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Tinkering learning in classroom: an instructional rubric for evaluating 3D printed prototype performance

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Abstract
This study aims at alternatively assessing the 3D-printed prototype performances showed by young pupils during tinkering activities, as well as developing an instructional rubric that can be evaluated in line with the requirements of tinkering learning. In this direction, a draft rubric has been created by literature review and 3D product observation. In order to ensure the validity of it, a study group consisting of nine fifth grade students have also been observed during a tinkering activity and expert opinions have been sought for it. According to the results, an analytical and general-type instructional rubric has been developed, which includes definitions about 17 performance indicators under 7 criteria and whose internal consistency, scope, appearance, language validity has been ensured at a certain level. The teachers of the primary or secondary schools wanting to perform in-class tinkering activity with 3D printers can feedback to the 3D printed prototype performance of their students rapidly purposefully and effectively by using this rubric.

Keywords 3D printer · Formative feedback · Tinkering · Instructional rubric · 3D printed prototype

Introduction

Until recently, concrete and abstract learning has been dealt with epistemologically separate according to the special meanings that are attributed to human development stages (Piaget 1952) or manner of life (Lévi-Strauss 1966). As a result, the dominant understanding in our education system has been preferring one to the other instead of covering the two together. Since Papert and Harel (1991) explained that they consider the concept of learning as a process of being, making, knowing and becoming, the connection between these two phenomena has been discussed by social scientists, philosophers and educators.

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This article focuses on the use of tinkering by the students in the classroom as a constructive approach that supports abstract and concrete thinking in the process of production and construction with technology. The advanced correction facilities offered by the technology extend the opportunity for a tinkerer in the classroom to make mistakes again and again and to construct what he learns from these mistakes based on his current knowledge and experience. However, in such an environment where every student is constantly pursuing his own unique way of learning with try out and revisions, the role of teachers is changing—shifting to supporting abstract and concrete learning equally. It is known that this new role, which requires to be more guiding rather than presenting the information, increases the need for alternative assessment tools.

3D printing in education

According to many observers, the digital revolution, the start of which we are witnessing at the moment, makes fabrication personalized with modern desktop fabrication systems thanks to their ability transforming data into the product, and the product into the data (Gershenfeld 2006). This democratization impact also causes questioning the role of technology in our current sense of education more day by day. To fully realize answers to this question, the role of new technologies in classrooms must be well understood in terms of pedagogical aspects. With the impact of do-it-yourself and maker movement, the advent of personal fabrication systems gives individuals the opportunity to see their ideas bits to atoms for the first time ever (Bull and Garofalo 2009; Bull and Groves 2009). One of them used by thousands of amateurs all around the world and captured public attention is three-dimensional (3D) printers, which allow consumers to tinker with 3D modelled and printed prototypes.

Hobbyists and professional users are now able to design, download, and print out a wide (and quickly growing) range of physical objects with 3D printers. There are several plausible reasons for this sudden burst of excitement. While most prominent features of these are availability of low-cost and formation of the goods at home by "ordinary" users, the printed goods are limited with the printing volume and materials of current 3D printers, typically (Eisenberg 2013). Despite all these constraints, the rapid development of 3D printers that also lead to democratization of the fabrication with the potential of solving the real problems with physical objects, makes it possible for schools to begin exploring the educational implications of the digital fabrication revolution today (Bull and Groves 2009).

Following initial enthusiasms for digital fabrication and the "Maker Movement" use of 3D Printing tools and equipment, one of the most popular Maker technologies, is becoming widespread and available at class activities with various aims (Nemorin 2017). Simply, the teachers may download the educational materials or manipulatives along with certain needs according to the educational purposes and print or they may customize to produce. Another use of it is by students who easily and instantly may design physical objects within the activities permitting to test; these generally reinforce the competencies related with engineering and mathematics (Berry et al. 2010). However, despite its promotion for deep and coercive learning, each making cannot enable this conclusion at the same level of learning. According to the manner of the student to interact with the digital production tool, educational making-doing experiences are divided into three (Bevan 2017): ready robotic kits with step by step instructions; construction experience in which the steps are provided by requiring creative decisions and tinkering. The tinkering among them is the one that is the most appropriate to encourage the students to do something during the making activities inside or outside the school and support the development of the natural learning (Papert 2000).

Papert, who pioneered the fabrication-oriented use of digital technologies in education, attaches a special value to tinkering, which is regarded by Resnick and Rosenbaum (2013) as the closest translation to the bricolage. Despite its association with a physical construction typically due to its roots in the past (Honey and Kanter 2013), the real matter in tinkering is not the objects to be used but the manner in which the learner interacts with these objects (Resnick and Rosenbaum 2013). Therefore, when it is compared with physical manipulative tools, the digital production tools are more suitable for tinkering as it permits students to play with not only the materials but also the ideas (Washor and Mojkowski 2013).

The works to be performed by Papert (1993) indicated that providing sufficient access and freedom to the digital production tools is supportive for the acceptance of children the tinkering strategy. The mixture of the production tools with rich cognitive activities including tinkering strategy is supportive for the students to connect with scientific and engineering applications through open ended and creative making-doing activities (Bevan et al. 2014). In this context, it must be considered for the employment of 3D printers in education that instead of the production of certain objects, the students are referred with tinkering in terms of the production and the learning dimension of tinkering.

What is tinkering?

As a mental strategy, tinkering is based on three basic principles: “Use what you’ve got, improvise, make do” (Papert 1993). Papert, points tinkering as the way of natural learning process, which is based on constructing knowledge while building, making and openly sharing (Papert 1980). Nourished by curiosity and imagination, tinkering is a method and type of work, which does not have a certain plan, starts with an idea but may end up with a totally unexpected result and can be adapted to various disciplines including education (Resnick and Rosenbaum 2013). In this method, in which the accurate or inaccurate way to do something or the instructions and directions demonstrating how to do that work are disregarded, the process of building and design is based on testing ideas through repetitive experiments. Tinkerers used to try to solve problems through trial and error, mess it up and see the result approach by using methods, which they did not think through, and the tools found in their bags without planning anything.

Students test their current ideas and usually rearrange their ideas based on the feedback they receive from the errors they make while tinkering. This repetitive and cyclical process, in which students try and constantly re-define their objectives, is the heart of tinkering. The most critical characteristic of that process is the fact that making an error is not considered a failure, but a process of fabricating a draft. According to Vossoughi et al. (2013), this emphasis on repetition helps viewing “errors” or “failed attempts” as drafts (the moments which provide understanding and an efficient basis for new ideas during the process of fabrication), which is a new perspective. Therefore, as drafts turn into tools, through which new ideas are expressed, the errors become a source of feedback for students in the same manner.

In this process, which is described as bogging down and trying to escape by Petrich et al. (2013), the continuity of tinkering is directly associated with how accurate students can detect their errors and deficiencies in their journey of perfect performance. In this way, the learner is taught the debugging in a sense with the experience of defining what works and what does not work (Bers 2008). The other side of the coin shows that the tinkering just needs to find the point where there is the trouble to be successful. As the tinkerers start to develop their own questions, structure and create their own ideas, they will face the errors they make, and it is necessary to find a new idea to save itself from uncertainties.

