a change to knowledge structures***

According to Jonassen (1991), cognitive perspectives are less concerned with behavioral responses, but instead focus on "what learners know and how they acquire it" (p. 6). Cognitive perspectives stress the role of mental processing in responding to environmental stimuli. Processes of knowledge acquisition within cognitive learning theory focus on the manner in which the learner processes, encodes, and stores information (Ertmer & Newby, 1993). Learning, according to Langley and Simon (p. 367), is concerned with making changes to a system in order to improve performance on subsequent and similar tasks (1981).

### ***Learners are active***

Central to cognitive conceptions of learning is the idea that learners are engaged in constructive mental activity (Glaser, 1991) and that learning is dependent on learners' mental effort (Shuell, 1986). As Glaser notes, "students' active processing of information in instructional exchanges with a teacher should support knowledge construction and develop the abilities that enable students to build from what they know."

### ***Objectivism***

Cognitivism is concerned with the objective and systematic observation of cognitive processes. Similar to behaviorists, cognitivists derive theories from empirical research. As Ormrod notes, however, cognitivists differ from behaviorists in that they infer internal mental processes based on observable behavior (Ormrod, 2004).

Though there are a variety of perspectives that fall under the cognitive theory, one of the most prominent is the range of theories that comprise Information Processing Theory.

## Information Processing Theory

Information Processing Theory considers the ways that humans receive information from the environment, create organized mental structures that store information, and utilize strategies to retrieve information from memory (Ormrod, 2004). The most common model of human information processing includes a sensory register, used to perceive information from the environment, alongside a dual-component model of memory, composed of a working memory component used to manipulate and temporarily store information and a long-term memory component that is used to form associative mental structures that allow humans to retain and retrieve information (Atkinson & Shiffrin, 1968).

### *Working Memory*

Working memory is analogous to consciousness and provides the mechanism through which humans process information (Schunk, 1991; Sweller, van Merrienboer, & Paas, 1998). As Bower (1978) notes, the purpose of working memory is to maintain a model of the environment and recent events. Information held in working memory is understood to have an extremely limited lifespan, on the order of 30 seconds, if not rehearsed (Peterson & Peterson, 1959). Similarly, working memory has a finite capacity that limits human ability to manipulate more than around seven pieces of information at once (Miller, 1956). Central control processes can be used to direct the way in which working memory processes information, including the movement of knowledge in and out of memory and the use of strategies such as rehearsal, that can be used in part to overcome the limitations of working memory (Baddeley, 2001; Peterson & Peterson, 1959; Rieber, 1994; Schunk, 1991).

Working memory is also understood to have auditory and visual components. Baddeley (1992) proposed a model including three stores: a phonological loop, a visuo-spatial sketchpad, and a central executive. The phonological loop is responsible for processing auditory information such as verbal information. The visuo-spatial sketchpad is responsible for processing visual information, such as graphics (Kalyuga, Chandler, & Sweller, 1999). The central executive coordinates working memory and moves information in and out of long-term memory.

***Long-term Memory***

Long-term memory can store apparently unlimited amounts of information (Sweller. van Merriënboer, & Paas, 1998). Learning occurs due to changes to long-term memory (Kirschner, Sweller, & Clark, 2006) through the formation of schema (Schunk, 1991). Schemas are cognitive constructs that organize information according to the way in which it will be used (Sweller & Chandler, 1994). These cognitive constructs are formed via associative structures to create a representation in memory; these associations are strengthened the more frequently a memory is accessed (Bower, 1978; Schunk, 1991). An additional function of schema is to increase the amount of information that can be held in working memory by chunking discrete pieces of information into larger groups (Sweller, 1994).

Sweller (1994) presented a number of example schemas. For instance humans form schemas for recognizing and classifying animals or making sense of text based on only some of the letters or words. Likewise, expert learners engaged in problem-solving may possess schemas that direct their problem-solving strategies and enable them to focus on those aspects of the problem that are most relevant to achieving a goal.

Activation of memory occurs when querying long-term memory for specific information, a process that is essentially instantaneous (Cooper, 1998). Knowledge schemas that are frequently activated can become automated. Automation enables people to apply cognitive processes without consciously attending to them. As Sweller (1994) notes, automated schemas stored in long-term memory can reduce the burden on working memory. Sweller offers the example of a student who is competent in algebra and has established a schema for multiplying out the denominator in an algebraic equation. Because of the existence of this schema, the student can immediately recognize and solve problems that require this step. Given the practice involved in developing automated schema, such schema typically only develop for tasks that are consistent across a variety of problems, common examples being schema for dealing with standard positions in chess or using software applications (Merriënboer & Sweller, 2005).

The presence of domain specific knowledge in the form of schemas is a defining characteristic of experts. Differences between novice and expert problem solvers can be explained by the way in which schemas direct problem-solving strategies (Sweller, 1988). One area in which expert/novice differences are manifested is in the cognitive load required to address a complex problem, an issue that is addressed through cognitive load theory.

**Cognitive Load Theory**

Because working memory has a finite capacity, it can easily be overwhelmed by the requirements of a cognitive task. Cognitive load is a term that describes the total amount of mental activity required of working memory at any given time (Cooper, 1998). Cognitive Load Theory (CLT) is concerned with the limitations of working memory and the design of instructional materials to achieve adequate levels of cognitive load (Kirschner, 2002; Sweller et al., 1998). The design of instruction can influence cognitive load; poorly designed learning activities can impose cognitive load that is not relevant to the process of creating or restructuring mental schemas and therefore interferes with learning (Chandler & Sweller, 1992). Given this view, CLT has clear instructional design implications. Designers must consider and address the possibility of learners achieving a state of cognitive overload in which they have exhausted their existing cognitive capacity (Mayer & Moreno, 2010), leading to unproductive learning. There are three forms of cognitive load that should be considered in the design of instruction: intrinsic cognitive load, extraneous cognitive load, and germane cognitive load.

### *Intrinsic Cognitive Load*

Intrinsic cognitive load is related to the nature of the material being presented. The extent to which elements of the materials to be learned interact, termed element interactivity, is one mechanism that drives intrinsic cognitive load (Sweller & Chandler, 1994). Instructional materials that feature high levels of element interactivity are difficult to learn; understanding in these cases is dependent upon the development of cognitive schemas that incorporate the interactive elements (van Merriënboer & Sweller, 2005). Elements that interact very little impose a small amount of cognitive load (Paas, Renkl, & Sweller, 2003). As Paas et al. note, knowing the purpose of the 12 function keys within a photo-editing program involves understanding of relatively discrete pieces of information with limited interaction. Elements that interact with other elements impose significantly more intrinsic cognitive load. The process of editing a photo in a photo-editing program, to continue with the example from Paas et al., requires knowledge of a high number of interactive elements.

Because intrinsic cognitive load is a function of the material and the learner, it cannot be altered (Sweller et al., 1998). To achieve a measurement of intrinsic cognitive load, we can count the number of elements that must be simultaneously processed in working memory in order to learn a particular process (Sweller & Chandler, 1994). As described by Sweller and Chandler (1994), that which constitutes an element can differ based on the expertise of the individual. Individuals with a high level of expertise around a particular topic may already possess an automated schema that includes the interacting elements.

### *Extraneous Cognitive Load*

Extraneous cognitive load is affected by the ways in which the material is presented or the specific activities in which the learners are engaged. Extraneous cognitive load requires learners to engage in cognitive activities that are unrelated to schema construction or automation. To facilitate learning, extraneous cognitive load can be considered when developing instructional interventions (Sweller et al., 1998). For example, instructional designers can structure the organization of materials or ensure that learners are presented appropriately framed, typically non-specific, goals designed to reduce element interactivity.

### *Germane Cognitive Load*

Germane cognitive load relates to the effort involved in the conscious construction of schemas (Sweller et al., 1998). The implications of germane cognitive load are focused on learning activities in which intrinsic and extraneous cognitive load are sufficiently low as to result in unused surplus cognitive capacity. Instruction that produces an increase in germane cognitive load by directing the user to consciously engage in schema construction can result in more productive learning.

### *Additive Nature of Cognitive Load*

Intrinsic, extraneous, and germane cognitive load are additive, meaning that when intrinsic cognitive load is high, extraneous cognitive load must be lowered such that it fits within working memory limits. Likewise, when intrinsic cognitive load is low, instructional activities that impose relatively high levels of extraneous cognitive load may not be detrimental to the extent that total cognitive load falls within the limits of working memory (van Merriënboer & Sweller, 2005; Paas et al., 2003).

### *Worked Example Effect*

The worked example effect involves providing students with procedural solutions to problems (Sweller, 2010; Sweller, Ayres, & Kalyuga, 2011). As with the goal-free effect, problem-solving requires novices to consider a large number of interacting elements. Rather than acquiring problem-solving schemas through the act of solving problems, engaging students in studying worked examples is intended to be an efficient method of schema acquisition.

A recent study on college students supports the use of worked examples in both group and individual settings (Retnowati, Ayres, & Sweller, 2010). The study was conducted across four conditions in which students were assigned to individual work or group work and exposed to either worked examples or minimally guided problem-solving. Students were then tested on similar problems, conceptually different problems as a test of transfer, and numerical and reasoning skills. Results indicated that students who received worked examples performed significantly higher on every measure than students who did not.

### *Problem Completion Effect*

Similar to the worked example effect, the problem completion effect (Sweller et al., 2011) was intended to address concern that learners, in being provided with worked examples, were engaged in passive learning. Problem completion can involve several strategies that actively engage learners in acquiring problem-solving schema. One approach involves alternation between worked examples and active student problem-solving, such that students immediately apply the example strategies within their own approaches. Another strategy involves the presentation of partially completed problems that learners complete on their own.

### *Expertise Reversal Effect*

The expertise reversal effect occurs when a learner's expertise interacts with instructional design elements, such as worked examples, intended to manage cognitive load. When this occurs, learners are required to devote cognitive effort to process the information and compare it to their existing knowledge structures (Kalyuga, Rikers, & Paas, 2012). This process reduces the cognitive resources available for schema construction and limits opportunities for learning (Sweller et al., 2011). For example, for a student who has developed a sophisticated problem-solving schema, the delivery of worked examples is not relevant to their processes of schema construction and negatively impacts learning by requiring the learner to process the examples.

A recent study by Rey and Fischer (2013) sought to investigate the influence of instructional explanations on the expertise reversal effect among college students. The study was successful in replicating the expertise reversal effect. The study found that novices who received instructional explanations of statistical methodologies performed better on transfer than students who did not receive explanations. Among experts, however, the study indicated that those who received the explanations performed worse on transfer and spent marginally more time completing the task than those who did not receive explanations.

### *Guidance Fading Effect*

The guidance fading effect is related to the expertise reversal effect. For more advanced learners, the performance of problem-solving in absence of assistance is likely to be more productive than when provided with worked examples and other redundant supports that are not required for them achieve success (Sweller et al., 2011). Guidance fading simply refers to the practice of gradually removing support as learners gain competence and the support becomes unnecessary.

## Metacognition

A key principle that originates within cognitive perspectives is that of metacognition. Metacognition is a term first introduced by Flavell (1979) and essentially involves a process of thinking about thinking. According to Ormrod (2004), metacognition includes the following knowledge and skills:

- Having an awareness of learning and memory capabilities along with knowledge of what can be reasonably accomplished;
- Knowing which learning strategies are the most useful;
- Capability to plan an effective learning strategy;
- Using effective learning strategies;
- Monitoring one's own knowledge; and
- Possessing strategies for retrieving information.

Metacognition is of particular importance within problem-solving (Ge & Land, 2003; Martinez, 1998) in which the learner must frequently monitor and adjust their knowledge and strategies related to a goal. In an early study by Swanson (1990), metacognitive ability was a significant predictor of performance within problem-solving.

### Self-regulation

Self-regulation builds on metacognition and considers the ways that learners apply specific strategies to achieve learning goals. There are a number of models of self-regulation (Hadwin & Winne, 2001; Pintrich, 2000; Zimmerman, 1989), but most models typically emphasize monitoring and control of cognitive processes, behaviors, and environmental factors during learning (Lajoie, 2008). Self-regulation is believed to be cyclical in nature wherein the results of prior learning experiences are used to adjust processes for future learning (Puustinen & Pulkkinen, 2001). Self-regulated learners typically demonstrate goal setting, planning, self-motivation, attention control, application of learning strategies, self-monitoring, self-evaluation, and self-reflection (Ormrod, 2004). Azevedo (2010) describes self-regulated learning as "an active process whereby learners set learning goals and then attempt to monitor, regulate, and control their cognitive and metacognitive processes in the service of those goals" (p. 229). Like metacognition, self-regulation is a significant aspect of self-directed learning approaches that require relatively independent thinking and problem-solving, such as PBL.

## CONSTRUCTIVIST PERSPECTIVES

Whereas cognitive learning theories stress the acquisition of knowledge, constructivist learning theories consider the role the learner plays in constructing their own knowledge. Perhaps the most distinguishing claim of constructivism is the idea that the learner constructs an independent reality based on his or her personal experiences and perceptions of the world (Cooper, 1993). As Jonassen (1991) notes, the process of knowledge construction is influenced by prior experience, existing cognitive structures, and the beliefs through which one interprets objects and events. As described by Ertmer (1993), constructivists do not share the behaviorist and cognitive belief that knowledge is objective and mind-independent. Constructivists do not deny the existence of an external reality, but consider knowledge construction to occur both individually and through our social interactions and experiences (Ertmer & Newby, 1993; Jonassen, Cernusca, & Ionas, 2007).

Constructivist perspectives have significant implications for processes of instructional design, fostering a shift towards the design of learning environments that engage learners in authentic fields of practice. Constructivists favor experiences that reflect the messy attributes of real-world problems (Lebow, 1993). Learning environments that make use of simulation, problem-solving and inquiry, apprenticeship, and communities of practice are all consistent with constructivist views on learning (Jonassen, Cernusca, & Ionas, 2007).

While constructivism as a term refers to a wide range of theoretical perspectives, two of the most prevalent are cognitive constructivism and social constructivism. The related perspective of situated cognition, in turn, builds on many elements of both perspectives, but draws substantially from social constructivism.

**Cognitive Constructivism**

Cognitive constructivist perspectives are often ascribed to Piaget and center on the notions of cognitive equilibration and schema. Learners encounter cognitive conflict, or disequilibration, when their current knowledge is found to be inconsistent with their experience (Palincsar, 1998). When learners encounter disequilibration, they first attempt to incorporate new information into their existing cognitive structures through a process known as assimilation. When existing knowledge structures are found to be inconsistent with new information, learners must undergo processes of accommodation, whereby schema are modified to incorporate the new information.

## Social Constructivism

Social constructivism is reflected most in the work of Lev Vygotsky (1978). A central tenet of social constructivism is that knowledge construction occurs through a process of negotiation with others and the environment. Through these interactions, knowledge becomes gradually internalized such that a learner acquires the shared knowledge of the community. A key concept of social constructivism that has broad implications for the design of student-centered learning environments is the notion of the Zone of Proximal Development (ZPD).

### *The Zone of Proximal Development*

The ZPD refers to the gap between that which a learner can easily accomplish on their own and that which they can only accomplish through the support of an expert or more capable peer. Instruction within social constructivist perspectives involves determining a learner's position on the ZPD and offering an appropriate level of support designed to facilitate the development of independent thinking and problem-solving skills. The notion of the ZPD provides essential guidance for the implementation of scaffolds in technology-based learning environments, particularly within problem-based learning environments.

## Situated Cognition

Brown, Collins, and Duguid (1989) argued for the situated nature of cognition, declaring that knowledge was inseparable from the context and activities through which it was learned. According to their view, situations and learner activity co-produce knowledge. These theories further specify the manner in which learners engage in knowledge building, address the important dimension of learning in context, and further elucidate the manner in which learners engage in a dialectic interaction with their environment and its affordances. These situated theories have been applied broadly within the field of instructional technology and underscore the manner in which well-designed technologies can be used to create context-rich learning experiences that address many weaknesses of the traditional classroom.

Situated cognition suggests that learning occurs in a variety of multiple interdependent ways through learners' interactions with their environment, engagement in cultural practices, and negotiation with others. At its core, situated cognition seeks to situate knowledge construction within the real-life settings in which the knowledge is commonly applied. As Greeno (1998) notes, situated perspectives are based on the notion that the individual is interacting within systems that subsume the behavioral and cognitive processes of the learner. Within this perspective, the activities of the learner and their environment are considered as a systematic, mutually constructed whole (Bredo, 1994; Hung & Der-thanq, 2001).

In writing on situated cognition, Lave and Wenger (1991) often relate their work to the idea of apprenticeship. Their findings support the idea of learning through social action and a process -- known as legitimate peripheral participation -- through which novice learners acquire expertise in a community of practice by initially engaging in tasks at the periphery of the community. Cognitive apprenticeship refers to processes of learning that feature situated and contextual guidance designed to facilitate the development of cognitive and metacognitive skills (Collins, Brown, & Newman, 1989). Brown, Collins, and Holum (1991) outline several key principles for the design of learning environments. In particular, the authors suggest processes of modeling, coaching, scaffolding, learner articulation of knowledge, reflection, and exploration as ways of promoting the development of expertise. In addition, cognitive apprenticeship seeks to conceptualize larger global tasks before directing students to execute component parts and engage students in tasks that gradually build in complexity as expertise develops.

Many of the notions found within situated cognition are consistent with the sociocultural theory of Vygotsky, particularly with relation to the learner in social context, the internalization of social processes, and the role of the social environment in mediating knowledge building. Most importantly, situated cognition considers the influence of environmental affordances on the learner's knowledge building processes. Affordances provide important support for learners' interactions with their environment, as the properties of the affordance contribute factors that mediate the nature of the learner's interaction (Greeno, 1994). An example of this view of co-construction might be found in a learner attempting to understand a new software application. Characteristics of the software application help define and guide its use. Coupled with the user's interaction with the tool, a relationship is created in which the user and the environment engage in mutual modification (Bredo, 1994); the user shapes the environment while iteratively modifying their interactions with it.

## Problem-based Learning

Problem-based learning represents one methodological approach to the design of student-centered learning environments. Problem-based learning engages students in conducting research and applying knowledge and practical skills in order to develop viable solutions to ill-structured problems (Savery, 2006). It is an instructional approach that was first developed in the 1970's, as many medical institutions began to reform their curricula to emphasize the development of clinical reasoning skills (Barrows, 1996). One of the original goals of PBL was to support students in making use of their knowledge in clinical settings; in one instance fewer than 50% of physicians receiving traditional non-

PBL instruction were able to perform a clinical task, whereas 82% of those physicians performed well on a test intended to measure their ability to perform the task (Schmidt, 1983).

Savery and Duffy (1995) compiled eight constructivist principles that guide the design of problem-based learning environments. Those principles are:

1) Anchor all learning activities to a larger task or problem;
2) Support the learner in developing ownership for the overall problem or task;
3) Design an authentic task;
4) Design the task and the learning environment to reflect the complexity of the environment the learner should be able to function in at the end of learning;
5) Give the learner ownership of the process used to develop a solution;
6) Design the learning environment to support and challenge the learner's thinking;
7) Encourage testing ideas against alternative views and alternative contexts; and
8) Provide opportunity for and support reflection on both the content learned and the learning process.

**PROBLEMS AND PROBLEM-SOLVING**

Jonassen (2000) describes two attributes of a problem. First, it is an unknown entity in some situation that represents the difference between the current state and the goal state. Second, the act of finding or solving for the unknown should have some social, cultural, or intellectual value.

Problems have different levels of structure and complexity (Jonassen, 2000). Well-structured problems have concrete solutions, present all relevant elements to the learner, and require the application of a limited number of well-structured rules and principles. Ill-structured problems may have unknown elements, possess multiple solutions, have multiple solution criteria, and require problem solvers to exercise judgment and express personalized opinions and beliefs. Complexity relates to the number of interacting elements within a problem and governs the difficulty of the problem.

Jonassen (2000) also notes that problems possess some measure of domain specificity and are dependent on the context in which they are embedded. Ill-structured problems are often more situated than well-structured problems. An important consideration in designing for problem-solving is the manner in which a problem is represented. Within PBL, problems are often designed to have high levels of fidelity, meaning they are often presented with the natural complexity and messiness of real-world problems.

The selection of an appropriate problem is an important aspect of PBL. According to Hmelo-Silver (2004), problems need to be complex, ill-structured, and open-ended, yet also posses a realism that resonates with students' experiences. Good problems provide inherent opportunities for feedback through which students can evaluate their knowledge. The level of familiarity with a problem is also a consideration. Problems with which learners are highly familiar may lend themselves to routine problem-solving approaches. Because expert learners may have an existing schema for a familiar problem, it may appear more structured than an unfamiliar problem (Jonassen, 2000).

Problem-solving, according to Jonassen (2000) has two features. It requires the problem solver to generate a mental representation or mental model of the problem, a concept known as the problem space. Secondly, problem-solving requires some manipulation of the problem space, whether it is via the internal mental representation of the problem or an external physical representation.

According to van Merriënboer (2013), there are several types of problem-solving: weak methods, strong methods, knowledge-based methods, and real-life problem-solving.

Weak methods refer to problem-solving approaches used within new, unfamiliar problems in any domain and are most often comprised of means-end analyses concerned with the application of operations designed to reduce the difference between the goal state and the current problem state. In this approach, problem-solving can be cumbersome and require significant cognitive load.

A second approach to problem-solving involves strong methods that can be used to address problems in a specific domain. Van Merriënboer describes the application of if-then rules designed to address a well-structured problem with a knowable, concrete solution. While learners can typically apply strong approaches with little effort, they are specific to domains and problem-solving contexts and often cannot be applied to different types of problems. Strong methods may involve a level of expertise in which the learner has developed automated schema for certain aspects of the problem-solving process.

Knowledge-based methods involve the application of prior domain knowledge and problem experience to develop strategies for addressing an ill-structured problem. In this approach, having a deep understanding of a domain -- including conceptual, causal, and structural models of the domain -- provides the necessary referents for learners to systematically address new forms of problems. The reinterpretation of existing knowledge for use in a new problem scenario requires significant cognitive effort.

Finally, real-life problem-solving involves a mixture of ill-structured and well-structured problem-solving. In real-life problem-solving, strong methods are used for those aspects of the problem that are well understood or routine for the learner, while knowledge based methods support productive engagement with novel aspects of the problem.

## EXPERT PROBLEM-SOLVING

While van Merriënboer and Jonassen suggest the influence that expertise has on problem-solving, a number of additional researchers have more fully considered the role of expertise. A seminal work is Bransford and Stein's (1993) "The Ideal Problem Solver: A Guide to Improving Thinking, Learning, and Creativity," in which the authors propose five components of effective problem-solving, known as the IDEAL model: identifying the problem or problems, defining the problem, exploring possible strategies, acting on the strategies, and looking and learning from the results of the strategies. An examination of this model reveals potential opportunities for technology scaffolds to model and sequence productive problem-solving processes. Gick (1986) proposed a four-component model of problem solving in which learners generate a problem-representation, conduct a search for a possible solution, implement the solution, and, either achieve success or iterate through the steps once again. Central to this model is the notion of schema. In cases where a learner identifies an existing solution schema for a given problem, they are capable of bypassing the search step and proceed to the immediate application of a solution. In this way, learners who have established a high level of expertise in a given problem space have the potential to be more efficient, productive, and successful problem-solvers. Within this study, the most ideal problem-solving schema was similar to the familiar scientific method, and thus, scaffolds were designed to promote application of scientific procedures in achieving a solution.

## CHALLENGES IN IMPLEMENTING PBL

Several researchers illustrate the potential challenges that educators often face in applying problem-based learning (Ertmer et al., 2009; Hoffman & Ritchie, 1997; Jonassen, 2000). Progress in adapting problem-based learning to the classroom has been relatively slow, a trend that many researchers attribute to a lack of pedagogical knowledge on how to effectively engage students in ill-structured problem-solving, a reliance on didactic instructional approaches, and curricular and assessment demands that place substantial constraints on instructional innovation in the classroom (Ertmer, 2005; Kim & Hannafin, 2011). These challenges underscore opportunities for technology-based supports that facilitate the classroom implementation of PBL.

Despite the efficacy of PBL as an instructional approach, middle school students often struggle with the open-endedness and ill-structured nature of problems. In one study (Krajcik et al., 1998), observations of sixth grade students engaged in scientific problem-solving revealed specific challenges in developing appropriate scientific questions, planning and conducting experiments, evaluating data, and articulating findings. Similarly, Land's (1999) meta-analysis on open-ended learning environments suggests a number of ways in which student are often ill prepared for the cognitive tasks such environments require. Students routinely attach meaning to irrelevant information, make biased, incomplete, and unreliable observations, fail to refine problem-solving strategies over time, and attempt to apply incomplete and potentially inaccurate knowledge of the domain. These findings highlight the importance of both teacher-provided and technological support for students engaged in problem-based learning.

### SCAFFOLDING

Scaffolding is the primary mechanism through which support is provided within problem-based learning. Wood, Bruner, and Ross (1976) identified scaffolds as any form of assistance or support that a learner receives in order to accomplish a task that is too difficult for them to complete unassisted. Historically, scaffolding considers the role of an expert, often a teacher, who could provide the necessary guidance or support for a less expert learner or apprentice (Collins, Brown, & Holum, 1991). While teachers continue to play a significant role in scaffolding student learning, in recent years, technology has advanced such that it can be used to support cognitive processes (Pea, 1985). Scaffolding, though never addressed as such directly by Vygotsky (1978), is an operationalization of the ZPD (Choi & Hannafin, 1995; Puntambekar & Hubscher, 2005).

**Scaffolding Framework**

Scaffolds accomplish two primary goals: channeling and focusing and modeling (Pea, 2004). Channeling and focusing reflects the idea of providing constraints and guidance that centers the learner's attention on the most salient elements of a given task with the goal of directing their action towards achievement of the task. Scaffolds applied in this way can be used to structure learners' tasks (Quintana et al., 2004) or offload secondary or irrelevant cognitive tasks such that learners can appropriately direct their cognitive resources (Hannafin & Land, 1997). Modeling can be used to present the learner with hints or coach them in applying a more advanced or expert solution to the task (Pea, 2004).

Scaffolds can take on a variety of forms. Hannafin, Land, and Oliver (1999) suggested that scaffolds provide the following functions:

- Conceptual guidance on concepts related to the problem;
- Metacognitive guidance on how to reflect, plan, and monitor;
- Procedural guidance on how to use the environment's features and proceed through the environment; and
- Strategic guidance on how to approach the task or refine strategies.

Quintana (2004) proposed a scaffold design framework that considers three categories of tools: (a) sense-making tools that support learners in interpreting data and testing hypotheses; (b) process management scaffolds that support learners in negotiating the process of inquiry; and (c) tools that support learners in articulating and expressing their knowledge. Saye and Brush (2002) propose two broad categories: hard and soft scaffolds. Hard scaffolds are types of support that can be planned, designed, and implemented in advance based on the difficulties that students typically encounter with a task. These types of scaffolds are primarily technology-based (Sharma & Hannafin, 2007) and can free teachers to provide soft scaffolding. Soft scaffolds are more situational and require continuous re-evaluation of learners' understandings. Hadwin and Winne (2001) proposed the idea of tacit and explicit scaffolds. Tacit scaffolds direct students' attention to specific tasks without providing explicit direction or instruction. Explicit scaffolds, by contrast, provide direct guidance for students who are struggling. In their investigation of a study tool for self-regulation called *CoNoteS2*, explicit scaffolds were proposed that would provide students with brief tutorials on study skills.

**Fading**

Scaffolds, as with their physical counterparts, are intended to be temporary -- to be put in place when required by the learners and removed once no longer needed (Lajoie, 2005). In this way, scaffolds support a process through which learners assume increasing control over their learning and cognitive tasks. Once learners begin to gain confidence in the scaffolded task, the scaffold is gradually faded until the learner is able to accomplish the task independently (Puntambekar & Hubscher, 2005; Sharma & Hannafin, 2007). A result of scaffolding is a "cognitive residue" in which learners' thinking processes are altered as a result of the partnership (Hannafin & Land, 1997). Scaffolds play a key role in allowing learners to productively interact within complex learning environments.

**Research on Scaffolds**

A number of studies evaluated the use of scaffolds in supporting student-centered learning.

***Question Prompts***

Ge and Land (2003) investigated the effect of guiding prompts on ill-structured problem-solving performance by undergraduate students in an introductory information science and technology course. Students were presented with a written scenario that asked them to consider a possible information technology solution that would enable grocery store shoppers to more easily locate items. Students in the treatment conditions were presented with 10 question prompts across four categories: problem representation, solution, justification, and monitoring and evaluation. A rubric was then used to evaluate students' problem-solving reports on the basis of problem representation, developing solutions, justifications for generating or selecting problem solutions, and monitoring and evaluating the problem space and solutions. Quantitative findings indicated that students who received the prompts performed significantly better than students who did not receive the prompts. Qualitative findings suggested that students who received the prompts engaged in the following cognitive and metacognitive activities: (a) making intentional efforts to identify factors, information, and constraints during the problem-representation process; (b) organizing and planning for the solution process and articulating solutions explicitly; (c) constructing arguments grounded in factors identified during problem representation and providing justification for each suggestion proposed; and (d) intentionally evaluating the selected solutions, comparing alternatives, and justifying the most viable solution.

***Up, Up & Away!***

Simons and Klein (2007) investigated the effect of strategic and conceptual scaffolds (Hannafin, Land, & Oliver, 1999) on problem-solving behavior in 7th grade students. Using a program called *Up, Up, and Away!* (Illinois Mathematics and Science Academy, 2002) that challenges students to plan a global circumnavigation using a hot air balloon, the authors evaluated three scaffolding conditions: no scaffolding, optional scaffolding, and required scaffolding. A series of hard scaffolds were implemented to support problem-solving performance, constrain the problem-solving task, and free teachers' time to engage in soft scaffolding. Examples of scaffolds included a collection of guiding questions and responses, expert suggestions, a tool that allows students to design a balloon, and a travel plan scaffold that enables students to plan a route based on information presented in the environment. Results from the study indicate that students who received no scaffolding scored significantly lower on the travel plan component than those who received either of the two scaffold conditions. However, there were no significant differences in pre/post knowledge test performance across the three conditions. The findings of this study suggest the possibility that hard scaffolds may positively impact achievement in problem-based learning environments, particularly in absence of soft scaffolds.

