Augmented Reality Environment for the Training of Carpenters

Sébastien Cuendet, I&C, EPFL

Abstract—Carpenters are required to have excellent spatial skills. Because of the profession history, they currently develop their spatial skills essentially during drawing classes. However, those drawing classes do not match with the reality of the work environment anymore. Parallely, tangible environments have proven very effective for learning. We suggest a new tangible learning environment to develop spatial skills and how it could be used in the carpenters’ curriculum.

Index Terms—spatial skills, spatial ability, tangible, learning, carpenter, augmented reality

I. INTRODUCTION

In Switzerland, more than two-thirds of the population start a vocational training directly after the completion of mandatory school. The vocational training system is mostly organized in a dual way: apprentices go to school one day a week and work within a company for the remaining of the week. The day spent at school is used to teach the apprentices profession-specific theoretical knowledge (5 hours) as well as general knowledge (3 hours). The practical knowledge is acquired during the remaining four days spent in the company and during intensive practical courses that occur once a year over 10 days. The apprenticeships last for 3 to 4 years depending on the profession. Upon completion of its apprenticeship, the apprentice is then considered as a qualified worker in their field.

One difficulty with the Swiss dual system is the gap between the practical work in the company and the theoretical teaching at school. Indeed, while apprentices have to learn all facets of their profession, it is often the case that the theoretical courses they attend at school seem irrelevant to the tasks they accomplish in the company.

For example, the syllabus for the carpenters’ apprenticeship weekly dedicates 3 hours – i.e. 60% of the profession-specific teaching – to drawing. However, in practice, apprentices almost never draw anything, since most of the plans are either done with a computer aided design (CAD) software or by a more experienced worker. Apprentices therefore do not understand why they have to spend so much time learning how to draw while drawing will most probably never be part of their work tasks. The disconnection between school and the workplace results in a lack of engagement and interest of the apprentices at school.

In this work, we study how technology at school could help carpenters to be more efficient in their work environment. Section II reviews how technology in the form of tangible interfaces has been used in the context of education and what are the key factors for the technology to be pedagogically efficient. In Section III, we report the conclusions of a field study which analyzes in what domains carpenters are having the most trouble finding a connection with their workplace. In Section V, we suggest ideas to design an efficient solution based on the technical setup described in Section IV. Section VI sketches a roadmap for the research to follow.

II. TANGIBLES AND EDUCATION

Tangible environments have started to be popular in 1997 with the seminal paper on Tangible Bits [1]. Since then, education has been a well suited field of exploration for tangible environments; the importance of external representations in learning having been long demonstrated, tangibles indeed turn out to offer a great way of increasing representational power. However, despite the many applications of tangibles in the field of education, there has been very little study of the real learning gain provided by tangibles. Examples of tangibles for education are described in Subsection II-A. Subsection II-B describes a framework presented in [2] that helps analyze tangible environment and their effects on learning.
A. Tangible environments for learning

An excellent review of tangible interfaces in the domain of learning is available in [3]. Of particular interest to this research are Digital Manipulatives [4], Smart Blocks [5], Tinkersheets [6], Cognitive Cubes [7], and the work of Andersen et al [8].

Digital Manipulatives are computationally-enhanced versions of children’s toys. They allow children to discover systems phenomena such as feedback and emergence. Smart Blocks are augmented blocks that allow users to build 3D models and to explore concepts such as the surface and the volume of a 3D model. Smart Blocks use the RFID technology and smart connector to compute the surface and volume of the 3D model. The TinkerLamp is a tabletop environment that is rather directed towards problem solving and simulation than concept exploration. It allows its users to build warehouses using small physical shelves and then run simulations or visualize characteristics of the warehouse. As opposed to Digital Manipulatives and Smart Blocks, the output in Tinkersheets is not embedded in the objects, but projected on them. A slightly more complex system is presented in [8], in which physical building blocks self-describe and interpret the structure in which they are built, making it possible to infer the geometry of the 3D model. Cognitive Cubes also use connecting cubes to build a 3D model whose shape is automatically determined. However, in this case the aim is to be able to assess the users’ spatial and constructive abilities.