When the students develop a new idea to fix the problem they made, there are other problems which have not been estimated and new targets are required to be defined (Sennett 2009). This means that the student should be open for new targets and ready to be for new troubles as long as the tinkering continues. Since there is no instructions and directives during the tinkering, the right and wrong ways to do something have not been defined, yet (Banzi 2009). Therefore, the learning experiences of the student during the tinkering with reference to the uncertainties vary according to the trial-and-error and the way of decision making in addition to the implementations of the decisions.

Tinkering learning: intentionality

For a student to learn with tinkering, the requirements are the performance of the idea, its test and fixation, in other words, an environment that supports the student to chase the ideas. In this environment, the child can move forward and backward to discover and experience the alternative instantly instead of straight or step by step moving. The phase of the design or the step on the research process or the requirements to go up to next step has no meaning and importance for the child. However, it does not mean that these steps are not any significance for the child since they are cared.

Vossoughi et al. (2013) referred to the formation of generous learning environments emphasizing the repetition from the point of view of the equality between playing and learning. Bevan et al. (2014) suggested to provide many ways to be followed with coercive subjects with more than single solution ways in order the tinker to make a context for learning. Vossoughi and Bevan (2014) stated that the tinkering can be enabled to support the learning by promoting cognitive risk taking, testing and repetition. As a result of the researches to be made after 2 years the Tinkering Studio researchers (Bevan et al. 2014; Petrich et al. 2013) defined the tinkering learning dimensions and indicators. According to the researchers, one of the dimensions of the tinkering to be valuable for the learning is the initiative and having purpose. This dimension is that the student develops an idea or plan for a purpose and follows it with the decisions to be taken by the self. One of the four indicators to be defined by the researchers under the initiative and having purpose is to "insist on to reach the targets inside the field of problem".

According to Bers (2008), students are often disappointed when current technologies do not accomplish what we exactly hope for from them. Even though this situation depends on various factors such as level of complexity of the targeted product and how advanced 3D printer in question is, what matters is student's acceptance of the possibility that the product they produce may not work at first. The reaction the student gives when they realize the product does not operate as expected is significant for the sustainability of tinkering. In such cases, it is possible for the student to gain self-confidence by obtaining the solution through different ways, repeatedly trying or seeking help from their teacher.

It is important for the deepening of the tinkering and continuation of the learning in the dimension of intentionality, if the students try to keep going despite the problems and disappointments they encounter to reach their targets. This is possible with the insistency on the optimization of the strategy and the solution together with the use of alternatives for the ways to be chosen or the labour to be spent. Bu it will not be realistic at all to expect students to be insistent enough instantly if they could not reach their intentions due to the uncertainties. This situation makes the role of the educator important for students in experiencing the disappointments for the first time. Students, especially younger ones, generally need simple, easy and accessible opportunities to learn new ideas, relations or tools (Blikstein 2013). Thus, one of the points which should be considered to enhance certain opportunities for the tinkering learning of intentionality, is the principle of facilitation including the attitude, support and point of view of the advisor (Petrich et al. 2013).

The instructors in the environments in which the tinkering strategy is activated, are generally defined as the "facilitators" or the "assistants". Thus, as the control of the instructors on the project or the support to be given to the child decreases, the role on the concrete thinking of the child becomes less effective (Dickens et al. 2016). According to Vossoughi et al. (2013) the tinkering instructors generally use a pedagogic language emphasizing the development of the idea and the repetition process like "test it and see what will happen" to encourage the learners to repeat. This indicates for us that the instructors in the tinkering activities require being away from the word "teaching" and having the role that is a kind of a cheerleading to encourage chasing the ideas and producing drafts.

In order to play a constructionist role in considering the mistake as a learning experience, the facilitator should need to understand why the students have difficulties and to support to keep searching with a deeper tinkering experience. One of the ways that the teacher can have this information is evaluating the 3D printed prototype, which is a proof of concrete thinking. 3D printed prototype performance is an attempt of the student by modelling with Tinkercad and produce with 3D printer to test an idea. A wide range of product design indicators can be used to assess prototyping performance, which tangibly demonstrates what the student does to realize his or her idea. Here, the product refers to a physical object printed in 3D. To summarize the key point in evaluating the product, it will be useful to superficially look at what the old and new design approaches have to offer. According to Buchanan (2001), in the twentyfirst century, the way how product designers perceive the products has shifted from the external view, which is limited to visuals and materials, to the internal view, which is based on human experience. In this respect, new features of the products emerge in relation to the experiences associated with the actions and the social and cultural context in which they are derived.

According to Papanek (1971), design as a problem-solving activity always produces an infinite number of answers and it is the function of design that helps each answer achieve its purpose. Although function is quite complex, it consists of 6 components which have dynamic and complex relations with each other: method, aesthetics, association, telesis, need and use. The experience provided by these relationships is mainly related to the discoverability of product which determines how people remember their interactions (Norman 2013).

According to Buchanan (2001), the features of product that make it useful, usable and desirable are gaining importance more than its features of form, function, materials and manner of production. Ergo, it is essential for design lessons to focus on human experience based on "wicked" problems as well as materials, tools and techniques. Defined by Horst Rittel in 1960, "wicked problems" are a class of social problems which are ill-formulated, where the information is confusing, values are conflicting and the whole problem is thoroughly confusing (Buchanan 1992). This definition also points to a fundamental issue behind the philosophy of tinkering: the relationship between uncertainties and try out and revision design.

In a typical tinkering learning, successful performance of students are not about how many drafts they produce but are about how much they improved their draft compared to their previous ones and how much they achieved their own intentions in this prototyping process. In line with this objective, evaluation in tinkering with 3D printers is all about monitoring growth and effectively using feedback functions as stated by Herman, Aschbacher and Winters (1992). In this context evaluation of every 3D printed prototype should aim at revealing information about either what the students know or do not know, providing formative feedback to support the student's intentionality (Brookhart 2013; Wiggins and McTighe 2012; Wortham 2008) and using alternative methods which can be able to blur the line between teaching and assessment (Dochy et al. 2006; Ito 2015; Wiggins and McTighe 2012).

Instructional rubrics consisting of performance definitions at acceptable/non-acceptable levels (Panadero and Romero 2014; Popham 1997; Wolf and Stevens 2007) can be used in order for this purpose. In a study carried out by Ito (2015), which analyzes the previous studies on instructional rubrics, the most frequently defined benefits of instructional rubrics are listed as ensuring the consistency and fairness of the evaluation process, elucidating the learning objectives, coordinating the teaching, and helping students learn by providing significant feedback. In the study conducted by Panadero and Jonsson (2013), it has been found out that the rubrics used in a formative role, in which feedback is directly given to the person developing the product, decrease the anxiety of students, improve their self-efficacy, and support their self-regulation.

According to Steven and Levi (2013), using instructional rubrics decreases the time required to provide students with feedback by 50% or more, especially in the evaluation of the tasks that require displaying complex performances. In a tinkering-based activity, although teachers exert effort to evaluate each task in a fair and individual manner, one of the most troubling issues among students is usually the timing of the feedback. The extensive evaluations made throughout the years confirm that the feedback given right on time increases learning. Instructional rubrics, which are time saving for teachers, are advantageous for the students, who need significant feedback right on time in tinkering-based activities.

