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Donal Healion & Sam Russell / National College of Art and Design

The development of an evaluation methodology to assess the efficacy of a furniture design for STEM education

The nature of the delivery of education is changing. Traditional "chalk and talk" methods of delivery, featuring hierarchical class structures where knowledge is handed down to students from a teacher located at the front of the class are moving towards collaborative and group learning methodologies where the teacher, as facilitator, guides learners on their own journey of self-discovery. This change is particularly prevalent in practice-based learning and collaborative problem-solving activities. These activities are commonly used in the teaching of Science, Technology, Engineering and Mathematics (STEM) subjects. A feature of this type of educational methodology is the use of collaborative, hands-on, open-ended projects and activities where learners solve real-world problems by making and testing prototype solutions, typically using programmable kits such as Arduino or Raspberry Pi. This type of project work presents challenges in the provision of a suitable classroom environment and relevant educational furniture as the work typically involves a diverse range of activities carried out in a collaborative manner. Using a case study of the development of the development of a Learning Analytics System (LAS) and a suitable physical environment in which to deploy it, this article aims to describe the development of an evaluation methodology, by which the efficacy of the proposed furniture design for STEM education can be measured against criteria set out in the design brief. The findings indicate that the application of an evaluation matrix with mixed method data inputs can be used to rate the performance of a design and the conclusion points to other potential scenarios to which this approach could be applied.

Introduction

The classroom of today is a very different place to that with which most adults would be familiar. New curricula, changing methodologies and the integration of technology have all served to alter the educational landscape. The role of the teacher has also changed with a shift in emphasis from the teacher as repository of knowledge to the student as discoverer of knowledge. This shift in the changing role of the teacher is characterised in the phrase *"sage on the stage to guide on the side"*. New pedagogical approaches highlight the importance of group activities where students, guided by their teacher/facilitator, tackle problems by collaborating, communicating and pooling resources to reach a common goal.

These collaborative group tasks are particularly effective in practice-based learning scenarios where students engage in physical computing and model-making to produce interactive solutions to a given problem (Banks & Barlex, 2014). The varied nature of the individual tasks, processes, materials, inputs and outputs associated with these activities presents a challenge to the design of an appropriate educational environment and the furniture within it. The affordances of school seating and desking typically found in our schools are not sufficient when faced with a requirement for mobile, technology-enabled furniture elements that encourage collaboration and group-work rather than solitary study and reflection. This change in the requirements of educational furniture poses the question of how to evaluate its efficacy during the

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design process and implementation. Apart for the obvious ergonomic and anthropometric requirements, how are more intangible factors like movement, collaboration and engagement measured and evaluated and can technology play a role in the quantification of such factors? This article aims to describe a methodology to evaluate some of these aspects of the Practice-Based Experiential Learning Analytics Research and Support (PELARS) educational furniture. It should be noted that this evaluation refers to the functional properties of the furniture in relation to the design intent and does not include any evaluation with regard to aesthetics, manufacturability or cost considerations. While these factors are obviously taken into consideration during the design process, this article will focus on the evaluation methodology of some of the more abstract elements that make up the proposed furniture design.

Background

The work described in this article has been carried out as part of the Practice-Based Experiential Learning Analytics Research and Support (PELARS) project, a three year, EU funded FP7 research and design project that seeks to create a LAS, suitable for implementation in the teaching of practice-based learning activities in three learning contexts, secondary STEM subjects, third level interaction design and third level engineering education. The LAS seeks to understand what and how students learn in these scenarios through the aggregation and analysis of various multi-modal data streams generated by sensing technologies embedded in the learning environment and user generated data.

The design of the learning environment itself is a core component of the project, being the most tangible and physically structural element. As well as providing the framework in which the sensing and feedback technologies are deployed, the learning environment and the physical components within it contribute to achieving the pedagogical goals of the learning activities within the project. The effect of the learning environment on educational outcomes is detailed by Prof Peter Barrett from the University of Salford in the summary report of the Holistic Evidence and Design (HEAD) project, published in 2015. The main finding of the study is that the physical characteristics of the classroom itself (as distinct from the overall school design) accounted for a 16% variance in student learning progress over a one year period (Barrett et al., 2015). Although this study related to primary schools only, it can be surmised that similar effects can be seen at secondary and tertiary levels also.

The physical nature of open-ended practice-based learning projects generates a specific set of requirements for any proposed workstation. Projects of this type tend to follow a trajectory of planning, building and documentation/reflection phases, all of which are carried out collaboratively. Each of these phases presents particular challenges in the provision of physical affordances to allow the task to proceed fluidly with minimum disturbance or distraction to the students.

