Instr Sci
DOI 10.1007/s11251-012-9251-4

Strategies for success: uncovering what makes students successful in design and learning

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Received: 22 November 2009 / Accepted: 11 January 2011

Abstract While the purposes of design and science are often different, they share some key practices and processes. Design-based science learning, which combines the processes of engineering design with scientific inquiry, is one attempt to engage students in scientific reasoning via solving practical problems. Although research suggests that engaging students in design-based science learning can be effective for learning both science process and content, more research is needed to understand how to overcome what Vattam and Kolodner (Pragmatics and Cognition 16:406–437, 2008) called "the design–science gap." This study, therefore, takes a first step at systematically delving into this issue of bridging the design–science gap by examining the problem-solving strategies that students are using when they solve a prototypical design task. Videotaped performance assessments of high and low performing teams were analyzed in depth. Results suggest that students use both science reasoning strategies (e.g., control of variables) and design–focused strategies (e.g., adaptive growth). However, the strategies commonly associated with success in science (e.g., control of variables) did not necessarily lead to success in design. In addition, while both science reasoning strategies and design–focused strategies led to content learning, the content learned was different.

Keywords Design-based science learning · Problem-solving strategies · Scientific reasoning

Introduction

In the past decade, there has been a growing interest in the use of design activities as a way to promote science learning (e.g., Fortus et al. 2005; Kolodner et al. 2003; Mehalik et al.

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2008; Puntambekar and Kolodner 2005; Silk et al. 2009). In part, this growing interest in the use of design activities for science learning arose from concerns about the declining quality, quantity and diversity of future engineers in the U.S. (Brophy et al. 2008). Providing students in P-12 with opportunities to engage in activities, such as design, is one way to increase interest and awareness of the role engineers play in society. Another rationale for the use of design activities in science arose from concerns about access to, and engagement of, students in science. Traditional science often fails to engage students' interests, make connections to students' everyday lives, and to teach science in ways that allows students' to put their knowledge into practice by solving practical problems (Kolodner et al. 2003). Design is a vehicle by which real-world problem solving skills can be cultivated (Vattam and Kolodner 2008) and can serve to open doors to possible science or engineering careers (Sadler et al. 2000).

Design-based science learning is an instructional approach that combines the processes of engineering design with scientific inquiry (Kolodner et al. 2003; Mehalik et al. 2008; Vattam and Kolodner 2008). In design-based science learning, the activity that is meant to promote learning is a design-project; students are required to use and extend their content knowledge (often of science or math) to develop a technological solution to a problem using available resources. The current literature suggests that engaging students in design-based science learning activities can help students develop problem solving skills and science inquiry skills (Kolodner et al. 2003; Silk et al. 2009), as well as gain scientific content knowledge (Fortus et al. 2004, 2005; Kolodner et al. 2003; Mehalik et al. 2008). However, one of the significant challenges to implementing design-based science learning is what Vattam and Kolodner (2008) called "bridging the design–science gap." This gap is described as one between (i) design, which consists of the creation of physical products and direct experience of phenomena and trends and (ii) science, which consists of abstract laws and causal explanations to explain the phenomena and trends (Vattam and Kolodner 2008). Prior research has shown that seeing the connection between design and science does not always happen naturally (e.g., Crismond 2001; Kolodner et al. 2003).

This study, therefore, takes a first step at systematically delving into this issue of bridging the design–science gap by examining the problem-solving strategies that students are using when they solve a prototypical design task. It is of particular interest if the strategies that are successful for design are the same as the strategies that are successful for science. Understanding the strategies that students use to solve design tasks has important implications for the design of future design-based science learning curricula and classroom instructional practices.

The relationship between processes of design and processes of science

The relationship between design and science is one that is often oversimplified. The purposes of design and science are often different, and yet they share some key practices and processes (Lewis 2006; Puntambekar and Kolodner 2005). At the level of purpose, scientific inquiry primarily involves the creation of knowledge with the goal of developing deeper understanding of natural phenomena. In contrast engineering design involves the creation of artifacts to meet human needs or wants with the primary goal being to devise solutions to problems.

At the level of process, the National Science Education Standards describes scientific inquiry as involving asking scientifically oriented questions, collecting and giving priority to evidence, formulating explanations from evidence, evaluating evidence in light of alternative explanations, and communicating and justifying proposed explanations (National Research Council 2000). Although there are many design models, the design process can be described as including: identifying and framing the problem; generating possible solutions taking into considerations constraints such as cost, safety, and current conditions; building and testing possible solutions; evaluating outcomes from testing, making revisions as necessary; and using evaluation-based decision making to choose the final solution (Lewis 2006).

What is important to note here is where the overlap between design processes and science processes occur. One salient overlap is experimentation, a process that is central to both design and science (Schauble et al. 1991). In design, the building, testing, and evaluation of design solutions to best meet specified requirements is key; while in science the collection and evaluation of empirical data is central (Lewis 2006). Scientific inquiry invariably includes some aspects of design (e.g., design of a research question, an experimental plan, the experimental apparatus), and design will include some aspects of inquiry (e.g., what caused this failure in the prototype?, does the redesign improve the product?).

Problem-solving strategies in design and science

Prior research suggests that when attempting to solve complex problems, such as a design task, individuals use different problem-solving strategies based on the nature of the event outcome (Tschirgi 1980). Tschirgi proposed that solving any complex problem, such as a design task, could be considered a hypothesis-testing situation wherein a hypothesis is generated as to the cause of an event, a test is conducted to produce evidence, and conclusions are drawn based on the tests results. When adults and elementary school children attempt to solve complex problems in everyday situations they are attuned to the nature of the outcome of the event and are likely to use one of two strategies, vary one thing at a time (VOTAT) or hold one thing at a time (HOTAT) (Tschirgi 1980). When an outcome is negative, both children and adults use a VOTAT strategy, changing the hypothesized 'bad' variable while holding all others constant (Tschirgi 1980). For example, when posed with the problem of baking a cake, if told that the cake turned out terrible, both children and adults employ a VOTAT strategy, *changing* the one thing (e.g., the use of honey) that they believe to be responsible for the bad result while holding all other things (e.g., the use of flour and butter) constant (Tschirgi 1980). However, when an outcome is positive, children and adults employ a HOTAT strategy, keeping the hypothesized 'good' variable while changing the surrounding context (Tschirgi 1980). Continuing with the baking a cake example, if told that the cake turned out great, both children and adults employ a HOTAT strategy, *keeping* the one thing (e.g., the use of butter) that they believe to be responsible for the good result while changing all other things (e.g., the use of whole-wheat flour instead of white flour, and using sugar instead of honey; Tschirgi 1980). Thus it seems that both VOTAT and HOTAT are strategies that students may use when attempting to solve a design problem.