***Crystal Island***

A study (Shores, Hoffmann, Nietfeld, & Lester, 2012) on a problem-based environment for fifth grade students, known as *Crystal Island*, sought to investigate the role of sub-problems in scaffolding problem-solving. The environment is intended to address geography skills and the development of problem-solving, critical thinking, and metacognitive skills. The environment prompts students to establish a village community among a group of shipwrecked passengers. To create sub-problems, the overall goal is divided into three quests that can be completed in any order. An example quest engages students in creating a model for a possible village. Results of the study found that the completion of the quests correlated with higher performance on a content posttest and greater degrees of situational interest.

### *Information Problem-solving on the Web*

A study (Raes, Schellens, De Wever, & Vanderhoven, 2011) of a problem-based instructional technique, known as *Information Problem-solving on the Web,* investigated the role of technology-enhanced scaffolds and teacher-enhanced scaffolds among university students. The technology-based scaffolds, in the form of questions, hints, suggestions, and reminders were designed to promote cognitive and metacognitive behaviors, enhance motivation, or guide cooperative activities. Teachers provided scaffolding by helping students acquire understandings of inquiry and prompting students to deploy strategies and processes. The study included four conditions: a control condition which did not have exposure to scaffolds, a condition which received the technology-enhanced scaffold condition only, a condition that received the teacher-enhanced condition, and a condition that received both teacher and technology-enhanced scaffolds. Students who received scaffolds significantly outperformed those students who did not receive scaffolds on knowledge acquisition and regulation of cognition. Students who received a combination of technology and teacher-enhanced scaffolds improved their knowledge about cognition relative to the other conditions.

## COGNITIVE TOOLS

Cognitive tools are technology-based solutions that extend or augment the thinking processes of learners (Jonassen, 1995). These tools serve as partners in cognition to support learners in accomplishing tasks that they otherwise would be unable to accomplish on their own (Salomon, Perkins, & Globerson, 1991). Cognitive tools can take on many forms, such as spreadsheets, semantic networks, expert systems, or multimedia authoring tools (Jonassen, 1995). Cognitive tools can and often do function as scaffolds within student-centered learning environments, though in many instances cognitive tools have a static and essential presence within a learning environment and are not withdrawn through fading as with traditional scaffolds.

Lajoie (1993) described four distinct categories of cognitive tools: (a) tools that support cognitive processes, (b) tools that support the learner by sharing cognitive load, (c) tools that allow learners to engage in processes that are out of reach, and (d) tools that support problem-solving by enabling learners to engage in hypothesis generation and testing. Lajoie's categories were based on work within two learning environments: *Sherlock* and *Bio-Worlds*. *Sherlock* was a learning environment designed to support instruction in avionics troubleshooting, while *Bio-Worlds* was developed for high school Biology. As an example of tools that support cognitive processes, Lajoie offers the use of a cognitive tool within *Sherlock* that provides an overview of all problem-solving steps that the user has previously performed, thus supporting metacognitive processes required to solve complex problems. *Bio-Worlds* offers students a tool that allows them to engage in the higher-level task of developing a medical diagnosis by automating the lower level task of performing diagnostic tests on a virtual patient. *Sherlock* provides simulated diagnostic equipment and problem scenarios that would either be potentially dangerous or rare in the real-world, thus allowing learners to engage in out-of-reach activities that are nonetheless required to accurately model the complexity of authentic avionics troubleshooting tasks. *Bio-world* enables hypothesis generation and testing by providing access to expert coaching on the formation of a diagnosis.

A wide range of research has been completed on scaffolds within constructivist learning environments and their relationship to student behaviors.

## Research on Cognitive Tools

### *MetaHistoReasoning Tool*

A recent study (Poitras, Lajoie, & Hong, 2012) of 32 undergraduate students investigated the effect of a metacognitive tool designed to support the interpretation of history texts on text recall and comprehension. The tool provided eight elaborative interrogations as students interacted with the text. An example interrogation is, "Why would the colonies contribute large amounts of money?" Participants then responded to the prompt via a text box. The study found that students who used the tool demonstrated higher levels of recall, but found no significant difference with regard to text comprehension.

### *MetaTutor*

*MetaTutor* is an adaptive hypermedia learning environment that teaches Biology (Azevedo, Behnagh, Duffy, Harley, & Trevors, 2012) and provides specific support for processes of self-regulation. Four pedagogical agents within the environment guide students through the learning process and prompt them to engage in planning, monitoring, and strategic learning behaviors. Based on results from quizzes, the pedagogical agents can provide adaptive feedback on students' self-regulated learning processes.

*MetaTutor* is termed a metacognitive tool by Azevedo, Johnson, Chauncey, and Burkett (2010). In addition to Lajoie's definition of cognitive tools, a metacognitive tool includes the following additional characteristics:

- it requires students to make decisions regarding instructional goals;
- it is embedded in a particular learning context and requires learners to make decisions regarding how that context may impact learning;
- it models, prompts, and supports learners' self-regulation;

- it models, prompts, and supports learners to use various learning strategies;
- it resides in a specific learning context in which peers, tutors, and pedagogical agents may also support student learning; and
- it is any environment where the learner deploys key metacognitive and self-regulatory processes prior to, during, and following learning.

A study on three variations of scaffolding was conducted using *MetaTutor*: a prompt and feedback (PF) condition in which learners were prompted to use specific self-regulatory processes and then given feedback on the execution of those processes, a prompt-only (PO) condition in which learners received identical prompts as the first condition without feedback, and a control condition (NP) in which learners received no prompts or feedback. Learners completed pre and posttest concept tests on the human circulatory system. Eye tracking data, facial expressions, and verbalizations were recorded and students engaged in a think-aloud protocol while working through the learning session.

Findings indicated that learners who did not receive any form of prompt spent a significantly longer amount of time with science content than did those who received prompts. Students in the PO condition took significantly more time than in the PF condition. The control condition visited significantly more content pages than did either prompt condition. The PO condition also viewed significantly more pages than the PF condition. Students in the PF condition also attempted fewer sub-goals than the other conditions. Using time on task and posttest score, the researchers calculated an instructional efficiency score. Students receiving the PF condition significantly outperformed the NP condition on this measure. The results demonstrate the potential of metacognitive scaffolds to support students learning processes and self-regulation.

### Cognitive Load and PBL

There is some disagreement surrounding the role of guidance in problem-based learning environments. Kirschner, Sweller, and Clark (2006) cast problem-based learning as belonging to a family of minimal guidance -- predominantly constructivist -- approaches to instruction in which student-directed inquiry is emphasized over direct instruction and structured learning activities. The authors claim that such minimal guidance approaches, when viewed through the lens of human cognitive architecture, are likely to be ineffective. Their arguments center on CLT and the idea that minimal guidance within complex learning environments results in high levels of element interactivity, thereby resulting in cognitive overload. This claim was supported by a recent study (Moos, 2013) investigating the impact of cognitive load on student problem-solving within a hypermedia learning environment. Findings from the study suggested that higher levels of cognitive load were associated with lower learning outcomes and the use of fewer problem-solving strategies.

Clark, Kirschner, and Sweller (2012) suggest that several problems arise as a result of minimally guided instruction in discovery-based methods. First, only those students who are well prepared achieve learning gains. Second, students often become frustrated, disengaged, or simply mimic the work of more expert learners. Third, students often develop misconceptions. Finally, the authors claim that minimally guided instruction is much less efficient than instruction that offers explicit guidance.

Hmelo-Silver, Duncan, and Chinn (2007) dispute Kirschner, Sweller, and Clark's (2006) claims on two bases. First, the authors claim that Kirschner, Sweller, and Clark's categorization of PBL as a minimally guided instructional method is flawed in that the extensive scaffolding often present in PBL environments provides substantial guidance to students. Additionally, the authors claim that the body of research supporting its use invalidates the premise that PBL is ineffective as an instructional approach.

This point of disagreement is a central foundation of this study. By investigating students' use of technology scaffolds and cognitive tools within a PBL environment, I hope to better understand the relationships between cognitive load, scaffolding, and open-ended, constructivist, student-centered learning environments.

## Summary

This review of literature highlighted the relevant theoretical foundations, issues, and research related to the application of problem-based learning within technology-based, student-centered learning environments. Of particular interest is the intersection between cognitive load theory, originally derived from cognitivist branches of learning sciences and the socio-cultural perspectives that frame situated cognition and the creation of environments for authentic, ill-structured problem-solving. Both theoretical perspectives lend credence to instructional approaches that aim to scaffold processes of learning and inquiry. Cognitive load theorists approach scaffolding from the perspective of schema construction and have identified a number of strategies that can be used to help learners maintain productive levels of cognitive load, thus freeing mental capacity for the creation of new knowledge. Socio-culturalists view scaffolding as an ongoing process of knowledge construction through which learners come to internalize the practices of a given field or discipline. Vygostky's Zone of Proximal development features prominently in socio-cultural views of scaffolding. Technology-based scaffolds and cognitive tools have been applied in ways that resonate with the ZPD to support learners in building the necessary expertise to accomplish sophisticated tasks while unassisted.

In reviewing the literature, I identified a number of issues that require further investigation. First, a preponderance of research, particularly in the cognitive load domain, but also within the general body of research concerning learning environments, lacks a focus on middle school student populations. There is insufficient research to address how these students can be supported in acquiring problem-solving expertise. In particular, there is a substantial gap in the literature concerned with the measurement and analysis of cognitive load within this population as it relates to problem-solving.

Much of the existing research on cognitive load is based on traditional laboratory experiments and has not been replicated within authentic classroom settings. There is a significant opportunity for classroom-based research that addresses the effects of cognitive load and scaffolding over an extended period of time and that, through mixed methods approaches, can consider the complexity and issues associated with implementing learning environments in authentic contexts.

Overall, there is insufficient research on the use of scaffolds to manage cognitive load within PBL.

The next chapter will describe the specific methodologies I employed to further the research in these areas.

# CHAPTER 3: METHODOLOGY

The review of literature identified an area of research that is currently lacking: the role of technology-based guidance in managing cognitive load within problem-based learning environments. This study sought to evaluate the effectiveness of two strategies for managing cognitive load among sixth grade students engaged in a three-week problem-based learning unit. In addition, the study investigated the effects of the scaffolds on students' problem-solving processes and overall performance. This chapter will describe *Alien Rescue*, the research context for this study, the design of three treatment conditions, and the research design used to address the research questions.

## Research Context

The context for this study was *Alien Rescue*, a multimedia enhanced problem-based learning environment intended for use in sixth grade science classrooms. The program presents an open-ended scientific scenario in which six alien species have appeared in Earth's orbit seeking new homes in our solar system after their home planets have been destroyed. Students are tasked with identifying suitable habitats by matching the characteristics of a subset of planets and moons with the specific requirements of the alien species. Student problem-solving is situated within a futuristic space station environment, known as "Space Station Paloma." The space station environment provides a collection of cognitive tools that students use to solve the problem.

*Alien Rescue Online* is a stable version of the program intended for widespread distribution to schools around the world. It represents the fourth major version in the development history of the *Alien Rescue* (Liu, Williams, & Pedersen, 2002) program and is the first version to be delivered to classrooms via the Web. This version was built using a number of web, multimedia, and 3D game technologies including Unity game engine, Luxology modo, Photoshop, Ruby on Rails, JavaScript, HTML, and CSS. The web-based delivery of *Alien Rescue* facilitates the distribution of multiple treatment conditions and the collection of usage data, including student problem solutions and activity logs.

The current version of *Alien Rescue* presents an ill-structured problem for which there are no prescribed problem-solving steps. Students are responsible for considering the problem and exploring the affordances of the environment to develop their own problem-solving strategies. To support the students in solving the problem, the program presents 11 cognitive tools, each of which has been classified based on Lajoie's (1993) categorization.

Figure 1 is a screenshot taken from *Alien Rescue* and illustrates the 3D environment along with two cognitive tools. Figure 2 shows students using *Alien Rescue* in a typical sixth grade classroom similar to those included in this study.

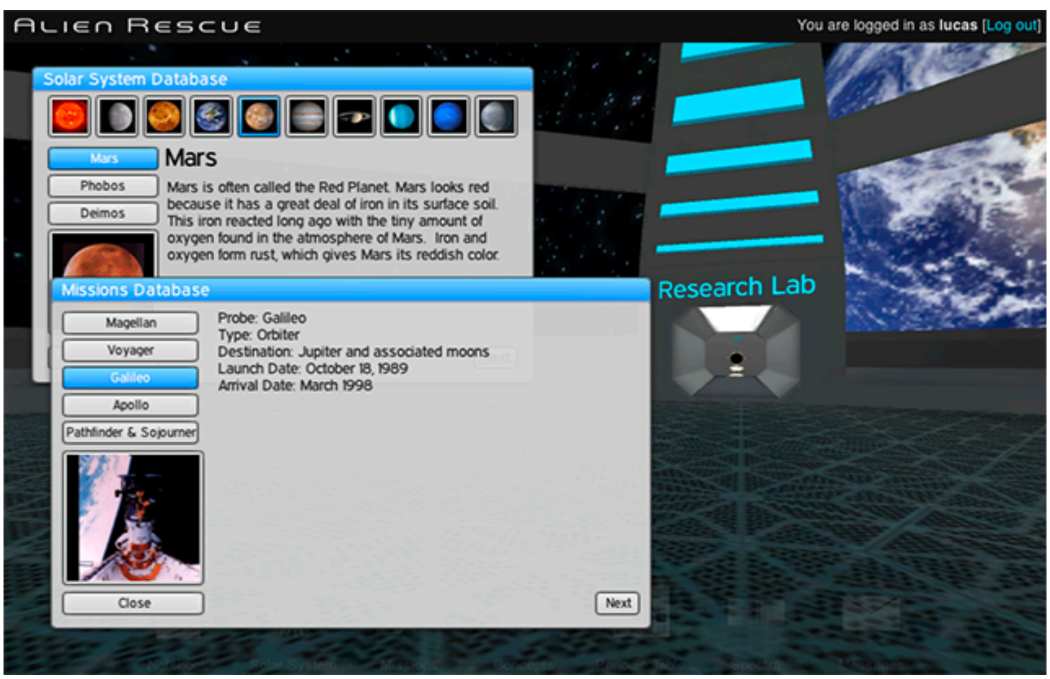


Figure 1: *Alien Rescue*

Figure 2: Sixth Grade Students Using *Alien Rescue*

## Cognitive Tools

The following sections highlight each of the cognitive tools present within *Alien Rescue*, grouped by Lajoie's (1993) categorization.

### Tools that support cognitive processes

#### *Notebook*

The Notebook tool enables learners to record and store information on the aliens and our solar system and provides a basic level of scaffolding. Prior to the submission of a solution for the first alien species, the Notebook tool is highly structured and prompts the learners for specific information, such as seismic activity, essential chemical elements, and temperature. Following the submission of a solution for one alien species, the tool removes the prompts but provides empty cells (much like a simplified spreadsheet) for the student to populate. Once the student has submitted a solution for three alien species, the Notebook tool transitions into a single freeform text box for students to record and organize information in whatever manner they deem appropriate.

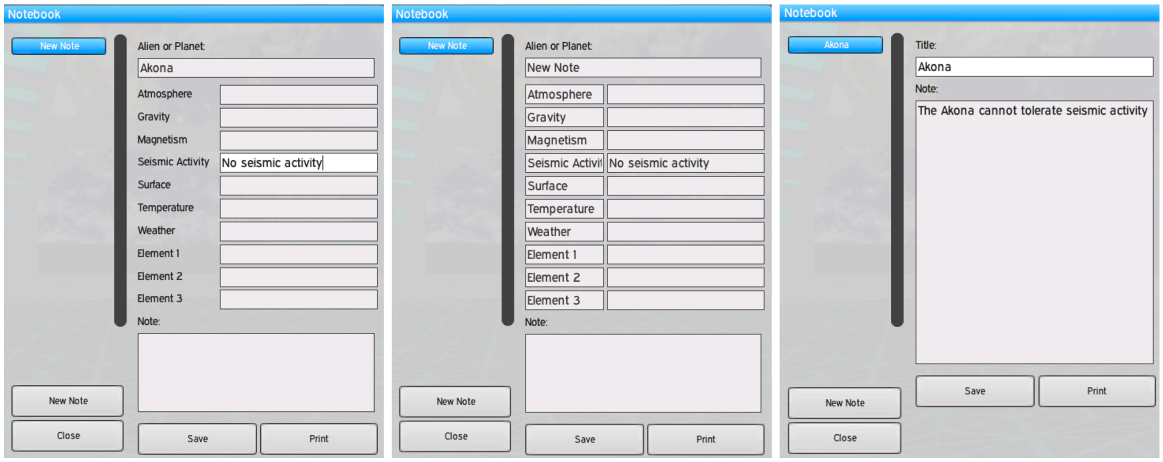


Figure 3: The Three Levels of the Notebook Tool

## Tools that share cognitive load

### *Spectra*

The spectra tool is used to interpret various visual spectra found throughout problem-solving environment. The tool enables learners to determine the specific chemical element that corresponds to a given spectrum. For instance, data on the alien species may display their food requirements as a series of spectra. Students must then use the spectra tool to determine which specific elements should be present in the aliens' environments.

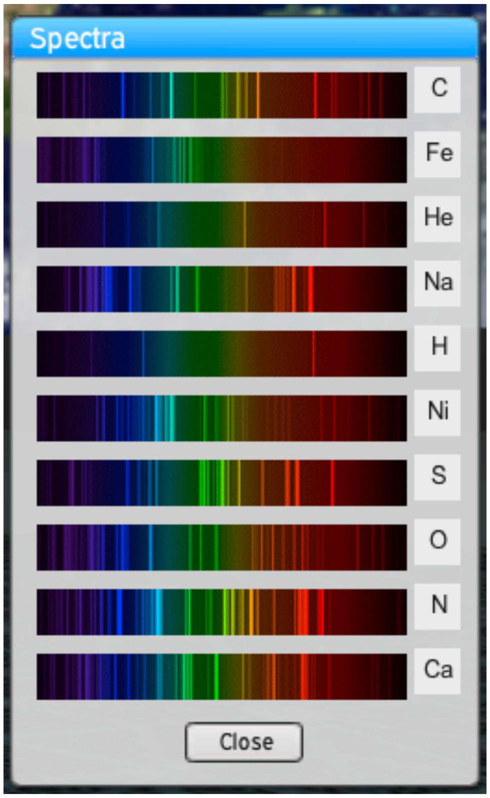


Figure 4: The Spectra tool

***Periodic Table***

A traditional Periodic Table of the Elements provides symbols and names for each element along with information such as atomic weight.

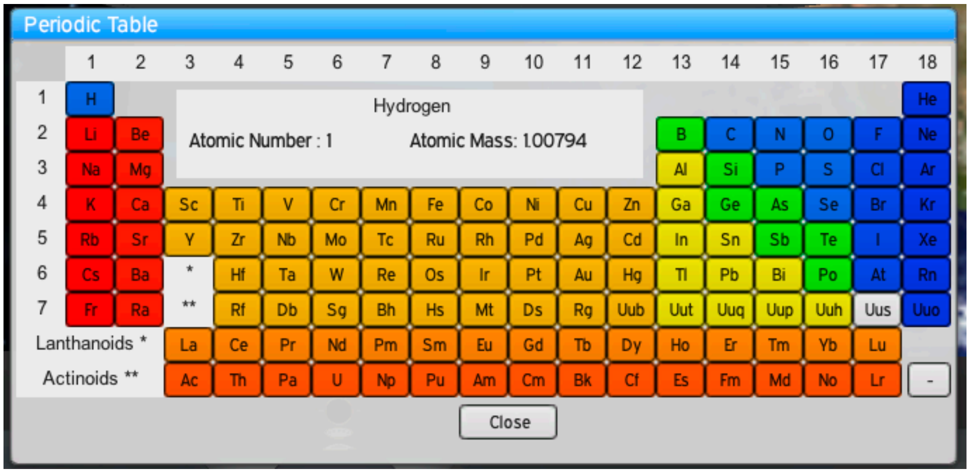


Figure 5: The Periodic Table of the Elements tool

### *Solar System Database*

The Solar System Database provides data on selected planets and moons within our solar system. Data within this tool are intentionally incomplete and ill-structured. The tool is of key importance as students develop hypotheses around potential alien habitats. While the tool does not provide sufficient information for students to solve the problem, it does contain enough information for students to establish initial hypotheses and engage in hypothesis testing.

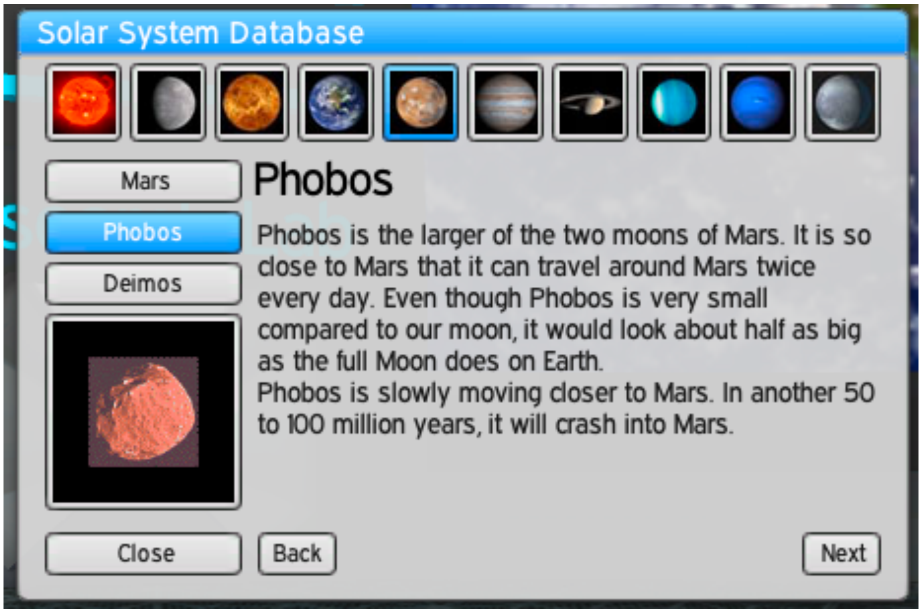


Figure 6: The Solar System Database

***Concepts Database***

The Concepts Database provides interactive multimedia modules that present information on various scientific concepts that are germane to the problem-solving environment, such as atmosphere, temperature, and gravity. Students use the Concepts Database on a just-in-time basis to address potential gaps in understanding when they encounter an unfamiliar concept.

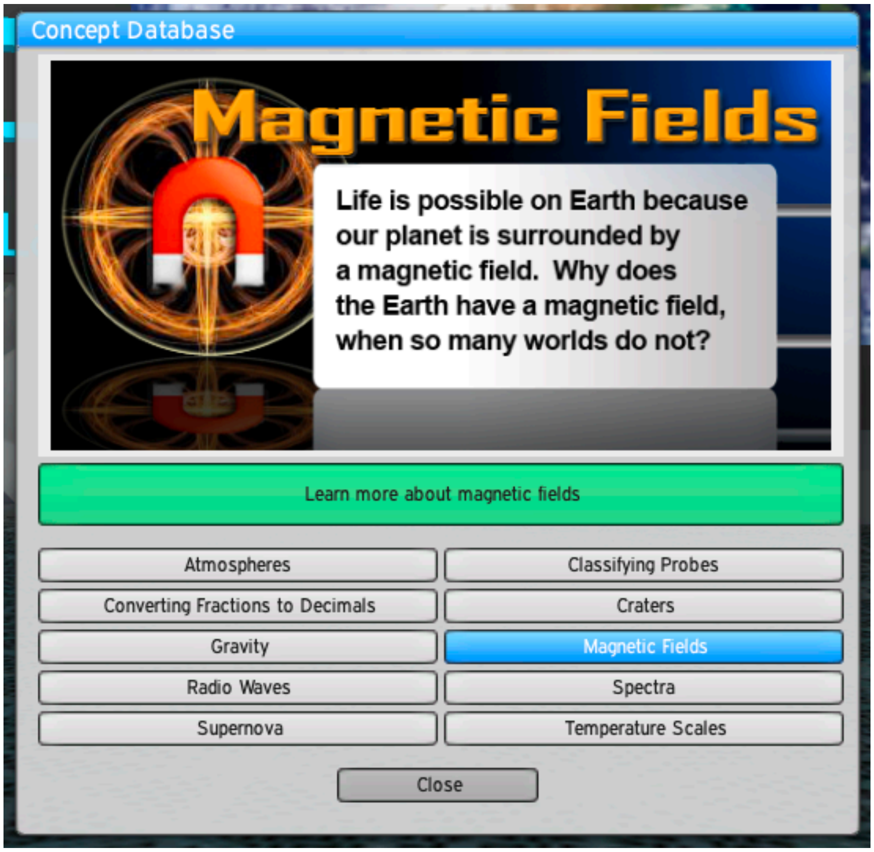


Figure 7: The Concepts Database

### *Missions Database*

The Missions Database contains data on NASA space missions such as the Apollo program and the Galileo space probe. This tool describes the scientific purposes of the missions, illustrates the history of each mission, and provides data on the scientific instrumentation used. The tool is of use to students in understanding the nature of space missions and for providing models for their own space probes.


Figure 8: The Missions Database

***Alien Database***

The Alien Database (also referred to as the Research Lab) provides information on the aliens' journey to our solar system, information on their home solar system, and comprehensive data on each of the alien species. The tool provides detailed illustrations and 3D models of the alien species, their original habitats, and their food sources. The Alien Database is the only source of information on the alien species and, as such, is an essential component in the problem-solving process.

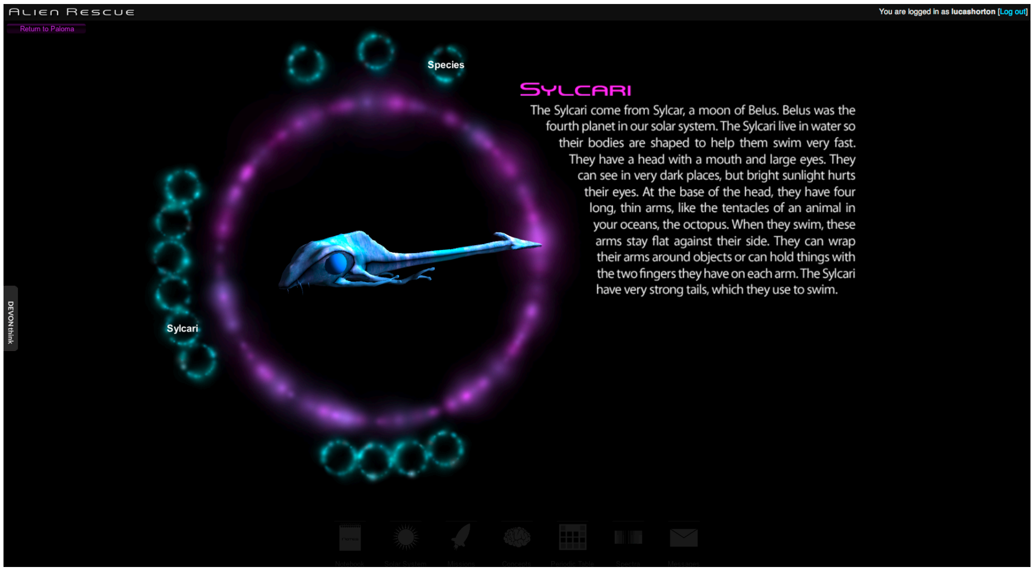


Figure 9: The Alien Database

**Tools that support activities that are otherwise out-of-reach**

***Probe Design Center***

The Probe Design Center allows students to configure space probes to collect data from planets and moons. When designing a new probe, the tool first prompts students to select one or more destinations and to provide a brief summary of their mission objective. Having provided an objective, students then choose a probe type: flyby, orbiter, or orbiter with lander. The tool enables students to select from a range of power sources and antenna options. Finally, students can select up to nine different scientific instruments to include on their probe. Each option presented to students has an associated cost that, coupled with a predetermined budget, encourages students to be strategic in designing and launching space probes.

Given the range of options available to the students, it is possible to design a probe that malfunctions. For instance, the inclusion of a seismograph on a flyby probe results in an error at the data collection stage because a probe must contact the surface of a planet or moon to record a seismographic reading. Limited feedback is provided to students on the probe errors to encourage them to deduce the source of the errors and modify their probe design strategies.