In contrast to all of these advantages, Wolf and Stevens (2007) assert that instructional rubrics damage creativity since they evaluate learning in a certain pattern. Because instructional rubrics are not clear enough to not require explanation, it would be inaccurate to try and completely replace them with a good education. Therefore, the level of the formative role attaches to this type of rubrics is directly related to the performance definitions (Anderson 1998; Jonsson and Svingby 2007; Tierney and Simon 2004). The primary sources used for the creation of the performance definitions in instructional rubrics, are instructional objectives and learning outcomes (Brookhart 2013). However, since performances do not directly involve learning outcomes, but the indicators of these outcomes, the method and time of use of the rubric depend on when and under what circumstances the indicators reveal themselves. Due to that reason, it should be kept in mind that it is more appropriate to use instructional rubrics to evaluate the tasks with observable performance indicators, which allow learners to display the expected learning outcomes rather than the quality and characteristics of the task. In summary, the instructional rubrics used in a formative role are quite effective tools in directing students to think about the work conducted and thereby informing them of how to fix that work (Anderson 1998; Panadero and Romero 2014).

The purpose of research

It becomes apparent that in formal tinkering activities, in which 3D printers are used, there is a need for a rubric for the purpose of both supporting the learning progress and enabling teachers to provide quicker and more effective formative feedback on 3D printed prototypes fabricated by primary and secondary school students. The purpose of this study is to develop an analytic instructional rubric, illustrate 3D printed product evaluation dimensions and criteria well as to test the validity of this rubric. In this context, the answer to the following research question has been searched: "How can be an educational rubric developed to assess the draft products to be produced by the learners tinkering with 3D printers?".

Methods

Study design

The method of this research is the single case study design. In a research, having multiple data sources is better than having only one source (Bogdan and Biklen 1998). For that purpose, literature review, document review and observation data collection methods have been used together. The case in this study is focused on 3D printers in production and Tinkercad tool in 3D modelling. Therefore, the results obtained are limited in the situations where these tools are used.

Participants

The study group of this research consists of nine primary school fifth grade students studying at a private school in Turkey in the second semester of the academic year of 2015–2016. The study group has been determined via purposive sampling method among the students, who had prior experience with 3D printing and digital fabrication. All the participants consisting of four male and five females in the study group are 10 years old. Additionally, they all have the experience of working with 3D spaces in the course of information technologies for a semester.

Data collection

According to Wortham (2008), the process of rubric development (RD) consists of two fundamental stages including determining the type of rubric to be used and its development. At first it has been determined that the rubric will be general and analytic type. Since a specific type of 3D printed prototype performance is not in question in tinkering, the rubric must focus on as many different tasks as possible, not directly on a specific product. Secondly, development of rubric has been carried out according to four stages (Reflecting, Listing, Grouping and labeling, Application) defined by Stevens and Levi (2013), which can be used for developing any rubric regardless of the number of participants. To answer research question, literature review, document review and observation were used, in line with these development stages.

After a comprehensive literature review about 3D modelling and printing, 209 digital 3D models were reviewed by researchers. Primary and secondary school students different from participants modelled these before by using Tinkercad in a longer-term tinkering activity like the one described below. On the other hand, participants were observed through unstructured observation in a tinkering activity called “failure is a must!”. In this activity one of the researchers observed participants as a non-participant role and took field notes about their opinions and behaviors for each failed 3D printed prototype.

The tinkering activity

Any type of rubric that is attentively designed, has the potential to produce valid and reliable results (Moskal and Leydens 2000). Despite having a set of advantages (Andrade 2005; Goodrich 1997; Wiggins and McTighe 2012), since leaving the whole control to students increases some instructional concerns such as, class level, importance of task objectives and time dedicated to this work (Anderson 1998; Andrade 2000; Brookhart 2013), the contribution of students to the process of RD has been limited to discussion and questions at the fourth stage, in line with the limitations of the study. However, comparing rubrics to the published standards, it is known that they can be improved by discussing them with another teacher or cooperating with students (Andrade 2005). Therefore, in the direction of presentation model of Stevens and Levi (2013), participants in this study were involved in the process through the tinkering activity.

The class teacher completed this activity within one class hour in the computer laboratory. At the beginning, the students were randomly divided into to the groups of three. Each group sat around a table and was shown a product pre-designed by Tinkercad, which they had never seen before. The first group was shown a basketball hoop, the second group was shown a caravan, and the third group was shown a night lamp. Since the products were printed by being scaled according to build volume of the printer, their dimensions were $14 \times 14 \times 14$ cm at maximum. After distributing the products, an experienced ninth grade student was assigned to each group in order to direct the group discussions. The group moderators firstly informed the group of the target audience of the product and the reason why the product was designed and fabricated. Afterwards, the groups detect the unsuccessful points in performances and discuss how they could fix them for about 25 min. After the discussions, each group explained solutions in a 2-min presentation to the classroom thereby the activity was completed.

Data analysis

In this study, qualitative content analysis and the RD processes were conducted at the same time and intertwined. Data collection methods and how the analysis was done in practice according to RD stages are shown in Table 1. In the first stage of RD *(reflecting)*, the title of the rubric and the student performance to be evaluated are defined in accordance with the results of the literature review. Besides, the qualitative data to be included in the coding were determined considering the performance and context. Then, content analysis was performed with a holistic approach on the qualitative data collected by just document review in the second stage *(listing)*.

Table 1 Data analysis according to RD stages

RD stage	Data collection	Analysis
1. Reflecting	Literature review	Performance was defined, and possible performance-related indicators were identified. Thus, the data for qualitative content analysis was determined
2. Listing 3. Grouping and labeling 4. Application	Document review	With the qualitative content analysis, all performance indicators were listed and grouped in detail. Performance criteria were determined, and draft rubric was created
	Observation	Another criteria/indicators list was identified with the qualitative content analysis and compared to draft rubric

The STL file of each 3D digital model was reviewed and features that made it a good or bad performance were coded. One of the researchers completed the coding scheme using *MAXQDA (A qualitative data analysis software)* with open coding. Similar codes are grouped by constant comparative method and each group is considered as a performance indicator, which can be observed on 3D printed prototype performance by naked eye. In the third stage *(grouping and labeling),* the list of performance indicators, which were deemed associated or overlapping with one another, have been analytically classified into groups (a scale for each criterion). During this process, balanced distribution of performance dimensions according to types (Wiggins and McTighe 2012) and labeling them with single-worded (Stevens and Levi 2013) and distinguishable (Brookhart 2013) keywords were paid attention to ensure for a quality sustainability.

In the last stage *(application),* all listings and classifications were transferred to a rubric table. It is considered that three performance level degrees is adequate in revealing the significant differences in the performance quality in accordance with the intensity of formative feedback and the level of the target audience. In the direction of some researchers (Andrade 2000; Brookhart 2013) these levels were named as “excellent, satisfactory, developing”. After the criteria and performance level degrees were written on the rubric table, the high-level performance definitions were defined and placed under the “excellent” column. The lowest level performance definitions obtained by simply making these definitions negative, were placed under the “developing” column. While defining satisfactory level and in cases where it was not possible to the exact opposite of a definition (Andrade 2000), mostly typical and rare errors were taken into account.