While Tschirgi's (1980) research demonstrates that the outcome of an event influences problem-solving strategies used, Schauble et al. (1991) suggest that the perceived goal of the task can influence the use of different strategies. Schauble et al. (1991) suggest that the strategies fifth and six grade students use to solve a task they perceive as an 'engineering' problem, differ from the strategies they use to solve a task they perceive as a 'science' problem. Schauble et al. (1991) defined 'engineering' problems as those wherein the objective is to optimize a desired outcome. In contrast, 'science' problems are tasks wherein the goal is to determine the relations (primarily causal) among variables and outcomes. When working on a task perceived to be an engineering problem the most efficient strategies for achieving a desired outcome may include: comparing highly contrastive instances, making inclusion or causal inferences about the variables at play, and focusing on variables believed to cause the outcome (Schauble et al. 1991). In contrast, when working on a task perceived to be a science problem, the most efficient strategies for determining the relations among variables and outcomes may include: establishing the effects of each potentially important variable, making exclusion (non-causal) and indeterminacy (unable to determine causal status) inferences about the variables at play, and testing all combinations of variables when possible using a reasoning strategy such as VOTAT (Schauble et al. 1991). Schauble et al. (1991) found that, as expected, fifth and six grade students working on an "engineering problem" explored fewer variables focusing instead on the variables they believed to have a causal relation to the desired outcome, and made more inferences about causality than students working from a science model.

While the strategies commonly used when exploring an engineering problem may be effective for achieving the desired outcome, they may not be effective for knowledge change, or understanding of the relationships between the variables at play (Schauble et al. 1991). Conducting logically valid experiments using strategies such as VOTAT, (also known as the control of variables strategy) is a fundamental skill at the heart of scientific thinking (Klahr et al. 2001; Chen and Klahr 1999; Ford 2005). The VOTAT strategy includes being able to design unconfounded experiments and deriving valid inferences from the evidence the experiments yield (Klahr et al. 2001). However, using a strategy like VOTAT is not a skill that many students are able to master, even after years of instruction in school (Klahr et al. 2001), and may not be one they use spontaneously.

Understanding the ideas and strategies that students bring with them to the classroom environment has important implications for the design of curricula and classroom instructional practices. This study further explores the problem solving strategies that students use when attempting to solve a prototypical design task, and the relationship of these problem-solving strategies to students' learning of science when engaged in design-based science learning units. The studies by Tschirgi (1980), Schauble et al. (1991), and Klahr et al. (2001) used situations which were biased towards scientific experimentation in that the experimental setup involved pairs of conditions in each "experiment", rather than sequential testing of prototypes as is more natural in design. Different strategies may emerge or different strategies may be preferred in a sequential testing case given that clean contrasts between two conditions are less salient. Further, the study by Tschirgi (1980) used a paradigm that did not really allow students to learn from experimentation, but instead simply examined student choices from hypothetical situations. When a design situation also allows for learning to occur, student strategies might not be as immediately focused on the design outcome. Thus, a study is needed to examine design strategies in a situation more prototypical of design and with opportunities to learn through design.

The research questions of primary interest in this study are:

1. What task strategies separate more successful design teams from less successful teams?
2. Do students learn design principles from a design challenge that does not include instructions for content learning?
3. What is the relationship between strategy use and what students learned?

With regards to the first research question, in addition to understanding what task strategies highly successful teams and less successful teams use, it is of particular interest if the strategies that are successful for design are the same as the strategies that are successful for science. This is especially interesting in this sequential testing context that is more typical of design. If it is the same strategies that are useful in design as in science, then design tasks per se support science strategy learning. Whereas if the strategies that are useful in design and science are different, then the inquiry phases within design will need to be made more central and salient in order to support science process learning in design projects.

One strategy that is not typically found in science-oriented pairwise testing environments but may be found in design-oriented sequential testing environments is adaptive growth (AG) (if successful, attempt a better outcome; if unsuccessful, stay the same or try something more basic). This strategy applies to any situation in which the relative complexity of a sequential test can be varied. Variations of this strategy can also be found within experimental design in science (Schunn and Anderson 1999), but it is fundamentally a design–focused strategy in that its variation is relative to the success of design outcomes rather than understanding.

The second research question deals with an issue separate from questions of *whether* students use scientific reasoning strategies, but rather focuses on trying to determine what type of learning can happen from a design challenge that does not explicitly require students to learn either design or science related information. Regardless of whether or not scientific reasoning strategies are used to solve design problems, students may come to understand important design principles though their prototyping and testing cycles.

Finally, the third research question is meant to explore how the type of strategy used might influence learning. Do only the more 'scientific' strategies lead to strong content learning (e.g., design principles) or are other strategies useful for content learning in a design context? Perhaps different strategies simply lead to different content being learned rather than leading to differences in amount of knowledge acquired. For example, strategies that focus on theory testing may lead to knowledge growth more closely tied to student's existing domain theories whereas other strategies might be more likely to expose students to new conceptual avenues (either by chance or by analogy to real world exemplars of successful designs).