B. A framework to investigate tangible environments for learning

In order to analyze the effects of tangibles on learning, Price and her colleagues designed a framework based on the language and concepts relative to learning and the theory of cognitive psychology [2]. External representations play a key role in problem solving and learning([9], [10], [11], [12]), by helping the learner to make inferences or freeing up cognitive load to allow the learner to focus on the core of its task. Most of the research on external representations has been done on visual representation and the use of tangibles is thus of interest since it allows to use the physical dimension of the representation. However, while central to learning, the use of external representations can also have drawbacks such as a reducing the cognitive effort done by the learner, or narrowing the student’s comprehension of a phenomenon.

Another important dimension for learning is the coupling between cognition and physical experience [13]. This takes a particular importance with tangibles, as they are not only external representations but also physical objects on which actions can be exerted. The framework is thus designed to particularly study the relationship between the artifacts, the actions, and external representations, and how this relationship affects cognition in terms of inferences and conceptual understanding.

The framework distinguishes four parameters which are summarized below.

1) Location: Location is a discrete parameter that specifies the location of the representation in the physical space with respect to the object or the action. The accepted values are:
   - discrete: the input and the output are located separately (for example on a separate screen)
   - co-located: input and output are contiguous (e.g. Tinkersheets [14])
   - embedded: a digital effect occur within an object

Different values of the location parameter will impact attention demands, ease of problem solving, potential for representing multiple level of abstraction, and the kind of actions that can take place.

2) Information flow: The information flow parameter serves to describe how information is put in or out of the system.

The way in which the system outputs feedback has an impact on the learning experience, since students will infer causality between their action and the output of the system. The causality can be either simple, in which case the digital effect immediately follows an action, or complex when the feedback is dependent on multiple actions and/or occurs with a delay. In the complex case, the causality between an action on an object and its effect is harder to establish but might lead to more exploration. An example of the simple causality is given by Tinkersheets where moving two shelves too close to each other changes the color beamed on top of them to indicate that the forklifts would not have enough space to go through the two shelves. On the other hand, if the system was to not beam any color on the shelves and simply provide a global quality score for a warehouse based on multiple parameters, the causality between the effect of moving a shelf with the global score would be complex.

The second dimension of the information flow is the intensionality, which depicts how the information input are triggered. It can be either intentional when digital effects occur together with an action, generating an expected effect, or serendipitous, when digital effects are unexpected and the result of actions.

3) Correspondence: The correspondence parameter categorizes the mapping between objects, actions, representations, and the learning concept.

   a) Physical correspondence: The physical correspondence is the extent to which an artifact possesses the physical properties of the object that it represents. The two extremities on the scale are symbolic objects, which have no characteristics of the object they represent, and literal objects, whose physical properties are the same as the domain they represent.

   b) Representational correspondence: An object can be either a direct or an ambiguous representation of the concept it represents. In the Tinkersheets framework, the shelves are typically a direct representation of the real shelves they represent, while the pieces that represent the docks and the trucks park in them are more ambiguous. Representational correspondence can impact reflection, computational offloading, or facilitate the grasp of abstract concepts.

   c) Action correspondence: Tangible environments make it possible to act upon the objects. It is then of particular interest to analyze the relationship between actions, external representations and cognition. The authors distinguish two
dimensions to classify actions: \textit{manipulations} as a kind of actions (e.g. hold, press, squeeze, turn, gesturing), and \textit{movements}, which refers to the characteristics of the action (e.g. duration, flow, regularity, directionality).

Identifying and analyzing the three correspondences described in this section in a tangible environment is key to understand how they impact learning, for example by encouraging exploration, reflection, or by creating cognitive conflicts.

4) \textbf{Modality}: Location, information flow, and correspondence are parameters that help analyze a tangible environment. However, they do not mention the type of modality on which the interaction between the user and the system is based. Although most information is currently represented visually, one should not forget the power of the tactile and audio representations. Varying modalities can be used to reduce screen overload, grab the user’s attention more easily, or output feedback in a different way.

\section{The Carpenters and their Syllabus}

Because vocational professions are very different from one another, it is not possible to build an environment that would fit all professions. We therefore decided to investigate one particular profession. After two rounds of analyzes, carpenters were selected.

\subsection{Identifying the problem}

As explained in the introduction, our goal is to build a learning environment that will help apprentices learn their profession in a way that makes them more efficient on their workplace without weakening them on the theoretical side. In order to find out in what domain a learning environment is most needed, we visited 5 companies currently training carpenters as well as the apprentices’ school.