The challenge of designing educational furniture to encompass pedagogical aims is proving that the proposed design meets what can be rather abstract requirements. There is very little in the literature regarding the functional evaluation of educational furniture other than ergonomic and anthropometric case studies, cost benefit analyses from a facilities viewpoint or generalised guidelines on the distribution of furniture within a space to allow access, circulation etc. Some of the more intangible aspects of the function of educational furniture such as design to encourage collaboration, motivation, sharing or engagement have been described as desirable outcomes but there is little available research in terms of methodologies or approaches by which to evaluate educational furniture to objectively measure if these outcomes are being achieved or the desired effects are being produced. This article proposes a methodology for the evaluation of these factors and traces the development of the evaluation methodology itself as the furniture and learning environment is iteratively developed through a series of user trials.

Design Methodology

In order to put the evaluation process in context, an outline of the project design process and direction is required to define the objectives of the design of the physical elements of the project and give an example of a trial to illustrate the nature and origin of the data used in the evaluation process.

In general, the first step of a design project is to establish the user requirements which can then be translated into a design brief and create the criteria by which the design is to be evaluated. The user requirements in the PELARS project are the result of a literature review, extensive user studies, observations and interviews conducted with students and teachers/lecturers in each of the three learning contexts (secondary level STEM subjects, third level interaction design and third level engineering education). Necessarily, the design requirements for a project of this nature are very detailed and broad ranging. For the purposes of conciseness, what could be regarded as the more typical requirements of a piece of furniture, such as anthropometrics, ergonomics (detailed in previous work by the authors), (Healion & Russell, 2015), manufacturing, assembly, cost and aesthetics are not dealt with in this article. Those listed below refer to some of the more abstract requirements specific to this project and that necessitate diverse methods of evaluation to test whether any proposed design meets these criteria or not.

Requirements from user research:

- The task furniture should cater for the social and collaborative needs of the users and facilitate multiple types of interaction – peer-to-peer, educator-to-student, individual and reflective work and interaction within groups of varying sizes (2-4 students).
- Design to foster a culture of movement.
- Solutions should support both focused and relaxed behaviours and postures.
- Solutions should promote regular postural changes to *'invisibly'* support active teaching and learning.
- Task furniture systems should support and integrate the mobile devices and toolkits associated with practice-based experiential learning.
- The design of the task furniture should be mindful of the ergonomic implications of the intensive use of technology in the classroom.
- The furniture should be mobile, of appropriate height, bringing the work to the learner rather than the learner to the work.

The requirements above raise questions around how to evaluate whether or not a proposed solution meets such intangible ideas as fostering movement or facilitating interaction. The proposed evaluation process centres around a series of iterative trials in which it is intended to test a hypothesis in a real world setting using students groups drawn from the intended user contexts. While a discussion of the development of the current design is beyond the scope of this article, it is necessary to briefly outline the nature of the proposed furniture and the rationale behind it. The starting point for the concept of the furniture and environment design for the PELARS project reflected the need to provide a collaborative working area for groups of two to four students while engaged in PBL. The second main requirement of the design was the need to integrate various technological elements of the LAS within the furniture. Following a concept and mock-up phase, a design was suggested based on an adjustable height table, preferably set to standing height with a separate adjoining unit containing the LAS technology, a computer screen and a vertical display surface. These elements formed the basis of the design and an iterative and agile series of prototyping, user-trials and evaluation cycles sought to develop and refine this concept. There have been four main cycles in the project to date - each guided by the finding from the previous cycle. To demonstrate the methodology of trials conducted, the nature of the data gathered and how this data inputs into the evaluation methodology, one of the user-trials to test the furniture concept (as well as the LAS) is detailed below.

Design Trial

In order to test our hypothesis, it was necessary to identify particular variables and conduct a trial to evaluate the effect of those variables in as controlled and objective a manner as possible. This user trial was conducted in (removed for review) June, 2015 and proved a key hypothesis during the design process which has formed the basis of the subsequent furniture design. The hypothesis of the trial was that students engaged in a practice-based learning task at standing height tables would physically move more than those seated at typical height tables and that these movements would give rise to more interactions with their peers.

Aim:

- To observe and compare the working method of standing groups versus sitting groups.
- To observe and compare the learner peer-to-peer dynamics of standing versus sitting groups.
- To observe and compare the teacher/

Table No.	Moves away from table	Initiated interaction with peers	Subject of interaction by peers	Facilitator visits to table	Group reforms: Same configuration	Group reforms: Different configuration
HTR	37	8	8	19	5	26
HTH	39	9	1	18	4	17
HTS	12	2	2	19	7	5
LTR	4	2	6	19	0	1
LTH	1	0	5	24	0	0
LTS	9	9	1	23	0	0

Table 1. Movement and interactions during Trial 1.