It is also important to note that what is learned directly from design experiences is typically called design principles and what is learned directly from science experiences is typically called science content knowledge. Both are declarative knowledge that describes causal relationships in the world, one connected to the man-made world, the other connected to the natural world. From one simple set of experiments or tested designs, it is unreasonable to expect the discovery of major scientific laws. Indeed, in studies of science processes, rather mundane variable relationships were the object of study. Thus, although we will talk about the targets of student learning as design principles, we do not seem them as so different from what other researchers called science content knowledge in their studies.

To address these three research questions teams of high school science students were asked to complete a design challenge, allowing us to closely examine the problem solving strategies they would use to approach the task. Our expectations about the results are based on findings from the literature that have examined student problem solving in practical, science, and design tasks. With regard to the first research question, based on Tschirgi's (1980) findings, we expect that students will make some use of both the HOTAT and VOTAT strategies. However, in light of the findings from Schauble et al.'s (1991), and Klahr et al.'s (2001) research, we expect that use of the VOTAT strategy will be minimal. Instead, strategies more natural to sequential testing (e.g., AG) may become more prevalent. With regard to the second research question, based on the literature (e.g., Crismond 2001), we posit that although students will likely learn important design principles through the process of building and testing of designs, they will not likely "bridge" the design–science gap because the task is not structured to do so. Finally, with regard to the third research question, following the literature (e.g., Schauble et al. 1991) we hypothesize that the type of strategy used will differentially influence content learning, with students that do engage in the use of scientific reasoning strategies acquiring different knowledge (i.e., understanding of design principles) than those that use other strategies simply because they are likely to focus on different aspects of the task.

Method

Participants

A total of 191 students (42 % female, 58 % male) from 9th, 10th, 11th and 12th grades participated in the study. Participating students were drawn from nine urban high schools with a moderate to high proportion of traditionally underserved students—e.g., schools ranged from 30 to 100 % African American and similar proportions of low socio-economic status.[1]

Sampling procedures Convenience sampling was used to select participants for the study. Teachers who implemented a design-based science learning unit in their chemistry, physics or biology classroom held *design competitions* within their classrooms to identify the top student team design projects. The design-based science learning units implemented in the science courses utilized an engineering design approach to teach students a select range of difficult concepts that are central within a science domain (e.g., chemistry, biology or physics) over a 6-to-8 week period. The units covered a wide range of topic areas from genetics in biology to projectile motion in physics. In the units, students work in teams as they go through a design process to create a prototype (e.g., a heating or cooling system that relies on chemical energy and meets a personal need in their own life). This process is akin to the process used by engineering designers. The main design strategies taught during the units were subsystems decomposition, careful documentation, and connecting science to design. More micro-level strategies, as examined here, were not explicitly taught in the units. Teachers then invited these top student teams to participate in a *Regional Design Competition* (See Reynolds et al. 2009 for more details).

Participating students worked in same or mixed gender teams of 2–5 students that were pre-existing teams from their classroom design-based science learning unit activities. The advantage of using these pre-existing teams is that they better represent the performance of stable teams that would occur in the classroom context; newly formed teams sometimes spend considerable initial efforts on social rather than design goals. The use of teams already attending the design competition and having already participated in almost 2 months of a design process suggests that these students may be more experienced than average in design for high school students. However, the goal of this study is not to characterize the strategies used by a perhaps-non-existing "typical" high school student, but rather to examine the range of strategies high school students bring to a design task and the relationship each of those strategies has to design success and task-related content learning. Data were collected from 59 teams over the two years (29 teams in 2007 and 30 teams in 2008). There was no overlap in student participation from 1 year to the next.

[1] Ethnicity and socioeconomic data was not recorded at the events to avoid stereotype threat effects and thus are estimated from school-level information.

Procedures

The primary method of data collection for this study was performance assessment. Data were collected during the *Regional Design Competition* in both 2007 and 2008. Up to six teams, seated at separate tables, each with an earthquake machine and a video camera and microphone, and dividers separating the tables to prevent teams from observing the other teams, were able to complete the earthquake task at the same time. Each team was given 54 wooden blocks to build as high a structure as possible that would withstand a 20-second simulated earthquake (see Fig. 1). Teams were allowed to build and test as many structures as they wanted and were given approximately 20 min to complete the task. Students were allowed to complete a design in progress and timing was approximate in the context of the ongoing design competition, meaning the 20-minute time limit was not strictly imposed. However, time on task was accounted for in the final data analyses.

The earthquake design task, adapted from Azmitia and Crowley (2001), was chosen because it met three important criteria. First, the earthquake task has the three elements that Cross (1994) describes as being common to all design problems: (a) a specified goal, (b) constraints within which the goal must be achieved, and (c) criteria for recognition of a successful solution. Second, the task did not require students to have any discipline-specific knowledge about the domain beyond elements of everyday experience. Third, these East coast students were unlikely to have much prior knowledge about factors that influence earthquake resilience. Thus, design success would be more a function of design strategies than existing differences in content knowledge and post-test measures of knowledge about relevant design principles would primarily be influenced by task-related learning rather than prior knowledge.

Teams' performances were videotaped, and during the task students were asked to explain their designs (e.g., Why did you build your structure this way?) to help shed some light on their design choices. During the 2008 session, at the end of the task each student within a team was asked to respond individually (in writing) to the open-ended prompt:

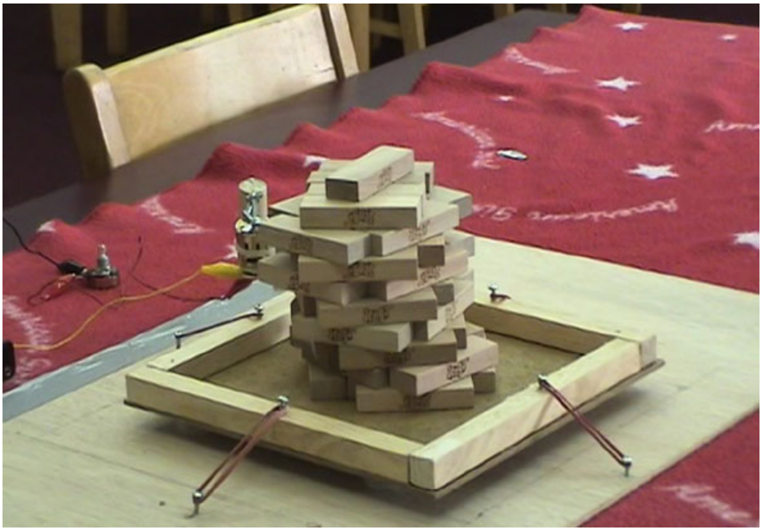

Fig. 1 Sample student-designed earthquake-proof structure on the earthquake simulator

"If you had to tell someone else how to make a structure that stands for 20 s on the earthquake machine, what's the advice you would give them?"