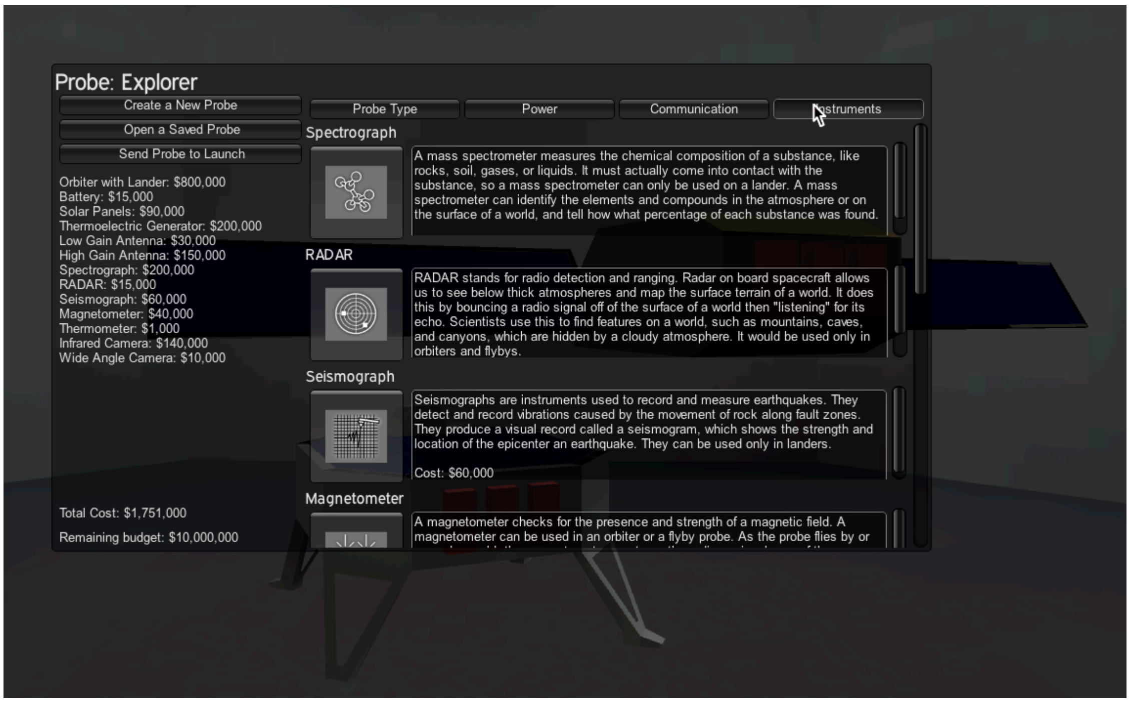


Figure 10: Probe Design Center

***Probe Launch Center***

Once students have designed a probe, the Probe Launch Center enables them to launch it into space. Before launching the probe, the tool presents the learner with an overview of its configuration, mission, and destinations. The tool also provides an animated sequence of a rocket launch to simulate the process of deploying a probe.

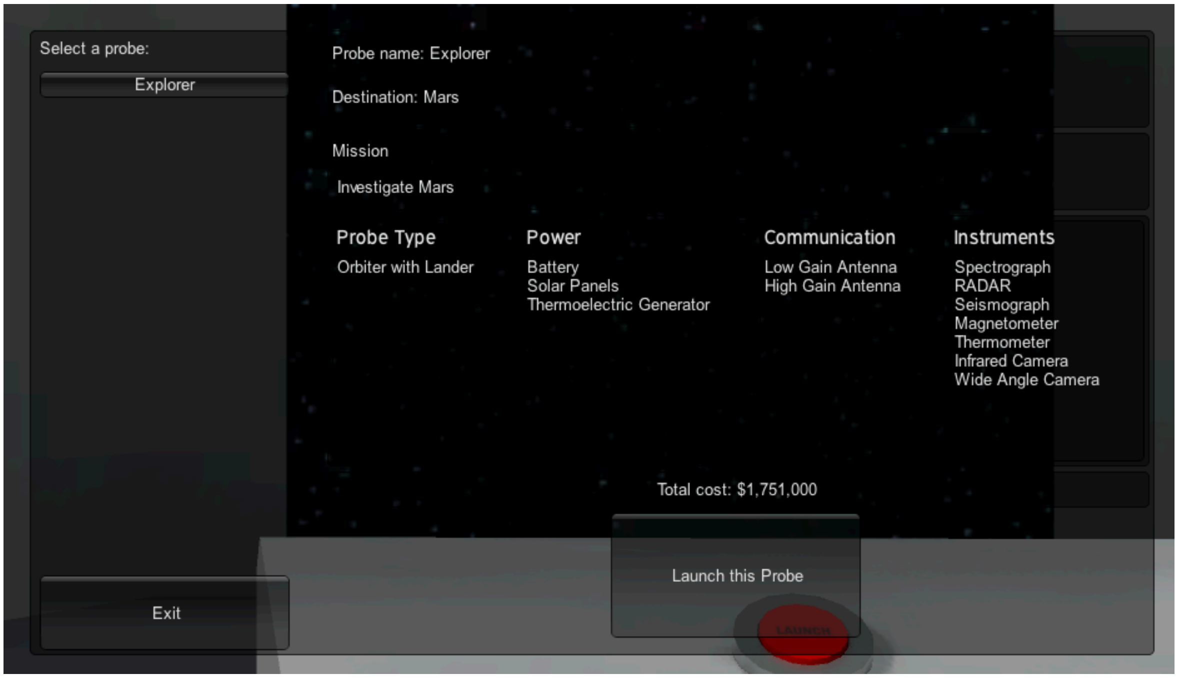


Figure 11: Probe Launch Center

**Tools that support hypothesis generation and testing**

***Mission Control Center***

Following probe launch, data from the probes are available in the Mission Control Center. Much of the data presented in the Mission Control Center are in the form of images. For instance, data on planet terrain are represented as a radar map of the surface. Students interpret these data to generate a more complete dataset on the world in question.

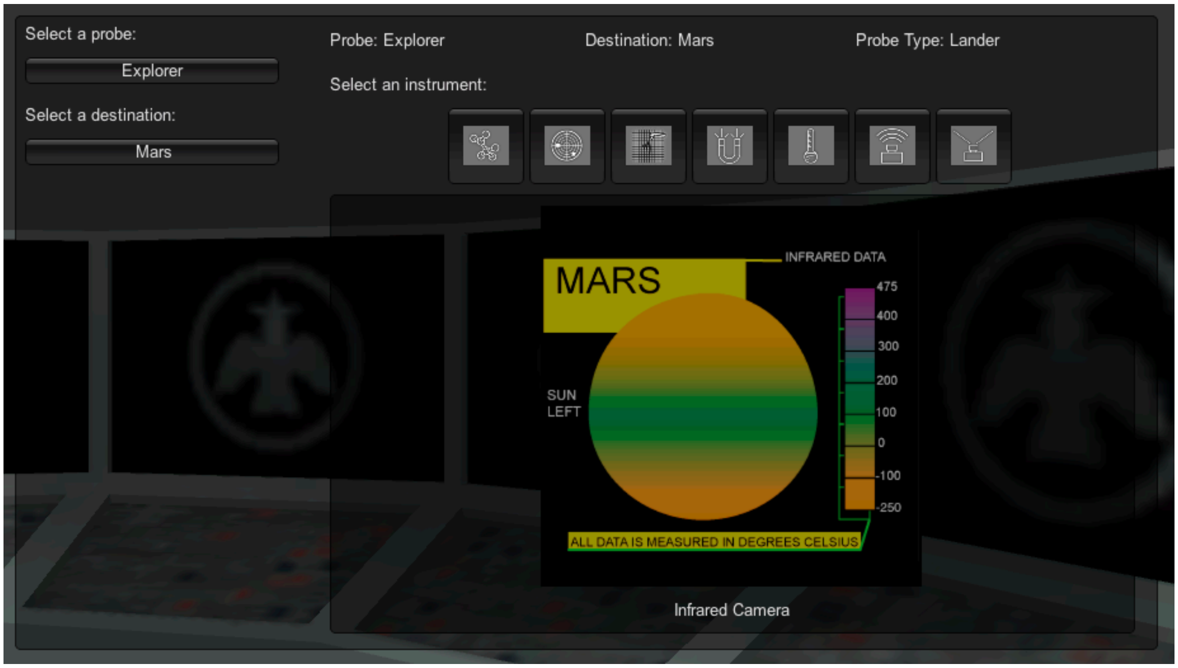


Figure 12: Mission Control Center

***Communication Center***

The Communication Center is an email like tool whose primary purpose is to allow students to submit problem solutions. The tool allows students to select a planet or moon, an alien species, and a rationale describing why the chosen world is the best habitat for the selected alien species. The tool also provides a repository of messages generated by the program, such as a welcome message from the fictional Interstellar Relocation Commission director, a message from the aliens, and messages confirming the receipt of student-submitted solutions. The Communication Center is only available once students have accessed each tool required for hypothesis generation and testing.


Figure 13: The Communication Center

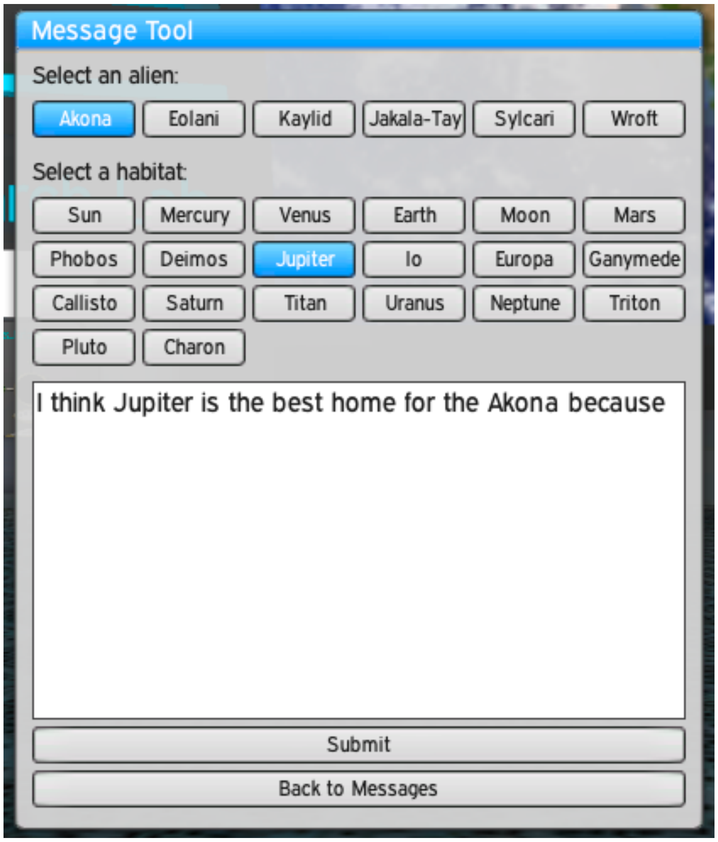


Figure 14: The Solution Form

**3D Environment**

In addition to the eleven cognitive tools, student problem-solving within *Alien Rescue* is situated within an immersive 3D virtual environment intended to mimic science fiction settings from film and digital games. Five of the cognitive tools -- the Communication Center, Alien Database, Probe Design Center, Probe Launch Center, and Mission Control Center are placed within the 3D environment itself. Thus, to access the Alien Database tool, students navigate their character in 3D space to the Research Lab. The experience of navigating within this environment is similar to that found within modern 3D games.

### Persistent Tools

The Notebook, Solar System Database, Concepts Database, Missions Database, Spectra, and Periodic Table are "persistent tools" and are accessible to students from any location and during any point in the problem-solving process via a toolbar at the bottom of the screen. Additionally, the persistent tools are capable of being used co-currently. For instance, a student conducting research within the Solar System Database can simultaneously record notes using the Notebook tool.

## PREVIOUS RESEARCH

Many research studies have been conducted using *Alien Rescue* as the research context. Several of those studies consider the role of scaffolding and cognitive tools in facilitating problem-solving.

A key study (Liu & Bera, 2005) investigated the use of *Alien Rescue*'s cognitive tools across five problem-solving stages, including initial exploring, background research, hypothesis generation, hypothesis testing, and solution generation. Results indicated that sixth grade students' use of cognitive tools varied according to their problem-solving stage. The study suggested that students were strategic in their selection and use of the tools. A similar study (Liu et al., 2009) conducted on undergraduate students supported these findings as well, noting a strong correspondence between the selection and use of the various cognitive tools provided by *Alien Rescue* and the stages of problem-solving.

Li and Liu (2007) investigated the effect of a database tool on cognitive load, problem-solving performance, and academic achievement within *Alien Rescue*. The study organized students into three treatment conditions: students who received a computer database, a paper database, and no database. Using self-report measures of cognitive load and student performance on the problem-solving task the researchers calculated an instructional efficiency score (Paas & van Merriënboer, 1993) for each student. Results of the study found that students who received the computer-based tool reported higher instructional efficiency scores and demonstrated better academic achievement on a pre/post knowledge test than students who received either the paper database or no database tool. The study concluded that the computer database tool was effective in managing cognitive load, and thus, allowing for more productive interaction within the PBL environment.

Several studies (Liu, 2004; Liu, Bera, Corliss, Svinicki, & Beth, 2004; Liu, Hsieh, Cho, & Schallert, 2006) support the effectiveness of *Alien Rescue* in supporting students' scientific knowledge building.

### CHALLENGES WITH *ALIEN RESCUE*

A challenge in the classroom use of *Alien Rescue* is the significant element interactivity effect that occurs at the beginning of the problem-solving process. Many students lack the requisite schema to interact productively within the open-ended learning environment and often require significant support from teachers and peers.

Classroom observation of students engaging with *Alien Rescue* for the first time often reveals significant confusion and struggle as students generate internal representations of the problem, orient themselves to the learning environment, and develop a strategy for applying the cognitive tools in developing problem solutions.

Previous research on student motivation within *Alien Rescue* (Liu, Horton, Olmanson, & Toprac, 2011), found that, although students frequently described the environment as fun and engaging, they also considered it to be challenging, frustrating, and taxing. One student commented, "there were a lot of planets to choose from and that was hard. Then the species were very picky which was annoying." Feelings of frustration and difficulty were one of the most common responses when students were asked, “What did you dislike about *Alien Rescue*?”

Although previous research validates the use of *Alien Rescue* in supporting problem-solving and learning, very little is known about the cognitive load required to engage with it and the consequent design and use of scaffolds to manage cognitive load. The current study intended to address this knowledge gap.

## Research Questions

This study addressed the effects of guidance on problem-solving ability and learning outcomes within a problem-based learning environment. Specifically, the study investigated the following research questions:

1) How do varying levels of scaffolding affect students’ cognitive load, as measured by instructional efficiency?
2) What are the characteristics of problem-solving behavior among students who received different forms of scaffolding?
3) How do different forms of scaffolding affect students’ content knowledge and performance within the problem-solving scenario?
4) What are student and teacher perceptions of *Alien Rescue* and the different treatment conditions?

## Participants

Participants included a convenience sample of 218 sixth graders from a suburban middle school in a large southwestern city. The school had used *Alien Rescue* as part of its sixth grade science curriculum for the past four years. The student demographics were as follows: 14.4% African American, 28.6% Hispanic, 42% White, 0.6% Native American, 8.3% Asian, 2% Pacific Islander, and 5.9% two or more races. Gifted and talented students comprised 9.3% of the populations, 10.3% were enrolled in Special Education, and 3.6% were bilingual/ESL. The students were comfortable using computers and had used various applications in other instructional activities, including computer games, web, multimedia, and productivity software. 51% of the students were female and 49% were male. Students worked in pairs using a shared computer. Small group work is consistent with the recommended classroom implementation for *Alien Rescue*.

Three teachers taught the intact classes. The teachers had six, eight, and 13 years of experience teaching middle school science at the time of the study. Each teacher had used *Alien Rescue* in the past. Two teachers had used *Alien Rescue* for four years and the other for two years. One of the teachers had completed a one-day professional development workshop during the previous year on *Alien Rescue* and the use of problem-based learning in the classroom.

## Treatment Conditions

Three treatment conditions were used: a problem constraint scaffold condition, prompt scaffold condition, and a control condition featuring minimal guidance.

### STRUCTURED CONDITION

In the structured condition, students were presented with a series of sequential sub-problems that provide strategic scaffolding on the problem-solving process and that model a process of expert scientific inquiry. This condition introduced several modifications to the cognitive tools presented in the environment to affect constraints. The following narrative explains the overall student experience as a result of the scaffolds:

During students' initial use of the program, all cognitive tools were disabled and students were prompted by the program to visit the Communication Center to receive additional information. Once there, they were informed of numerous technical difficulties aboard the space station and told that it is not yet fully operational. As a first step, students were instructed to visit the research lab to attempt to power up the Alien Database. They were also presented with a set of virtual reality goggles that provide access to some of the persistent tools, as follows:

- Solar System Database: only included partial information on two potential planetary homes
- Concepts Database
- Spectra
- Periodic Table
- Notebook

The Mission Database was omitted from the set of persistent tools provided to the students. Additionally, locked doors prevented access to the Probe Design Center, Probe Launch Center, and Mission Control Center, and Communication Center (following their initial use of the Communication Center).

Once the students enabled the Alien Database, it was discovered to be partially functional, only providing information on the aliens' journey, a single habitat, and a single alien species. Students were then prompted to record as much information as possible on the aliens and planets in their Notebook. Once the program had detected that students conducted some research on the alien species and two planets, they were prompted to develop and submit a hypothesis in which the alien species was tentatively matched to one of the planets in the Solar System Database. The prompt also asked students to submit a list of all additional information required to evaluate their hypothesis.

After submitting a hypothesis, the Mission Database was enabled and students were allowed access to the Probe Design Center. Students were prompted to design a probe -- using the information in the Mission Database as a guide -- to collect any data necessary for them to evaluate their hypothesis. Once students completed their probe design, they were given access to the Probe Launch Center. Launching the probe from the Probe Launch Center subsequently unlocked the Mission Control Center. After reviewing their probe results in the Mission Control Center, students were asked to evaluate their hypothesis. If students decided to accept their hypothesis, they were directed to the Communication Center to submit a solution. If the students determined that their hypothesis is not valid, they were instructed to form a new hypothesis and repeat the process of designing and launching a probe to evaluate it.

After submitting a solution for the first alien, the Probe Design Center, Probe Launch Center, Mission Control Center, and Communication Center were once again locked. The student was then informed that the rescued alien helped restore some functionality to the space station. The Alien Database then featured information on two additional alien species and three additional habitats, while the Solar System Database presented data on six potential relocation planets. The students were prompted to choose one of the new alien species and repeat the hypothesis generation and testing process. After submitting a second solution, the program removed the constraint scaffolds altogether and allowed students to freely access the fully functional tools within the environment.

### Prompt Condition

In the prompt condition, students could access any tool in any order, but were presented with prompts that described specific operations related to each cognitive tool that can be taken to facilitate progress towards a solution. For example, when accessing the Alien Database, students were prompted to consider the specific requirements of each alien species and to match those requirements with planets from the Solar System Database. When using the Probe Design Center, they were prompted to design probes that provided missing information. Once a student submitted one solution, the guiding prompts became less direct in nature. After submitting two solutions, the prompts were disabled entirely.

### Control Condition

The control condition provided a minimally guided implementation of the program using the cognitive tools as described in the description of *Alien Rescue*. With the exception of the scaffolded Notebook tool (which is part of the main *Alien Rescue* program), students were provided with no additional technology-based guidance or scaffolding that either constrained the problem space or provided explanations on how to approach the problem. Students were free to access the cognitive tools in whichever order they desired.

Distribution of the treatment condition assignments is presented in Table 1.

Table 1: Treatment Condition Assignments

| Teacher | N |
| --- | --- |
| Control Condition | |
| Teacher A – Class 1 | 12 |
| Teacher A – Class 2 | 10 |
| Teacher B – Class 1 | 15 |
| Teacher B – Class 2 | 9 |
| Teacher C – Class 1 | 10 |
| Total | 56 |
| Prompt Condition | |
| Teacher A – Class 3 | 18 |
| Teacher A – Class 4 | 17 |
| Teacher B – Class 3 | 8 |
| Teacher C – Class 2 | 6 |
| Teacher C – Class 3 | 8 |
| Total | 57 |

Table 1: Treatment Condition Assignments (continued)

| Structured Condition | |
|---|---|
| Teacher A – Class 5 | 23 |
| Teacher B – Class 4 | 20 |
| Teacher B – Class 5 | 23 |
| Teacher C – Class 4 | 21 |
| Teacher C – Class 5 | 18 |
| Total | 105 |

## Data Sources

This study employed quantitative data sources including a task difficulty instrument, student activity logs, student-submitted problem solutions, and content knowledge tests. In addition, qualitative data in the form of an open-ended student questionnaire, student interviews, and teacher interviews were collected. The following sections summarize each of the data sources.

### DATA SOURCES

### Problem Solutions

Student solutions were used to evaluate overall problem-solving performance. Using a submission form built into the program, students submitted solutions for each alien, indicating the planetary home that they selected as a result of their problem-solving efforts along with a written rationale. There are multiple solutions for each alien species;

some are better than others, requiring each student to carefully weigh the data they have collected and to justify their solution in their rationale. To help ensure that students submitted a complete rationale, the Solution Form could only be submitted once students entered at least 300 characters.

The solutions were evaluated using an eight-point rubric (Appendix B) used in previous studies (Bogard, Liu, & Chiang, 2013; Liu et al., 2009). The rubric was used to evaluate solutions on the following criteria (a) the correctness of the solution, (b) the number of justifications provided, and (c) discussion of specific limitations. Thus, a student who provides a correct solution along with a substantial justification for the solution and discussion of specific limitations will receive a high score.

Solutions were evaluated by a panel of three raters. An interrater reliability analysis was performed on a subset of solutions (10%) using the kappa statistic to determine level of agreement between the raters prior to allocating 1/3 of the solutions to each rater for final scoring.

**Cognitive Load**

Researchers have proposed a variety of subjective and objective measures of cognitive load. Self-report measures of mental effort (Paas & van Merriënboer, 1993) require learners to respond to Likert scaled items in which they rate the perceived cognitive effort required for them to complete certain tasks. Dual-task methodologies (Brünken, Plass, & Leutner, 2003, 2010; Schoor, Bannert, & Brünken, 2012) measure learners' responses to secondary tasks (such as clicking a letter when it changes color) or learners' interactions with a primary task when also addressing a secondary task. Physiological measures may apply measurements involving electroencephalography (van Gog, Kester, & Paas, 2011), pupillometry (Zheng & Cook, 2012), or cardiography to identify physiological responses associated with various levels of cognitive load.

Perhaps the most common measure of cognitive load is the self-report measure first proposed by Paas and van Merriënboer (1993) and based upon a previous scale developed by Bratfisch, Borg, and Dornic's (1972) measure of perceived task difficulty. Though many variations of the task difficulty scale exist, the essential format involves learners providing an indication of their mental effort on a task via one or more 9-point Likert items with a range from "very low mental effort" to "very high mental effort." There is a lack of consensus in the literature regarding the timing of the subjective measures. Some studies make use of a single measure at the end of all tasks, while other studies make repeated measures following each task. A recent study (van Gog, Kirschner, Kester, & Paas, 2012), however, suggests that repeated measures following each task may result in a more accurate measure of cognitive load. This measure serves as a relatively unobtrusive measure for classroom research. While the scale cannot differentiate between intrinsic, extraneous, and germane cognitive load, it does provide a measure of overall cognitive load. Paas and van Merriënboer (1993) obtained a coefficient of reliability of $\alpha = 0.90$ for this scale, indicating that it is a highly reliable measure of mental effort.

A 9-point scale was administered directly within *Alien Rescue* following the submission of each solution and was comprised of a single item: "How much effort did it take find a home for this alien?" Although students worked in groups, each student was asked to submit a mental effort rating independently. An example rating form is below.

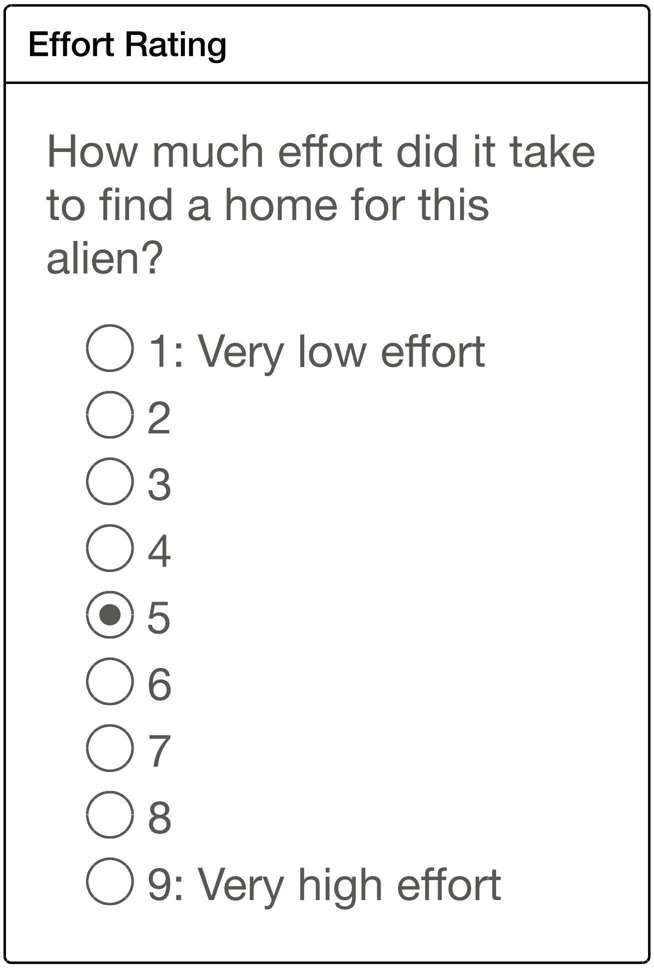


Figure 15: Mental Effort Rating Form

Measures of mental effort alone, however, are not sufficient to evaluate the instructional efficiency of a given condition and therefore, some measure of performance is required. High task performance associated with low mental effort is called high instructional efficiency, while low task performance and high mental effort represents low instructional efficiency. Paas and van Merriënboer (1993) proposed a calculation intended to compute relative condition efficiency using subjective measures of mental effort and task performance data. To calculate instructional efficiency, the measures are first transformed into *z* scores. The standardized performance (P) and effort (E) scores are then entered into the following formula:

$$Efficiency = \frac{zP - zE}{\sqrt{2}}\ .$$

To calculate relative condition efficiency for *Alien Rescue*, the solution score corresponding to the mental effort rating was used as the performance measure.

**Student Activity Logs**

Because *Alien Rescue* was developed as a research platform, it is configured with the ability to record student activity. The program logs nearly every instance of each student's interaction with the program. Data recorded include the date and time, a student identifier, the cognitive tool with which the student is currently interacting, the action they are taking, and any additional notes on the student's interactions.

Using the log data, it is possible to determine students' sequence, frequency, and duration of cognitive tool use.

**Content Knowledge Test**

To measure potential differences in student knowledge as a result of using *Alien Rescue*, the Space Science Knowledge Test (SSKT) was administered. The SSKT is composed of 24 multiple choice questions that measure factual and applied knowledge introduced by the program. It was developed over a number of years through feedback from teachers and astronomers. The highest possible score on the SSKT is 24 and the lowest score is zero. Because classroom implementation of *Alien Rescue* involves limited or no direct teaching, a high score on the posttest SSKT, relative to the pretest administration, is a potential indicator that the student acquired knowledge through the learning activities presented by the program and through peer interaction. The SSKT has been applied in previous research (Bera & Liu, 2006; Liu, 2006; Liu, Horton, Olmanson, & Toprac, 2011) and was found to have a coefficient of reliability of $\alpha = 0.73$.

Examples of the questions are as follows:

Factual: Which of these worlds is a planet (not a moon)?

a. Io
b. Phobos
c. Uranus
d. Not sure

Application: You need to design a probe to go to Titan to find out if it has a magnetic field or earthquakes. Which of the following would you choose to include on your probe?

a. a battery and a solar panel
b. a barometer and a seismograph
c. a magnetometer and a seismograph
d. Not sure

Each question has four answer choices, including a "not sure" option. The science knowledge test was administered before and after students used *Alien Rescue* to measure any change. The complete SSKT can be found in Appendix A.

**Open-ended response questions**

After completing the *Alien Rescue* unit, participants were asked to respond in writing to eight open-ended prompts:

1. What did you like about *Alien Rescue*?
2. What did you dislike about *Alien Rescue*?
3. What parts of *Alien Rescue* helped you the most?
4. What parts of *Alien Rescue* were the least helpful?

5. What did you learn from *Alien Rescue*?
6. What advice would you give to a friend who is using *Alien Rescue* for the first time?
7. If you could change something about *Alien Rescue* what would it be? Why?
8. Where did you get help when using Alien Rescue? What kinds of help did you need?

The questionnaire can be found in Appendix C.

**Interviews**

Interviews were conducted with students at various points throughout the 15-day science unit. These interviews were used to understand student perceptions of the technology scaffolds present within *Alien Rescue* and the usefulness of the scaffolds in supporting student problem-solving.

Sample questions include:

1. What do you think about *Alien Rescue?*
2. What parts of *Alien Rescue* have helped you learn?
3. What parts of *Alien Rescue* could be improved to help you learn better?
4. What are some parts of *Alien Rescue* that are the most difficult for you?
5. Describe what you are doing right now. Why did you decide to do that? What will you do next?

The interviews were conducted face-to-face, audio recorded, and transcribed for analysis. Students were randomly chosen to participate in interviews. In total, 56 student interviews were conducted. Thirty-eight of those interviews were with a single student. Eighteen interviews were performed with a pair of students. Interviews were approximately 5 – 6 minutes in length.

Teacher interviews with the three participating teachers were conducted on the final day of the *Alien Rescue* unit. Teacher interviews were approximately 20 minutes in length. Sample questions include:

1. What are your overall thoughts about *Alien Rescue*?
2. What do you think students learn from *Alien Rescue*?
3. What parts of *Alien Rescue* do you think are most helpful to students?
4. What parts of *Alien Rescue* do you think should be improved?
5. What are your thoughts on the three versions of *Alien Rescue* that were used?
6. What parts of the problem-solving process are most difficult for students?
7. Describe your role when students are using *Alien Rescue*?
8. What is your ideal role? How can the technology help with that?
9. Why are the workbooks important?
10. If you had the chance to design *Alien Rescue*, what are some things you would change?
11. What advice would you give a peer who is using *Alien Rescue* in their classroom for the first time?

## Analysis

### QUESTION 1: EFFECT ON COGNITIVE LOAD

To determine the effects of the treatment conditions on cognitive load, a repeated measures ANOVA was performed using treatment condition as the between-subjects independent variable and data collection points as the repeated measures independent variable. The dependent variable was instructional efficiency score.