During this process we experienced the challenges of the dual training. The directors of the companies insisted on the necessity to reduce the part dedicated to drawing at school, emphasizing that drawing was merely a legacy from the times when carpenters needed to draw complicated structures by hand and that almost no carpenters would ever draw plans by hand nowadays. Insisting on the metamorphosis of the profession, they explained that most of the work of a modern carpenter was to perform other tasks than pure carpentry, such as roof covering or applying insulation to the roof. In their opinion, the most pressing matter to address was therefore the one of \textit{physics building}.

The teachers, on the other hand, had a completely different take on the subject: they insisted on the fact that drawing was the basis of the profession and that it should definitely not be abandoned. They acknowledged that drawing was not per se used in the professional environment anymore, but emphasized that it was key to learn the concepts of the profession, helped apprentices learn to read plans, and especially developed their spatial skills. The latter turned out to be the only point on which company directors and teachers would agree: being a carpenter requires excellent spatial skills.

However, the claims that spatial skills were (1) trainable and (2) that the drawing done by carpenter apprentices indeed trained their spatial skills were yet to be verified. The next two sections examine the veracity of those two claims.

\subsection{Background on spatial skills}

As asserted by Sorby in \cite{Sorby2000}, “spatial skills have been a significant area of research in educational technology since the 1920s or 30s”. For the purpose of this article, three main findings made in the field of spatial skills research are of interest to us. First, in the course of time, and throughout many studies, researchers have discovered that activities requiring eye-to-hand coordination lead to a development of spatial skills. Typical such activities include playing with construction toys at a young age, attending classes of drafting or mechanics, or playing 3-dimensional computer games. This is key to this research since it means not only that spatial skills are trainable, but also that we know what kind of activities can train them.

Sorby designed a special course for developing spatial skills that was based both on drawing and on multimedia activities. During more than a decade, she has systematically trained first year engineering students with weak spatial skills. On a shorter period of time, she then also trained middle school and high school students, showing that in all three cases, the training consistently impacted the success rate of students (especially girls).

Second, spatial skills depend on the gender, men consistently outperforming women \cite{Hedqvist2000}. Thirdly, highly developed spatial skills lead to a higher success in some school subjects such as organic chemistry. In the professional world, spatial visualization skills and mental rotation abilities are especially important for technical professions \cite{Cowan2000}.

\subsection{Spatial skills and carpenters}

The importance of spatial skills reported by both the carpentry teachers and the directors of carpentry companies matches with the scientific finding that technical professions require some well-developed spatial skills \cite{Cowan2000}. According to \cite{Sorby2000}, drawing contributes to the development of spatial skills, as was postulated by the teachers. However, to assess the truth of those claims in the special context of carpenters, we conducted a study with the goal of finding out (1) whether carpenters indeed have more developed spatial skills than other populations of the same age, and (2) whether their spatial skills improve throughout their training.

We created a test composed of three different kinds of questions:

- \textit{mental rotation}
- \textit{paper folding}
- \textit{orthographic projection}

Mental rotation (MR) and paper folding (PF) are two widely used tests to measure respectively mental rotation abilities and spatial visualization \cite{DeStavola2000, DeStavola2001}. The Orthographic projection part (OP) was designed specifically for this test. There were a total of 50 questions, distributed as follows: 24 questions of MR, 20 questions of PF, and 6 questions of OP. Example questions of each of three tests are shown in Figure 1.
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(a) Mental rotation

(b) Paper folding

(c) Orthographic projections

Fig. 1. Example questions for the three tests used to assess spatial skills. For the mental rotation test, two of the four figures on the right are a vertical rotation of the left image. For the paper folding, the piece of paper is folded and then punched as shown on the left. The subject is to find which one of the five figures on the left matches with the piece of paper once unfolded. For the last example, subjects must tell which one of the four 3D model matches the three orthographic projections. A variant of this question, also used in the test, is to show one 3D model and an angle from which it is observed. The subjects must then determine out of four possibilities which 2D drawing matches the 3D model when seen from the given view.