Research design

This study utilized a high–low extreme-groups design to carefully analyze videos of student design team performances on the earthquake task. Teams of students completed the task, and the videos of the most successful and least successful performances were analyzed in detail. Extreme-groups comparisons provide greater statistical power without bias, and are particularly useful for labor-intensive studies such as those involving video-data coding. Extreme-groups comparisons are also a commonly used strategy in the expertise literature for identifying strategy differences. Because the students are already selective rather than 'average' high school students, the issue of generalizability of effect sizes to the full range of students is moot.

Video-data were analyzed in multiple passes by the researcher (Miles and Huberman 1994). First, the videos were segmented at naturally occurring breaks in the design activities (i.e., when students began a new design or when students began testing their design, etc.). Success or failure of the design, height of the design, and notable features of the design were coded. An initial coding scheme was developed to establish the common features present in student designs. A set of 4 videos, not included in the final analysis, were viewed and coded, and the final coding scheme was developed based on this coding. The features included in the final coding scheme included: shape (e.g., pyramid, rectangular); symmetry (e.g., single planar); top and bottom (e.g., base size); and pattern (e.g., parallel layers). Two coders (including the first author) then independently coded 8 of the final 17 videos that were included in the final analysis and inter-rater reliability was calculated, using a subset of 4 videos. Cohen's κ was calculated to determine the inter-rater reliability for coding each of the features. See Table 1 for an overview of the design features that were coded and the inter-rater reliability values. One coder (the first author) independently coded the remaining 9 videos using the established coding scheme.

Next, the most successful teams (i.e., those teams that built the highest structure able to withstand the simulated earthquake) and the least successful teams (i.e., those teams that had either no successful structures or very low successful structures) were identified from the data. From each data set (2007 and 2008) the 4 teams with the highest successful structures and the 4 teams (5 teams from 2008) with the lowest, or no successful structures were selected for further analysis. These teams were categorized as high performing (8 teams) or low performing (9 teams), and their video data were coded for two primary factors that were hypothesized to relate to design success: (a) breadth of the design space explored (i.e., the extent to which students searched the set of design alternatives widely enough to discover the design types that were most successful), and (b) the problem-solving strategies students used to solve the design problems (i.e., the extent to which strategies made salient which designs were successful and why). As it happens, the high and low performing groups were balanced in terms of the courses in which they were currently enrolled (e.g., biology, chemistry or physics), which allows us to focus on strategy-level explanations for performance differences. See Table 2 for a summary of the distribution of courses in which teams were enrolled. In addition, most teams consisted of three members, with no difference in success rates between the smallest and largest teams.

Based on Schauble et al.'s (1991) finding that students' exploration of the set of possible variable choices (also called a design space) when focused on an engineering problem is often limited to the variables believed to have a causal relation to the desired outcome, a

Table 1 Design features coded

Feature category	Feature	Cohen's κ
Structure shape	Pyramid solid	1.0
	Pyramid hollow	1.0
	Rectangular solid	1.0
	Rectangular hollow	0.50
	Other (e.g., no distinct shape)	0.3
Symmetry	Single planar	0.71
	Double planar	0.71
	Triple planar	0.71
Top/bottom	Antennae	0.88
	Wide base	1.0
	Rail support	0.70
Pattern	Parallel layers	0.71
	Irregular	1.0

Table 2 Distribution of courses across high and low performing teams

Course	Number of high performing teams	Number of low performing teams
Biology	3	4
Chemistry	2	2
Physics	3	3

coding scheme was developed to analyze students' exploration of the design space. Analysis of the design space exploration included coding: (1) time on task, (2) the total number of designs, (3) percentage of successful design trials, (4) total number of design features explored (calculated by tallying how many of the 13 possible features were present across a team's designs), (5) number of features varied between design trials (calculated by tallying which features were added and/or removed from each design), and (6) focus on specific features (calculated by tallying how frequently a specific feature, e.g., wide base, was present across a team's designs). These features were coded by reviewing the videotaped performances and analyzing teams' designed structures (for each trial) immediately prior to subjecting it to the simulated earthquake. That is, each designed structure was examined and coded for the presence or absence of each of the 13 possible design features.

Based on Tschirgi's (1980) work related to the hypothesis testing strategies of VOTAT (vary one thing at a time), and HOTAT (hold one thing constant at a time), a coding scheme was developed to analyze students' approaches to solving the design task. Analysis of the design process used by students (i.e., the problem solving strategies used) included coding for the use of a VOTAT, HOTAT, Hold Particular Things Constant (HPTC), and an AG (if successful, build higher; if unsuccessful, stay the same or go lower until successful) strategy. Both the HPTC and the AG strategies were codes that were derived from the data through an inductive analysis process (Ezzy 2002), that is, these two coding categories were not predetermined. However, variations of the HPTC strategy can be found in the literature (e.g., HOTAT, Tschirgi 1980) as can the AG strategy (e.g., within experimental design in science, Schunn and Anderson 1999). Use of each of these strategies was coded on a trial-by-trial basis. Use of a VOTAT strategy was coded when only one design feature (of the possible 13 features) was varied from one trial to the next (e.g., antennae present in one design trial but absent from next trial). A HOTAT strategy was coded when one feature was kept constant from one trial to the next (e.g., antennae feature present in two consecutive trials). The use of the HPTC strategy was coded when at least one *category* of features was kept constant from one trial to the next (e.g., *structure shape* was kept constant from one trial to the next, while other categories of features were manipulated) (See Table 1). The use of the AG strategy was coded when a team used the strategy of building a taller design only if their previous design trial was successful, otherwise they would build a design that was the same height or lower.