After a draft rubric including definitions with reference to the performance dimensions and quality degrees was developed, observation data was analyzed with the same analytic to test the validity of it. Accordingly, a second coding scheme was obtained by the other researcher for the same performance. Then, the draft rubric was compared with this second coding scheme by both researchers. The researchers discussed all the criteria and indicators until they reached a consensus. According to the results of these discussions;

- The usability criterion was placed in the quality,
- The attractiveness criterion was converted into visual and the performance definitions were updated,
- The performance indicators of the ratio, symmetry and scale criteria that were previously independent were grouped under dimension and visual criteria,

- The indicators of various Tinkercad operations, which are considered alone in the draft rubric, were placed in appropriate criteria,
- Fabrication criterion, which did not exist in the draft rubric, was added, and
- For each criterion necessary changes were made on the performance definitions.

Finally, the validated draft rubric was presented to seven experts in face-to-face interviews to determine the reliability. One of them is an expert in language and grammar, 3 in product design, 1 in teaching techniques and 1 in 3D digital modeling. In addition, the opinions of the information technologies teacher executing the activity were consulted as an expert view. In accordance with the feedback received from all, it has been confirmed that language is appropriate for the target audience and all criteria comply with the purpose and are adequately involved with the performance that will be evaluated; thereby, the rubric was put into its final form by ensuring its internal consistency and scope of validity at a certain level.

Findings

Research findings showed that an instructional rubric, which aims to evaluate 3D printed prototype performance, comprises of seven different criteria; effectiveness, innovativeness, quality, dimensions, visual, detail and fabrication. The findings were described in detail below.

Effectiveness

The observations suggest that the students in all three groups theoretically tested whether the product worked, before producing a new idea to fix their unsuccessful product performance. One of the students in the first group: "If this is a basketball hoop, this should be a circle, not elliptical… it has to be exactly a circle. That's why this hoop wouldn't work". Another student from the same group:

> The props of the hoop are not strong, it cannot stand still on its own, it could be dangerous because it may easily fall down when the ball hits…. It would be good if we could add a support to the back of the hoop to make it strong and balanced. Let's strengthen this part to make it stand stable.

A student from the third group expressed the necessity of making what has to be done to improve performance, applicable by saying "For one thing, this lamb cannot stand still. The plastic right underneath the base is torn into pieces. Its base is too small and since its base is torn, we have to make sure it stands still, before anything''.

On the other hand, the product analysis suggests that approximately two third of the products consisted of random performances, which do not aim at responding to a valid need, such as cake, eggs, statute, penguin, and logo of super heroes. Since such performances, which are not based on a certain context, do not require testing their ideas, they may be insufficient at guiding students towards tinkering. According to this, as a result of the analysis of the researchers, the indicators of 3D printed prototypes' being based on a certain context and responding to a need have been classified under the effectiveness dimension. Effectiveness is defined as achieving the objective and the level of achieving these objectives (Yükçü and Atağan 2009). Therefore, in order to discuss the effectiveness of a 3D printed prototype performance, the product has to be based on a certain context and focus on a valid need within a cause and effect relation.

Innovativeness

According to document review, it has been detected that the innovativeness dimension, which is one of the most significant inputs in the modern economy, can be found in almost all of the rubrics that are prepared for the evaluation of 3D digital products. As a result of the observations, it was observed that the participants tried to compare the 3D printed prototypes with their counterparts before making any suggestions about that product and often based their suggestions, which targeted at improving the product, on the differences they obtained through comparisons. A student from the second group stated his/her ideas on innovativeness by saying:

> I think we should consider the bed part above to fix this (caravan.) In a normal caravan, the beds are inside and in the upper part. But in this one, it is at the upper part. I think they put the bed there to make a difference, but I am not sure. If the bed is at the upper part, then if it rains the person laying there will get wet.

Another student supported this idea and explained why it should be fixed by saying: "Yes, bigger families could also use it if it is a two-story caravan. Since this is not the case in other caravans, it could be more preferred".

A student from third group:

> It is too tall for a table lamp. Taking that into consideration… I think we should shorten it. As differently from other lamps, kids should be able to adjust its length however they like. It should be extended if desired. For example, the user should be able to shorten it while studying on the table.

In the presentation they made in the classroom, the third group stated that they discussed to add a new feature to this product, however, could not arrive at a clear conclusion, because the feature they thought of may already be available in other lamps and they needed extra time to make a research to find out. According to OECD/Eurostat (2005) product innovation, which is one of the innovation types, refers to a product, which is new compared to its available features or projected use, or the significant improvements in a product. Therefore, the indicator of features and method of use of 3D printed prototypes being new compared to its counterparts is defined under the innovativeness dimension. The findings retrieved from document analysis support this situation.

Quality

It is remarkable that during the discussions in the tinkering activity, the students tried to detect user preferences before making any suggestions for performance improvement. The students put themselves in the shoes of users and tried to detect what the user would prefer by making comments such as ''I would like the lamb to be longer if it was me reading a book'', ''There has to be a comfortable seat to drive this caravan'' and ''The hoop was printed with green plastic, but it would not be suitable for a color-blind person''.

A student from the third group emphasized the importance of user preferences by saying "Since the night lamp is made for children, first of all its appearance must be suitable for them… in order to do that, a furry textile could be wrapped around the lamp or the lamp could be printed pink". The spokesperson of the second group emphasized this important matter by saying

> There has to be window openings in the caravan. So that the children riding in the car can easily look out the window during the ride. … Also, we must make a guard to prevent the second floor from being affected by natural events. Because in this form of caravan, if a person wanted to sleep during the day, he/she would be under the sun.

According to economists, users try to select the most beneficial product for them or to maximize the benefit they get from that product. With the recent change in the mentality of the studies, which take this fact into account, the quality of products now focus on people (Buchanan 2001). Within that context, it is also important for 3D printed prototypes to reflect user preferences, in terms of the benefit the user will get. All of this information showed us that the students must hold knowledge about the preferences of people, who will use the 3D printed prototype, and will only increase their product performance if they take these preferences into consideration.

According to Erkılıç (as cited in James 1996), in the product-oriented quality approach, product's level of conformity to user preferences is accepted as the quality indicator of the product to be fabricated. Therefore, the indicators of 3D printed prototype's ability to respond to the needs of user, and the relative level of the benefit it offers according to user preferences are classified under quality criterion.

Dimension

In accordance with the patterns obtained from activity observations, it was observed that the correction suggestions of the participants generally focused on dimensions of the product. The fact that almost all of the rubrics, on which document analysis was carried out, included a criterion about dimension also supports this idea. One of the students in the first group made the following statement to support this: "Since the hoop is elliptical, it has to be turned into a circle. … the circle is almost as big as the basket. I think the circle must be minimized according to the basket" and a student from the third group also said "The upper part of the lamp is unevenly designed. We have to open the design file and adjust the dimensions of the object there", which support the findings.

As a consequence of the document review, it was understood that the dimensions of 3D printed prototypes are directly related to 3D modeling task, therefore the first indicator about the dimension was found as dimensional transformation operation, which is performed by the student on the simple building blocks in Tinkercad software (Fig. 1). Dimensional transformation is changing one or multiple dimensions any figure by reserving their geometrical features and transforming them into a totally new figure (Ching 1996). In the evaluations on dimension criterion, it is necessary to take into account of not only dimensional transformation, but also scale and proportioning indicators. In fact, as a result of product analysis it was detected that almost all of the products, which include one or multiple dimensional transformation errors that are coded as typical errors, also had errors in their scaling and proportioning. It was observed that the disproportion among the dependent (directly inter-dependent) or the independent components, which make these products up, cause imbalance and inconsistency in product dimensions.