To determine the performance score needed to calculate instructional efficiency, scores were assigned to each of the problem solutions submitted by the students. Solutions were divided into two groups: incorrect scores, which received a score of 0 and correct scores, which were scored using the eight-point rubric by a panel of three scorers. Prior to scoring the solutions, the scorers scored the same 10% of the correct solutions (36 total). Inter-rater reliability was determined to be kappa = 0.59 ($p < .0001$), which was considered an acceptable level of agreement for this study. Follow-up training was conducted with each trainer to emphasize correct use of the rubric. Each rater was then randomly assigned 1/3 of the solutions. Solution scores from all three raters were collected and were merged with the effort ratings submitted by each student. The data were then filtered to ensure that only scores for the first three solutions were included.

Effort rating data was extracted via SQL query from the *Alien Rescue* web application and matched to student scores. Instructional efficiency was then computing in SPSS.

Multiple comparisons were performed using the Tukey procedure at the $\alpha = 0.05$ significance level. A follow-up one-way ANOVA was performed to investigate differences at time one only.

### QUESTION 2: EFFECT ON PROBLEM-SOLVING BEHAVIORS

Prior to performing the analysis, the data were extracted via SQL query from the *Alien Rescue* web application. Calculations were performed on the data to determine the number of days that each user logged into *Alien Rescue*. Users who used *Alien Rescue* across fewer than nine days and greater than 11 days were excluded from the analyses to eliminate participants with extremely low and high amounts of activity. Log data for 128 users were included in the analyses. Variables were then created to aggregate duration of tool use (in seconds) and total tool use frequency for the four cognitive tool categories proposed by Lajoie (1993). A one-way MANOVA was performed to determine if there is a difference in frequency of cognitive tool use across the different categories and the conditions. A second one-way MANOVA was performed to determine differences in cognitive tool use duration. Multiple comparisons were performed using the Tukey procedure at the $\alpha = 0.05$ significance level.

Graphs illustrating tool use duration and frequency over the duration of the science unit were also generated.

### QUESTION 3: EFFECT ON SCIENCE KNOWLEDGE

A one-way ANOVA was performed to determine the effect of scaffolding condition on change in test performance, calculated based on the difference between pretest and posttest score. Post hoc comparisons were performed using the Games-Howell procedure at the $\alpha = 0.05$ significance level.

### QUESTION 4: STUDENT AND TEACHER PERCEPTIONS

To address question four, an interpretive analysis was performed on the students' open-ended responses and student and teacher interviews. The researcher created open codes from a line-by-line analysis of the response data. Common themes and patterns were extracted from the responses, analyzed, and used to describe student and teacher perceptions of the program.

Word clouds were also generated for each treatment condition using responses on each of the eight student questionnaire items. An additional word cloud was produced using aggregate responses across all three treatment conditions. Student responses were spell-corrected prior to use in the word clouds in order to improve the visualization of frequently used terms. However, the Results chapter presents selected student questionnaire responses as written.

## Procedures

During the week of May 6, 2013, teachers distributed parent permission forms (Appendix D) to the students in order to obtain parental consent for students participating in the study. Students whose parents did not consent to their participation used *Alien Rescue* as part of their regular science unit, but no data was collected from them for research purposes. Each intact class was assigned to one of the three treatment conditions. The study occurred over a three-week period with students using *Alien Rescue* during their daily 45-minute science class. The study began on May 10, 2013 and ended on May 31, 2013. Small, two to three member student groups were assigned a wireless-enabled Notebook computer and worked collaboratively for the duration of the project. Before using the program, students completed an assent form (Appendix E) and a scan form version of the SSKT. Students then began using the program. Students coordinated with each other to divide tasks and plan their problem-solving approach. The teachers provided the initial overview of the unit and specific instructions for the study, but provided minimal guidance and no direct instruction for the duration of the unit. Students were required to complete a school-issued workbook packet that prompted them to record information obtained through their use of *Alien Rescue*. Use of the workbooks, while undesirable for this study, was a requirement of the teachers. Two researchers were present in the classroom to address issues with the program and to conduct observations and interviews as part of the study. At the conclusion of the unit, students completed the SSKT posttest and the open-ended questionnaire. Student activity data, mental effort scores, and problem solutions were extracted from an online database for analysis in SPSS.

# CHAPTER 4: RESULTS

This chapter will summarize the results obtained through analyses of both quantitative and qualitative data sources.

## Research Question 1: How do varying levels of scaffolding affect students' cognitive load, as measured by instructional efficiency?

The first research question assessed the affect of the different treatment conditions on cognitive load, as represented by an efficiency score. As described in the previous chapter, efficiency score was calculated using the following formula:

$$Efficiency = \frac{zP - zE}{\sqrt{2}}.$$

Data from the first six effort ratings submitted by each student were used to evaluate the internal consistency of the scale. A coefficient of reliability of $\alpha = .821$ indicated a high level of reliability.

A repeated measures ANOVA was performed using treatment condition as the independent variable and efficiency scores at time one, two and three as the dependent variables. Prior to performing the ANOVA the data were evaluated for violation of assumptions. A visual inspection of a boxplot revealed two outliers at time one and two at time two. The outliers represented cases of either extremely high efficiency (high solution score with low effort rating) or low efficiency (low solution score and high effort) and since they represented valid cases, they were kept in the analysis. Efficiency score was not normally distributed at time one for the control and prompt conditions, as assessed by the Shapiro-Wilk's test ($p < .05$). Efficiency scores at time two and time three were normally distributed ($p > .05$) across all treatment conditions. Because ANOVA is robust against deviations from normality, it was decided to run the test. Levene's Test of Homogeneity of Variance determined that the homogeneity assumption was met ($p > .05$). Mauchly's test was performed to check the assumption of sphericity and it was determined that sphericity was not violated ($p > .05$).

Results of the ANOVA suggest that there was not a statistically significant interaction effect between time and treatment condition on efficiency score, $F(4, 136) = .932$, $p = .447$, partial $\eta^2 = .027$. However, there were significant differences in efficiency score across the main effect of time, $F(2, 136) = 3.313$, $p = .039$, partial $\eta^2 = .046$. Pairwise comparisons suggest a significant difference ($p = .026$) between times one and three with respect to efficiency score. Scores at time three ($M = -.0073$, $SD = .99$) indicate lower efficiency scores than were observed at time one ($M = .3226$, $SD = .94$), a mean difference of .344, 95% CI [.042, .645]. There were no significant differences between times one and two or times two and three. In addition, there was no significant main effect of treatment condition, $F(2, 68) = .060$, $p = .942$, partial $\eta^2 = .002$. Mean efficiency score by time and treatment condition are presented in Table 2 and Figure 16.

Table 2: Mean Efficiency Score by Treatment and Time

| Treatment | Mean | Std. Deviation | N |
|---|---|---|---|
| | Time 1 | | |
| Control | .1775 | .79834 | 16 |
| Prompt | .4992 | 1.16124 | 15 |
| Structured | .3145 | .93149 | 40 |
| Total | .3226 | .94933 | 71 |
| | Time 2 | | |
| Control | .2478 | .81603 | 16 |
| Prompt | -.1770 | 1.00063 | 15 |
| Structured | .0597 | .85448 | 40 |
| Total | .0521 | .87737 | 71 |
| | Time 3 | | |
| Control | .0585 | .72093 | 16 |
| Prompt | -.1000 | 1.07126 | 15 |
| Structured | .0012 | 1.06038 | 40 |
| Total | -.0073 | .98500 | 71 |

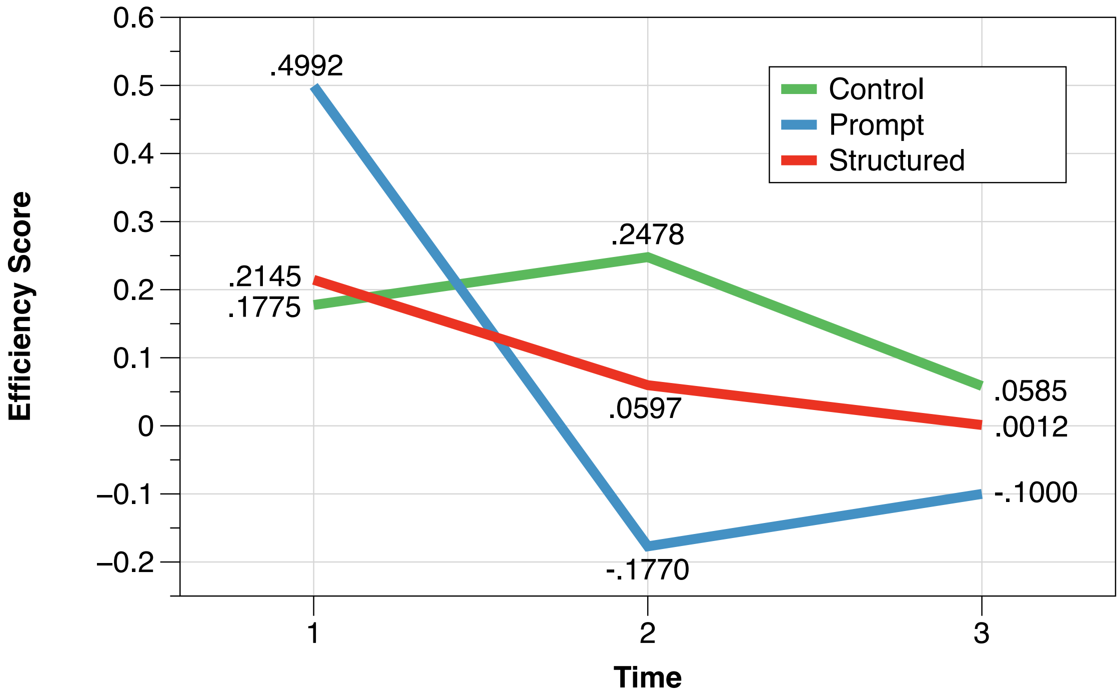


Figure 16: Efficiency Score by Treatment and Time

Descriptive data on solution score and effort ratings suggest that students responded with lower effort ratings over time, yet solution scores also decreased over time. To determine potential validity of this apparent trend, I performed two additional repeated measures ANOVA procedures using difficulty rating and solution score at times one through three as the dependent variables. The results of this additional analysis do not suggest significant interaction effects or main effects for time or treatment condition ($p > .05$).

Due to the requirements of repeated measures ANOVA, cases that lacked data in one or more of the three time points were listwise excluded from analysis. This caused a low sample size ($N = 71$), particularly among the control ($N = 16$) and prompt conditions ($N = 15$). It is possible that the non-significant results of the analysis were partially due to the sample size. To explore this possibility, a follow-up one-way ANOVA was performed on efficiency score associated with the first solution only. No outliers were identified in the data, though the data did not meet the assumption of normality as tested by the Shapiro-Wilk's test ($p < .05$). Levene's Test of Homogeneity of Variances indicated that the assumption of homogeneity of variances was met ($p > .05$). As the ANOVA procedure is relatively robust against departures from normality, the test was run.

Results of the ANOVA suggest an overall significant difference between treatment condition and efficiency at time one, $F(2, 158) = 3.096$, $p = .048$. Post-hoc analysis using the Tukey procedure found statistically significant differences ($p = .041$) in efficiency between the control condition ($M = -.1927$, $SD = 1.0995$, $N = 38$) and the prompt condition ($M = .4145$, $SD = .9721$, $N = 39$). No significant differences were found between the control condition and the structured condition ($M = .1972$, $SD = 1.1138$, $N = 84$) or the prompt condition and the structured condition. Mean efficiency scores are presented in Table 3 and Figure 17 below.

Table 3: Mean Efficiency Scores by Treatment Condition

| Treatment | N | Mean | Std. Deviation |
|---|---|---|---|
| Control | 38 | -.1927 | 1.09950 |
| Prompt | 39 | .4145 | .97206 |
| Structured | 84 | .1972 | 1.13764 |
| Total | 161 | .1578 | 1.10517 |

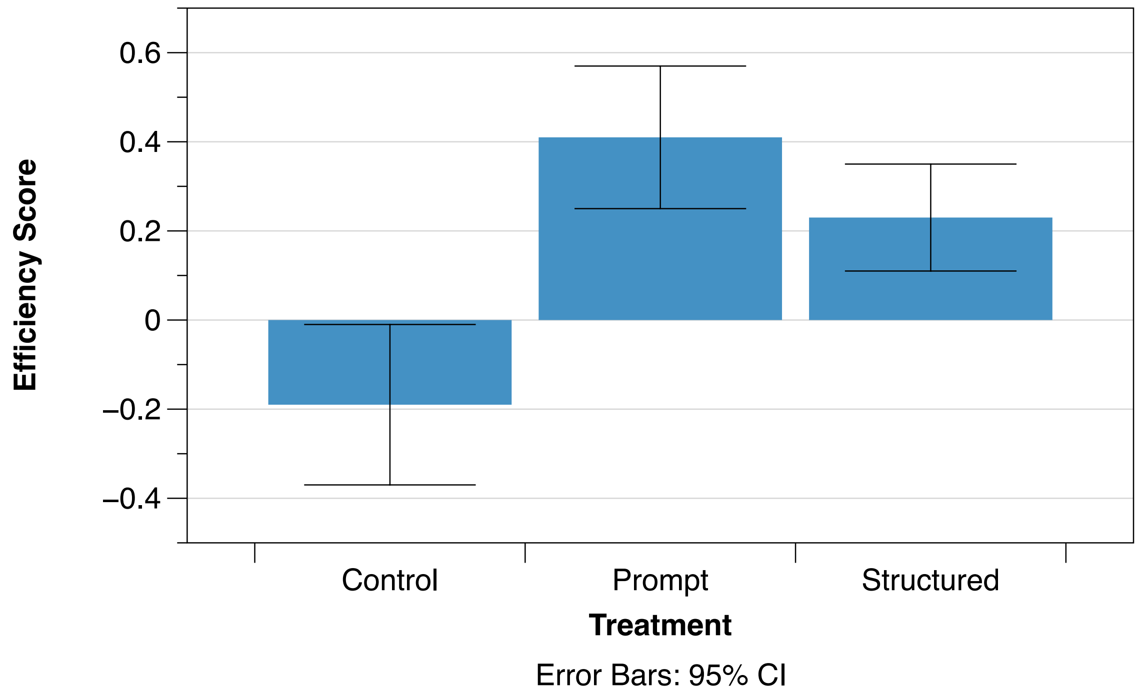


Figure 17: Efficiency at Time One by Treatment Condition

## Research Question 2: What are the characteristics of problem-solving behavior among students who received different forms of scaffolding?

To determine if there were statistically significant differences in problem-solving processes across the three treatment conditions, two one-way multivariate analysis of variance (MANOVA) procedures were performed: one on duration of cognitive tool use and one on frequency of cognitive tool use.

### TOOL USE DURATION

Figures 18 – 20 visually represent tool use duration for the three treatment conditions across 17 days of problem-solving. Allowing for differences in sample sizes across the three treatments, the graphs illustrate relatively predictable patterns of tool use corresponding to different phases of the problem-solving process. Tools that share cognitive load, such as the Alien Database and Solar System Database along with the tools that support cognitive processes (the Notebook), reflect high usage throughout the duration, but are used the most during the early stages of problem-solving as students conduct background research on the aliens and planets. Tools that support out-of-reach activities and hypothesis testing show a marked increase during the second week of problem-solving (days seven – 11) as students begin to launch probes, interpret results, and submit solutions. Small spikes in the use of tools that share cognitive load and support cognitive processes may correspond to the solution generation process as students return to those tools to validate and double-check their solution rationales. Days five, six, 12, and 13 are weekend days; while the graphs do show some evidence of activity on the weekends they show visibly less activity across all treatments. These graphics are useful in visually portraying how student problem-solving unfolds over time.

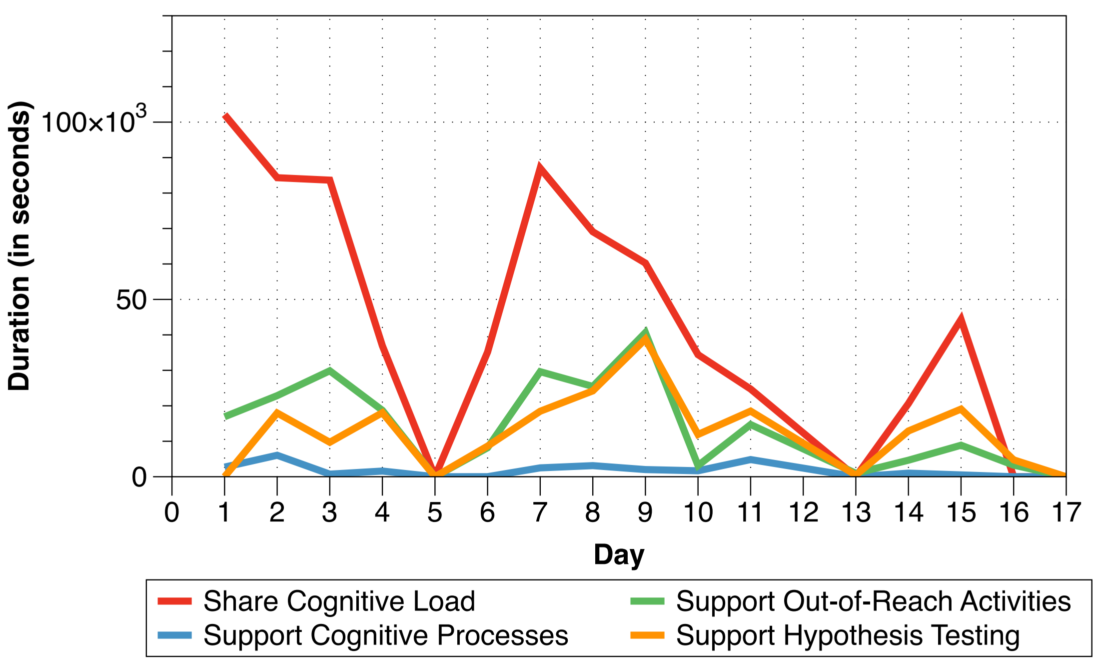


Figure 18: Tool Use Duration for Control Condition

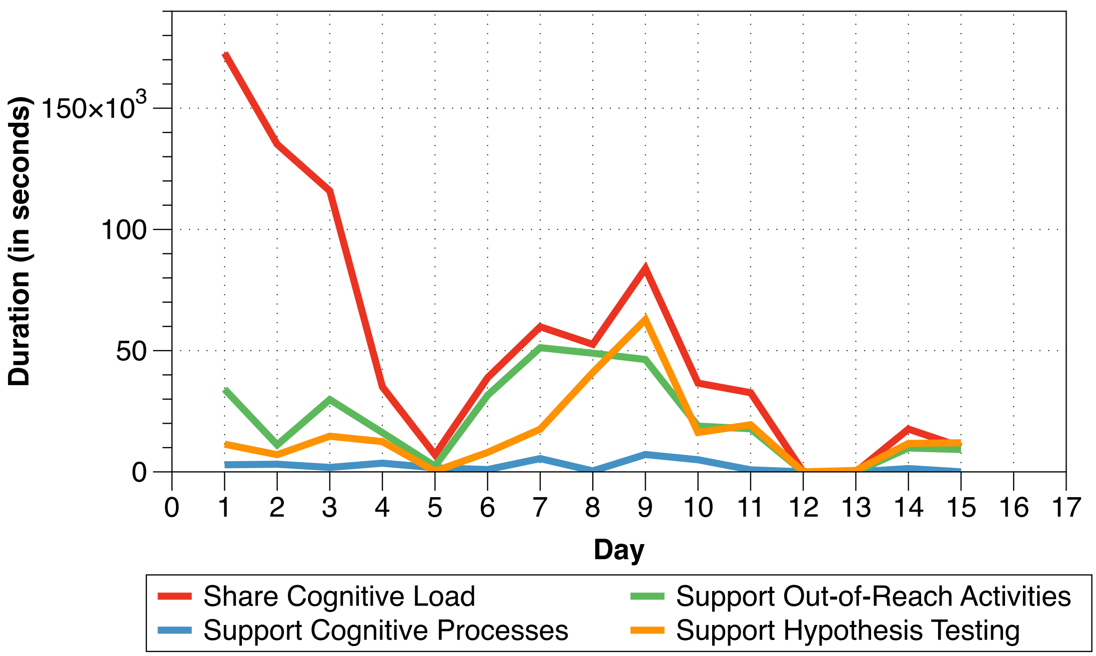


Figure 19: Tool Use Duration for Prompt Condition

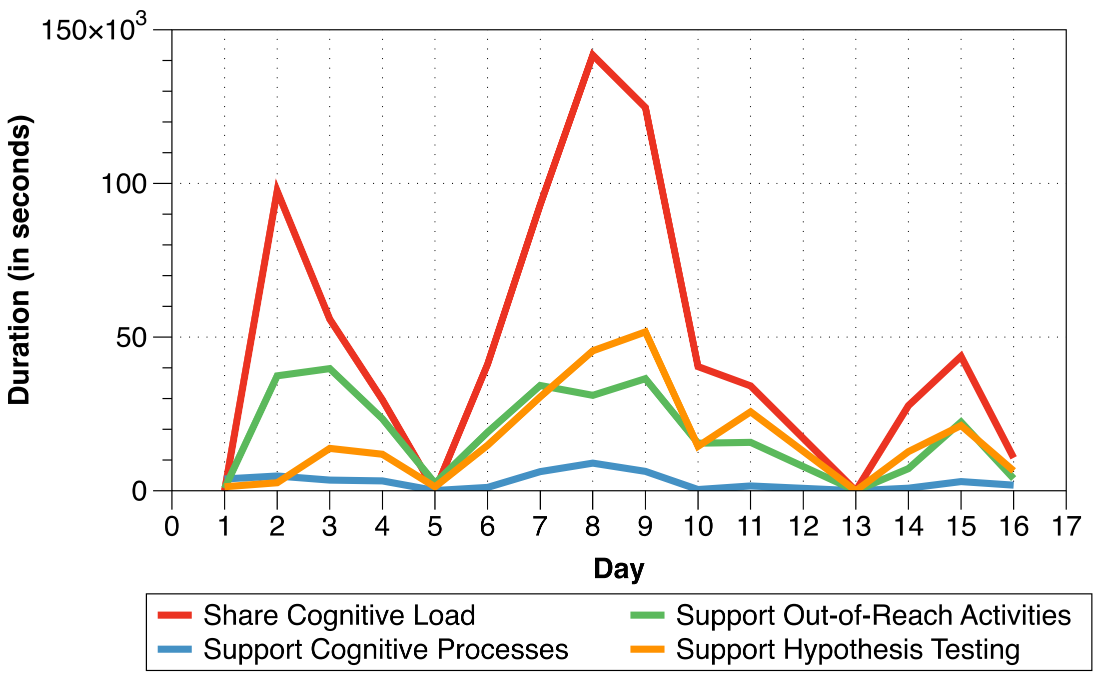


Figure 20: Tool Use Duration for Structured Condition

A one-way MANOVA was then run to determine the effect of the three treatments on duration of cognitive tool use. The four tool category variables were assessed as dependent variables. Assumptions were checked prior to performing the analysis. The Shapiro-Wilk test ($p < .05$) indicated that the data were not normally distributed; however, since the MANOVA procedure is relatively robust against departures from normality, it was decided to run the test. Pearson correlations were performed to determine that there was no multicollinearity. Box's M test ($p < .001$) suggested that there was a violation of the homogeneity of variance-covariance matrices. However, since the sample sizes were relatively similar, I decided to continue the analysis, but interpreted the results using Pillai's Trace instead of Wilk's Lambda. There was not an overall statistically significant difference between treatment conditions and the combined dependent variables with respect to tool use duration, $F(8, 122) = .913$, $p = .506$; Pillai's Trace = .058; partial $\eta^2 = .029$. Means for tool use duration are presented below in Table 4.

Table 4: Mean Tool Use Duration by Tool Category and Treatment Condition

| Treatment | Mean (in seconds) | Std. Deviation | N |
|---|---|---|---|
| | Support Cognitive Processes | | |
| Control | 658.78 | 1302.430 | 36 |
| Prompt | 730.95 | 2356.275 | 44 |
| Structured | 758.33 | 1955.854 | 48 |
| Total | 720.92 | 1940.273 | 128 |

Table 4: Mean Tool Use Duration by Tool Category and Treatment Condition (continued)

| | | | |
|---|---|---|---|
| Share Cognitive Load | | | |
| Control | 16869.67 | 6868.567 | 36 |
| Prompt | 15755.20 | 5670.737 | 44 |
| Structured | 15365.42 | 8372.467 | 48 |
| Total | 15922.48 | 7086.087 | 128 |
| Support Out-of-Reach Activities | | | |
| Control | 5947.72 | 2386.048 | 36 |
| Prompt | 6386.23 | 3730.061 | 44 |
| Structured | 5180.02 | 2101.235 | 48 |
| Total | 5810.57 | 2860.804 | 128 |
| Support Hypothesis Testing | | | |
| Control | 5211.78 | 2408.286 | 36 |
| Prompt | 4760.00 | 5653.857 | 44 |
| Structured | 4266.42 | 2227.045 | 48 |
| Total | 4701.97 | 3795.205 | 128 |

### Tool Use Frequency

Similar to the duration graphs, Figures 21 - 23 illustrate tool use frequency over the 17 days (including weekends) that *Alien Rescue* was deployed.

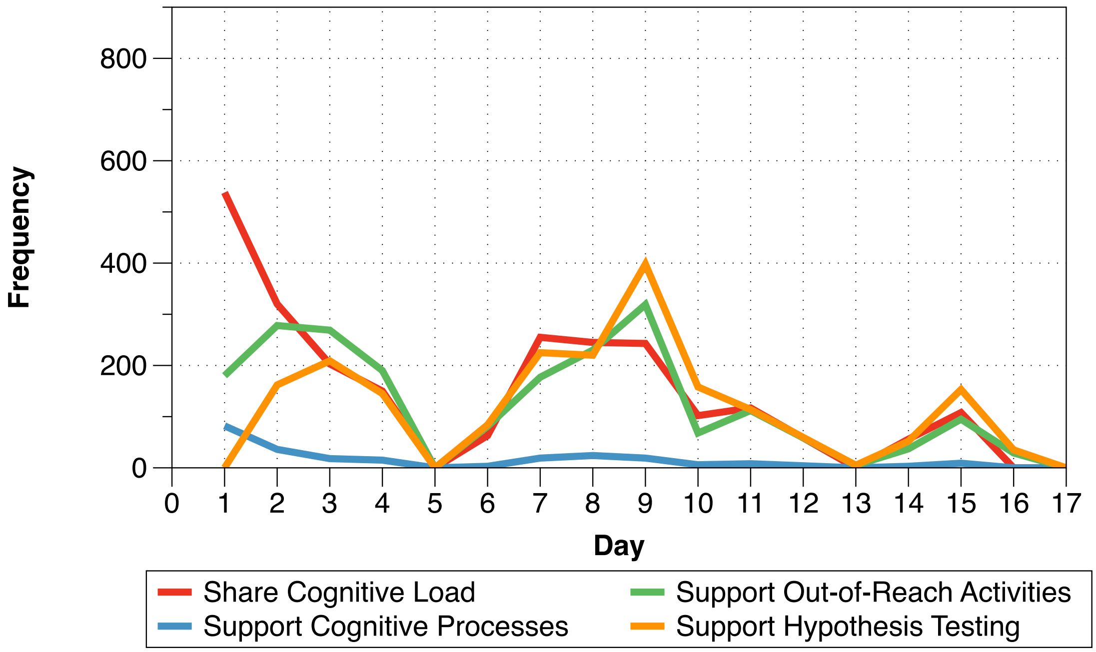


Figure 21: Tool Use Frequency for Control Condition

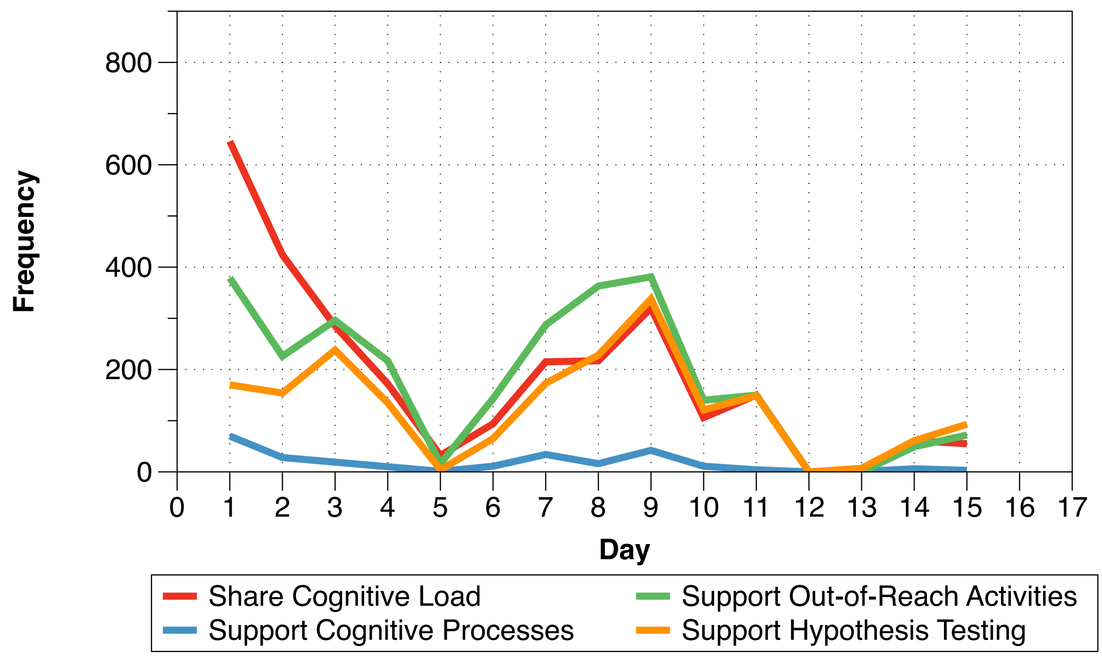


Figure 22: Tool Use Frequency for Prompt Condition

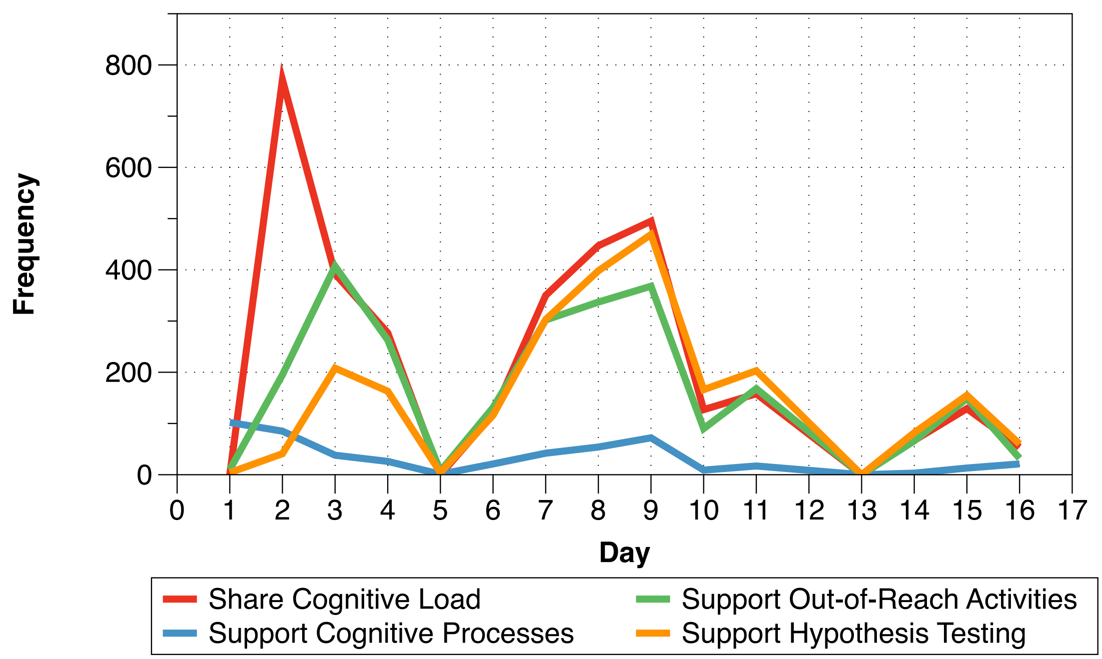


Figure 23: Tool Use Frequency for Structured Condition

A second one-way MANOVA was run to determine the effect of the three treatments on frequency of cognitive tool use. The four tool category variables were assessed as dependent variables. Assumptions were checked prior to performing the analysis. The Shapiro-Wilk test ($p < .05$) indicated that the data were not normally distributed; however, since the MANOVA procedure is relatively robust against departures from normality, it was decided to run the test. Pearson correlations were performed to determine that there was no multicollinearity. Box's M test ($p < .001$) suggested that there was a violation of the homogeneity of variance-covariance matrices. However, since the sample sizes were relatively similar, I decided to continue the analysis, but interpreted the results using Pillai's Trace instead of Wilk's Lambda. There was an overall statistically significant difference between treatment conditions and the combined dependent variables with respect to tool use frequency, $F(8, 246) = 3.737, p < .001$; Pillai's Trace = .217; partial $\eta^2 = .108$. Follow-up univariate ANOVA's suggested that there were significant difference across the treatment conditions on usage frequency for tools that share cognitive load, $F(2, 125) = 8.189, p < .001$, partial $\eta^2 = .116$ and tools that enable hypothesis testing, $F(2, 125) = 3.500, p = .033$, partial $\eta^2 = .053$. Tukey's post-hoc analysis showed that, with respect to tools that share cognitive load, students in both the control condition and prompt condition made less frequent use of the tools than students in the structured treatment condition ($p = .013$). In addition, students in the control condition made more frequent use of tools that support hypothesis testing than students in the prompt treatment condition ($p = .025$). Mean tool use frequency is presented in Table 5 below.