Finally, for the 30 teams who participated in the 2008 design competition, individual students' written responses regarding how they would tell someone else how to build a successful structure were analyzed using a thematic analysis procedure. That is, the written responses were explored, units of meaning were identified, codes were developed and categories and sub-categories were created (Ezzy 2002). This process was followed until a 'master list' of codes was developed, which reflected the recurring themes and patterns in students' responses (Merriam 1998).

Results and discussion

The primary purpose of the current study was to examine the strategies that teams of students spontaneously use to solve a prototypical design task, and to determine the relative value of these strategies for achieving design success and learning of design principles. Results will be presented in this section according to the specific research questions addressed.

What separates more successful design teams from less successful teams?

Exploring the feature space

As Schauble et al. (1991) noted, students working on an engineering problem are likely to explore fewer variables (or features) instead focusing in on the ones they believe to have a causal relation to the desired outcome, thus, one possible explanation for the variability between high and low performing teams is that highly successful teams did a more expansive search of the design space. This could include building and testing more designs, or trying a wider variety of design features. Since the time on task was not strictly limited to 20 minutes, there was some variability in the amount of time teams spent completing the earthquake task. Thus it is important to first examine whether there were significant differences in the amount of time spent on task between the high and low performing teams. Highly successful teams spent directionally a greater number of minutes on the task than lower performing teams ($M_{high} = 24.8$, $M_{low} = 22.3$) however, this difference was not statistically significant, $t\ (15) = 0.94$, $p = 0.18$. Despite spending approximately the same amount of time on task, the number of designs built and tested by teams varied greatly, ranging from 1 to 15 designs. On average, highly successful teams built and tested more designs than the lower performing teams ($M_{high} = 9.0$, $M_{low} = 5.6$, $t\ (15) = 2.09$, $p = 0.05$, $d = 1.0$). This result is in line with the hypothesis that highly successful teams would do a more expansive search of the design space, thus requiring the building and testing of more designs. In addition, the highly successful teams' percentage of successful designs was directionally greater ($M_{high} = 47$, $M_{low} = 28$), however, this difference was not statistically significant, $t\ (15) = 1.18$, $p = 0.26$.

Despite having constructed a different number of designs, both high and low performing teams explored the same number of features ($M_{high} = 8.8$, $M_{low} = 9.1$, t (15) = 0.30, $p = 0.77$). That is, of the 13 possible features that were coded for, both high and low teams used approximately 9 of those features in at least one of their designs. Contrary to expectations, this finding suggests that the number of features explored does not distinguish high and low performing teams. In addition, there was no significant difference between high and low performing teams in the number of features that were varied from one trial to the next ($M_{high} = 1.9$, $M_{low} = 2.3$, t (11) = −0.74, $p = 0.47$, d = -0.4). Thus, both high and low performing teams appeared to be varying on average, 2 design features per trial. While there was no difference in the exploration of the feature space, there was a marginally significant difference in the use and focus on one particular useful design feature, the antenna. The antenna feature was one that was characterized as use of a single or multiple blocks that extended vertically from the top of the structure for more than 3 'stories' (See Fig. 2). High performing teams included this feature in a greater percentage of their designs than did low performing teams ($M_{high} = 51$, $M_{low} = 24$, t (15) = 2.06, $p = 0.06$, $d = 1.1$), which is likely the result of their improved search rather than an index of a different search process per se. Table 3 provides an overview of high and low team performances related to these factors. In sum, the findings provide some support for the hypothesis that highly successful teams conduct a more expansive search of the design space than less successful teams. Highly successful teams built and tested more designs. And although there was no difference in the total number of features explored, highly successful teams used and focused on a particular feature, the antenna.

Strategy use

Another possible explanation for the variability in performance on the earthquake task between design teams is that highly successful teams used a more appropriate strategy for solving the task. Table 4 provides a summary of the strategies used by teams to solve the design challenge. The VOTAT strategy, also known as the Control of Variables, (e.g., Li et al. 2006) is an important scientific inquiry skill that students learn throughout school for designing unconfounded experiments. It is also a skill that is included in many state and national science education standards. Thus, it was of interest to see if students would use this strategy (which they have likely had extensive experience with throughout their schooling) as an approach for solving this novel design task. Overall, on a trial-by-trial basis, there was no significant difference between the high and low teams in the percentage of trials for which a VOTAT strategy was used ($M_{high} = 24$, $M_{low} = 19$, t (16) = 0.07, $p = 0.95$, $d = 0.03$). The minimal use of the VOTAT strategy supports the hypothesis and findings from previous literature (e.g., Schauble et al. 1991; Klahr et al. 2001). Thus, being a good scientist in the traditional sense was not the path to design success.