According to the literature, the dimensions of a figure that is not regulated by a proportioning system, may not be objectively and definitely perceived as the same (Ching 1996). Therefore, while evaluating the dimensions of a 3D printed prototype, it is very important to compare them with a generally accepted reference point. It has been decided to evaluate the product according to the scaling settings that reflect the consistency with the dimensions of other objects in the same context, and the dimension criterion of the consistency of proportions of each component that makes up the product.

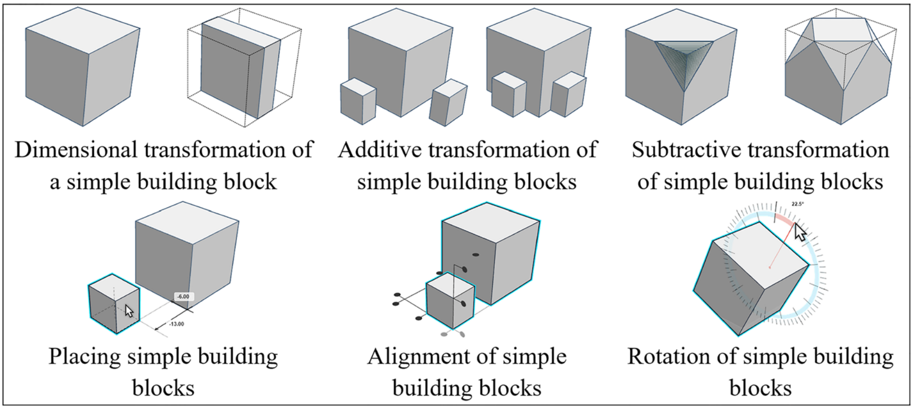


Fig. 1 Transformations and operations in Tinkercad

Visual

The results of product evaluation suggest that one of the typical errors in 3D product performances is the visual disorder resulting from placing simple building blocks that should be in contact with one another, away from each other. Thereby, it was found out that the products that are not designed in a certain visual order, look more complicated and contain errors that can only be detected in 3D printing. According to Tjalve (1979), the more complex the product, the higher the level of order in the product must be. According to the researchers, in order to achieve a visual order in a product, the simple building blocks of a product must be placed on the 3D work platform according to the relative level of importance, dimensions or relations. As a consequence of the document analyses based on the literature and product evaluation, it has been decided to evaluate the indicator of the order of simple building blocks in 3D printed prototype performance.

The analysis of the rubrics, which were previously prepared to evaluate 3D design and modeling performances, suggests that almost all of them have fundamental design principles such as alignment and symmetry. The expert opinions also confirm that achieving visual order in 3D printed prototype performance is directly associated with student's ability to use fundamental commands that will realize these principles during 3D modeling. Therefore, at what level aligning, creating symmetry, and free transformation commands, which are considered related to applying these principles in Tinkercad software, has been decided as the second indicator.

Lastly, the results of product analysis showed that it is quite difficult to immediately detect visual errors in digital medium. The proper visual order of all displays of the product on 3D platform is of utmost important for minimizing the errors in 3D printed prototype performance. Therefore, the product's ability to provide an acceptable visual order at different displays has been determined as the third indicator. Lastly, all of these indicators were gathered under the visual criterion.

Detail

Examining the data collected from the activity observations, it was observed that all groups suggested focusing on detailing the product in order to improve the performance. During discussions, a student from the second group emphasized the need for details by saying "Let's add headlights to the front. So that it does not look flat. … Also, let's add a trunk lid at the back, because I think there's no room for them to put their luggage in the car".

Moreover, a 3D printed prototype's being detailed or not is directly related to the way it is designed in a 3D digital modeling tool. As a result of product evaluation, it was detected that in the products that are fabricated by using a certain type of object in transformation operations through adding and subtracting, which are coded as typical errors, are very similar to one another. However, considering the detailed products, it is observed that the simpler building blocks used, the more realistic the product looks. Within that context, the product's including an adequate number of simple building blocks of different variety has been accepted as one of the indicators of detail in performance.

Considering that the result of a 3D printing depends on the 3D design, student's knowledge level of the transformation operations by adding and subtracting on the simple building blocks, is an effective factor in how realistic and detailed the products looks. In fact, it is possible to fabricate products in an as detailed manner as desired, by using both transformation operations together (Ching 1996). Finally, it was decided to evaluate the understanding of transformation operations by adding and subtracting on simple building blocks, the type and amount of the simple building blocks used, as well as their appearance indicators, under the detail criterion.

Fabrication

The feedback received from the subject field experts points out that fabrication limitations are one of the biggest obstacles, which prevent the designer from putting the projection in his/her mind into application. In line with that feedback, it was decided to take into account of the limitations about fabrication while evaluating 3D printed prototype performance. According to the literature review on 3D printers, it is observed that the most frequently observed problems in 3D printers are related to maximum build volume and material type. The findings based on activity observations support this idea; the students focused on different materials such as rubber, textile, and rope in their performance improvement suggestions.

Even though 3D printers offer the designer the advantage of consuming less resources compared to other types of fabrication, the amount of materials used is directly linked with the form of the product as much as automation. Just like everything else in nature, resources are limited too. And from that perspective, it is very important that while 3D modeling their products, students be aware of this mentality of saving materials of nature and reflect it on their product design. Therefore, it was decided that to evaluate indicators such as taking into account of fabrication limitations, integrating alternative materials with plastic, and improving the understanding of consuming less resources, under the fabrication criteria.

Results

As a result of this study, 17 indicators were found under 7 dimensions for 3D printed product performance (Appendix). Based on these results, an analytic and instructional rubric which has 3 performance level degrees has been developed to evaluate 3D printed prototype performance of young students in tinkering activities. The type of each criterion and the performance questions related to the indicators are summarized in Table 2.

Table 2 Types of the criteria and related performance questions

Criteria	Related performance question	Type
Effectiveness	Does the product aim at responding to a reasonable and valid need that is based on a certain context?	Impact
	Does the product respond to the need? Does it serve its purpose?	Impact
Innovativeness	Do the available features/projected use of the product include improvements compared to its counterparts?	Impact
Quality	Is the product useful for the user compared to its counterparts?	Impact
	Do the available features/method of use of the product display compatibility with the preference(s) of user?	Impact
Dimension	Does the product offer an understanding of dimensional transformation operation of simple building blocks?	Content
	Are the proportions of the dependent and independent components, which consists of the product, consistent with one another?	Quality
	Are the product dimensions perceived as consistent with the dimensions of the products in the same context?	Quality
Visual	Does the product offer an understanding of the operation of placing simple building blocks according to their relationships with one another?	Content
	Does the product offer an understanding of alignment/rotation operation of simple building blocks?	Content
	Do the products' displays on 3D platform create a feeling of an acceptable visual order?	Quality
Detail	Do the simple building blocks of the product offer an understanding in additive and subtractive transformation operations?	Content
	Are the number and variety of the simple building blocks used in the product adequate?	Quality
	Does the product look detailed and realistic?	Quality
Fabrication	Does the product take into account of the maximum build volume limitation of 3D printer?	Content
	Does the product reflect the comprehension of integrating plastic with various materials?	Content
	Does the product reflect the comprehension of using less resources in fabrication?	Content

The first criterion is *effectiveness*. An effective 3D printed prototype must aim at responding to a highly reasonable need and can greatly serves to its purpose. The second criterion, *innovativeness* concerns important developments of the product's available features and projected use when compared to their equivalents. Third, is about *quality* of product, which relates the usefulness and total compatibility with the user preferences. Forth criteria is about product's *dimensions*. It simply includes comparison of the 3D printed prototype with other products in the same context. Even it is possible to scale a product in 3D Slicer or in Autodesk Tinkercad, what is important for an excellent performance is how consistent is the size of the parts of the product consistent with each other and the product. For this reason, it also includes the inferences about the student's understanding of the dimensional transformation operations.