D. Test settings

A total of 512 subjects were tested. The subjects were either carpenter apprentices, logistician apprentices, or high school students. The target populations were chosen as to represent various parts of the population, i.e. apprentices of another profession (logisticians), but also more academic subjects (high school students). Tables I and II summarize the data by year and by gender with the type of curriculum. Note that all three curricula are done in three years, but that because of practical reasons, data for the third year is only available for carpenters. The test were taken at the very end of the academic year, meaning that first year students already had an entire year of training behind them. The test took about 35 minutes and was taken in the classroom by all students of the class at the same time. A timed powerpoint presentation displayed the instructions for the test to ensure equality of treatments among the subjects.

<table>
<thead>
<tr>
<th>Curriculum</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
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<td>148</td>
<td>65</td>
</tr>
<tr>
<td>Highschool</td>
<td>38</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td>Logistician</td>
<td>33</td>
<td>30</td>
<td>0</td>
</tr>
</tbody>
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TABLE I
NUMBER OF SUBJECTS BY YEAR AND BY CURRICULUM.

E. Test results

The score to the test was computed as the mean of the Z-scores of each part of the test. When comparing across the three populations, the data needs to be adjusted in two ways. First, to account for the different distribution of men and women among the three types of population and since carpenters were almost exclusively men, girls were excluded from the data. Second, only carpenters had data for the third year. To avoid a potential year effect, we also removed the third year carpenters from the data.

Figure 2 shows that there is no significant difference between the carpenters and the high school students. The only significant difference is between the logisticians and the rest of the subjects ($p < 0.0001$). The fact that the carpenters top the high school students may suggest that carpenters have specially developed spatial skills, since it is generally admitted that high school students perform better at intelligence tests. The significantly lower score of logisticians is a second point towards this interpretation.

Figure 3 shows that there is no year effect on the score of carpenters. This means that carpenters’ spatial skills do not improve between the end of their first year and the end of their third year. The stagnation of spatial skills along the apprenticeship can be interpreted as either a null effect or as a ceiling effect on the development of spatial skills of the drawing activity. Giving the test to apprentices before they get any training should allow to determine whether carpenters enter the apprenticeship with extraordinary spatial skills or whether they simply develop them during their first year of apprenticeship.

So far, we have seen that spatial skills are central to the activities of professional carpenters. The literature on spatial skills reports that they are trainable, and that sketching 3D objects and manipulating 3D blocks in a multimedia software are efficient ways to train spatial skills [15]. A field study has revealed that carpenters indeed have well developed spatial skills. However, despite lengthy drawing classes, their spatial skills do not improve beyond the first year of their apprenticeship. In parallel, we have emphasized the strength of tangible environments for learning. The question that rises is then: could a tangible environment supplant or complement the drawing classes to accomplish the development of the carpenters’ spatial skills? If so, what kind of environment?

1In accord with the literature, we found a significant gender difference in our data. However, since this is neither a new result nor the main focus of this article, those results are not mentioned explicitly here.
IV. THE SETUP AND THE TECHNICAL CHALLENGES

A. TinkerLamp

The TinkerLamp is a tabletop environment developed at CRAFT [20]. It is composed of a camera and a projector facing the table at approximately one meter height. The projection area, i.e. the playground for applications, is of dimension 50 by 35 centimeters. The lamp is able to detect tagged objects placed under it thanks to a tag tracking library and can provide visual feedback through the projector. Many papers have described what can be achieved with the TinkerLamp or how it affects interaction between people using it (see for example [14] and [6]).

One aspect of the TinkerLamp that has not been leveraged yet is the possibility to detect 3D forms. This is also a direction that other more popular tabletop environments such as multitouch tables are exploring [21]. However, 3D detection seems more natural in the case of the TinkerLamp since the field of vision of the camera is the 3D space as opposed to camera-based multitouch environments whose cameras only see a plane. 3D vision of a scene cannot be accurately achieved with one static camera only. One option is to allow a single camera to move, but that implies that the scene shot by the camera is static while the camera is moved to take multiple shots. Another less limiting option is to have two cameras looking simultaneously at the same scene. Multiple view geometry algorithms can then be used to compute the depth of each point of the scene [22].