Table 5: Mean Tool Use Frequency by Tool Category and Treatment

| Treatment | Mean | Std. Deviation | N |
|---|---|---|---|
| Support Cognitive Processes | | | |
| Control | 6.17 | 7.045 | 36 |
| Prompt | 5.34 | 6.678 | 44 |
| Structured | 8.02 | 10.907 | 48 |
| Total | 6.58 | 8.612 | 128 |
| Share Cognitive Load | | | |
| Control | 59.11 | 21.047 | 36 |
| Prompt | 54.86 | 22.062 | 44 |
| Structured | 74.85 | 29.583 | 48 |
| Total | 63.55 | 26.282 | 128 |
| Support Out-of-Reach Activities | | | |
| Control | 51.83 | 26.267 | 36 |
| Prompt | 49.64 | 22.184 | 44 |
| Structured | 45.85 | 17.940 | 48 |
| Total | 48.84 | 21.955 | 128 |

Table 5: Mean Tool Use Frequency by Tool Category and Treatment (continued)

| | | | |
|---|---|---|---|
| | Support Hypothesis Testing | | |
| Control | 48.89 | 30.036 | 36 |
| Prompt | 35.89 | 14.347 | 44 |
| Structured | 41.98 | 20.308 | 48 |
| Total | 41.83 | 22.300 | 128 |

## Research Question 3: How do different forms of scaffolding affect students' content knowledge and performance within the problem-solving scenario?

### CHANGE IN SCIENCE KNOWLEDGE

To address the third research question concerning the role of the three treatment conditions on pre and posttest scientific knowledge, a one-way ANOVA was performed using treatment as the independent variable and change score as the dependent variable. Change score was calculated by subtracting the pretest score from the posttest score.

The data were first evaluated to ensure they met all assumptions required for the ANOVA procedure. A visual inspection of a boxplot indicated that there were three outliers. Based on review of the data, the outliers were determined to be valid data points. In two cases, student scores decreased by four points when comparing the pre and posttest. In the third case, a student gained nine points on the posttest as compared to the pretest. I decided to include these data points in the analysis. The data met the assumption of normality, meaning that the change score was normally distributed across all three treatment conditions, as assessed by the Shapiro-Wilk's test of normality ($p > 0.5$). By applying Levene's Test of Homogeneity of Variance, it was determined that the assumption of homogeneity of variances was violated (*p* = 0.04). Due to this violation, a more robust ANOVA procedure was required; therefore, Welch's ANOVA was used.

Results from the ANOVA indicated significant differences between the treatment conditions with respect to change score (Welch's $F(2, 95.190) = 3.801$, $p = .026$). Using the Games-Howell post-hoc test, it was determined that there was a statistically significant ($p = .025$) difference in change score between the structured condition ($M$ = 2.1, $SD$ = 3.4, $N$ = 57) and the control condition ($M$ = 4.0, $SD$ = 3.8, $N$ = 44), a mean difference of 1.9, 95% CI [0.2, 3.7]. There were no statistically significant differences between the control condition and the prompt condition ($M$ = 2.4, $SD$ = 2.9, $N$ = 53) or the prompt condition and the structured condition. Mean change scores are presented in Table 6 and Figure 24.

Table 6: Mean Change Score by Treatment Condition

| Treatment | N | Mean | Std. Deviation |
|---|---|---|---|
| Control | 44 | 4.0227 | 3.79405 |
| Prompt | 53 | 2.4151 | 2.91834 |
| Structured | 57 | 2.0877 | 3.40840 |
| Total | 154 | 2.7532 | 3.44388 |

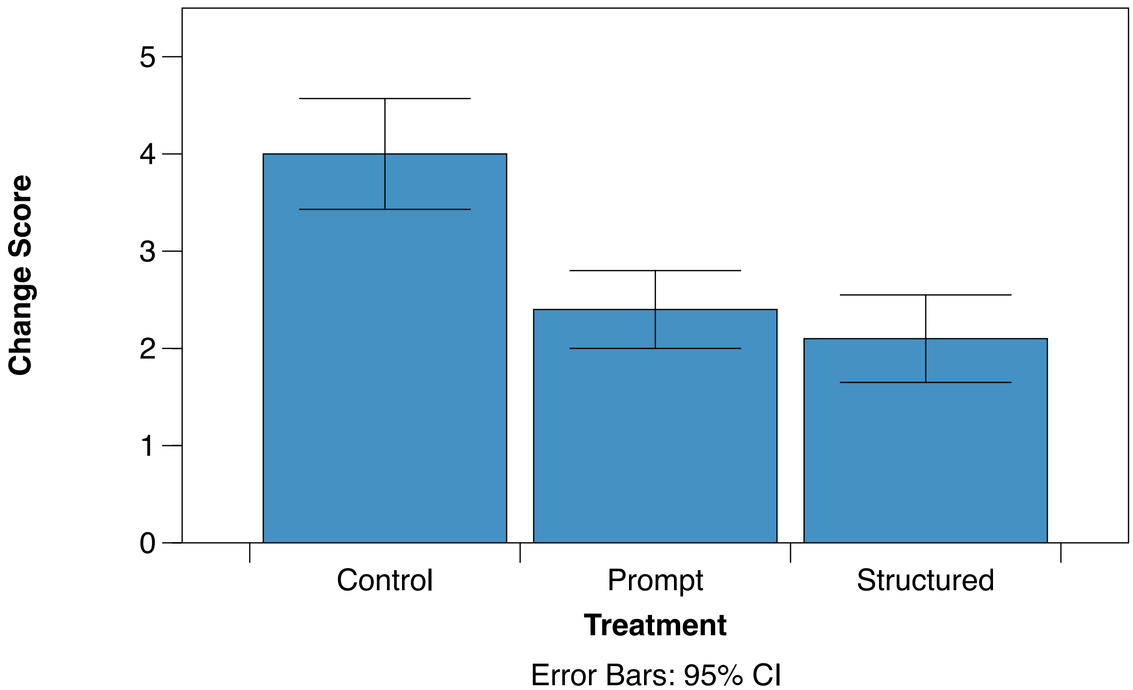


Figure 24: Change Scores By Treatment Condition

### CHANGE IN UNSURE RESPONSES

Because each item on the science knowledge test allows students to record "not sure" as an answer, an additional ANOVA was performed on the change in unsure responses between the pre and posttest. The change score was calculated by subtracting the posttest unsure count from the pretest count.

A visual inspection of a boxplot revealed the presence of 10 outliers, all of which were the result of substantially lower unsure counts on the posttest. Given that the data were identified as valid data points, I decided to include all observations in the analysis. The Shapiro-Wilk test of normality indicated that the data violated the assumption of normality ($p < .05$). Because ANOVA is relatively robust against departures from normality, I decided to continue the analysis. The data also violated the assumption of homogeneity of variance as indicated by Levene's Test of Homogeneity of Variance ($p <$

0.5). Due to this violation, a more robust ANOVA procedure was required; therefore, Welch's ANOVA was used.

Results from the ANOVA indicated significant differences between the treatment conditions with respect to unsure count (Welch's $F(2, 3.377) = 93.477$, $p = .038$). Using the Games-Howell post-hoc test, it was determined that there was a statistically significant difference in unsure count between the prompt condition ($M = -1.5$, $SD = 2.64$, $N = 53$) and the control condition ($M = -3.3$, $SD = 3.9$, $N = 44$), a mean difference of 1.8, 95% CI [0.2, 3.4]. There were no statistically significant differences between the control condition and the structured condition or the prompt condition and the structured condition. Mean change scores are presented in Table 7 and Figure 25.

Table 7: Mean Change in Unsure Answer Frequency by Treatment Condition

| Treatment | N | Mean | Std. Deviation |
|---|---|---|---|
| Control | 44 | -3.3409 | 3.87564 |
| Prompt | 53 | -1.5472 | 2.64260 |
| Structured | 57 | -2.0175 | 3.45114 |
| Total | 154 | -2.2338 | 3.38932 |

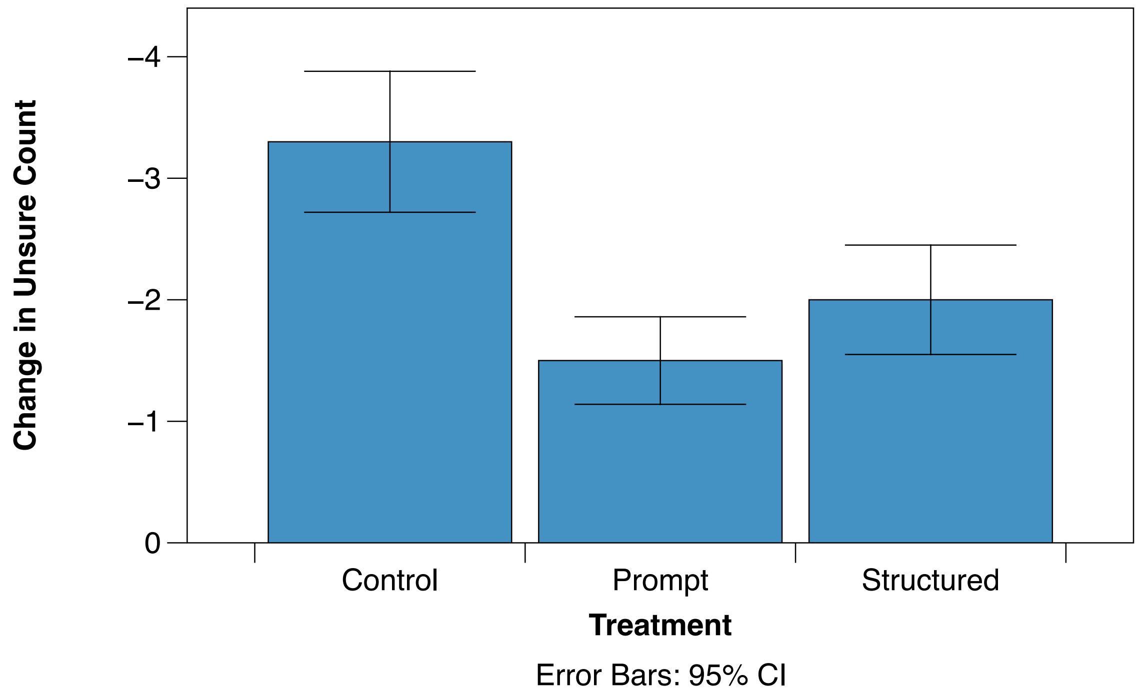


Figure 25: Change In Unsure Count By Treatment Condition

## Research Question 4: What are student and teacher perceptions of *Alien Rescue* and the different treatment conditions?

### Student Perceptions

Prior to beginning analysis of student interview and questionnaire responses, I generated a series of word clouds for each questionnaire response that visually represent the frequency of words used. Figure 26 provides an overview of students' compiled responses across all eight questionnaire items. Though the figure lacks the context gained through an analysis of individual student responses, a number of recurring themes are readily apparent. Most notably, students frequently discussed the aliens, their characteristics and requirements, and the process of placing the aliens on new worlds across a variety of contexts. In addition, students frequently cited the experience of designing and launching probes along with the process of interpreting probe results, challenges and problems with the probe design process, and general perceptions – likes and dislikes – of the probe functionality within *Alien Rescue*. In addition to these most frequently used terms, there are a number of peripheral terms that are also used in various contexts. Terms such as “work”, “think”, “game”, “info”, “teacher”, “rooms”, “space”, “confusing”, “challenging”, “friends”, and “cool” provide useful reference points in interpreting students’ overall responses.

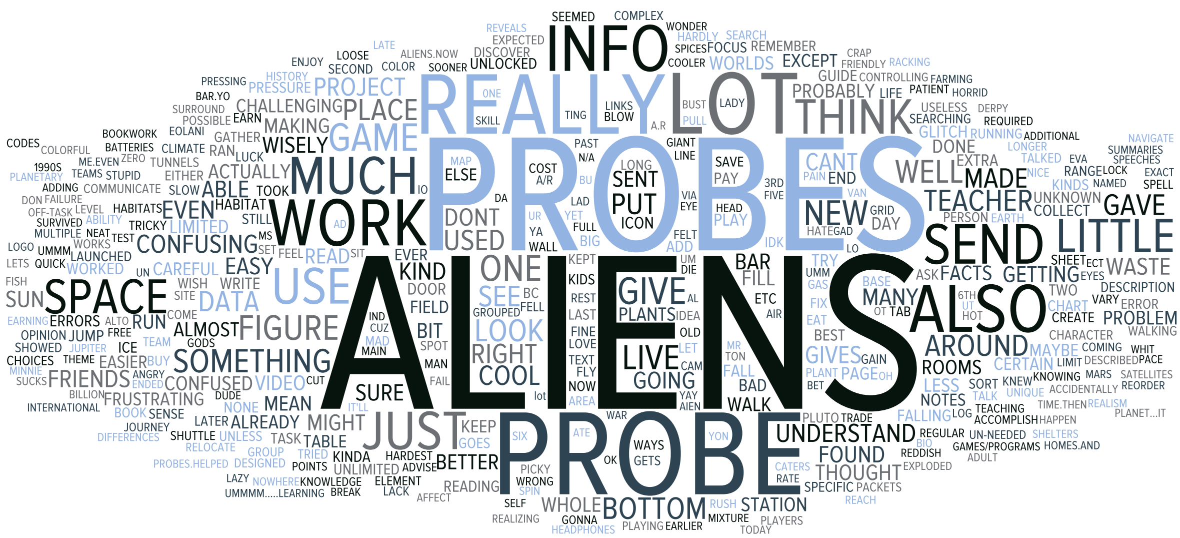


Figure 26: Word Cloud of Compiled Responses

Using the student questionnaire items as an organizing framework, I will discuss themes shared across the three treatment conditions as well as themes that were distinct to a single treatment.

### What Did You Like About *Alien Rescue*?

Figure 27 includes three word clouds that indicate word frequency across the three treatment conditions. Visual inspection of these word clouds reveals connections to student responses that were thematically similar. As with the aggregate word cloud in Figure 26, the terms “Aliens” and “Probes” again featured prominently to various degrees across the treatments. In addition, some new terms emerge. In particular, student responses to this question often followed themes relating to fun, the processes of learning new information about the planets and the aliens, the video game like qualities of the experience, and the extent to which the program represented a departure from the familiar learning experience within their sixth grade science classes.

The themes were consistent across all treatment conditions. Features of the treatments themselves, such as the use of guiding prompts or the manner in which the structured condition scaffolds access to program components were typically not discussed in the student responses.

The following sections provide questionnaire and interview excerpts that support these themes.

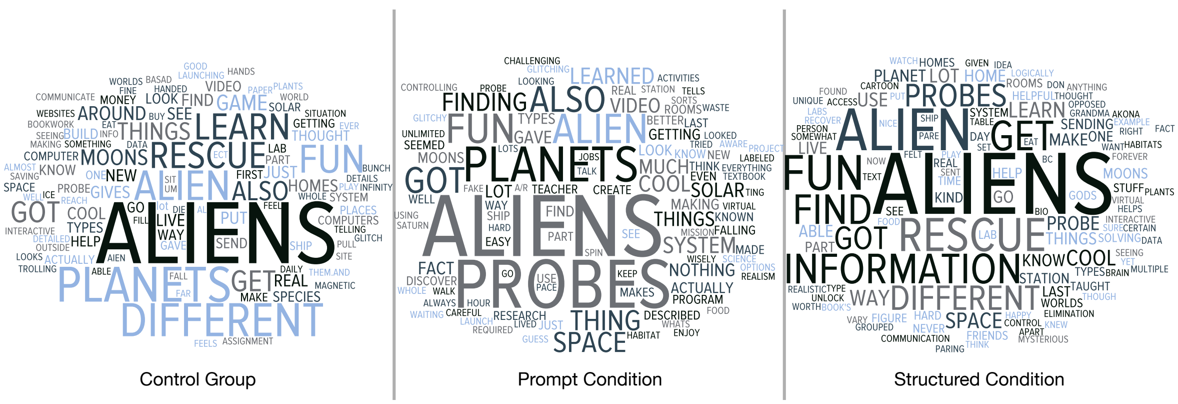


Figure 27: What did you like about *Alien Rescue*?

***Fun and Engaging***

Students frequently described the program as different from traditional classwork and involving the use of computers instead of textbooks. Many students enjoyed the collaborative nature of the activity, citing the opportunity to work with partners. Student comments also suggest that they enjoyed the inquiry-based nature of the experience.

The following questionnaire responses illustrate student descriptions of *Alien Rescue* as fun and engaging.

- "that it was very fun. it was not a bookwork assinment. and we had partners"
- "Alien Rescue is fun. It gave us a new way to learn. It was educational."
- "it was fun and we got to have time to do a project without the teacher"
- "The thing I liked about alien rescue is that we were researching and learning about planets while having fun learning about aliens.Another fun ting was being able to use computers instead of reading out of the text books and completing worksheets.The last most fun thing was having a partner."
- "i liked that it was a fun way of doing this project instead of just sitting and working out of a text book and haveing a partner to work with"

The following interview excerpts further support student perceptions of *Alien Rescue* as fun and engaging.

> It's fun for me because I like the challenge like finding places that match for the aliens and so I think that part's fun like the temperature, the habitat and stuff. I think that's the fun part.

> It's a lot of fun. It's very interesting and a lot of it is kind of like, with building probes, it's kind of realistic. It's fun to build probes and send them off and stuff.

> I enjoy that I'm learning, but I'm having fun at the same time.

***Content Knowledge***

Student questionnaire responses frequently cited the opportunity to learn about the planets, aliens, and space science as an aspect that they particularly enjoyed. Students describe learning about the aliens, their characteristics, home planets, and appearance. Students also described their interest in learning about the solar system.

The following questionnaire responses illustrate these perspectives.

- "the part that liked about the aien rescue is that we can learn about the diffrent aliens and how they live and how they move and how they do there stuff, and how there planets are and what they do in a daily basad to figure . and how we had to figure out diffrent things. learning about the aliens was intersting a little.:)"
- "i learned about the 6 types of aliens and what they need to survive. also about planets and if they have what the aliens need"
- "i like the think we learn in alien rescue because of the fact that i love space. i love the fact that i found out this much about our solar system"
- "How we get to design things and learn about the aliens and the planets and moons in our solar system."
- "It was fun researching about the Aliens and the planets. I learned a lot about the planets and it was fun to work with a partner. I had trouble paring up the aliens and the planets but we were able to pare them up."

The following interview excerpts illustrate student descriptions of learning within *Alien Rescue*.

> I look at the species of aliens and what their habitat and what they look like and what they eat. Also, like how to send different probes to other planets and moons to see

> what they have on their. Like it's like a miniature version of being an astronaut at NASA.

> It's kind of cool, you know, to kind of get to learn about the planet. Like, I never knew a lot about the planets that I now know because of this.

> Well, the fact that we could make probes and figure out about the planets. I love space so I like the fact that I — I learned stuff that I never really knew about the planets.

> Um, well learning about the atmosphere and all like the planets like how um, how the aliens like habitat like the dwellings of how they live there, um we have to go find the planets and it gives us information about the planets. So it's helped us about the atmosphere like if it has any - is it below or high temperatures. So, yeah that's helped us learn or helped me learn.

***Video Game Characteristics***

Other questionnaire responses referenced the video game characteristics of *Alien Rescue*. Students described the manner in which *Alien Rescue* was perceived as a hybridization of games and learning. Some students referenced the apparent novelty of using a video game in an educational context; others specifically referenced the dual entertainment and educational purpose of the program.

- "How it's like a video game but you can learn at the same time"

- “i liked it how we get to walk around like a video game and not just just sit there.”
- “I liked the way you get to learn while playing an awesome game and the way you get to interact with it instead of just going on to a web site and researching things about planets and the ‘Aliens’”
- “I like how it was like a video game mixed with an educactional thing, its alot better than doing paper and book work”
- “I liked how it had a fun computer game aspect to it and it was also educational at the same time.”
- “that i got to play and learn in a video game”

The following interview excerpts also reference the video game characteristics of *Alien Rescue*.

> I think it’s a really, really good project. Like, we should do more of these kind of projects at school. And it’s really nice because it’s kind of a like a video game type of thing. So you can learn while doing something that is sort of like a video game. And i just — it’s a really, really good program that I’d recommend to other people.

> I think it’s really cool because it teaches you about like the solar system and like the species of like different aliens and you can like determine where they could live. So I think it’s really cool the way they put it all together to make like a little video game.

> It's fun having a game that you actually play. You actually control the character while you're learning.

> It's like a video game, but it's still teaching you and you learn and it's helping you.

***Different Learning Experience***

In many cases, students described the experience of *Alien Rescue* relative to the familiar classroom experience. Students described the situated nature of the *Alien* Rescue experience, highlighting the opportunity to be a scientist conducting authentic research. Interactivity was commonly cited as a particularly appealing aspect of the program.

The following interview excerpts highlight these perspectives.

> You get to know about these different species that live out in outer space. It's not something we usually do in science. We get to actually be a scientist, and do all the research and stuff. It's not like … we have to go find it out by ourselves. We don't have … it's not like we have a textbook, and we could just find it anywhere. You have to go with the probes, and get that information by yourself.

> It's not like looking in a text book or just flipping a page and I think. I don't really know. It's just more interactive."

> Well like at school, sometimes the teachers just tell us to get a textbook out and then to like write some questions. Well this is like somewhat the same thing except it's on the computer and you're walking around and you're interacting

> with it and it's really, it's just better this way and kids want to do it unlike the other thing which makes them more likely to get things right and higher grades and stuff so that's why i think you should do this more.
>
> It's um, better than just sitting in class and just like not doing book work and that you can like play games on it. And try to um like figure out hypotheses and why they came to earth and stuff.

**What did you dislike about *Alien Rescue*?**

Figure 28 illustrates some themes related to aspects of *Alien Rescue* that students disliked. In general, the budgetary restrictions of the probe design process and a perceived lack of instructions were frequently mentioned by the students as particularly problematic aspects of the program. Students also described the challenging, difficult, and confusing aspects of the program. All treatment conditions voiced dislike of the workbook that accompanied the *Alien Rescue* unit.

Students in the structured treatment condition often disliked the constrained aspects of the program, including that doors restricted access to areas of the space station and that availability of information was restricted in the early stages of the problem-solving process.

The following sections provide questionnaire and interview excerpts that support these themes.

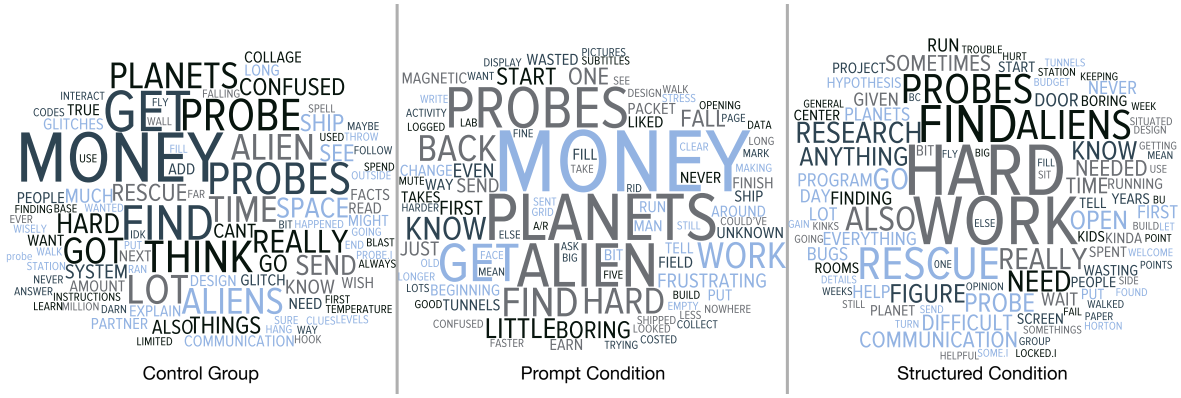


Figure 28: What did you dislike about *Alien Rescue*?

***Budget Limitations***

In describing the budget limitations in their questionnaire responses, students often portrayed the budget allocations as insufficient for their needs. Students frequently described the hampering effect that the budget limitations had on their ability to gather information. Many students discussed problems with running out of funds or being so restricted in their ability to design and launch probes that it threatened their ability to complete the learning experience.

The following questionnaire responses indicate student dislike of the budget feature.

- “What i disliked is that we had a budget. My partner and I ran out of money pretty darn quick.”
- “HAving to have a limited amount of money, in alien rescue was a big problem! We almost did not finish!!!!!!!!”
- “…Another thing is that we should have a bigger budget because some of the probes we needed costed two million dollars and only explore one planet at a time except for a flyby but that didn't have enough information.Therefore we could only explore five planets.”

- "I don't like how we have to have money to build the probes because we might run out of money when we're still trying to figure out stuff."
- "I disliked that you could only have a certain amount if money when you were creating the probes, because if you needed to get information on another planet, but you had already spent it all, then there was nothing much that you could do."

The following interview excerpts also highlight student perspectives on the budget limitations within *Alien Rescue*.

> And with probe design you have to…you're under a budget so you can't just go all willy lilly and like download — like put everything on one probe. Like nothing on the others. So when you're done with the budget, you're done with the budget. Yeah.

> I think it would be a lot easier if we had an unlimited amount of money. Well, not really that. But because some of the tools that I need to fill out this chart, they can only be used on the expensive-type probe, so it's a lot easier to lose money when you're trying to fill out a big chart like this. So, I think it would be a lot easier if all of the tools could be used on just one type of probe. Or, at least make the lander a lot less expensive.

> bought a lot of probes, so now we don't have that much money. We're just trying to find information in other ways, besides buying probes.

### *Insufficient Direction*

Students across the treatment conditions felt that insufficient direction was provided at the outset of the project. They described experiences of being confused about aspects of the program including how to get started, how to design probes, or sensing an overall lack of direction.

- “I disliked that on the probe making, i had no instructions, and i diddnt know how to work it.”
- “I didnt like the way i had to build a probe. For me it was very difficult because it didnt really explain how to build them and there was so much things to add to the probe like radar and more which confused me. Maybe next time i think they should add something to explain how to build a probe for next year in the communication center.”
- “We were given no instruction on what to to and were expected to figure it out on our own”
- “what i dislike about the alien rescue was evething like there was no derctions and stuff”
- “and me and my parttern didn’t know what to do in the beginning.”