Fifth criteria of the rubric is *visual*. Visual is related to the fact that the product is an acceptable visual scheme in all directions. In addition, it includes the inferences about the student's understanding of the placing, rotation and alignment operations which affect the visual appearance of the product. Sixth, is about looking *detailed* and realistic. If you want to design a detailed product in Tinkercad, you should always use more shapes in more creative ways by adding or subtracting. Therefore, detail dimension also includes the inferences about the student's understanding of the transformation operations. Since 3D print process is required to produce the product, *fabrication* is the last dimension of the rubric. This criterion is consisting of 3D printer's fabrication limitations and an understanding of working with plastic material.

Discussion and conclusion

In formal tinkering activities, in which 3D printers are used by primary and secondary school students, it is important to ensure the continuity of the tinkering learning (intentionality). This highlights critical needs for teachers: providing quicker and more effective formative feedback on every prototype and making an individual tinkering learning plan for each student. This plan involves the teacher evaluating the prototypes of students and analyzing their development. It contains to determining which subjects the students have mastered and which ones should be strengthened and what kind of new information can be added to keep the students inside the process flow zone while forcing them a little. In this study, 3D printed product performance evaluation dimensions and criteria were illustrated, an analytic instructional rubric aiming to evaluate this performance of young students was developed and tested the validity of this rubric.

In the Rubric, performance of a product printed in 3D is evaluated under 7 criteria. Papanek (1971) reported that it is more satisfying for people to meet economic, psychological, technological, and intellectual needs in the product design, rather than the fashion and intriguing demands. Besides, people may have needs in various areas, such as utility, functionality, aesthetics, prestige, usability and pleasure (Khalid and Helander 2004). Consistent with the literature, effectiveness indicators have focused on the need of the product for the user and the expectation of meeting it, but the type of need was not included in line with the level of target audience.

The product innovation, which is covered in terms of technology, organization or design in the literature, is considered to be a multi-dimensional concept (Talke et al. 2009). In the Rubric, this dimension was defined by reducing to 'a new feature or manner of use' level to bring the creative thinking skills of students to the forefront.

Another product evaluation criteria is quality. According to Norman (2013), one of the factors that determine the quality of product is the extent to which the user likes and remembers his interaction with the product. Norman described this as the interaction or relationship between user and product and named it as the affordance. Khalid and Helander (2006) emphasizes the aesthetic appeal of the product, the pleasure it creates and the usability of the satisfaction it provides to the user. According to Buchanan (1992), evaluating usability clearly requires thinking about human and cultural factors, as it will reveal problems related to product experience. In fact, the functionality of 3D printed prototypes designed by students is not enough by itself. They must also fully adapt to the body and mind of the person who uses it. For this reason, the actual aim was for students to think about their actions and interactions related to their products by ensuring that the quality indicators for product experience like useful, usable and desirable are taken into account.

Other criteria in the rubric, namely dimension, visual and detail, consist of basic design principles such as size, ratio, scale, visual order, detail and realism, together with certain 3D modeling operations in Tinkercard. According to Papanek (1971), one of the most important tools in the product design that satisfy and prompt the user is the aesthetic. These three criteria approach the design from an external point of view contrary to the previous ones. And also, these are complementary to the evaluation as they include indicators that are effective in shaping the product form, shape and visual pattern. Therefore, it is thought to be complementary to the evaluation since they include indicators that are effective in shaping the product form, shape and visual pattern.

The developed rubric has content and construct validity within the framework of the research limitations and its internal consistency has been achieved at a certain level. Therefore, it is important to evaluate the results obtained within the limitations of the research. One of the limitations is that the contribution of the students to the process of RD had to be limited, even though researchers are in a more active role than participants. Therefore, it is necessary to carry out different studies with students from different class levels, in which students will have more say, so as to increase the content validity of the rubric.

A second limitation is that as we focused only on Autodesk Tinkercad as a CAD tool, the rubric describes only the performance of 3D modeling with Tinkercad in various dimensions. Tinkercad's use of a block-based design style makes it easier for the teacher to assess performance on these topics by observing directly on the 3D printed prototype. Even though it looks different, 3D modeling understanding, and skills of students affects the production performance. For this reason, various Tinkercad operations were also included as indicators under the relevant criteria. Therefore, it is important to use the developed rubric primarily for the activities in which Autodesk Tinkercad is included, in order to obtain healthier results.

In tinkering learning activities, which focus on developing product-oriented solutions to uncertain and complex problems by students, the way a performance is evaluated is closely related to the quality and continuity of the learning. Because these problems, which belong to the real world and may cause other unexpected problems during the process of finding a solution as a result of ever-changing requirements, are usually uncertain, moreover, each student has different needs, therefore it is not possible to plan teaching word by word or put it in a framework with sharp lines. This increases the need for adapt the pre-defined criteria or using rubrics instead of the success levels or covert criteria that exist in teachers own minds (Bloxham et al. 2011; Ito 2015; Stevens and Levi 2013).

It is important that thanks to the developed rubric, the effort students will spend on increasing the performance of 3D printed prototypes, will also support them to conduct tinkering at the same time. According to Jonsson and Svingby (2007), in order to make reliable scorings in an authentic evaluation, the rubrics must be analytic, general but still specific to a certain subject. Furthermore, through this rubric, not only the students will be able to see at what level their 3D printed prototypes are and get an idea of what to do at the next stage in order to improve their product; but also, teachers will be able to observe the changes in the performances of students throughout the tinkering process and to follow their performances with each draft. Brookhart (2013) confirms that using the rubric developed in this study, in similar learning activities could help with students' learning.

Such a rubric to be developed is believed to contribute to the educators in every field, in terms of responding to the instant feedback needs of young tinkerers, who are comparatively more likely to be disappointed, or monitoring students' in-class tinkering performance with evaluating each 3D printed prototype. In terms of its type and construct, this rubric can be used for any kind of tinkering project from a simple keyring to a complex robotic arm. And also, educators will be able to evaluate complex performances like 3D printed prototypes, faster and more effectively and much shorter than before. In the future, it is recommended to work with students at different levels in different contexts. In addition, the development of similar alterative evaluation tools for fabrication with different digital tools, such as Scratch, Arduino, etc. will make an important contribution to the adoption of the tinkering strategy in learning environments.