Another current limitation of the TinkerLamp is that all objects are required to be tagged in order to be detected. Advantages of tags are the speed of processing and the reliability of the detection. Drawbacks of tagging objects include the loss of an object when the tag is partially or fully occluded and a limitation on the design of the objects. For example, the current tag library used with the TinkerLamp [23] requires the tag to have a size of at least two by two centimeters. This is a limitation for the 3D-BuildFrame approach described in Subsection V-A. Fortunately, edge detection techniques can be used to recognize shapes and match them with the known object database to recognize objects without the help of tags.

B. Edge detection

Edges indicate strong variation of the signal of an image. Their orientation and length convey information about the features of an image. Edges can be the result of discontinuities in depth or surface orientation, changes in material properties, and variations in scene illumination. There are several ways to perform edge detection. However, the majority of the methods can be split into two categories: first order derivative, and second order derivative based methods.

Let the continuous luminance function \( I(x, y) \) represent the luminance of the point of an image at coordinates \( x \) and \( y \). We distinguish two main families of algorithm.

1) First order derivative approaches: The intensity gradient vector is defined as the gradient \( \nabla I(x, y) \) of the luminance function. The amplitude of the norm of the gradient can then be used to detect edges. Indeed, a gradient of value zero will be observed in area of constant luminance, while the extreme values of the norm of the gradient will be considered as edge. The edge strength is given by the magnitude of the norm of the gradient and its direction by the angle of the gradient. Canny edge detection is an efficient first order derivative approach. Although discovered at the dawn of computer vision, the Canny edge detection method is still widely used nowadays. It is based on the gradient of each pixel and on hysteresis thresholding. If the gradient value of a pixel is higher than the upper threshold, the pixel is set as an edge pixel. If the gradient value of the pixel is in between the two thresholds, it is accepted only if one of its neighbors is an edge pixel. The Canny edge detection method therefore not only detects potential edge pixels, but also assembles them into contours.

2) Second order derivative approaches: Second order operators capture the rate of change of the gradient. This implies that a change of the signal in the luminance function will not lead to one but to two extrema of different signs in the Laplacian function. The zero between the two extrema
is where the first derivative reaches a local extremum. One famous second order derivative method is the Laplacian of Gaussian. The Laplacian being sensitive to noise, the method includes sequential processing of noise suppression and second derivative computation. Points where the second derivative of the filtered image is equal to zero are identified as edges.

V. SUGGESTED ENVIRONMENTS

One problem with the current drawing classes is that apprentices spend most of the time on tasks that are not essential to learning, such as drawing construction lines, or basic drawing tasks. However, the main goal of drawing is admittedly to develop their spatial skills. One requirement on the design of the learning environment is therefore to help them focus on cognitively important tasks. We present three approaches that go into this direction. All approaches are based on tangible interfaces and imply learning in a collaborative fashion with the TinkerLamp, much like in [14]. After a brief presentation of each approach, we compare them, select one of them and describe how it could be used in the carpenters’ curriculum.

A. 3D-BuildFrame

The first idea is to ask the apprentices to physically build a wireframe structure out of pieces and connectors, as can be done for example with ConstruMath [24]. The rationale for such an approach is that apprentices build a wireframe instead of drawing it. They therefore have to represent the data given to them as partial drawing or measurements as a 3D object almost directly, without relying on drawing techniques. They also avoid wasting time on drawing technicalities. The system is able to recognize the structure built by apprentices, thanks to multiple view geometry and edge detection.

B. 3D-BuildBlocks

In this setting, apprentices are given solids of various shape and size. Putting them together, they build a solid object that is then reconstructed by the system. To do so, the system recognizes and locates each block separately thanks to a unique tag that is placed on it. The shape of each block is known by the system. The main technical issue of this solution is the occlusion. Edge detection and heuristics could then be used to match the detected shape with a possible combination of the solids registered in the system.

C. 3D-Sketch

3D-Sketch leverages the proven benefits of sketching on the spatial skills, while making the causality direct. Assuming the system can recognize sketches, the apprentices are asked to sketch one of the orthographic projections at a time. The system then gradually builds the 3D model based on the three orthographic projections.