The following interview excerpts highlight student perspectives on the level of direction provided by *Alien Rescue*.

> I think it’s a really cool program, and that whoever made this is really smart. I think it needs maybe a little bit instruction at the beginning, because we didn’t really know what to do at the beginning. We were kind of lost. I spent a lot of money making probes and doing stuff that I really didn’t need to do.

Directions; I'm a big direction person. I don't really … a lot of times, I'll go off and figure out directions, too. Sometimes I'll already know the directions, if I've done something before, and I may just start. Sometimes, when I [inaudible], and something's just put in front of me and I don't really have a lot of directions … "We're doing what with this?" That's kind of how it was with this, but I did have some directions, so it made it easier.

I think it needs maybe a little bit instruction at the beginning, because we didn't really know what to do at the beginning. We were kind of lost.

Probably the instruction at the beginning. There were a whole bunch of things where people were like just messing around, and not really on task. Some people were … they were just like trying to fall out of the spaceship or something, using glitches. They got off task and stuff. That's pretty much it.

Yeah, that was really kind of it. I was just so lost. Then I was flipping through the big packet that I got, and then I got to the probe design and I was like, "I've already made six probes." There were three papers in the packet. Yeah, there's something wrong. I'm like, "Hmm, I'm not sure what to do now.

> I was trying to follow the book. I listened to the welcome message at the beginning, and then I just … I was told like all the instruction that I got besides that was just following the packet, and do what's in the packet, and do it in order. I did this, and I answered all of these questions. I got to here, and I just started making probes. I didn't even know that I should write down what I did, and this probably would have helped.

> What really confused me the most was trying to figure everything out. It took me a while to figure out like where to get all of the information about the aliens, but eventually I figured it out. But, I just found it a little hard at the beginning.

***Challenge and Difficulty***

For many students, *Alien Rescue* presented a challenging and difficult learning experience. For some, the experience was confusing. Others described the intensity of the work required by the program. Students also pointed to specific aspects of the program as problematic. For instance, poorly designed probes, such as those that omit a key component such as a power source or proper antenna, often present intentionally ambiguous error messages to the students. In many cases, students had difficulty interpreting the meaning of the errors and making necessary corrections.

- "that we had to send probes to gather more info. and we had to go throw a lot of processess to know what alien goes where"

- “that we had to do a whole lot of reasearch and write a whole bunch of stuff i mean like i  know this was apart of the lesson but it was to much work”
- “In the beginning the space station was very confusing.  I did not like that the pictures for the aliens did not match the description given.  I did not like when probes would not collect information...  it wasted the small amount of money that I was given.  I also did not like that there was so much information for each alien it was too hard to match the alien with a home.”
- “…Sometimes the probes would blow up so it’s frustrating.  At first, the space station was also confusing.”
- “I disliked alian rescue because i thought it was very confused and it never got eaisier for me it was just too complicated.”

The following interview excerpts highlight student perspectives on the challenge and difficulty of *Alien Rescue*.

> And we started on the messages like um, we went to the research center or whatever. We went through there and then we clicked on everything and we read it and went through that. And then when that didn’t work we were all like, “well I guess there must be some secret thing, or passage. So we tried the passage to the, what was it? The right or something. We went through there and we got through but then at the end of the passage there was nothing. Like it was in a dead end. So we were like “okay” so we must be doing something wrong. So we went back and we tried to do it again and it still didn’t work.

> Some of the challenges are loading the probes and stuff because the tools are expensive and stuff, so the money adds up and you only have certain amount of money. Other challenges are finding out the information you need, figuring it all out and stuff, like figuring out alien rescue, and figuring which planets are good for them.

> And like we did a lot of probes and we didn't get like a whole bunch of information from them and the information is kind of hard to read when you get it back.

> Like, like these are things you haven't even heard of and like, like they're all like popping up and you have to like find them. And like make things to land on the planets. Like probes. And like, designing probes are hard. And like choosing what like to do and stuff - it's kinda weird. And hard.

***Worksheet Packet***

Many students complained about the use of the worksheet packet alongside *Alien Rescue*. Aside from general dislike of the packets, students often described the packet as confusing, their inability to find all of the information required by the packet, or the manner with which the packet integrated with the project as a whole.

- "A thing i disliked about alien rescue was filling out the information in the packet & searching to find where to go to get the information."
- "I HATED the paperwork/packet..."

- “The packet was really confusing. I think that if my teacher hadn’t told me to follow the packet in order, I would have been less confused, might have finished the project, and would have wasted less money.”
- “all the paper work and haveing to stop and wright ever 5 secondes”
- “I didn’t like how it was read , write , and read some more.”

The following interview sequences highlight student perceptions of the worksheet packet.

**Sequence One**

*Student 2:* So I don’t think that you should like have to write down the probes because you get the information out and think that you need to like record it, but …

*Researcher:* You don’t think that you need to record it in your packet here?

*Student 2:* Yeah, I think they should just get the information, like we don’t need to describe how the probe is made and what’s on it and stuff because I think that’s just extra work, and I think things should be the simplest that they can be. So I think that the extra pages and stuff are just extra work.

*Student 1:* And we run out of time if we focus on one thing and try to finish it completely, so if you just see it later like just flip to it, write it down and continue with what the other thing is.

*Student 2:* It makes your mind, like it makes you focus on one thing, you don't have to worry like, "Oh I have to go record this new probe," and just work on the most important thing which is getting all the information and having the answer.

*Researcher:* OK, instead of like filling out the papers?

Student 2: Yeah

**Sequence Two**

*Student 1:* It probably would have been more experimental; you don't need to stop every five minutes to fill out some information about the –

*Student 2:* You'd have a lot more time on the computer itself.

*Researcher:* Tell me, how would you have interacted with the computer if you didn't have to fill out that packet?

*Student 1:* Probably would have used it a lot more ... not spending so much time working on this, but more seeing if we can figure out how to make the aliens find their homes. You wouldn't have to stop every five minutes and then lose your train of thought once you break down what you've written down.

***Structured Condition Constraints***

Students voiced dislike of the structure imposed by the structured treatment condition, the manner in which it restricted access to data, the use of the doors as a mechanism to restrict access to certain cognitive tools, and general frustration with the experience.

- “How we had to keep going to the communication place and sending messsages just to get the rest of the information for the aliens.”
- “I did not like how the information came given to you in chunchs.  I would have perfered that all the infomation was given at the same time.”
- “that sometimes it didint let us go on the room because we had to do a hypothisis to go in”
- “that the doors werent open from the begginig so you can find more information”
- “the beginning all the door were loocked ecept for the reserch lab and the communication room.  i was kind of frustrated.”
- “Finding the right homes for the aliens was kinda hard when the doors were locked.I hate when all the information is kept from me.Even when everyone got all the reaserch lab aliens and we only had some.I wish we could just start with all the information.”

The following interview excerpts illustrate student frustration with the structured treatment.

> Oh like you try to like walk into them and like to try to like walk through the door and it won’t like open up or anything. And like we thought you should like if you walk into the door you’d have to press the space bar just like to open one. And like, you have to like walk in. And just like you have to walk through it. Just like you walk and like you yeah you have to walk through the door like this.

> Like one door can open like if you want to go back to that door and you try to press the space bar it opens…it's…oh no it's stuck. So it's just like let me go around. So you go around, the other door is stuck and ahhh go back and that door is stuck. And like this door you just went to opens up and like yay! You have to go in a different order to like every door.
>
> It was just kind of frustrating when I couldn't get to the probe design room. Cuz I didn't know how to and yeah."
>
> We were just like … whenever we first logged on, we were just trying to see how we get through the doors at first. We went to every door, and we couldn't open any of them until research lab came along, and we could finally walk into it. We went to the chair, and we started reading a whole bunch of stuff in there. It gave us a start.

**What parts of *Alien Rescue* helped you the most?**

Students listed several aspects of *Alien Rescue* as the most helpful. These aspects were well distributed across the treatment conditions and cover the Research Lab, the Probe Design Center, and the Solar System Database.


Figure 29: What parts of *Alien Rescue* helped you the most?

***Research Lab***

Students described the necessity of the Research Lab in providing essential information that allowed them to complete the project. Some students characterized the information-richness of the Research Lab, discussing specific types of information they obtained by interacting with it. Others referenced the quantity of information provided by the tool.

The following questionnaire responses represent student perceptions of the Research Lab.

- "The reasurch lab that helbed a lot on the work we were doing. and also the probe desing did help for some of the packet. like figuring out how much money everything was, and about them too."
- "the computer about the aliens. it was cool how it worked. the way it explained alot about the aliens."
- "The resaerch lab helped me the most. It had the most information in the whole program. It also made things easier for me."
- "The research lab because it told me exactly what an alien needed, it's food, it's dwellings and things. That really helped me decide where the aliens go."

- "...the reasearch center with information about the aliens the information and how it had told us about the planets and the moons and how it talked about its atmosphere its climate and other stuff and the information on the aliens. Mostly the reaserch lab and the little sun icon at the bottom."

The following interview excerpts describe the student perspectives on the role of the Research Lab.

> The research lab. The research lab gives us information about Akona, the aliens, and it also gives us information about our sun. We learn about that. It can … I'll show you. We haven't checked it today, but we only have Akona. When you go to the research lab, and you click "species", maybe … "species", you get Akona. We got all the information about it, and we started to fill it out. We just didn't really understand that at first. We were like, me and my partner were talking about it, it really wasn't working. We were trying to find more information about it, but it wasn't working
>
> *Researcher:* What parts of Alien Rescue helped you learn?
> *Student:* Um, the computer part where you go into the first research lab and you click on the stuff and learn about the aliens and stuff.

### *Probe Design Center*

Students described the usefulness of the probe design center in allowing them to efficiently retrieve information that was unavailable elsewhere in the program. In general, students enjoyed the interactive aspects of the tool and the extent to which the probes themselves could be customized for different purposes. The following questionnaire responses represent student perceptions of this tool.

- "I think the probes helped me the most because i could get information way easier and faster and much less work to do then going in each and every door to found out information."
- "Launching the probes helped me the most out of all and it was just more interactive than the research choices."
- "The infomation about the planets and probes were very helpful. The infomation about the probes were helpful becasue they made showed you how to use the probes and different intrusments"
- "The probe design because it helped me learn what probes to use like a flyby can go to many planets while an orbiter cannot."
- "The Probe Launch, Probe Design, and Research Lab helped a lot because they gave us a lot of information. You had to design a probe in Probe Design, then a message tells you to go to the Probe Launch. From there, you launch your probe-obviously. Then another message sends you to the Research Lab and then you get additional information about the aliens and some alien planets- if you get the aliens to the right spot."
- "The probe design and mission control hepled me a TON because it helped me and my peers figure out more about the planets so we could know which aliens could go to which planets."
- "Probe design was good too because we had lots of options for customizing our probe. Very neat!"

***Solar System Database***

Like the Research Lab, the Solar System Database represented a vital source of information for the students. Students specifically discussed the role of the Solar System Database in identifying potential homes for the aliens. The following questionnaire responses represent student perceptions of this tool.

- "The infomation about the planets and probes were very helpful. The infomation about the probes were helpful becasue they made showed you how to use the probes and different intrusments. The planets are very helpful to learn about to place the aliens correctly."
- "the information and how it had told us about the planets and the moons and how it talked about its atmosphere its climate and other stuff and the information on the aliens."
- "reasearch lab and the little sun button it helped us by many parts i mean we had to think and think and think about what the aliens are and things and there homes"
- "the parts of Alien Rescue that helped me was studying the planets and thier moons. I learned about the planets and moons when i was litttle but i frogot them."
- "The information about the palnets,aliens,and the probes help us look the plantes up close or see if they have earthqukes or their weather or there surface."
- "the most helped me was the solar system, because i nned to learn more about it, and there was alot of information were i could find my answers!!!"

**What parts of *Alien Rescue* were the least helpful?**

Analysis of this question did not reveal a high degree of convergence around particular codes across the treatment conditions. The budget limitations, confusion about the probe design process, and worksheet packets were somewhat common themes in the students' responses to this question across all treatments. The prevalence of the word "probes" within Figure 30 specifically reflects the budget limitations and challenges in designing probes. Within the structured treatment condition, however, the Communication Center and the constraints imposed by the treatment were frequently cited.

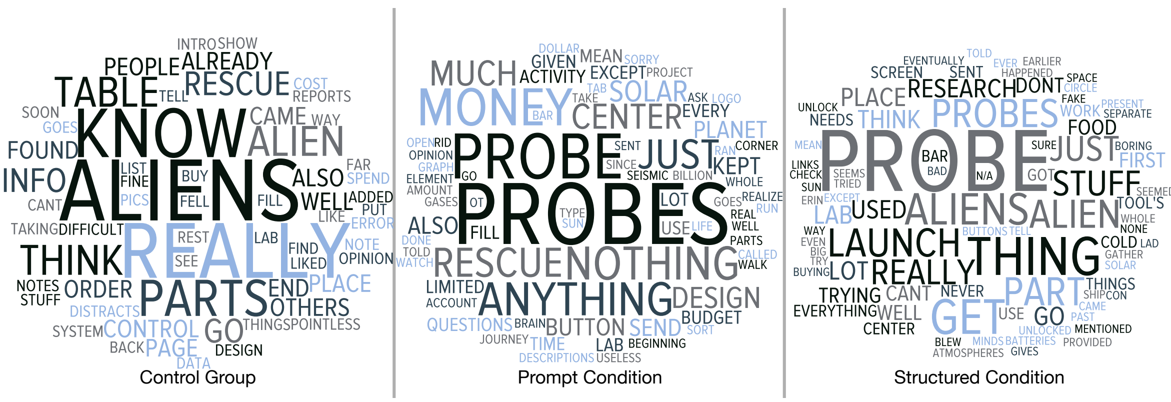


Figure 30: What parts of *Alien Rescue* were the least helpful?

***Communication Center***

Students in the structured treatment condition appeared particularly frustrated by a perceived lack of information in the Communication Center. Some students viewed the Communication Center as irrelevant to the problem-solving process. The following questionnaire responses reflect these themes.

- "I think the communication because it doesnt do anything so it cant help with any of the research we need."
- "the communication BECAUSE WE GOT NO INFORMATION JUST THINGS TELLING US WHAT THEY DO"

- “The communication center when we had to go find all the information without any hints or anything the help me.”
- “The communication place because their wasnt that much infromation.The other doors.”
- “what wrere some of the most least helpful tool’s on alien rescue were the communication lab it was still helpful but not the most it was the least i rarely went there because it was the least of my use of all the other tool’s they offered.”

***Structured Condition Constraints***

As in Question Two, students in the structured condition continued to question the role of the constraints, particularly the doors that prevented access to parts of the space station. Some students described how the structured condition blocked access to required information. Others described a general sense of confusion around how to open the doors. The following questionnaire responses provide examples of their perspectives related to the constraints.

- “The least helpful part was when we has to acomplish something to get more information.I know that you were only trying to foucus our minds on one thing but i would have like to get all the information on all of the aliens at one time.”
- “the the part where some of the doors would not open because we needed to do the questions that were alot of questions”
- “Trying to open the rooms. Because at first we couldnt get into probe design and it was hard to open that room.”
- “Not getting all the same information at the same time. Like not getting all the aliens and only getting one.”

- “when the doors wouldnt open and i couldnt figure out how to open them. i did eventualy but it was a setback”

The following interview excerpts further illustrate student perceptions of the structured condition.

> We were just like … whenever we first logged on, we were just trying to see how we get through the doors at first. We went to every door, and we couldn’t open any of them until research lab came along, and we could finally walk into it. We went to the chair, and we started reading a whole bunch of stuff in there. It gave us a start.

> It doesn’t work here. It just ... No matter which room you go in, you can’t go through there; I’ve gone through there before.

> Yeah, but sometimes you can’t go through the doors, I’m not sure if that’s like a glitch or if they’re blocked off.

> And we started on the messages like um, we went to the research center or whatever. We went through there and then we clicked on everything and we read it and went through that. And then when that didn’t work we were all like, “well I guess there must be some secret thing, or passage. So we tried the passage to the, what was it? The right or something. We went through there and we got through but then at the end of the passage there was

> nothing. Like it was in a dead end. So we were like "okay" so we must be doing something wrong. So we went back and we tried to do it again and it still didn't work.
>
> I think like, understanding how to get through the doors. Like, I, we'll read the message thing over and over. But then like, so we went two days and we've been trying to get through the door. But, and then today like something finally popped up and told us that this is the way to get through the door. Like, we were confused on how like if we were supposed to be able to get through the door before. Like we were doing something wrong. So we spent a lot of time going through all of this stuff trying to get through the door.

**What did you learn from *Alien Rescue*?**

Student responses to this question, as visualized in Figure 31, were decidedly content focused and equally distributed across the treatment conditions. Far and away the most cited response concerned aspects of the solar system. In addition, students cited that they learned about the aliens. A smaller group of responses indicated that students learned about problem-solving.

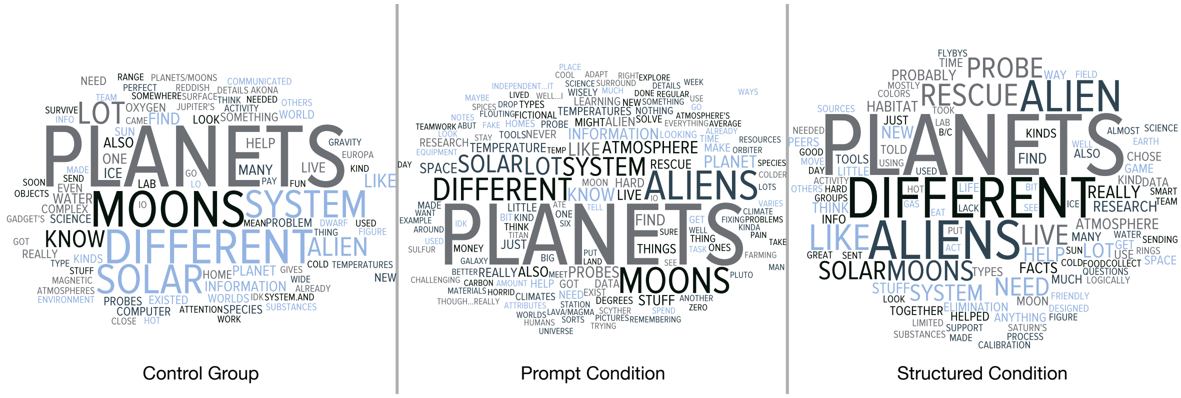


Figure 31: What did you learn from *Alien Rescue*?

***Solar System***

Student responses typically made either generic reference to learning about planets or moons or more specific references to scientific concepts and the characteristics of planets and moons. The following questionnaire responses represent typical student responses that were coded as relating to the solar system.

- "I did not know some of these planets they are weird never seen it before. that some planets don't have a magnetict system and some have big ones."
- "I learned a lot about planets. Another thing I learned was just there was more places than just a couple of planets with only a few moons."
- "I learned a lot that I didn't know about planets and moons and probably would not have learned about for a while if it weren't for this"
- "I learned more about the planets and about its atmosphere. And that there's water or ice."
- "I learned some thing about the planets in our solar system, like one of the planets in our solar system are colder than 200 degrees celsius."

The following interview excerpts provide examples of student perceptions of the solar system knowledge gained through *Alien Rescue*.

> Um, hmm…I'm not sure about that. I mean I've learned a lot from it. We learned about the planets and there is nothing to improve about that. We are learning - I'm actually learning a whole bunch about the planets.

> Um, well learning about the atmosphere and all like the planets like how um, how the aliens like habitat like the dwellings of how they live there, um we have to go find the planets and it gives us information about the planets. So it's helped us about the atmosphere like if it has any - is it below or high temperatures. So, yeah that's helped us learn or helped me learn.

> I was just learned a lot more about the planets by researching it.

***Aliens***

Students also described learning about the aliens as an outcome of their experience with *Alien Rescue*. The following questionnaire responses illustrate how students describe learning about the aliens.

- "I learned about….about tons of different alienas and what they ate and how they survived."
- "I learned about….species of aliens and how they live and what they eat and what kind of habbitat they live in. And their invironment."
- "I learned about fictional aliens that don't exist. I also learned about fictional planets that the "aliens" used to live on."

- "the most thing that i learn about alien rescue is how the aliens could be different some of the time and the different moon in the solar system"
- "what the aliens are like and there comfort zone and whaty they what tempeture they like and what there best maybe fixing things remebering things or farming"

The following two interview excerpts illustrate student perceptions of the aliens.

> You get to know about these different species that live out in outer space. It's not something we usually do in science. We get to actually be a scientist, and do all the research and stuff. It's not like … we have to go find it out by ourselves. We don't have … it's not like we have a textbook, and we could just find it anywhere. You have to go with the probes, and get that information by yourself.

> *Researcher:* Yeah? What, in particular, do you like about it?
> *Student*: Learning about the different aliens there is.
> *Researcher*: About learning about the different aliens?
> *Researcher*: What, in particular, do you like?
> *Student*: All the information about their habitat and how they are, how they act. Learning about them. How we can help them, you know? Try to find them homes.

***Problem Solving***

Students described how *Alien Rescue* helped them learn about problem-solving. Some students discussed more abstract outcomes, such as learning to negotiate difficult problems, while others describe specific problem-solving elements of the program, such as launching probes or finding homes for the aliens. The following questionnaire responses illustrate the students' perspectives.

- "i learned about different planets and to solve really hard questions on my own without a teacher"
- "I also learned about problem solving because we had to figure out where the aliens would go."
- "I learned more about problem solving, and the diferent planets, moons, and other worlds in the solar system."
- "I learned that sending probes into space cost alot of work and money, and you have to work together for these kinds of things, like how 3 groups worked as a team."
- "The way the teacher was not allowed to guide us helped me learn to be more independent and not just do what was instructed."

The following interview excerpts discuss problem-solving.

> I think it was cool … I think we learned a lot about how to fix … how to determine how to fix a problem in real life and stuff like that.

> There's a lot of process and elimination in this. Especially with placing the aliens and stuff.

> Like you just don't look at the screen and just see the answer are right there, you have to kind of get somewhere.

**What advice would you give to a friend who is using *Alien Rescue* for the first time?**

When asked what advice they would share with a friend when using *Alien Rescue* for the first time, students consistently described advice across three themes: budget management, the probe design process, and the research process. Though students in each treatment condition described the importance of budget management, it was a significant perception within the prompt treatment condition: 25 students in the condition mentioned budget management as an important strategy. Figure 32 clearly displays “money” as the most frequently used word in the prompt condition responses. In addition, students in all categories suggested key metacognitive guidance related to the problem-solving and probe design processes.

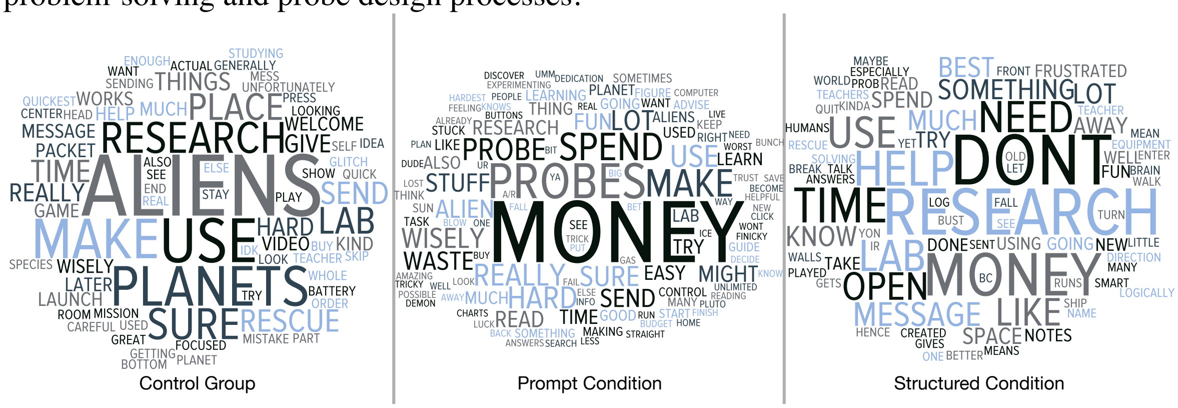


Figure 32: What advice would you give to a friend who is using *Alien Rescue* for the first time?

***Budget Management***

Students suggested that new users carefully mind their budget in order to maximize opportunities to design and launch probes. In similar fashion, students suggested a need to be moderate in sending probes and to send probes strategically to address missing information. The following questionnaire responses represent common student responses to this question with respect to budget management.

- “MAke sure you dont spend all your money!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!”
- “That you should NOT spend all your money on probes that don’t help at all, you should research a lot about the planets and aliens before you send probes, and don’t play with it at all”
- “Watch your money make a budget, at first it wont be easy finding things , know that if something wont open then that means that you havent done something to need it yet.”
- “i would tell them to NOT waste all of their money on the probes like i did. And choose wisley on the information that they need and the information they get.”
- “i would say dont send to many probes because you can run out of money and be left with nothing and not enough data to finish the project.”
- “umm... where to start i would say dont make a probe right away and waste alot of money because it does cost ALOT of money”

***Probe Design Process***

Students felt that new users to *Alien Rescue* should carefully design probes based on research into the probe components. Some students suggested the need to evaluate available information to ensure that probes were not designed to obtain redundant information. The following questionnaire responses illustrate these suggestions.

- “To try everything that he or she can use and look closey at the information he or she have. When he or she is chosing his or her probe, choose the probe’s things carefully.”

- "Be careful when sending probes, make sure you don't already have that information. Also have fun learning about our solar system in a fun and interactive way!"
- "Your going to love it!!!!! But pay attention because many things can trick you like the probes or the climate of the planet."
- "The advice I would give to a friend would be read about the instruments before launching them with a probe."
- "First do a lot of studying on the parts of the probes they give you before building an actual probe."
- "Don't buy probes right away. Use different resources to find info on planets and moons."

***Research Process***

Some students offered advice on how to undertake the research process. In some cases, students suggested the need to be attentive to the expository content presented by the program. Other students stressed the need for new users to take an exploratory approach to the environment by familiarizing themselves with the tools and rooms within the space station. The following questionnaire responses illustrate this theme.

- "If i were to tell a friend of mine who has never played this game is i would tell them to do some research on things they need to to learn so they have a jump start onn this game."
- "Play around with stuff. Make sure you where every thing is, how to operate it, and what it does. But definetly stay on track because it can get hard."
- "read stuff before you decide cause you can end up srewing up as in (wasting stuff money on stuff that doesnt work on it or stuff that isnt real.)"

- “to make sure to use all the right tools stay focused on the mission and make sure the aliens you choose have a good home , the right home.”
- “Always look aroud for all the information and click around on the buttons because it could really help you later in the project.”
- “i would say dont spend all your time trying to find information in one place, you will find alot of information everywhere.”

**If you could change something about *Alien Rescue* what would it be? Why?**

Students’ suggestions for *Alien Rescue* follow predictable patterns. Across all treatment conditions, students suggested revisions to the budget system used in the probe design process. In addition, students noted the need for technical changes, such as resolving bugs within the program and improving overall production values by enhancing the graphics and design of the space station. Twenty-seven students in the structured treatment condition recommended that the constraints be removed.

Figure 33 highlights “money” as a significant issue across all three categories. Student references to “doors” in the structured treatment condition responses relates to the constraints.

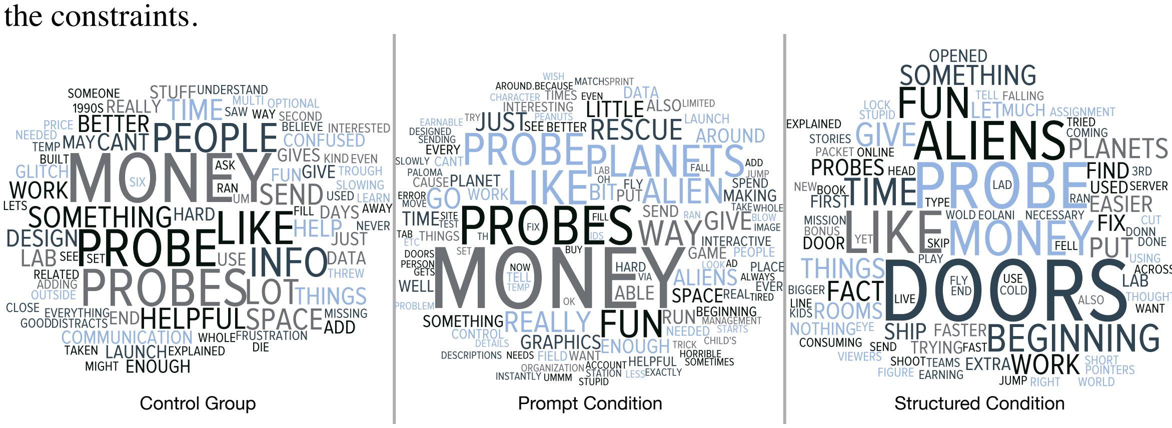


Figure 33: If you could change something about *Alien Rescue* what would it be? Why?

### *Improve Budget System*

Many students requested that the budget system implemented within the Probe Design Center be modified, either by providing more funds, creating mechanisms for students to earn funds, or removing the feature entirely. The following questionnaire responses provide examples of these suggestions.

- "If i could change anything it would be the money issue. If you want to find the rocks the temp the pull the magnometer or sisg mograph you need to have money and that would mean that the other things you can not do becaues all that was drainned so you can complete the assignment"
- "MAke it were there is unlimited money so we dont have to conserve it!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!"
- "I would change would be the money problem. When you spend money, you don't get more. I want to change that by making if you save a alien species, you get more money."
- "More money for probe making. I thought that the challenge of the money management was a challenge for me. but it the program a bit harder which can be a good thing"
- "I would change the money wise, so all of the probes would be free and you would NEVER run out of money so you can get all the reasearch you need and want."