Appendix

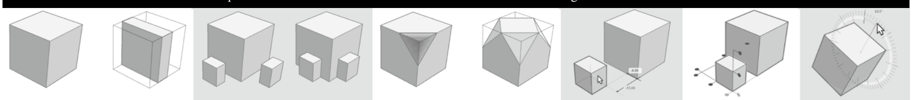
Student:	Class:	Reviewer:	Review date:	Prototype No:

Three Dimensional Printed Prototype Rubric

Criteria	Excellent (3)	Satisfactory (2)	Developing (1)	Score
Effectiveness 6 points	□ It aims at responding to a highly reasonable and valid need that is based on a certain context □ It can respond to the need in a highly effective manner and greatly serves to its purpose	□ It aims at responding to a need that can considered reasonable that is based on a certain context □ It can respond to the need in a partially effective manner and generally serves to its purpose	□ It is not based on a certain context and does not focus on a valid need □ It is ineffective at responding to the need and does not serve its purpose because an unexpected result is obtained	
Innovativeness 6 points	□ Compared to its counterparts, its available features/projected use include comprehensive and significant improvements	□ Compared to its counterparts, its available features/projected use are effective but only include limited improvements	□ Compared to its counterparts, its available features/projected use do not include any improvements	
Quality 6 points	□ Compared to its counterparts, it seems highly useful for the user preferences □ Its available features/method of use display total compatibility with the preference(s) of the user	□ Compared to its counterparts, it seems neither useful nor non-useful according to the user preferences □ Its available features/method of use only display compatibility with the primary preference(s) of the user	□ Compared to its counterparts, it seems non-useful according to the user preferences □ Its available features/method of us e do not display compatibility with the preference(s) of the user	
Dimension 9 points	□ It offers a perfect understanding of dimensional transformation operation of simple building blocks □ The proportions of the dependent and independent components, which consists of the product, are totally consistent with one another □ They are perceived as totally consistent with the dimensions of the products in the same context	□ It offers a satisfactory understanding of dimensional transformation operation of simple building blocks □ The proportions of the dependent and independent components, which consists of the product, are partly consistent with one another □ They are perceived as consistent at a certain level with the dimensions of the products in the same context	□ It offers an inaccurate understanding of dimensional transformation operation of simple building blocks □ The proportions of the dependent and independent components, which consists of the product, are not consistent with one another, at all □ They are not perceived as consistent with the dimensions of the products in the same context	
Visual 9 points	□ It offers a complete understanding of the operation of placing simple building blocks according to their relationships with one another □ It offers a perfect understanding of alignment/rotation operation of simple building blocks □ All of its displays on 3D platform create an acceptable visual order	□ It offers an incomplete understanding of the operation of placing simple building blocks according to their relationships with one another □ It offers a satisfactory understanding of alignment/rotation operation of simple building blocks □ Only some of its displays on 3D platform create an acceptable visual order	□ It offers an inaccurate understanding of the operation of placing simple building blocks according to their relationships with one another □ It offers an inaccurate understanding of alignment/rotation operation of simple building blocks □ None of its displays on 3D platform creates an acceptable visual order	
Detail 9 points	□ It offers a profound understanding of transformation operation of simple building blocks by adding/subtracting □ It is understood that an adequate number of simple building blocks in as much variety as possible has been used □ It looks quite detailed and extremely realistic	□ It offers an incomplete understanding of transformation operation of simple building blocks by adding/subtracting □ It is understood that an adequate number of simple building blocks in only a limited variety has been used □ It is generally detailed but does not look realistic	□ It offers an inaccurate understanding of transformation operation of simple building blocks by adding/subtracting □ It is understood both the variety and the number of the simple building blocks used is inadequate □ It lacks details and looks basic	
Fabrication 9 points	□ It takes the maximum build volume limitation of 3D printer into account from head to tail □ It reflects an advanced comprehension in integrating plastic with various materials □ It reflects the comprehension of using less resources in fabrication from start to finish	□ It does not take the maximum build volume limitation of 3D printer into account, but can be printed when minimized □ It reflects an incomplete comprehension in integrating plastic with various materials □ It generally does not reflect the comprehension of using less resources in fabrication	□ It does not take into account of the maximum build volume limitation, and cannot be printed even when minimized because of the errors □ It reflects an inaccurate comprehension in integrating plastic with various materials □ It does not reflect the comprehension of using less resources in fabrication	
Scoring: 51-40: Perfect performance; 39-28: Satisfactory performance; 27-17: Performance that should be improved			Total Score:	

Holistic Evaluation: Please take the whole product into consideration and mark only one definition				
This 3D printed prototype demonstrates a perfect work □	This 3D printed prototype demonstrates a very good work □	This 3D printed prototype demonstrates a good work □	This 3D printed prototype demonstrates an average work □	This 3D printed prototype demonstrates an insufficient work □

Explanation : Demonstration of various tasks related to 3D modelling inAutodesk Tinkercad



Dimensional transformation of simple building block | Additive transformation of simple building blocks | Subtractive transformation of simple building blocks | Placement of simple building blocks | Alignment of simple building blocks | Rotation of simple building blocks

References

Anderson, R. S. (1998). Why talk about different ways to grade? The shift from traditional assessment to alternative assessment. *New Directions for Teaching and Learning, 1998*(74), 5–16. https://doi.org/10.1002/tl.7401.

Andrade, H. G. (2000). Using rubrics to promote thinking and learning. *Educational Leadership, 57*(5), 13–18.

Andrade, H. G. (2005). Teaching with rubrics: The good, the bad and the ugly. *College Teaching, 53*(1), 27–30.

Banzi, M. (2009). *Getting started with Arduino*. Newton: O'Reilly Media.

Berry, R. Q., Bull, G., Browning, C., Thomas, C. D., Starkweather, K., & Aylor, J. H. (2010). Preliminary considerations regarding use of digital fabrication to incorporate engineering design principles in elementary mathematics education. *Contemporary Issues in Technology and Teacher Education, 10*(2), 167–172.

Bers, M. U. (2008). *Blocks to robots: Learning with technology in the early childhood classroom*. Amsterdam: Teachers College Press.

Bevan, B. (2017). The promise and the promises of making in science education. *Studies in Science Education, 53*(1), 75–103. https://doi.org/10.1080/03057267.2016.1275380.

Bevan, B., Petrich, M., & Wilkinson, K. (2014). Tinkering is serious play. *Educational Leadership, 72*(4), 28–33.

Blikstein, P. (2013). Digital fabrication and 'Making' in education: The democratization of invention. In J. Walter-Herrmann & C. Büching (Eds.), *FabLabs: Of machines, makers and inventors*. Bielefeld: Transcript Publishers.

Bloxham, S., Boyd, P., & Orr, S. (2011). Mark my words: The role of assessment criteria in UK higher education grading practices. *Studies in Higher Education, 36*(6), 655–670. https://doi.org/10.1080/03075071003777716.

Bogdan, R., & Biklen, S. K. (1998). *Qualitative research for education*. Boston: Allyn & Bacon.

Brookhart, S. M. (2013). *How to create and use rubrics for formative assessment and grading*. Alexandria: ASCD.

Buchanan, R. (1992). Wicked problems in design thinking. *Design Issues, 8*(2), 5–21. https://doi.org/10.2307/1511637.

Buchanan, R. (2001). Design research and the new learning. *Design Issues, 17*(4), 3–23. https://doi.org/10.1162/07479360152681056.

Bull, G., & Garofalo, J. (2009). Personal fabrication systems: From bits to atoms. *Learning & Leading with Technology, 36*(7), 10–12.