D. Discussion of the proposed environments

Activities pursued by the apprentices during the drawing classes include:

- given two orthographic projections, find the third one
- given the 3D model, draw the 3 orthographic projections
- calculate the real surface and dimensions on part or all of a 3D model
- draw the 3D model based on its three orthographic projections
- draw an A-A section of a 3D model

Ideally, the chosen tangible environment should implement all those activities. Although it looks like a perfect match with the tasks of carpenter apprentices, 3D-BuildFrame has some drawbacks. First, it is not possible to easily add or remove part of the structure once built, making it hard to create a simple causality between the action on the physical structure and its digital representation. Second, wireframes are not solids while in most cases they represent solids, meaning that their representational correspondence is ambiguous. 3D-BuildFrame would be more appropriate to study the structure of the carpentry, which is another part of the carpenters’ curriculum. 3D-BuildBlocks obviously addresses the second shortcoming of the wireframes, since it uses solid blocks. Because it is easier to move blocks than rebuild a wireframe, it also somewhat addresses the first shortcoming, leading to a simple causality relationship between actions and representation. 3D-Sketch takes the opposite approach to the first two environments. Indeed, instead of building a 3D model directly, the model is built through its orthographic projections. One drawback of this approach is that it does not make use of the tangibles.

For all three environments, the speed of manipulation would be key to a successful learning experience and should therefore be taken into account. For example, in the case of 3D-BuildFrame, magnetic bars and balls would allow a faster speed of manipulation than Construmath. Also, note that the three environments are progressive in the level of representation of solids: blocks are concrete, wireframe are figurative, and the drawings are symbolic.

Considering all of the above, 3D-BuildBlocks is the most suited to allow coverage of the activities, the exploitation of the TinkerLamp setup, and rapid implementation of a first prototype of the learning environment for carpenters.

E. Activities using 3D-BuildBlocks

One key in the first year of the drawing class is to draw the three orthographic projections of a given 3D model. With 3D-BuildBlocks, apprentices are first allowed to play around in a mode where the orthographic projections of the 3D models that they build are displayed. The orthographic projections are then hidden, except for the construction lines. Two options are then available: the first one is to have users draw the projections as usual, but using the projected construction lines. The second option is to have them simply show to the system pairs of points that ought to be linked together. The second option allows users to truly focus on the task of finding the
orthographic projections, which is the goal of the learning environment.

The same approach of selecting points rather than drawing lines can be applied to the activity of finding the third orthographic projection from the two others. In this case, some 3D models will be pre-registered in the system, either by the teacher or by another group of students. The latter option would certainly increase the motivation of students because of the competition created between the groups. Once the third orthographic projection found, the students could be asked to rebuild the 3D model with the solid blocks instead of drawing it.

Drawing sections is the first step towards being able to find the true length of any piece in the carpentry. For this task, users first build a 3D model. An section is selected either directly on the physical model, or on the wireframe representation of the 3D model. In both cases, two points and an angle of orientation are necessary to define the cutting plane. The drawing of the section is done the same way as for the orthographic projections, i.e. by linking points. Another activity could be to show an section to the users and ask them to find the corresponding cutting plane.

A typical exercise in the case of calculating the real surface and dimensions is to find out the real surfaces of a roof from its slope and top projection. The procedure is very similar to the first two activities and the same mechanisms could therefore be used.

VI. CONCLUSIONS AND ROADMAP

The goal of this article was to explore how technology could improve the learning environment of apprentices in the Swiss dual system of apprenticeship. We have first analyzed the difficulties that carpenter apprentices encounter during their training. Teachers and practitioners agree on the fact that carpenters need to have excellent spatial abilities to accomplish their day-to-day tasks. A comparative study among carpenter apprentices, locksmith apprentices, and high school students, has confirmed that the spatial skills of carpenter apprentices are particularly well-developed. However, the study has also revealed that their spatial skills do not improve beyond the first year of their training, despite lengthy drawing classes which are supposed to improve their spatial skills.

Based on the literature on spatial skills and tangible environments, three designs for a tangible learning environment are proposed. We select one of the three and then explain how they can be adapted to the tangible learning environment and what gains can be obtained.

In the near future, we plan on completing the study on spatial skills with students and apprentices who start their training. As for the design and implementation of the learning environment, one key point of design-based research (DBR) is to go through iterative analysis, design, development, and implementation [25]. The first iteration is now in the implementation stage since we have started to implement the 3D-BuildBlocks environment. We plan to bring it into classrooms at the beginning of the Fall 2010, and to iterate from there on....

REFERENCES