HTR = High Table Round, HTH = High Table Hexagonal, HTS = High Table Square, LTR = Low Table Round, LTH = Low Table Hexagonal, LTS = Low Table Square

facilitator to learner dynamics of standing versus sitting groups.

- To observe and compare the impact of the shape of the table surface on any of the above.
- To observe (and possibly quantify) if the table shape and height had any impact on learner peer-to-peer sharing (physical objects), collaboration and task engagement.

Method:

- Six 18mm MDF table tops were produced for this trial, two circular tables (1000mm diameter), two hexagonal tables (1000mm diameter with 50mm radius to corners) and two 900mm square tables (with 50mm radius to corners).
- One table top of each shape was mounted on a frame at 770mm (sitting height).
- One table top of each shape was mounted on a frame at 1020mm (standing height).
- Groups of three students were asked to carry out a task at each of the six tables while being observed and recorded.
- Researchers took observational notes and conducted post trial interviews with four students
- (in Spanish which were translated to English) and two facilitators (in English).

Results

Table 1 below shows the number of movements away from the appointed table, interactions with other students, number of interventions by facilitators at each table (four facilitators) and number of times the students reform at the table in the same or different configurations. Each group consisted of three secondary school students between 12 and 14 years old, five groups being mixed gender and one group all male. The activity took place over 57 minutes, 45 seconds. The figures shown in the rows for each table are the aggregated totals for each of the three students at that table.

Albeit a small sample size, the trial results suggested the following:

- High tables at which students stand encourages greater physical movement of the students during an activity.
- This greater ease of movement encourages students to initiate interactions with their peers.
- Groups at the high tables were much more likely to change the group configuration during the activity and to reform it according to their needs and changing roles within the activity.
- Of the groups at the high tables, the round table seemed to encourage the most configuration changes, followed by the hexagonal table and the square table. From observations, it was noted that the facets or sides on the hexagonal and square table seem to act as locators for students to denote positions that they were more likely to return to – the more defined the facet, as in the square table, the greater the likelihood that the students return to their previous position.
- The high tables encouraged the students to work closer together physically.
- Typically the standing students stood shoulder to shoulder as close as personal space would allow to view a laptop, discuss the task or during the component building in angles between 90 to 180 degrees, whereas students at the low tables sat at 90 degrees or faced each other.
- Only one of the students in one of groups at the low tables changed their position during the task. The sitting groups tended to stay in the same position within the group for the duration of the task and maintained traditional facing or right angle configurations around their tables.
- While there was a higher number of facilitator engagement at two of the

low tables, from observation it was noted that the engagements at the high tables tended to be of a longer duration. (Possibly explained by the fact the facilitators did not have to lean or bend over the high table to demonstrate a procedure).

Trial Conclusions

There is evidence from the trial to suggest that standing tables enable greater physical movement during task work than sitting tables. Additionally, round tables are perceived to encourage the formation of closer and less structured groupings during task work. Standing tables allow a more upright body position for teachers and facilitators during *"at table"* interactions with students and may promote a more equal status between teacher and students during these interactions. The position around the table adopted by students depends upon the particular phase of the task or activity at a given time. Although the trial described above is just one of eight conducted to date within the project, it demonstrates how the data that is used in the following evaluation methodology section was generated and illustrates the nature of the trials conducted.

Figure 1: Set-up of Trial 1. Comparison of table top shapes and table height

Table 2: General instruments for furniture and learning environment evaluation

Instrument	Interpretation/Coding	Output
Design Process Design Intent Prototyping Process	Human	Design Cycles (Heuristics)
Video Analysis Video with audio recording Timelapse and still images	Human	Quantitative Heuristics Evaluation Interaction Analysis
Interventions (at Trials) Observation Surveys Interviews	Human	Qualitative and Quantitative
Learning Analytics System* Computer vision system	Machine	Multimodal Learning Analytics

* Added in the later stages of evaluation

Evaluation Methodology

The intent of the evaluation process is the objective measurement of the performance of given aspects of the design against the specified criteria above. By setting key performance criteria informed by user-centred design principles, the intention is to generate an evaluation matrix which can be completed after each round of trials. The approach to the evaluation of the educational furniture and learning environment involves the combination of quantitative data from video analysis, interaction analysis and multi-modal learning analytics (Nielsen, 1994; Jordan & Henderson, 1995) triangulated with qualitative data collected from a series of user trials and iterative prototyping. The overall methodology is to establish the instruments through which evaluation can be conducted, develop a structure to ensure the capture of the required data and establish a framework in which the data can be analysed and compared.