Bull, G., & Groves, J. (2009). The democratization of production. *Learning & Leading with Technology, 5191*(November), 36–37.

Ching, F. D. K. (1996). *Architechture: Form, space, and order*. Hoboken: Wiley.

Dickens, M., Jordan, S. S., & Lande, M. (2016). Parents and roles in informal making education: Informing and implications for making in museums. In *ASEE's 123rd annual conference & exposition*. New Orleans.

Dochy, F., Gijbels, D., & Segers, M. (2006). Learning and the emerging new assessment culture. In L. Verschaffel, F. Dochy, M. Boekaerts, & S. Vosniadou (Eds.), *Instructional psychology: Past, present and future trends*. Amsterdam: Elsevier.

Eisenberg, M. (2013). 3D printing for children: What to build next? *International Journal of Child-Computer Interaction, 1*(1), 7–13. https://doi.org/10.1016/J.IJCCI.2012.08.004.

Gershenfeld, N. (2006). Unleash your creativity in a Fab Lab. http://www.ted.com/talks/neil_gershenfeld_on_fab_labs. Accessed 18 Mar 2018.

Goodrich, H. (1997). Understanding rubrics. *Educational Leadership, 54*(4), 14–17.

Herman, J. L., Aschbacher, P. R., & Winters, L. (1992). *A practical guide to alternative assessment*. Alexandria: ASCD.

Honey, M., & Kanter, D. E. (2013). Introduction. In D. E. Kanter & M. Honey (Eds.), *Design, make, play: Growing the next generation of STEM innovators*. Newyork: Routledge.

Ito, H. (2015). Is a rubric worth the time and effort? Conditions for success. *International Journal of Learning, Teaching and Educational Research, 10*(2), 32–45.

James, P. T. (1996). *Total quality management: An introductory text*. Upper Saddle River: Prentice Hall.

Jonsson, A., & Svingby, G. (2007). The use of scoring rubrics: Reliability, validity and educational consequences. *Educational Research Review, 2*(2), 130–144. https://doi.org/10.1016/j.edurev.2007.05.002.

Khalid, H. M., & Helander, M. G. (2004). A framework for affective customer needs in product design. *Theoretical Issues in Ergonomics Science, 5*(1), 27–42. https://doi.org/10.1080/1463922031000086744.

Khalid, H. M., & Helander, M. G. (2006). Customer emotional needs in product design. *Concurrent Engineering, 14*(3), 197–206. https://doi.org/10.1177/1063293X06068387.
Lévi-Strauss, C. (1966). The savage mind. In G. Weidenfield & Nicholson Ltd. (Eds.), *The science of the concrete*. Chicago: University of Chicago Press.
Moskal, B. M., & Leydens, J. A. (2000). Scoring rubric development: Validity and reliability. *Practical Assessment, Research & Evaluation, 7*(10), 71–81.
Nemorin, S. (2017). The frustrations of digital fabrication: An auto/ethnographic exploration of '3D Making' in school. *International Journal of Technology and Design Education, 27*(4), 517–535. https://doi.org/10.1007/s10798-016-9366-z.
Norman, D. (2013). *The design of everyday things*. United States: Basic Books.
OECD/Eurostat. (2005). *Oslo manual: Guidelines for collecting and interpreting innovation data* (3rd ed.). Paris: OECD Publishing.
Panadero, E., & Jonsson, A. (2013). The use of scoring rubrics for formative assessment purposes revisited: A review. *Educational Research Review, 9,* 129–144. https://doi.org/10.1016/j.edurev.2013.01.002.
Panadero, E., & Romero, M. (2014). To rubric or not to rubric? The effects of self-assessment on self-regulation, performance and self-efficacy. *Assessment in Education: Principles, Policy & Practice, 21*(2), 133–148. https://doi.org/10.1080/0969594X.2013.877872.
Papanek, V. (1971). *Design for the real world human ecology and social change*. New york: Bantam Books Inc.
Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. New York City: Basic Books.
Papert, S. (1993). *The children's machine: Rethinking school in the age of computer*. New York City: Basic Books.
Papert, S. (2000). What's the big idea? Toward a pedagogy of idea power. *IBM Systems Journal, 39*(3.4), 720–729. https://doi.org/10.1147/sj.393.0720.
Papert, S., & Harel, I. (1991). *Constructionism*. Norwood: Ablex Publishing.
Petrich, D. D., Wilkinson, K., & Bevan, B. (2013). It looks like fun, but are they learning? In M. Honey & D. E. Kanter (Eds.), *Design, make, play: Growing the next generation of STEM innovators*. Newyork: Routledge.
Piaget, J. (1952). *The origins of intelligence in children. (M. Cook, Trans.)*. New York, NY: International Universities Press, Inc. https://doi.org/10.1037/11494-000.
Popham, J. W. (1997). What's wrong—and what's right—with rubrics. *Educational Leadership, 55*(2), 72–75.
Resnick, M., & Rosenbaum, E. (2013). Designing for tinkerability. In M. Honey & D. E. Kanter (Eds.), *Design, make, play: Growing the next generation of stem innovators*. Newyork: Routledge.
Sennett, R. (2009). *The craftsman*. New Haven: Yale University Press.
Stevens, D. D., & Levi, A. J. (2013). *Introduction to Rubrics: An assessment tool to save grading time, convey effective feedback, and promote student learning*. Virginia: Stylus Publishing.
Talke, K., Salomo, S., Wieringa, J. E., & Lutz, A. (2009). What about design newness? Investigating the relevance of a neglected dimension of product innovativeness. *Journal of Product Innovation Management, 26*(6), 601–615. https://doi.org/10.1111/j.1540-5885.2009.00686.x.
Tierney, R., & Simon, M. (2004). What's still wrong with rubrics: Focusing on the consistency of performance criteria across scale levels. *Practical Assessment, Research & Evaluation, 9*(2), 1–10.
Tjalve, E. (1979). *A short course in industrial design*. Amsterdam: Elsevier.
Vossoughi, S., & Bevan, B. (2014). *Making and tinkering: A review of the literature*. http://sites.nationalacademies.org/cs/groups/dbassesite/documents/webpage/dbasse_089888.pdf. Accessed 3 Dec 2017.
Vossoughi, S., Escudé, M., Kong, F., & Hooper, P. (2013). Tinkering, learning & equity in the after-school setting. In *annual FabLearn conference*. Stanford University.
Washor, E., & Mojkowski, C. (2013). Making their way in the world Creating a Generation of Tinkerer-Scientists. In M. Honey & D. E. Kanter (Eds.), *Design, make, play: Growing the next generation of STEM innovators*. Newyork: Routledge.
Wiggins, G., & McTighe, J. (2012). *The Understanding by design guide to advanced concepts in creating and reviewing units*. Alexandria: ASCD.
Wolf, K., & Stevens, E. (2007). The role of rubrics in advancing and assessing student learning. *The Journal of Effective Teaching, 7*(1), 3–14.
Wortham, S. C. (2008). *Assessment in early childhood education*. New Jersey: Pearson.
Yükçü, S., & Atağan, G. (2009). Etkinlik, etkililik ve verimlilik kavramlarının yarattığı karışıklık. *Atatürk Üniversitesi İktisadi ve İdari Bilimler Dergisi, 23*(4), 1–13.