An alternative strategy that teams may have used to solve the earthquake task is the HOTAT strategy. When faced with a good result people prefer a strategy that keeps the hypothesized 'good' variable while changing the surrounding (Tschirgi 1980). Thus, it was hypothesized that the HOTAT strategy was one that might have been adopted frequently by teams particularly those that experienced successful design trials early during the task. Analysis of the data showed that the percentage of trials in which a HOTAT strategy was used did not significantly differ for the high and low teams ($M_{high} = 3$, $M_{low} = 1$, t (8) = 0.65, $p = 0.53$). However, while in science the use of HOTAT is predicted to occur when a successful outcome is obtained, from an engineering perspective the use of HOTAT is most likely to occur after a failed outcome. This is because, in engineering design,

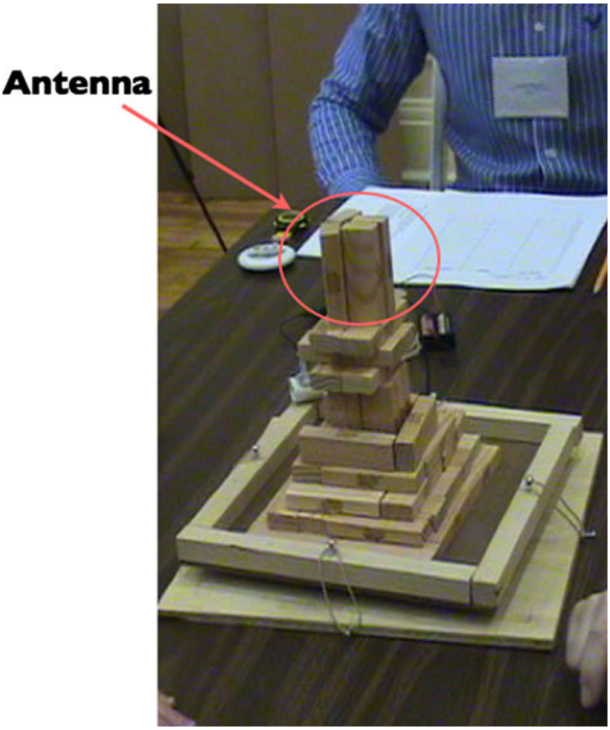

Fig. 2 Structure with an antenna feature

Table 3 Overview of team performances on earthquake task

Mean scores	High teams	Low teams
Height of highest successful design	25.6*	3.6*
Number of designs	9.0*	5.6*
Percentage of successful design trials	47	28
Number of features explored	8.8	9.1
Number of features varied between design trials	1.9	2.3

* Indicates a statistically significant difference ($p < 0.05$) between high and low performing teams

the primary objective is to get something to 'work' as opposed to in science, where the primary objective is to understand 'why' something works. Yet, use of a HOTAT strategy after a failed attempt did not significantly differ between high and low teams, being rarely used by anyone ($M_{high} = 3$, $M_{low} = 0$, $t\ (15) = 1.\ 07$, $p = 0.15$, $d = 0.4$). Thus, the general HOTAT strategy was not the way that students approached this design task.

A variation of the HOTAT strategy, the HPTC strategy, is also a plausible strategy that design teams would utilize for solving the earthquake task. For example, teams might decide that the feature of having a 'wide base' for their structure is key for a successful design, and decide that they will hold that feature constant while varying other features such as the shape of the structure, or the symmetry of the structure. This strategy was indeed fairly commonly used. In addition, teams significantly differed in their use of this

Table 4 Strategy use by high and low performing teams

Strategy	High performing teams (% of trials)	Low performing teams (% of trials)
VOTAT	24	19
HOTAT	3	1
HOTAT (after successful design attempt)	0	1
HPTC		
Structure shape	80*	53*
Parallel layers	88	60
HPTC (after successful design attempt)		
Structure shape	34*	8*
Parallel layers	39*	9*
Antenna	35*	10*
Adaptive growth (AG)	74	48

* Indicates a statistically significant difference ($p < 0.05$) between high and low performing teams

strategy for the design feature of, structure shape ($M_{\text{high}} = 80$, $M_{\text{low}} = 53$, t (11) $= 2.23$, $p = 0.05$, $d = 1.2$) and marginally significantly differed in their use of this strategy with the design feature of parallel layers ($M_{\text{high}} = 88$, $M_{\text{low}} = 60$, t (10) $= 2.21$, $p = 0.06$, $d = 1.0$).

As with the overall HOTAT strategy, the strategy may be more sensible in a contingent basis of the success of the prior attempt. Indeed, after a successful design attempt, the successful teams used the HPTC strategy significantly more often with respect to the structure shape ($M_{\text{high}} = 34$, $M_{\text{low}} = 8$, t (15) $= 2.39$, $p = 0.03$, $d = 0.9$), parallel layers ($M_{\text{high}} = 39$, $M_{\text{low}} = 9$, t (15) $= 2.43$, $p = 0.03$, $d = 1.2$), and antenna features ($M_{\text{high}} = 35$, $M_{\text{low}} = 10$, t (15) $= 2.27$, $p = 0.04$, $d = 1.1$).

Finally, use of an AG strategy (if successful, build higher; if not, stay the same or go lower until successful) may be another good strategy for teams to use to be successful, and one that teams would naturally utilize for such a design task. It was predicted that the AG strategy would be more prevalent than either a VOTAT or HOTAT strategy because it is a more natural strategy in sequential testing situations. Although the use of the AG strategy was directionally greater for the high performing teams, the difference between the high and low teams was not significant ($M_{\text{high}} = 74$, $M_{\text{low}} = 48$, t (15) $= 1.68$, $p = 0.1$). The correlation between use of the AG strategy and the highest successful structure built was also not significant, r = 0.47 (15), $p < 0.10$. However, n = 17 is small for a correlational analysis. Analysis of the complete data set of 59 teams showed that there was a significant moderate correlation between use of the AG strategy and the highest successful structure built, r = 0.34 (57), $p < 0.001$. Despite the lack of significant difference between high and low performing teams' use of the AG strategy, this finding supports the hypothesis that use of the AG strategy would be greater than use of either the VOTAT or HOTAT strategy. In addition, the results suggest that use of the AG strategy may be key to design success.

In summary, highly successful design teams differed from the less successful teams in both their exploration of the feature space and their use of strategies for solving the design challenge. Highly successful teams built and tested a greater number of designs, and included an antenna in a greater percentage of their designs. In terms of strategy use, neither highly or less successful teams extensively used the VOTAT or HOTAT strategies. However, highly successful teams were more likely to use the HPTC strategy for features such as structure shape. Finally, the AG strategy, which was used most frequently by the highly successful teams and was significantly correlated with the highest successful structure built, may be the strategy that is most effective for achieving success on this design task.