Evaluation instruments

The instruments through which data is captured and analysed for the purposes of the educational furniture evaluation are: Design Process, Video Analysis, Interventions and LAS. A table showing the component parts of each instrument, the method of interpreting or coding the information generated by each instrument component and the output from each instrument is shown below.

Design Process

On-going evaluation is naturally embedded in the design process as there is an intrinsic evaluation component in the design decisions that are made during the concept and development stage of a project, based on the experience and knowledge of the designer. The objective of this element of the evaluation is to establish whether or not the design intent has been successfully manifested in the prototype and if it is achieving the desired effect as a result.

Video Analysis

The objective of this component of the evaluation is to capture activity within the learning environment for later analysis. By recoding continuous video from different camera positions, individual actions or movements can be tracked and quantified which would be impossible as an observer in real time. Typically in user trials conducted, each table had dedicated a video camera or a camera mounted over the table taking still images in 10 second time-lapses as well as a video camera taking a perspective of the classroom.

Interventions (Trials)

This evaluation instrument consists of observations, interviews and surveys that are generated by both the user and an experienced researcher during and after the user trials. The objective of this instrument is to capture the user experience and their feedback as part of the evaluation process. The researcher takes observation notes during the trial, highlighting any issues that relate to how the users interact with the furniture and environment and noting any incidents, either positive or negative that affect the interaction.

Learning Analytics System

The PELARS/LAS is combination of sensors, hardware and software, embedded in the learning environment that collects and analyses ambient and user generated data streams and visualises the analysis results. The purpose of this system is to understand the learning process of students while they are engaged in PBL activities. The Computer Vision System (CVS) of the LAS produces machine-coded information that is of use to the evaluation process of the furniture. The CVS consists of a Kinect camera and web camera that, in combination with the analysis software, can detect and establish (using the Viola-Jones algorithm) the number of faces looking at the display screen and the distance between each student. It can also track and determine (through marker wrist bands that students wear on their primary hands) the distance between hands in three-dimensional space and hand motion speed. In combination, these objective qualitative measurements give a good insight into how the students position themselves around the work surface and how actively they work together on the table surface.

Evaluation Matrix Development

The intention of this process is to develop a matrix into which the data collected in the trials can be input to produce comparative information through which the efficacy of the proposed design can be evaluated. The development of the evaluation methodology is an ongoing process in line with the development of the design itself. The technical development of the LAS during the project increased the availability of useful machine-generated data that could assist in the evaluation of the furniture usage. Also, earlier versions of the evaluation matrix included critical incidents like students sharing items, students moving items and students storing items. However, some of the categories were taken out of the evaluation as they did not provide meaningful data as to the efficacy of the furniture design (being primarily dependent on the nature and complexity of the students' designed solution and therefore not consistent across groups) and time consuming to code manually.

For the sake of conciseness, only the final matrix is shown below, which contains information listed in the results table of the trial above. The final matrix also contains information generated by the LAS which can be used to triangulate and validate the results produced by the other evaluation instruments.

Evaluation Matrix

In the matrix devised below, each of the evaluation instruments, Design Process, Video Analysis, Interventions and LAS is represented by a column, which has an associated Value (V) column to its right. The left most column contains Critical Incidents divided into categories of Interaction, Collaboration, Movement and Posture that represent the main aspects of the furniture and learning environment usage to be evaluated (for the purposes of this article). The first cell of each row contains a code which represents the actors and context to which the information applies. See abbreviations beneath the table for an explanation of the codes. For example *"St/St (AT)"* in the interaction category refers to a student- to-student interaction at a designated work table and *"St (AFT) %T"* in the movement category refers to the amount of time a student spent away from a designated work table expressed as a percentage of the overall activity duration.

At the conclusion of each trial, when the information from the various data streams has been collated and analysed, one of three values from a Likert-type scale (range -1 to +1) is attributed to each cell in the value column of the Design Process to denote what observable effect a design decision/intent has achieved (in relation to the relevant actor and category combination), 1 being the desired effect, 0 being no observable effect, -1 being an opposite or undesired effect. This is a qualitative heuristic evaluation based on observation during the trial activity. The entries in the value column of the Video Analysis are quantitative in nature, being a straight forward count of the number of occurrences of a particular incident. The values entered in the Interventions column are also from a Likert-type scale (range -1 to +1). This is also a qualitative heuristic evaluation, based on a combined analysis of observations, interviews and surveys from the trials and is designed to capture user feedback and gauge user experience, -1 being a negative experience, 0, a neutral response and +1, a positive experience.