### *General Program Improvements*

Students suggested various improvements to *Alien Rescue* such as graphical enhancements, resolution of perceived bugs, and the creation of new features such as being able to interact with peers within the space station. The following questionnaire responses provide examples of these suggestions.

- “If i needed to change somthing on alien rescue would be a couple of things like having other players on one server so we could exchange information and help each other  and putting a couple of things instead of one thing in that room like decoration for season’s and holiday’s because i find it to be a little boring when there is not a thing to really look at.  and one more thing you need to fix the falling out of spaceship glitch its distracting.”
- “More colors!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

  Because it AWESOME!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!”
- “The graphics, the aliens, the amount of money, the organization of the space station, the description of the aliens because all of thoses thing made alien rescue harder than what it already was.”
- “The glitches.  They’re fun and all.  I mean to like go outside the space station, but they are distracting.”
- “The graphics were terrible- 1990s Nintendo 64 days.  We have the technology, we NEED better graphics.”

***Remove Constraints***

Students in the treatment condition strongly suggested the removal of the constraints.  Students suggested enabling access to all rooms at the outset of the learning experience and ensuring that information provided by the database tools was complete.  The following questionnaire responses provide examples of these suggestions.

- “Get all the aliens at the beggining, because it was confusing.  Also to get more planets at the beggining because that was a little confusing.”
- “have all the info on the computer instead of unlocking them.  its just a waist of time trying to unlock them they should just have everything unlocked”
- “How they lock all the doors in the first time.  Because we were confused how to get in until the 3rd day.”
- “I would change the whole set-up.  I would give instuctions and a story line that would partially make sense.  I wouldn’t waste time unlocking doors.  I would give the cold hard facts.”
- “i would fix the fact that the doors would not open so i would leave the nesasary doors open.”
- “The doors.Becuase it makes poeple mad, and fustrauted becuse it would’nt work.”

**Where did you get help when using *Alien Rescue*? What kinds of help did you need?**

Fifty-six students cited that peers were a source of help when using *Alien Rescue,* while 15 described help from the teacher.  A number of students also listed various database tools within *Alien Rescue* itself as a source of help.  Students most frequently described a need for help with conducting research, finding a habitat for the aliens, and designing probes.

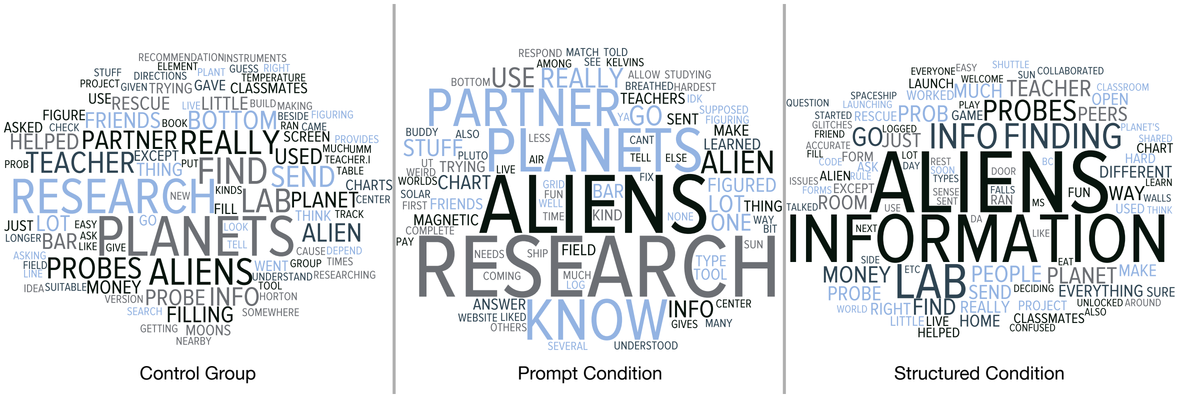


Figure 34: Where did you get help when using *Alien Rescue*? What kinds of help did you need?

***Sources of Help***

Peers

Students across all treatment conditions often cited their peers or lab partner as sources of support within *Alien Rescue*. Student comments suggest that peers provide support necessary for students to negotiate confusing or unclear aspects of the learning environment and provide feedback and suggestions on tasks such as designing probes. Student comments also provide a sense of the collaborative nature of problem-solving; some students described sharing tasks and workload with their partner or acquiring key information from peers in the classroom. The following selection of comments illustrates the role of peers as perceived by the students.

- “#opening the doors i got help from my fellows!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!1”
- “My friends help me from my class room. They had some information and we had some too, so we would just trade.”
- “from the otherpeople on it, i neede helpp with unlocking the doors and some of the other people and i shared what we learned from the planets.”

- “help from my classmates.I needed help with where to send the aliens because we did not have enough money to research everywhere”
- “I got help from all of my peers and that worked very very well. I just had to ask my friends and peers for information, i did not really need any other help.”
- “i got help frommy peers while doing this project. I needed help on filling out a few things because I ran out of money and could no longer send probes.”
- “i got my help from my partner who shall not be named and the help i needed was things like what should i write down and things like that”
- “Me and my partner and some other stidents figured out how to use alot of the information places among ourselves, so it wasreally the students helping each other find information and sharing all our found information with the others.”
- “When I would get confused, I would ask the nearby group beside me. I mostly needed help on some suggestions on where to send my probe to.”

Interview excerpts also describe collaborative approaches to problem-solving within *Alien Rescue*.

> Hmm, I just have to…To find the thing, like to write rationale. To launch the probe and all that stuff. Some of the information I cannot get it in this here, and so I just ask my friend.
>
> Um, we just skip or we share some information with our friends because my friends don’t know the things I know, so we share information.
>
> We got help from other groups who knew what they were doing

> I just asked some people and then they started to help me.
>
> Like we write and then we like read and we write and then we kind of like share things and then we like go turn a, like turn around and then we share like the work.

*Teacher*

Some students cited their teacher as sources of help. In many cases, students describe their teacher's role in supporting the procedural aspects of problem-solving such as determining tasks to be performed and interpreting information. The following comments illustrate the role of teachers as perceived by the students.

- "...my science techer because i am sure that she tells me the correct info."
- "I got help when i was looking at the temperature scales because i got confused on those parts so i got help from the teachers."
- "I got the help from my teacher and the UT testing volunteers. I needed help figuring out what stuff meant and how to do some things."
- "we got help from our teacher and we needed help on how to use it cause it was kind of difficult."
- "We got help from the teacher. The kinds of help we needed were how to build a probe and how do you send an alien to a planet"
- "When trying to figure out the aliens i did not know that the weirdlooking computer is what help us figure the aliens type comfort untill i asked my science teacher"

*Program*

Students also described features of the program itself as sources of support. In most cases, students explained the informational qualities of the tools. The following questionnaire responses describe those tools which students felt provided support.

- "well i used the reasarch lab, that gave me the most information!!!! and the paloma i guess?!?!?!?!?!?!"
- "i got help from the research lab to find information about the aliens and where they came from"
- "I used the icons and the research lab and my probes to help me do my research because I needed help filling out my charts and finding suitable habitats for the aliens."
- "The place that helped me would be the research lab. The kind of help I neede was were to lauch a probe so I needed to learn about the aliens."
- "The reaserch lab!! Gives you all the information!!!"
- "Where we got the help mostly the research lab and the probe design and the communtion and the help we needed was how to find the aliens forms how to do some of are work"

***Help Requirements***

*Conducting Research*

A number of students outlined a need for help with the various research tasks required by Alien Rescue. Some students suggested that they needed support finding information for the worksheet tasks. Others describe the process of negotiating the information within the program, such as dealing with seemingly contradicting information or reconciling new information with existing knowledge.

- "i needed help on filling in the charts, i needed to search for more informationn i needed help on where to go to find the information."
- "i got help from my fellow classmates. i needed help to finding extra info."
- "The contridicting information i neeeded clarification."
- "I just find my way through it see what i know and combined it with things i know and stuff i don't know."
- "I needed help finding the different parts of the information."
- "I got help from my friends and i needed help on how to get infomation on some are questions."
- "I got help form the clue they give us and i will need help in how do to the right way."

*Finding a Habitat for the Aliens*

Other students needed assistance with the overall problem in Alien Rescue. In some cases, students described receiving problem solutions from their peers. In other cases, responses indicate a need for procedural guidance on how to submit a solution or feedback on a tentative solution rationale.

- "I needed help with where to send the aliens because we did not have enough money to research everywhere"
- "where to put the aliens, where to planet to put the aliens cause their to lazy to find their own planet so i needed help on that"
- "prbly like how to send the aliens places"
- "when thincking of where to send some aliens"
- "My friends, they told me where some aliens could go."
- "I got help from my classmates to help me send aleins to the planets."

*Designing Probes*

Some students seemed to struggle with the process of designing probes. Students were often unclear as to why particular probe configurations did not work as expected. The following questionnaire responses highlight how students sought various forms of support for this process.

- “The help i got was very little because it was easy. But i asked [REDACTED] becaues he knew why and where it was. I needed help triing to figure out why the instruments wern’t working on certian probes.”
- “how to make the probe and what the probes use and cannot use”
- “When we sent our probes the reserch wasn’t coming back right. So I asked if we should fix our probes but we didnt know what to do...”
- “how to make the probes because we didnt pay attention at first but i can be a little distracted at times.”
- “I got help when we were trying to send a prob because i needed to know what the differant prob types were and how they would help the alian make it to the world without dieing.”
- “the probe lanch was dificult i need help on lanching the probe”
- “i got help from my peers. I needed them to send orbiters with landers because i had used all of my money”

*General Instructions*

Students also needed general help with the program, such as deciding what to do, where to go, or navigating the space station environment.

- “umm i needed to  know what each page ment because the directions weren’t as clear at times.”

- “i got help from some people trying to fill in my table about the planets i aalso got help with some things that i did not understand. I did not know what to do at some points.”
- “like were i was supost to go and i got the help from the people aaround me that knew what to do.”
- “navigating where on the ship to find the information needed.”
- “Directions that was the hardest part.After you find where you need to go and how to get there it becomes more easy.”
- “i neded help on what to do because at first it was confusing”
- “from my parntner but we figuerd out the game soon after we started”

## TEACHER PERCEPTIONS

Teacher interviews supported some of what students perceived as challenging and difficult, particularly with respect to the structured treatment condition. In addition, teachers described their role in facilitating problem-solving, including an emphasis on minimal guidance as an instructional strategy. Teachers also described how they perceive the usefulness of the worksheet packets and proposed ideas for strengthening the classroom implementation of *Alien Rescue*.

### *Alien Rescue* Learning Outcomes

In describing the learning outcomes of *Alien Rescue,* teachers suggested potential mismatch between the content of the program and the curriculum requirements of the Texas Essential Knowledge and Skills (TEKS). Teacher B in particular was concerned about the appropriateness of the cognitive level of the program.

> *Teacher A:* I think they get a lot of the solar system research. I worry, though, that for our TEKS, the way they read, it's very specific. The way the TEKS read, it's more like comparing inner planets to outer planets and stuff like that.
>
> *Teacher B:* They don't fit our TEKS very well. They set them on a very … they're, our TEKS are very broad. They're large. They just cover certain things; alien rescue is more to the point. It focuses on temperature; we don't even talk about temperature. It's good for 'em because it is problem-based. And we've always liked it because it does make them go in, figure out how to work it, find this information, but are they actually learning it to take to next year? No I don't think so. I think the information that they're being asked to find doesn't really fit their cognitive level. The information is way too deep for sixth grade. However, the problem-based is perfect. That's why the charts are good. Hey we have the temperature for Mars, go do it …

**Need for Student Feedback Mechanisms in *Alien Rescue***

In light of the minimal guidance provided by *Alien Rescue,* Teacher A and Teacher B suggested the importance of adding student feedback mechanisms to *Alien Rescue* to support the development of problem-solving strategies. They suggested modifications in which students would be presented with immediate feedback based on their problem solutions.

> *Teacher A:* That's one of the things that we work with a lot for the sixth graders in general is taking that feedback; now, what are you going to do with it? If it says you got the planet right but the rationale is wrong, go back and figure out why you're having those errors and tracking even along the way, okay, if you have a progress bar of this is where you're at, they can see, okay, right now if I finished here I would be failing my project.

> *Teacher A:* I think it makes it harder and I think it frustrates my kids, especially my Thai kids. They want to know if they're right or wrong and stuff. I think even if they didn't necessarily gives them the feedback on their reason, giving them the feedback on if they picked the world and stuff correctly, would probably be enough.

> *Teacher B:* And also the other thing I would change, I would let them know as soon as they submitted a suggestion for an alien, they need to be told whether they were successful or not. They have to have immediate feedback.

## Treatment Conditions

The teachers agreed that the control condition, with its open-ended design, was more successful than the structured condition. They identified a number of issues with the structured condition that resonate with feedback provided by students. Most notably, the teachers felt that the structured condition contributed to a sense of confusion among the students. Feedback from Teacher B, in particular, suggested that in cases where students did not immediately recognize a pathway to follow, the experience of using *Alien Rescue* became somewhat disjointed.

### *Control (Open-ended)*

> *Teacher B:* The other two … the open ended was the same right. I didn't have any problems with those classes at all.

> *Teacher C:* Overall, I think it went well, especially with the open-ended version. I think the students got more out of that.

### *Structured*

> *Teacher A:* I think it was more confusing for some of the kids with the three different versions. Not so much with the regular version. It was something that they were … it was used before and I could answer their questions and stuff. I feel like some of the kids got stuck on the structured and the guided one because it would only let them go into certain things but they couldn't figure it out. Yeah, I think it was a little bit more confusing for some of them.

*Teacher B:* Only being able to see to aliens, they are told they are sick, they can only see two; they are wondering what they are doing wrong and where is it, and why can't they see it and stuff like that. If we changed the structured to submit or fill out this much information before you could submit it might be easier but I think they should be able to see everything in the beginning. Otherwise they think they are doing something wrong.

*Teacher A:* I feel like some of the kids got stuck on the structured and the guided one because it would only let them go into certain things but they couldn't figure it out. Yeah, I think it was a little bit more confusing for some of them…..I'd like the missions where they're designing the probes to be locked until they have done other things, because some of my kids and I could think of plenty of them right now, like I said, went in and did the alien recommendations, they went in and launched all their probes, they spent all their money, and they have an empty packet with nothing to show for any of it. I think if it's going to be set up where it's guided, I like the idea of some of the things being unlocked as they go. I just think that some of it was a little too structured as far as they couldn't figure out what they needed to do to unlock some of them.

> *Teacher A:* I think because in trying to make it structured I feel like in previous years they could kind of figure it out. They went into all the rooms and stuff. Then with the structured and the guided ones it kind of funneled them into certain paths, and if they couldn't figure out how to get on that path, then they couldn't figure out what they needed to do to get the next step done. I like the idea of a guided or structured version. We had told you that we had done a modified version with some of our kids a few years ago, but we had given them a packet of, okay, do this, and then now do this. So it was still, it was telling them the steps ahead of time so that they knew what to do in the game. I feel like they needed the structure because they tried a couple things, it didn't work and then they give up.

**Need to Monitor Students**

Teacher C and Teacher A indicated that having features within *Alien Rescue* that would enable them to monitor student progress would be valuable. Teacher A suggested that a web-based monitoring system would potentially negate the need for the worksheets and inform classroom interventions based on observed student behaviors.

> *Teacher C:* Yes. I think just because of the packet that we have to give them to be able to grade them. If there was a way to access what they are actually inputting, I think that might make it easier….What I think would help is like I said, us having access to the hypotheses that they're

> inputting into the computer or when they are sending the aliens to certain places. I don't have any way to look up what they're doing by their ID numbers. I guess that's what you did.
>
> *Teacher A:* I think it would give them that kind of knowing that I'm watching. Even if I'm not necessarily on there the whole time, they know that I can log in and see what they've done. To be honest, if we had that kind of interaction online through Alien Rescue I don't even think we'd probably print the packets, because then I could go on and still use that to assess them….Even if there were some way that I could see what they were doing and I could give them that individual feedback of, well, look at this or provide comments on some of the stuff that they've done. I just worry sometimes that … and I know every year there's those kids that will just submit, submit, submit, and it will just be gibberish.

**Worksheet Packet**

All teachers suggested that the worksheet packet presented a form of scaffolding and guidance that was required for students to be successful within *Alien Rescue*. Teacher A indicates that the worksheets solve the problem of being able to monitor student progress while also helping to discourage off-task behaviors. Teacher C suggests that the combination of the worksheets with the structured condition was particularly problematic.

*Teacher A:* Actually the books came about because we had talked to Min [Dr. Min Liu, *Alien Rescue* faculty lead] several years ago about trying to keep tabs of what they were doing and stuff. At the time she had said that the goal was eventually that we'd be able to log on and see what they were doing and they could fill it in there. Since we can't do that right now, Min had given us the worksheets and everything to kind of keep it all together, and we just put it in as one packet grade, but they have the checklist and the rubric so they kind of know what they're graded on, and it gives them the guidance that I think you're trying to give them in the structured, but it gives them the steps so that they go, okay, so we're going to do everything in order of the packet, so I need to research those planets. They can see, oh, well, I've only researched a few planets; I need more. Then they always come to the question of, okay, well, I've run out of research and I still have blanks, what happens then? Okay, well, that's where the probes are going to come in. That's how that's going to help you. I think it gives them the tactile visual guidance of what you want them to do in Alien Rescue, and it gives us the ability to monitor that, yes, they are doing what we're expecting them to be doing.

*Teacher C:* I think not having the packet would make it easier on some of them, maybe just like the data sheets.

> The way we had it I think that, along with the way the structured version went was a little rough. If I could see what they were putting in online, then we could get rid of some of that paperwork.

> *Teacher A:* I don't know. I know in previous years when we had it without the packet, there's my kids that are going to do it without me in the room, without me telling them anything, and then there's the kids that unless they have to show me their work, they wouldn't do anything except for run around the hallways and stuff. It kind of was our happy medium of meeting in the middle with being able to back off enough that they could problem-solve it on their own but giving them enough where they still had to show that they were working.

**Minimal Guidance**

Ultimately, all teachers voiced agreement that minimal guidance instructional approaches were the most effective way of implementing PBL. Each teacher described the importance of resisting the urge to provide high levels of student support.

> *Teacher B:* Yeah. Anytime you tell a sixth grader, "I don't know go figure it out," it's going to teach them and help them to not expect answers so easily. There's a lot of these kids that they can go ask their parents or any teacher really, some teachers are questioned and they would just outright give the answer to them. It helps when you have teachers'

saying, "I don't know, go figure it out, problem based or question based," and I think it's good for that.

*Teacher C:* This was probably my first year doing this, so I really wasn't knowing what to expect. I really just came in, showed them how to log in, and we went through the mission video that they were supposed to watch. It was like, "There you go. You're on your own. This is what your mission is. Figure it out."

*Teacher A:* They usually get really mad at me because I won't answer any of their questions. Some of the kids that will keep asking and asking and asking I'll just start ignoring. I'll go, I don't know. They're like, well, you're a science teacher, you're supposed to know this. Sometimes I tell them, I don't know. I've never been on Alien Rescue, and they get really mad at me…..I've had kids in tears and stuff because I won't help them and everything. I try to avoid influencing them because I want them to talk to each other and figure it out, but I do interact every now and then with some of my kids that get really frustrated with it. I try not to mess with them at all if I can get away with it.

# CHAPTER 5: DISCUSSION

The purpose of this study was to investigate the role of various forms and levels of technology-based scaffolds as sixth grade students engaged with a multimedia-enhanced, problem-based learning environment known as *Alien Rescue*.

## Research Questions

This study addressed the effects of guidance on problem-solving ability and learning outcomes within a problem-based learning environment. Specifically, the study investigated the following research questions:

1) How do varying levels of scaffolding affect students' cognitive load, as measured by instructional efficiency?
2) What are the characteristics of problem-solving behavior among students who received different forms of scaffolding?
3) How do different forms of scaffolding affect students' content knowledge and performance within the problem-solving scenario?
4) What are student and teacher perceptions of *Alien Rescue* and the different treatment conditions?

## Review of Methodology

Participants included a convenience sample of 218 sixth graders from a suburban middle school in a large southwestern city.

Quantitative data were collected through a combination of four sources. A 24-question science knowledge test was administered immediately before and immediately after the conclusion of the *Alien Rescue* unit. The test was scored and differences between pre and post performance were calculated as a change score. In addition, each test item included an option for students to indicate their answer as "not sure." Differences in the unsure answers pre and post were also calculated. Student problem-solving performance was assessed through the use of scored problem solutions. A panel of three graduate students scored the solutions by applying an eight-point rubric. Each student was also prompted for a mental effort rating using a 9-point Likert scale each time a solution was submitted to assess the overall mental effort required by the student to develop the solution. The solution scores and corresponding mental effort ratings were converted into $z$ scores and entered into a formula to determine overall instructional efficiency as a measure of cognitive load. Finally, *Alien Rescue* maintains log files of all student actions within the program. From these log files, duration and frequency of cognitive tool use were calculated.

A repeated measures ANOVA was used to evaluate differences in problem-solving efficiency between the three treatment conditions during the first three solution submissions. A follow-up one-way ANOVA was performed to investigate differences specifically during the first solution. Two MANOVA procedures were run to evaluate potential differences in tool use duration and frequency across the treatment conditions. A one-way ANOVA was performed on the science knowledge change score to determine if treatment was associated with different science knowledge outcomes.

Three qualitative data sources were employed for this study. Student interviews were recorded throughout the study and later transcribed for analysis. Students also responded to an eight-item open-ended questionnaire. Interviews with the three participating teachers were conducted on the final day of the study, recorded, and later transcribed for analysis. The researcher created open codes from a line-by-line analysis of the response data. Common themes and patterns were extracted from the responses, analyzed, and used to describe student and teacher perceptions of the program.

# Results

Results from the quantitative and qualitative analyses are described below.

## Research Question One

**How do varying levels of scaffolding affect students' cognitive load, as measured by instructional efficiency?**

Results of a repeated measures ANOVA did not reveal a significant interaction effect of time and treatment condition with respect to efficiency score ($p$ = .447). However, significant main effect of time was found, suggesting that instructional efficiency was significantly lower for the third solution than the first solution ($p$ = .026). There was no significant main effect of treatment on instructional efficiency ($p$ = .942). Because cases were excluded listwise, as required for repeated measures ANOVA, this test suffered from relatively low sample sizes for the control ($N$ = 16) and prompt ($N$ = 15) conditions as compared to the structured condition ($N$ = 40). Since small sample size may challenge the ability to detect differences, a follow-up one-way ANOVA was performed at time one only. Results indicate a significant ($p$ =*.048)* difference between treatment conditions with respect to efficiency on the first solution. Post-hoc procedures suggest that students in the prompt condition achieved significantly higher levels of instructional efficiency than students in the control condition ($p$ = .041).

## Research Question Two

**What are the characteristics of problem-solving behavior among students who received different forms of scaffolding?**

A one-way MANOVA found no significant differences in tool use duration across the three treatment conditions ($p$ = .506). However, a second one-way MANOVA did reveal significant differences in treatment conditions with respect to tool use frequency

($p <$ .001). Follow-up one-way ANOVA's suggest differences across the treatment conditions with respect to two tool use categories: tools that share cognitive load ($p <$ .001) and tools that enable hypothesis testing ($p$ = .033). Post-hoc analyses indicate that students in the control and prompt conditions made less frequent use of tools that share cognitive load than students in the structured treatment condition. Students in the control condition also made more frequent use of tools that enable hypothesis testing than students in the prompt treatment condition.

### RESEARCH QUESTION THREE

**How do different forms of scaffolding affect students' content knowledge and performance within the problem-solving scenario?**

Results of a one-way ANOVA to determine differences in treatment conditions with respect to science knowledge, as measured by gain score, revealed significant differences ($p$ = .026). Post-hoc analysis found that students in the control condition achieved higher gains than students in the structured condition, a mean difference of 1.9 points ($p$ = .025). A second one-way ANOVA determined that there were significant differences in unsure answers across the treatment conditions ($p$ = .038). Post-hoc analysis suggests that students in the control condition had a greater decrease (-3.3) in unsure answers than students in the prompt condition (-1.5) when comparing the pretest to the posttest ($p$ = .025).

### RESEARCH QUESTION FOUR

**What are student and teacher perceptions of *Alien Rescue* and the different treatment conditions?**

### ***Student Perceptions***

Qualitative data suggest that in general, students perceive *Alien Rescue* as a fun and engaging learning experience that departs significantly from the familiar classroom experience. This finding reiterates findings from earlier studies on *Alien Rescue* (Liu 2006; Liu, Horton, Olmanson, & Toprac, 2011) that suggest the program is generally an enjoyable experience for students, that it has the potential to enhance attitudes and motivations towards space science, and is recognized by students as a novel and interesting approach to learning science. Though never explicitly referred to as a game, and though it lacks some of the common characteristics of digital games, students nonetheless refer to it as a "video game." These data suggest that the design of *Alien Rescue* has succeeded in promoting a fun and engaging learning experience.

Student perceptions centered on aspects of the program that supported the acquisition of content knowledge. A multitude of students reported that they enjoyed learning about the planets and aliens. This focus on content acquisition led students to three specific tools: the alien database, the solar system database, and the probe design center. The students viewed these tools as complementary of each other; when confronted with difficulty in obtaining information on the solar system, students resorted to launching probes. Students frequently cited these tools as among the most helpful features of the learning environment.

Students made less frequent reference to the problem-solving aspect of the program. A possible explanation for this is that the worksheet packets introduced an additional task to the problem-solving process that students viewed as primary to the problem-solving scenario *Alien Rescue* presents. Though student comments indicate some dislike of the workbook packets ("I HATED the paperwork/packet..."), it is also clear that many students perceived *Alien Rescue,* in part, as a fact-finding exercise in which content from the program was to be systematically recorded on paper.

Across all treatment conditions, students shared the perspective that the budgetary limitations of the Probe Design Center were a significant and unnecessary constraint to productive data gathering. Students simultaneously described the budget system as one of the chief aspects of the program that they disliked ("HAving to have a limited amount of money, in alien rescue was a big problem!"), the element that they most recommend be changed ("I would change the money wise, so all of the probes would be free and you would NEVER run out of money so you can get all the reasearch you need and want."), and the source of most students' hypothetical suggestions to a peer using Alien Rescue for the first time ("Spend your money wisely because there is not that much of it.").

Of particular relevance to this study, students perceived a need for more direction and procedural instruction within *Alien Rescue* ("We were given no instruction on what to to and were expected to figure it out on our own"). Others perceived the experience as challenging or difficult for various reasons, including perceived inefficiency in gathering information ("I disliked how it took us so long to get information about the aliens or the planets."), confusion about the source of probe errors ("…Sometimes the probes would blow up so it's frustrating."), or general perceptions that the program was too complex ("I disliked alian rescue because i thought it was very confused and it never got eaisier for me it was just too complicated.").

Students in the treatment condition voiced considerable dislike of the constraints designed to manage cognitive load. Students suggested that these constraints were unnecessary impediments that slowed the process of data gathering, added general confusion to the environment, and hindered the usability of the program.

When describing sources of support within *Alien Rescue,* there was no mention of the prompts or structure provided by the two experimental conditions. Instead, students often listed their peers as sources of support, describing how they worked in concert with their lab partners to perform tasks within *Alien Rescue* or turned to friends for guidance, information, or to share workload.

### *Teacher Perceptions*

Results from teacher interviews generally support the notion that the structured treatment condition was problematic, while the open-ended approach of the control condition was regarded as a success. Very little discussion occurred around the prompt condition, possibly due to the fact that, with the exception of an occasional prompt early in the problem-solving process, the prompt condition did not appear to be materially different from the control condition. Teachers generally supported minimal guidance approaches to PBL, and indeed, practiced this approach through the study. The most valuable aspects of the teacher interviews concerned potential modifications and enhancements to *Alien Rescue* that would enhance the classroom implementation of the program, provide greater insight into student behaviors, and present both students and teachers with actionable feedback. It is clear from the interviews that the worksheet packets are perceived as necessary to provide structure, guidance, and accountability as students progress through *Alien Rescue*, though input from the teachers also suggests opportunities to address these needs through the application of technology.

## DISCUSSION OF FINDINGS AND STUDY IMPLICATIONS

In the following sections, I will review the implications of the study and propose possible explanations of the findings.

## Cognitive Load

The study revealed a finding suggesting that the control and prompt condition differed with regard to cognitive load at time one; students in the prompt condition recorded somewhat higher levels of instructional efficiency. Possible explanations for this finding are that the prompts provided by the program were timed appropriately to the disequilibration of adapting to a new and unfamiliar problem-solving scenario. The prompts in this case, may have been effective in reducing extraneous cognitive load (Sweller et al., 1998) – aspects of *Alien Rescue's* design that do not materially facilitate problem-solving and may occlude students ability to determine appropriate problem-solving steps. It is possible that the guiding prompts provided a lightweight form of worked example (Sweller, 2010; Sweller et al., 2011) in which students were directed to use the tools in productive ways and in a sequence that could lead to more productivity within the problem-solving environment. The finding, while still somewhat inconclusive in the context of the broader study, is nonetheless promising. The use of moderate guidance, as implemented through the prompts, may represent a possible mechanism for orienting new problem solvers to the learning environment.

The overall finding that efficiency decreased over time is more puzzling and subject to multiple possible explanations. One explanation is that the problem-solving experience within *Alien Rescue* does indeed require more cognitive effort over time as students continue to uncover new information and assemble increasingly complex mental schema to accommodate new knowledge. However, despite a lack of statistical significance, the data do not suggest that students expended more mental effort later in the problem-solving process. The more likely explanation for the decrease in instructional efficiency relates to the apparent (though, again, statistically insignificant) decrease in student solution performance over time. This decrease may be attributable to a variety of factors: factors associated with the end of the school year, such as increasing distraction and decreases in motivation and engagement, increased absences or schedule disruptions, less rigorous approaches to solution construction given time constraints near the end of the unit, or prioritization of the worksheet packet tasks.