Do students learn design principles from a design challenge that does not include instructions for content learning?

Although many design tasks can be used to teach specific scientific concepts, the earthquake task used in this study was not specifically designed to do so. Therefore, rather than asking students what *explanatory* scientific principles they learned from the design task (e.g., the influence of force vectors or harmonic waves on the success or failure of their designs), students were asked to articulate the *design* principles they learned from the task (e.g., wide bases make for more stable structures). As noted in the methods, during the 2008 session, at the end of the task each student within a team was asked to respond individually (in writing) to the open-ended prompt: "If you had to tell someone else how to make a structure that stands for 20 s on the earthquake machine, what's the advice you would give them?" Table 5 provides a summary of the design principles articulated by students and the frequency with which they were proposed. Overall, students learned a number of design principles, raising the question of whether design success was related to learning of explicit design principles.

The 14 individual students from high performing teams, *correctly*, and more frequently stated that the use of a wide base was an important design principle to follow for achieving a successful design ($M_{high} = 36$, $M_{low} = 6$, $t\ (19) = 2.00$, $p = 0.03$). In contrast, the 16 students from low performing teams more frequently stated that reinforcing loose blocks was an important design principle ($M_{high} = 12$, $M_{low} = 44$, $t\ (28) = -1.79$, $p = 0.04$). While focusing on reinforcing loose blocks is important, using this strategy likely hindered students from designing structures that were both *tall* and *stable*, rather than just stable.

As expected, and in line with the hypothesis, students from both high and low performing teams were able to articulate a number of design principles for building tall and stable structures. However, students from high performing teams were able to articulate design principles, such as 'use a wide base' that are *necessary* for success on the earthquake task, with a greater frequency than students from low performing teams.

What is the relationship between strategy use and what students learned?

While specific strategies such as the AG strategy may contribute the most to success on the design task, the question remains, what is the relationship between strategy use and learning the design principles needed for achieving a successful design? Correlations were calculated between each of the three strategies used in the design task (VOTAT, HOTAT and AG) and the number of design principles expressed by the students. Use of the VOTAT strategy was not significantly correlated with the number of design principles articulated, [$r = -0.09\ (28)$, $p = 0.31$], as was use of the HOTAT strategy [$r = 0.00\ (28)$, $p = 0.5$]. In contrast, use of the AG strategy and the number of design principles expressed was significantly moderately correlated [$r = 0.30\ (28)$, $p = 0.05$]. Thus, the AG strategy appears most useful for articulation of explicit design principles as well as leading to design success.

To rule out the possibility that teams who used the AG strategy began the task with more 'design knowledge' in the earthquake task, and were therefore able to articulate more

Table 5 Principles for successful designs in earthquake task

Design principle	Responses from high performers (%) (n = 14)	Responses from low performers (%) (n = 16)
Wide base	36*	6*
Strong/good base	43	50
Pyramid/triangle shape	14	6
Narrow top	29	13
Reinforce loose blocks	12*	44*
Compact structure	14	0
Do not use parallel placement of blocks	7	0
Cross-pattern placement of blocks	0	0
Balanced blocks	7	0
Flexibility/give in design	0	13
Counteract shake	0	6
Less heavy top of structure	0	6
Jenga tower design	0	6

* Indicates a statistically significant difference ($p < 0.05$) between high and low performers

design principles as well at the end, we calculated the correlation between use of the AG strategy and success on the first design trial. If teams that used the AG strategy had more prior knowledge of the relevant design principles, we would expect a significant positive correlation between AG strategy use and success on the first design trial. What we found, however, was that use of the AG strategy was negatively correlated with success on the first design trial [r = −0.52 (28), $p = 0.00$]. Thus it appears that the relationship between AG strategy use and articulation of design principles is not mediated by prior design knowledge.

One can also examine the relationship between strategy use and particular principles being learned. Each of the 3 major strategies (VOTAT, HOTAT, and AG) used in the design task were correlated with the design principles expressed by the students. Table 6 provides a summary of the correlations between strategy use and the design principles learned by students.

Use of a VOTAT strategy was significantly correlated with stating that having a pyramid/triangle shaped structure [r = 0.55 (28), $p = 0.00$], as well as a compact structure [r = 0.60 (28), $p = 0.00$] are important design principles to follow for success on the earthquake task. Students who frequently used a VOTAT strategy were less likely to state that having a strong/good base was an important design principle to follow [r = −0.41 (28), $p = 0.01$]. Thus, while not so useful for overall design success, VOTAT did produce some design principle knowledge. Teams rarely used the HOTAT strategy to solve the earthquake task, and thus there were no significant correlations between use of the HOTAT strategy and any design principles.

Finally, use of the AG strategy, which was commonly used by highly successful teams, had a significant correlation with stating that a wide base [r = 0.55 (28), $p = 0.00$], and a narrow top [r = 0.38 (28), $p = 0.02$] are important design principles to follow. Thus, the AG strategy appeared useful for both design success and learning of explicit design principles.

Table 6 Correlations between strategy use and design principles learned

Strategy	Design principles				
	Pyramid/triangle	Compact	Strong/good base	Wide base	Narrow top
VOTAT	0.55*	0.60*	−0.41*	−0.05	0.09
HOTAT	0.00	0.00	0.00	0.00	0.00
Adaptive growth (AG)	0.03	0.00	0.06	0.55*	0.38*

* Indicates correlation significant at $p < 0.05$ level

Overall, it appears that the hypothesis was supported and that there is a strong relationship between the strategy used and the particular information learned from the design task. Moreover, use of the VOTAT and AG strategies are each correlated with different design principles, perhaps suggesting that the design strategy used mediates what is learned from the task.