After each trial, an evaluation matrix is filled in for each table or instance of the furniture in the trial and values are totaled both horizontally and vertically giving both category totals for each evaluation instrument and a total for each actor/category combination. An overall total for that particular table is generated by adding the category totals. In this manner, the efficacy of each instance of the furniture can be compared and the results analysed.

Results

Due to the changing nature of the delivery of education and the integration of technology into the fabric of both curricula and the lived experience of students, the design of our classrooms, learning materials and educational furniture needs to reflect these changes. This is particularly true for certain subject areas such as STEM education where the collaborative, project-based approach of practice-based learning creates a specific set of requirements to enable students to communicate efficiently and work together creatively. The PELARS project seeks to create such a suite of appropriate furniture in which a LAS can be implemented to analyse what and how students are learning while engaged in practice-based learning.

Typical furniture evaluation methodologies based on ergonomics and anthropometrics do not encompass some of the more intangible aspects of the pedagogical aims of the furniture such as the encouragement of sharing, collaboration, motivation and engagement. Through the combination of different sources of evaluation criteria, video analysis, machine coded analysis and heuristics generated by expert observers, an evaluation methodology was developed which can be used to measure and compare the efficacy of the proposed design in a series of progressive, iterative user trials. This evaluation mechanism seeks to capture the results of multi-modal sources of data analysis and tabulate the results in a matrix that can be used to document and tabulate the outcome of the evaluation process. This matrix formalises the evaluation process and ensures that all relevant aspects of the design are tested and enables the validation of the pedagogical aims of the educational furniture.

Conclusion and Future Work

The approach of evaluation combining heuristic input generated by observers, human-coded video analysis carried out by researchers and machine-coded data streams produced by the LAS sensing technologies allows a triangulation of data that seeks to ensure all relevant information is captured, analysed and the results form part of the overall evaluation. The creation of this mixed method framework opens up possibilities for the application of this evaluation methodology to other scenarios such as healthcare or occupational scenarios where complex variables resulting from a combination of human factors, ergonomic requirements, space usage analysis and task or situational specific criteria need to be tracked, analysed, prioritised and evaluated.

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Critical Incidents	Design Process	V	Video Analysis	V	Interventions	V	LAS*	V	Total Value
INTERACTION									
St/St (AT)	Table shape		Interact. subject		Nature of interact.		N/A		
St/St (AFT)	St mobility		Interact. initiate		Nature of interact.		N/A		
T/St (AT)	Shape/height		No. of interact.		Nature of interact.		N/A		
T/St (AFT)	Circulation		No. of interact.		Nature of interact.		N/A		
Cat. Total									
COLLABORATION									
St/St (AT)	Table shape		Group structure		Synchronous work		FLS		
St/St (AT)	Table scale		Discuss/Plan		Working method		DBL		
St/St (AT)	Table size		Shared task		Co-operation		DBH		
St/St (AT)	Work surface		Assign roles		St group roles		HMS		
Cat. Total									
MOVEMENT									
St (AT) GF	Table shape		No. of moves		Group formation		N/A		
St (AT) FC	Shape/access		No. of moves		Formation change		N/A		
St (AT) %T	Work space		% of time AT		St activity/role		N/A		
St (AFT)	St mobility		No. of moves		Reason for move		N/A		
St (AFT) %T	Work space		% of time AFT		St activity AFT		N/A		
Cat. Total									
POSTURE									
St Stand (AT)	Table height		% of time stand		Posture		N/A		
St Perch (AT)	Foot ring		% of time perch		Body Language		N/A		
St Sit (AT)	Adjustability		% of time sit		Signs of fatigue		N/A		
T Stand (AT)	Table height		% of time stand		Effect on interact.		N/A		
T Lean (AT)	Table height		% of time lean		Effect on interact.		N/A		
T Kneel (AT)	Table height		% of time kneel		Effect in interact.		N/A		
Cat. Total									
Overall Total									

Table 3: Evaluation Matrix For Furniture And Learning Environment.

St=Student, T=Teacher/Facilitator, AT=At Table,
AFT=Away From Table, %T=percentage time of activity duration,
GF=Group Formation, FC= (Group) Formation Change,
FLS=Faces Looking at Screen, DBL=Distance Between Learner,
DBH=Distance Between Hands, HMS=Hand Motion Speed.
* Added in the later stages of evaluation