Alternatively, problems may exist with the treatment conditions themselves that adversely effect cognitive load. One possibility supported by the qualitative results is that the structured condition, in an attempt to constrain the problem-solving environment and reduce extraneous cognitive load, actually introduces extraneous cognitive load, possibly by generating additional element interactivity. This notion is supported by student feedback that suggests a student view of the constraints as having a deleterious impact on productivity, a source of confusion, and an overall challenge to students' abilities to progress through the problem-solving scenario. The combination of the constraints and the worksheet tasks may also influence cognitive load. Students typically progressed through the worksheet linearly – recording nearly all the data points on the aliens before moving on to record all the data points on the planets. When confronted with an inability to complete the first step of the workbook task, students may have been unwilling or felt they were disallowed to set aside the structural approach prescribed by the worksheet packet in favor of the open-ended problem-solving approach that supports the design of *Alien Rescue*. In such cases, students may have expended unnecessary cognitive effort in an attempt to locate missing information for their workbook rather than progressing through the problem.

The study did not consider additional sources of support that may have led to more optimal levels of cognitive load. The collaborative nature of the problem-solving experience, consistent with an ideal PBL implementation, and as supported by the qualitative data may have been a substantial source of cognitive support. This view is consistent with theories of distributed cognition (Hutchins, 1996), in which interdependent groups of learners perform different though equivalent tasks towards accomplishing a goal. During classroom implementation of *Alien Rescue* it is not uncommon to see experts emerge throughout the classroom. One student may become an expert who excels in conducting background research, making tentative matches between alien requirements and planetary characteristics. Another student may take on the role of an expert hypothesis evaluator by taking the first student's tentative solutions and testing them through the design of probes. Yet another student may possess substantial skill in the type of argumentation required to articulate a well-founded solution rationale. Whereas this study measured individual cognitive load, future research should address the extent to which problem-solving within *Alien Rescue* is a distributed endeavor.

**Cognitive Tool Usage**

Results associated with cognitive tool usage suggest that student tool usage did not differ significantly with regard to duration. Students in all three conditions used the tools for roughly the same amount of time. The differences in tool frequency, however, may be due in part to the scaffolds themselves. Students in the structured condition may have been so constrained in their navigation options that the frequency with which they used tools that support cognitive processes was artificially high. Explanations for the differences in the control and prompt treatment conditions with respect to tools that support hypothesis testing are more elusive, though visual inspection of the frequency chart for the prompt condition may suggest that this condition simply followed a more optimal problem-solving process than other conditions. Additional research on the role of prompts versus the open-ended problem-solving scenario of the existing *Alien Rescue* implementation may lend clarity to this finding.

In addition, further research is needed on the role of cognitive tools in managing cognitive load. Student qualitative responses characterized aspects of the problem as confusing and often decried a lack of instruction. A clear opportunity for future research involves the measurement of cognitive load as students engage with the cognitive tools within the environment, the effect that concurrent use of multiple cognitive tools has on cognitive load, and the possible identification of tools and aspects of the learning experience in which levels of cognitive load are unproductively high.

**Science Knowledge**

Differences in performance between the control condition and the structured condition with regard to knowledge test scores may support the commonly cited PBL characteristics of open-endedness, limited structure, and minimal guidance as being effective forms of instruction. Without the presence of too much structure, in the form of the structured condition's constraints, the control condition could freely explore the environment and access any information required. These students may have been more successful, especially given the structure of the worksheet packets, at acquiring the factual and application knowledge necessary for improvements on knowledge test performance.

There are a number of challenges with measuring science knowledge through *Alien Rescue*. First, the repeated measures design may be problematic in that the pretest and posttest use the same instrument. The pretest may serve to provide cues to students on particular areas of factual or application knowledge needed for improved performance on the posttest. In addition, the instrument does not address one of the primary learning outcomes of *Alien Rescue*: the development of transferable problem-solving schemas. Follow-up research should consider tests of transfer to determine how various interventions improve the development of these schemas. An ideal approach would involve an end-of-unit transfer activity in which students are asked to solve a similar type of problem, though with different characteristics and in a novel context.

**Student Perceptions**

The qualitative data support the notion that novices engaged in open-ended problem-solving need some level of support. Students received support from a variety of sources, such as peers, teachers, and *Alien Rescue's* existing array of cognitive tools, yet did not cite any feature of the two experimental conditions in either their interviews or questionnaire responses as being helpful. At the same time, qualitative data support previous findings on *Alien Rescue*, namely, that it can be challenging, confusing, and characterized by a lack of direction or instruction. Though there are likely benefits to the struggle that students engage in as they orient to the problem-solving environment, student feedback also suggests that there is a need for some form of scaffolding to help bootstrap the problem-solving process.

A key finding is the extent to which students devalue constraints as a scaffolding device. Student perceptions regarding the presence of the structured condition's constraints were made quite clear through student questionnaire responses and interviews; their clear preference was for a learning experience that was more open-ended. The strongest message about constraints, however, concerned the budgetary limits imposed by the Probe Design Center. Students in all treatment conditions voiced concern that the budget limitations negatively impacted their ability to be productive within *Alien Rescue*. The budget system was intentionally designed to encourage students to be strategic in designing probes. The probe functionality is intended to address gaps in information that can be obtained through no other source within the program and is intended primarily as a mechanism that performs data collection in service of a hypothesis. In this sense, the most efficient use of probes involves a degree of moderation. Within this study, as evidenced by students' qualitative responses, the Probe Design Center was among the tools -- alongside the Alien Database and Solar System Database -- that were actively used to collect a wide range of data. One explanation for this application of the Probe Design Center is that students sought an efficient way to carry out the worksheet tasks. When compared with the Solar System Database and its intentionally ill-structured and incomplete data, well-designed probes can provide access to more direct forms of data. For example, data on the surface characteristics of a given planet may be somewhat obscured within the planet's description in the Solar System Database. A probe equipped with radar and a set of cameras however, will often provide immediate access to that information. In this way, removal of the budgetary constraints would provide an avenue for the students to conduct highly efficient information gathering, though in a way that lacks the pedagogical potential of forming a hypothesis through interpretation of ill-structured data. In fact, the student perspective with regard to budget may point to a larger opportunity to scaffold use of the database tools as a precursor to designing probes.

**TEACHER PERCEPTIONS**

Teachers generally agreed with the student perspective that the structured treatment condition was problematic and, given the benefit of observing all three treatment conditions, felt that the open-ended control condition was the most successful. Two areas of the teacher interviews suggest needs for future work. First, the teachers noted the significant cognitive requirements of *Alien Rescue*, an aspect that they felt differentiates the program from the traditional sixth grade science curriculum. At the same time, teacher comments about the importance of student feedback mechanisms, the use of the worksheet packets, and the desirability of tools to enable better teacher monitoring of student behaviors supports the goal of implementing technology tools to scaffold the learning experience. Their reliance on minimal guidance approaches suggests that hard scaffolds integrated within the learning environment may be necessary to an extent. At the same time, there are clear opportunities to embed analytical and feedback features into the program that support teachers in making appropriate instructional interventions and modifications in cases where students are off-track, have established misconceptions, or need additional support to overcome difficulties.

### PROBLEM-BASED LEARNING

The lack of strong findings supporting the use of prompts and constraints as scaffolds within PBL tends to support some of the foundational characteristics of PBL as described by numerous scholars (Barrows, 1996; Savery and Duffy, 1995; Savery, 2006). Among the most notable of these characteristics is the extent to which PBL environments situate learners within an ill-structured context, provide students with a sense of ownership in developing their own strategies and solutions towards a problem, and the realization of an environment that reflects some degree of authentic complexity within the domain. Though one intention of the scaffolds was to expedite the development of students' problem-schema in order to promote productive problem-solving, the present study lacks evidence that such an approach improved or facilitated the desired PBL outcomes. In particular, no evidence emerged suggesting that students performed better on problem-solving tasks as a result of the scaffolds. Moreover, student differences in pre and posttest performance suggest that the minimal guidance approach provided by the control version of *Alien Rescue* was potentially more optimal in helping students achieve knowledge gains related to space science.

## INSTRUCTIONAL DESIGN

More research is required to further validate scaffolding mechanisms for wide scale deployment in learning environments such as *Alien Rescue*. However, results from this study suggest that the scaffold implementations provided by the treatment conditions represented a potential source of confusion and increased extrinsic cognitive load. One consideration that emerged from this finding is the possibility that the scaffolds were poorly integrated with the overall structure of the problem-solving scenario. Considering the goals of PBL, it is important to evaluate the extent to which a particular tool or feature integrates with the authentic problem-solving context that the PBL environment seeks to create.

## CLASSROOM IMPLEMENTATION SUPPORT

Teacher reliance on worksheets highlights an essential need for technology support. Though they serve an important purpose -- to provide evidence of student learning and to implement some form of student accountability – they also create problems. In some cases, the worksheets prompt students to complete work that is redundant to work already completed within the learning environment. For instance, planet and alien matrices (which contain cells in which students are prompted to enter specific facts about a planet or alien) are analogous to some of the Notebook features provided by *Alien Rescue*. In addition, teachers interested in viewing student problem solutions often require students to submit handwritten solutions. Similarly, at present, it is difficult to discern student activity within *Alien Rescue* from a teacher perspective. It is at times unclear when a student is off-task, requires support or feedback, is operating based on critical misconceptions, or is otherwise pursuing a suboptimal problem-solving strategy. While *Alien Rescue* is presently capable of recording nearly every piece of data produced by students over the course of the problem-solving process, there are not yet mechanisms in place that present information to teachers in ways that are actionable, inform grading, and enable accountability. Such tools may provide pathways to enhance the overall usefulness of *Alien Rescue* from a teacher perspective and support effective classroom implementation of the program. I will discuss this opportunity further under Future Research.

### DESIGN-BASED RESEARCH

*Alien Rescue* was designed, in part, as a platform to support the implementation of design-based research. Many of the methodologies deployed in this study represent an evolution of the program's support for research design and analysis. The study provided an opportunity to assess *Alien Rescue's* performance as a research platform. It allowed me to assess many of the new features I developed to support my research. This study represents the first time that *Alien Rescue* was used to programmatically implement simultaneous treatment conditions and track data associated with those conditions. This feature will facilitate future design evaluations, multivariate testing of new features, and the use of the program by researchers interested in a wide range of topics. In addition, this new version of *Alien Rescue* supported web-based data collection by enabling the collection of student effort ratings and open-ended questionnaires directly from the program itself. These approaches validate new possibilities for unobtrusive data collection within *Alien Rescue* and allow researchers to have greater flexibility in implementing research data collection. The effort rating system in particular allows researchers to automatically collect data at arbitrary points throughout the study and connect it to other forms of learner data such as activity logs, problem solutions, probe designs, notes, and other artifacts from student engagement with the program. In addition, the study and the 151,946 activity records recorded during its duration created an opportunity to develop new methods of mining and visualizing these large data sets to better understand student tool use patterns, including sequence, duration, and frequency of tool use. The new features of *Alien Rescue* are critical in supporting frequent reiterative design-based research processes.

In addition, the study represents the latest iteration in a series of design-based research studies to better understand the theories that underlie problem-based learning, the design and implementation of scaffolds, classroom implementation of the program, and student motivation and engagement. An important outcome from this study is the extent to which it informs future research to further refine theoretical understandings of technology scaffolds. The findings described above will be used to guide the next design iteration.

## Recommendations

Results of the study do no support use of highly structured scaffolds, as implemented within the structured treatment condition. While qualitative findings lack strong indications of the efficacy, or lack thereof, of this condition, they do suggest that the structured condition was associated with lower student knowledge gains. Additionally, qualitative data highlights potential problems with the condition, with students often describing the condition as confusing or overly restrictive. These findings support recommendations for implementing problem-based learning and suggest that the structured treatment condition may contradict some of the goals of PBL. In particular, the treatment condition may have contributed to a lack of open-endedness in the problem solving environment while also restricting students' opportunities to engage with the problem in a self-directed manner.

Findings related to the prompt treatment condition were somewhat unclear, and additional research is needed to determine the extent to which well-designed prompt-based scaffolds may encourage the acquisition of problem-solving schema and help manage the extraneous cognitive load introduced by the problem-solving scenario. At the same time, it is possible that the control condition, in which the default configuration of *Alien Rescue* was deployed, may be the most ideal of the three conditions. Students in this condition were successful in achieving the highest knowledge gains and it is likely that the condition is the most consistent with the ideal characteristics of PBL. The study tentatively validates the minimal scaffolding used by the control condition and suggests that the widespread deployment of this condition in schools is appropriate.

The study also suggests that additional teacher supports may be of use in guiding the classroom implementation of the control version of the program.

## Limitations

This study had a number of limitations. Selection of research site is an important consideration when interpreting the results of the study. Three research site factors in particular are relevant to the study: timing, implementation, and population. First, the study corresponded to the last science unit of the year, following the completion of standardized testing and coinciding with a number of end-of-year activities. The timing generated many different competing priorities for teachers and students and may have created a scenario in which work on *Alien Rescue* was not a high priority. The timing also raises concerns that the unit was not well integrated with the school's science curriculum.

Second, the classroom implementation of *Alien Rescue* was not ideal primarily due to the use of the worksheets packets. The worksheets implemented low-level learning activities primarily concerned with recording information presented in the environment. I feel that there was significant contrast between the design goals of *Alien*

*Rescue* and the implementation that occurred. My primary concern is that the use of the worksheets created an alternative task that, as a graded assignment, outweighed the open-ended problem-solving tasks that *Alien Rescue* was designed to support. I feel that a higher fidelity implementation of *Alien Rescue* may have better supported this research.

Finally, 80 students failed to complete even a single solution within *Alien Rescue* and, given the size of the population, relatively small numbers of students completed at least three solutions. The data obtained quite often-violated assumptions necessary for statistical robustness. A higher number of submitted solutions and effort rating may have provided better data and statistical clarity.

There were two additional limitations. Sample selection was not evenly distributed across the three treatment conditions, with the structured condition having significantly more participants than the other two conditions. In addition, because treatments were deployed within intact classes, it is possible that not all treatment conditions were equivalent in terms of student ability level. Additional metrics to control for student ability level would have strengthened the findings.

Finally, the design and implementation of the treatment conditions themselves could be a factor in the results. The two experimental treatments were not strongly integrated into the narrative structure of the problem scenario and key narrative devices were easy for students to overlook. For example, the structured condition attempted to explain the locked doors and restricted access to information as relating to problems with the space station. However, because that information only appeared fleetingly, it was easy for students to neglect and may have contributed to a sense that the structured implementation was confusing.

## Future Research

This study suggests several possibilities for future research. First, it underscores the importance of additional research into the potential for scaffolds within problem-based learning environments. This research should assess the role of both hard and soft scaffolds.

In terms of hard scaffolds, future research may consider the design of the existing and well-integrated cognitive tools in facilitating problem-solving in a manner similar to previous research on the notebook tool within *Alien Rescue* (Li & Liu, 2007). The extent to which the cognitive tools support students in managing cognitive load is presently unknown. Research in this area may further the design of appropriate technology supports for learning environments like *Alien Rescue* and further our understanding of how students learn within complex, problem-based learning environments. Currently, the *Alien Rescue* design team is considering the redesign of a number of key tools including the Concepts Database, Probe Design Center, and Mission Control Center. As these new designs are deployed and evaluated through continuous processes of design-based research, there exist significant opportunities for unobtrusive data collection to assess student usage patterns and the overall influence of these tools on the problem-solving process.

Research on soft scaffolds may consider the role of teacher intervention and facilitation within the PBL process. Presently, *Alien Rescue* lacks mechanisms that make student learning within the environment visible to the teacher. With the growth of web-based tools and sophisticated analytics capabilities there exists substantial opportunity to develop and evaluate teacher dashboards, automated student and teacher feedback mechanisms, predictive analytics models, data visualizations, and other solutions that can provide both teachers and students with enhanced and actionable insight into the learning process. In addition, such tools may help bridge the potential gap between the idealized and actual implementation of *Alien Rescue* by providing tools and features that scaffold and support teacher implementation of the program. The *Alien Rescue* team is currently conceptualizing a Teacher Dashboard prototype for possible implementation next year.

## Conclusion

Through this study I attempted to better understand the role of scaffolds in promoting optimal levels of cognitive load and enabling productive problem-solving within open-ended learning environments. Findings from the study suggest that additional research is required to further refine our understanding of cognitive load, the relationship between cognitive load and constructivist learning environments, such as PBL environments, and the specific needs of middle school students and teachers with respect to problems and problem-solving, science instruction, and pedagogy. I have identified several opportunities for future research in these areas. Future design iterations of *Alien Rescue* will be deployed with the goal of refining our understanding of these issues.

## APPENDIX A: SPACE SCIENCE KNOWLEDGE TEST

Name ____________________ Teacher __________ Period________

# *Alien Rescue* Science Test

Circle the letter of the correct answer.

1. Which of these worlds is a planet (not a moon)?

A. Io

B. Phobos

C. Uranus

D. Not sure

2. Which of these worlds is a gas giant?

A. Saturn

B. Earth

C. Pluto

D. Not sure

3. Which of the following worlds is a moon of Jupiter?

A. Europa

B. Mars

C. Neptune

D. Not sure

4. Which of these worlds is farther from the sun than Saturn?

A. Earth's moon

B. Mercury

C. Charon

D. Not sure

5. Venus

A. is a gas giant

B. has an atmosphere denser than Earth's

C. is very cold because of a greenhouse effect

D. Not sure

6. Io

A. is the closest planet to the sun

B. has active volcanoes

C. is colder than Pluto

D. Not sure

7. Which of these worlds has the lowest surface gravity?

A. Earth

B. Triton

C. Jupiter

D. Not sure

8. What is the difference between a moon and a planet?

A. moons are closer to the sun than planets

B. planets have plant life and moons do not

C. moons orbit planets but planets do not orbit moons

D. Not sure

9. Which of the following does an atmosphere do for a world?

A. causes volcanoes to erupt

B. pushes heat out into space so the world doesn't get too hot

C. protects it from meteors

D. Not sure

10. Which of the following does a magnetic field do for a world?

A. protects it from the solar wind

B. lowers its temperature

C. gives it seasons

D. Not sure

11. Craters are caused by

A. earthquakes

B. magnetic fields

C. meteor impacts

D. Not sure

12. You are standing on the surface of a world and see the sun in the sky. The rest of the sky is black and you can see stars. What do you know about that world?

A. It is a gas giant.

B. It has no atmosphere.

C. It has no magnetic field.

D. Not sure

13. Which of the following is NOT the name of a temperature scale?

A. Fahrenheit

B. Titan

C. Celsius

D. Not sure

14. Ice

A. can be made of many substances, not just water

B. covers most of the surface of Io

C. is an element

D. Not sure

15. Which of these instruments can be used to learn about temperature on a world?

A. seismograph

B. infrared camera

C. spectrograph

D. Not sure

16. Imagine that you need to determine whether or not a moon's surface has carbon. What instrument would you use?

A. wide angle camera

B. spectrograph

C. seismograph

D. Not sure

17. Scientists want to measure the pressure of Mars' atmosphere. What instrument would they use?

A. barometer

B. thermometer

C. magnetometer

D. Not sure

18. Suppose that you want to take closeup pictures of features on the surface of Callisto, but you can only afford to send an orbiter. What instrument would you include?

A. infrared camera

B. narrow angle camera

C. barometer

D. Not sure

19. You need to design a probe to go to Titan to find out if it has a magnetic field or earthquakes. Which of the following would you choose to include on your probe?

A. a battery and a solar panel

B. a barometer and a seismograph

C. a magnetometer and a seismograph

D. Not sure

20. Scientists want to gain more accurate information about the atmosphere of Venus, especially what it's made of. What type of probe would they use and what instrument would they include?

A. an orbiter with an infrared camera

B. a flyby with a seismograph

C. a lander with a barometer

D. not sure

21. At a temperature of absolute zero

A. water melts

B. atoms stop moving

C. carbon changes from a liquid to a solid

D. not sure

22. Water boils at which of the following temperatures? (Remember to think about the different temperature scales.)

A. 32 degrees C

B. 100 degrees C

C. 100 degrees F

D. Not sure

23. Which of these could be considered a "signature" for an element?

A. a seismograph

B. an infrared picture

C. a spectrum

D. not sure

24. A world will have a magnetic field if

A. it has a thick atmosphere

B. it has liquid water

C. it has a core made of liquid metal

# APPENDIX B: SOLUTION FORM RUBRIC

| | |
|---|---|
| The world chosen for the alien species is not an acceptable choice. | 1 |
| The world chosen for the alien species is an acceptable choice. One correct specific reason for the choice is listed with facts to back them up. | 2 |
| The world chosen for the alien species is an acceptable choice. Two correct specific reasons for the choice are listed with facts to back them up. | 3 |
| The world chosen for the alien species is an acceptable choice. Three correct specific reasons for the choice are listed with facts to back them up. | 4 |
| The world chosen for the alien species is an acceptable choice. Four correct specific reasons for the choice are listed with facts to back them up. | 5 |
| The world chosen for the alien species is an acceptable choice. Five correct specific reasons for the choice are listed with facts to back them up. | 6 |
| The world chosen for the alien species is an acceptable choice. Six or more correct specific reasons for the choice are listed with facts to back them up. | 7 |
| The world chosen for the alien species is an acceptable choice. Six or more correct specific reasons for the choice are listed with facts to back them up AND limitations of the world are listed. | 8 |

# APPENDIX C: STUDENT QUESTIONNAIRE

What did you like about *Alien Rescue*?

What did you dislike about *Alien Rescue*?

What parts of *Alien Rescue* helped you the most?

What parts of *Alien Rescue* were the least helpful?

What did you learn from *Alien Rescue*?

What advice would you give to a friend who is using *Alien Rescue* for the first time?

If you could change something about *Alien Rescue* what would it be? Why?

# APPENDIX D: PARENTAL CONSENT FORM

**Title: Effects of Multimedia Problem-based Learning on Students' Learning: Alien Rescue (http://alienrescue.edb.utexas.edu/)**

Investigator: Lucas Horton, The University of Texas at Austin, Department of Curriculum and Instruction

Contact Information: Lucas Horton, lucas.horton@austin.utexas.edu or 512-496-5680

You are being asked to allow your child to participate in a research study. This form provides you with information about the study. The person in charge of this research will also describe this study to you and answer all of your questions. Please read the information below and ask any questions you might have before deciding whether or not to take part. Your participation is entirely voluntary. You can refuse to participate without penalty or loss of benefits to which you are otherwise entitled. You can stop your participation at any time and your refusal will not impact current for future relationships with UT Austin, district, or school. To do so simply tell the researcher you wish to stop participation. The researcher will provide you with a copy of this consent for your records.

**The purpose of this study** is to understand the effects of this problem-based learning environment on students' problem –solving skills and how teachers implement it in the classrooms.

**If you agree to be in this study, we will ask your child to do the following things:**

- Students will use Alien Rescue as part of their science class. As part of this participation, students will be asked to fill out questionnaires at the beginning and end of the semester. We may ask your child some questions regarding his or her view of the program.

**Total estimated time to participate** in study are the days students will use Alien Rescue as determined by their teachers. The questionnaires will take place when the teachers believe will be least disruptive to your child's normal schedule.

**Risks** of being in the study

- This procedure involves no risks. There may be a risk for loss of confidentiality, but will be guarded against by the protections outlined below.

**Benefits** of being in the study

The potential benefits of participating are using a state of art computer program, experiencing a new way of learning (problem based and collaborative) using technology, and learning and teaching science through an innovative approach. Additionally, UT researchers and teachers are engaging in a collaborative effort to find an effective way to teach problem-solving.

**Compensation:**

- None

**Confidentiality and Privacy Protections:**

- For students selected to be interviewed:
    - *interviews or sessions will be audio-taped;*
    - *tapes will be coded so that no personally identifying information is visible on them;*
    - *tapes will be kept in a secure place (SZB building 244N office)*
    - *tapes will be heard or viewed only for research purposes by the investigator and her associates;*
    - *tapes will be erased after they are transcribed or coded.*

- The data resulting from your participation may be made available to other researchers in the future for research purposes not detailed within this consent form. In these cases, the data will contain no identifying information that could associate you with it, or with your participation in any study.

The **records** of this study will be stored securely and kept confidential. Authorized persons from The University of Texas at Austin, and members of the Institutional Review Board have the legal right to review your child's research records and will protect the **confidentiality** of those records to the extent permitted by law. All publications will exclude any information that will make it possible to identify you as a subject. Throughout the study, the researchers will notify you of new information that may become available and that might affect your decision to remain in the study.

**Contacts and Questions:**
If you wish to stop your participation in this research study for any reason, you should contact: Lucas Horton <lucas.horton@austin.utexas.edu>. You are free to withdraw your consent and stop participation in this research study at any time without penalty or loss of benefits for which you may be entitled. Throughout the study, the researchers will notify you of new information that may become available and that might affect your decision to remain in the study.

In addition, if you have questions about your rights as a study participant, or are dissatisfied at any time with any aspect of this study, you may contact - anonymously, if you wish - the Office of Research Support by phone at (512) 471-8871 or email at orsc@uts.cc.utexas.edu.

You may keep the copy of this consent form.

You are making a decision about allowing your (son/daughter) to participate in this study. Your signature below indicates that you have read the information provided above and have decided to allow him or her to participate in the study. If you later decide that you wish to withdraw your permission for your (son/daughter/child/infant/adolescent youth) to participate in the study, simply tell me. You may discontinue his or her participation at any time.

______________________________
Printed Name of (son/daughter/child/infant/adolescent youth)

_________________________________ ________________
Signature of Parent(s) or Legal Guardian Date

_________________________________ ________________
Signature of Investigator Date

# APPENDIX E: ASSENT FORM

**Alien Rescue**

I agree to be in a study about using Alien Rescue. This study was explained to my (mother/father/parents/guardian) and (she/he/they) said that I could be in it. The only people who will know about what I say and do in the study will be the UT people in charge of the study.

I understand that I will be asked to answer questions on what I think is the best way to learn science. I understand that nothing bad or wrong will happen to me if I decide to stop my participation in this study at any time. I realize that my grades will not be affected if I choose to stop participation.

By clicking 'Yes' below, it means that I agree to be in the study. I know what will happen to me. If I decide to quit the study, all I have to do is tell the person in charge.

# APPENDIX F: TEACHER CONSENT FORM

**Title: Effects of Multimedia Problem-based Learning on Students' Learning: Alien Rescue (http://alienrescue.edb.utexas.edu/)**

Investigator: Lucas Horton, The University of Texas at Austin, Department of Curriculum and Instruction
Contact Information: Lucas Horton, lucas.horton@austin.utexas.edu or 512-496-5680

You are asked to participate in a research study. This form provides you with information about the study. The person in charge of this research will also describe this study to you and answer all of your questions. Please read the information below and ask any questions you might have before deciding whether or not to take part. Your participation is entirely voluntary. You can refuse to participate without penalty or loss of benefits to which you are otherwise entitled. You can stop your participation at any time and your refusal will not impact current for future relationships with UT Austin, district, or school. To do so simply tell the researcher you wish to stop participation.

**The purpose of this study** is to understand the effects of this problem-based learning environment on students' problem –solving skills and how teachers implement it in the classrooms.

**If you agree to be in this study, we will ask you to do the following things:**

- Researcher(s) will observe how you use Alien Rescue in your teaching. You will be asked to fill out questionnaire(s) after you use Alien Rescue and interviews may be conducted.

**Total estimated time to participate** in study are the days you will use Alien Rescue as determined by you. Questionnaires and interviews will be completed during a time that is determined and convenient to you.

**Risks** of being in the study

- This procedure involves no risks. There may be a risk for loss of confidentiality, but will be guarded against by the protections outlined below.

**Benefits** of being in the study

The potential benefits of participating are using a state of art computer program, experiencing a new way of learning (problem based and collaborative) using technology, and learning and teaching science through an innovative approach. Additionally, UT researchers and teachers are engaging in a collaborative effort to find an effective way to teach problem-solving.

**Compensation:**

- None

**Confidentiality and Privacy Protections:**

- *interviews or sessions will be audio-taped;*
- *tapes will be coded so that no personally identifying information is visible on them;*
- *tapes will be kept in a secure place (SZB building 244N office)*
- *tapes will be heard or viewed only for research purposes by the investigator and her associates;*
- *tapes will be erased after they are transcribed or coded.*

- The data resulting from your participation may be made available to other researchers in the future for research purposes not detailed within this consent form. In these cases, the data will contain no identifying information that could associate you with it, or with your participation in any study.

The **records** of this study will be stored securely and kept confidential. Authorized persons from The University of Texas at Austin, and members of the Institutional Review Board have the legal right to review research records and will protect the **confidentiality** of those records to the extent permitted by law. All publications will exclude any information that will make it possible to identify you as a subject. Throughout the study, the researchers will notify you of new information that may become available and that might affect your decision to remain in the study.

**Contacts and Questions:**
If you wish to stop your participation in this research study for any reason, you should contact: Lucas Horton <lucas.horton@austin.utexas.edu>. You are free to withdraw your consent and stop participation in this research study at any time without penalty or loss of benefits for which you may be entitled. Throughout the study, the researchers will notify you of new information that may become available and that might affect your decision to remain in the study.

In addition, if you have questions about your rights as a study participant, or are dissatisfied at any time with any aspect of this study, you may contact - anonymously, if you wish - the Office of Research Support by phone at (512) 471-8871 or email at orsc@uts.cc.utexas.edu.

You may keep the copy of this consent form.

You are making a decision about participating in this study. Your signature below indicates that you have read the information provided above and have decided to participate in the study. If you later decide that you wish to withdraw from participation in the study, simply tell me. You may discontinue at any time.

Printed Name of the Participant

Signature of the Participant

Date

Signature of Investigator

Date

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