Summary and recommendations

In this study, teams of high school students tried to solve a prototypical design task, one that was open-ended, complex, had no one ideal solution, and involved sequential testing of prototypes. When considering the question of what task strategies separate more successful design teams from less successful teams, results suggest that there are a number of differences between the two groups. Teams that were highly successful on this task shared a number of characteristics in both their exploration of the design space and their strategy use. Although successful teams do not explore more of the isolated feature space, they do build and test more designs. As we expected, based on other research (e.g., Schauble et al. 1991), limited exploration of the feature space is likely associated with a strategy of focusing on a subset of features that are believed to lead to the desired outcome, rather than exploring the relationships between all possible features. Our findings appear to be consistent with the prior research, although high performing teams built and tested more designs than low performing teams, both high and low performing teams explored the same amount of isolated feature space overall. The one difference in feature exploration that may be most responsible for separating more from less successful design teams is the focus on a particular useful design feature, the antenna, by high performing teams.

With regards to strategy use, we wanted to know if the same strategies that lead to success in science lead to success in design. Prior research suggested (e.g., Tschirgi 1980) that a VOTAT or HOTAT strategy is likely to be used to solve complex, everyday problems, such as a design task. Yet, because Tschirgi used hypothetical situations to study strategy use, it was unclear how the hands-on, experimentation aspect of our design task would influence strategy use. In addition, the open-ended nature of design tasks may not lend themselves to systematic testing and manipulation of variables (Azmitia and Crowley 2001), thus the extent of use of either a VOTAT or HOTAT strategy was in question. The results support our initial expectations, in that while teams did make some use of both the VOTAT and HOTAT strategy, use of these two strategies was very limited. In addition, use of the VOTAT strategy, which is often associated with scientific reasoning success, was not part of the path to design success. Rather, two design–focused strategies, HPTC and AG, emerged as strategies significant for promoting success on the design task. These findings suggest that strategies that lead to success in science to do not necessarily lead to success in design.

The second research question addressed whether or not students would learn design principles from a task that did not include explicit instructions for content learning? Despite students' minimal use of typically taught and tested scientific reasoning strategies, such as VOTAT, as expected, the data shows that students learned important design principles through their building and testing of multiple designs. In addition, highly successful teams were able to articulate some of the key underlying principles necessary for building a successful tower. This finding supports the notion that design, in and of itself, can be a useful activity for learning, and adds merit to the concept of using design projects for instruction.

Finally, we were interested in understanding the relationship between strategy use and what students learned. Thus, one of the most significant findings from this study is that strategies other than the 'scientific' strategies can lead to content learning (in this case, design principles rather than explanatory science principles). The results support our initial expectations, suggesting that use of a particular strategy mediates what is learned from the task. This finding again, lends support to the idea that design is a process that can be used to teach content, and perhaps suggests that design may be more appropriate for teaching particular kinds of content as opposed to more scientific strategies. Further research should investigate how and what kinds of content are best learned via use of more scientific or design–focused strategies.

It is important to note the limitations of the study, one being the selective group of students that participated in the study. The participating students had approximately 2 months of prior experience with design, making them perhaps 'above average' designers, and these students were the more successful students in those design experiences. Future research could investigate what influence, if any, students' prior design experiences, and levels of success within those design experiences, have on their strategy use and content learning when completing a new and unfamiliar design task.

A second potential limitation of the study relates to the nature of the earthquake task used in this study. The form of design activities or practices used in this task was very rudimentary. More advanced forms of design, much like more advanced forms of science, make regular use of models, in the form of sketches, simplified physical artifacts, computer models, and equations. The use of such models in design is likely to further change the kinds of strategies that are successful for design outcomes and for learning outcomes. Yet in the science classroom, it will be more difficult to include these more advanced forms of design into the crowded curriculum.

A third limitation relates to the issue of causal direction between strategies and design success and knowledge gain. The analyses reported here are inherently correlational and thus are causally ambiguous. Future work should explore manipulations in which students are trained on the use of particular strategies to assess the extent to which these strategies are causally important to design success and knowledge gains.

Despite these limitations, we have provided evidence of the various types of strategies that students use to approach open-ended complex problems, such as design tasks, in the hopes that the results will be useful to curriculum designers and instructors in the creation and instruction of design-based science learning projects. It is clear that our students come to these tasks with a wealth of ideas and strategies that they can utilize for successful learning. The challenge for us remains to determine how to best support student learning in the context of a design-based science learning curricula. Many questions still remain, and much research needs to be done, but this study provides us with a starting point for developing design-based science learning curricula that provides the right mix of support for optimal learning of science and design process and content.

If we are to use design-based science learning as a pedagogical approach in science classrooms, it needs to be made clear to students what the connections between design and science are, particularly if we are to "bridge the design–science gap". Design-based science learning curricula will need to make central and salient science inquiry processes in order to support science process learning in design projects. An articulation of both *how* and *when* scientific inquiry processes can and should be used in design to advance the design and understanding of how the design works, needs to be explicit if design-based science learning curricula are to be successful in the science classroom. The challenge for curriculum designers and teachers of design-based science learning curricula is to scaffold the scientific inquiry process for learners in a way that seamlessly integrates design and science, maintaining the integrity of the design process.

One way to make salient to students the relationship between design and science is to structure the activities in the design-based science learning curricula around a *cycle*. A *design–science cycle* can make explicit for students the connections between design and science. Learning cycles have been advocated by other learning scientists for effective classroom learning (e.g., Karplus 1977; Lawson et al. 1989; Novick and Nussbaum 1981), and are included in many design-based science learning curricula (for examples see Apedoe et al. 2008; Brophy and Bransford 2001; Fortus et al. 2004; Kolodner et al. 2003). Cycles can, and often are, repeated, which can allow students to learn and practice important science and design skills that they can use at increasingly higher performance levels (Kolodner et al. 2003). More research is needed to determine the optimal features of such a design–science cycle, so that students understand that all scientific inquiry includes some aspects of design, and all good design includes some aspects of science.

Acknowledgments We would like to thank Birdy Reynolds, Eli Silk, Erin Ward and the lab volunteers for their help with the data collection, as well as the numerous students who participated in this project. This material is based upon work supported by the National Science Foundation under Grants EEC-0808675 and DRL-1027629. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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