Embodied Search Processes in Creative Problem Solving: How Do People Learn in Makerspaces?

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Abstract: In creative problem solving, an essential component is the divergent idea generation phase before deciding on a plan of action for convergent, relatively well structured problem solving. In makerspaces and other sites where problems are posed in physical form, the material affordances of the objects and their spatial configurations can aid or hinder the search through problem space for possible solutions. In this study, we present the preliminary results of a study involving six pairs of grade eight students involved in a school makerspace context. Given sixteen littleBits modules housed in a small toolbox, along with some light construction materials, students were tasked to produce a prototype of a device that could attract teachers' attention during class work sessions. The material actions that students made in early exploration of project ideas were correlated to the creative outcomes of their project.

Keywords: embodied cognition, creative cognition, makerspaces, student learning, design

Introduction

Makerspaces are quickly gaining prominence as sites for creative problem solving, and the acquisition of STEM skills and dispositions. However, while studies have shown makerspaces to successfully engage students in such learning tasks, substantially less research has taken place to discern the curriculum and learning mechanisms involved in tinkering and making. For instance, constructionism supposes that learning is inherent whenever students have the opportunity to 'mess around' with things or complex systems in an intellectually engaged manner. While this may be the case, we know a lot less about the constituent processes that inform this form of learning. More generally speaking, beyond phenomenological analyses of learning by doing, and assertions of the primacy of tacit knowledge (Polanyi,2009), and the anti-intellectual philosophical position taken by Ryle (1945) and more recent contemporary revisions (Brock, 2015), we really have little knowledge of the mechanisms by which we learn when we 'learn by doing'. Coupled with the typical makerspace activity of tinkering, which noted design leaders (Kelley & Kelley, 2013) have dubbed 'thinking with your hands', the question arises as to the mechanisms through which tinkering and making are educationally beneficial activities, and what may be the specific benefits that may be derived from tinkering and making, beyond the much vaunted benefits of engagement and arousing interest in STEM.

Review

Based on social constructivist pedagogical principles, and sociology of science studies that repudiate the typical classroom practices of science instruction that privileges abstractions, makerspaces have been a recent phenomenon that has begun to receive attention of the scholarly community. Predominantly, researchers have looked at the increased engagement, creative output, and STEM learning gains (see, e.g. edited volume by Honey & Kanter, 2013; Bevan, Gutwill, Petrich, & Wilkinson, 2014), but considerably less attention has been paid to the particular cognitive mechanisms through which makerspaces are educationally beneficial. This consideration extends beyond research in the specific context of makerspaces, to also include general practices of 'learning by doing', and the insight and tacit knowledge generated.

In creativity research, a major recent change has been to consider not merely the divergent generation of ideas, but also the convergent selection and realisation of a particular creative idea. This is especially in light of the currently accepted dual level definition of what creativity constitutes—an idea of novelty, and of utility, as novel ideas may be generated by random processes but may not be useful. In parallel to this, very recent work (Goel 2014, Reed 2015) have identified particular cognitive tasks that appear to be congruent to the two major phases of what have been termed the geneplore model for creativity (Fink, Ward, Smith, 1994). Essentially, if the processes in creativity can be thought of as consisting of a divergent idea *gene*ration stage, followed or interspersed by a convergent ex*plor*ation stage, the cognitive tasks associated with these stages are respectively ill-structured and well-structured problem solving.

Divergent idea generation, especially when solving design problems, have similar characteristics to ill structured problem solving. With design problems, Goel and Pirolli (1992) point out that, among other things, design problems are: often large and complex; do not have right or wrong answers, only better or worse ones;

have many contingent interactions between components; and, components of design problems—start, goal, and intermediate states—are incompletely specified. Certainly, this is not to claim that design is solely made up of divergent, ill structured tasks; design solutions need to eventually be created, and the divergent possibilities need to collapse into a concrete instantiation of a design. Nonetheless, ill structured problem solving remains a central part of design problem solving, and the search for possible solutions within a problem space is an important task that designers need to grapple with. As Hills *et al*. (2015) point out, the process of search is a ubiquitous requirement for life, from animal behaviour, to individual and social human behaviour, to also include abstract, internal processes. The core problematic appears to be a trade-off between exploiting known opportunities and exploring for better opportunities elsewhere: whereas exploring elsewhere could reveal richer sources of food, information, or innovative solutions to problems, this is often done at the expense of being able to exploit whatever resources one has at hand.

In this regard then, we consider the design problem solving task from the perspective of search, and study the ways in which students assigned a problem make use of material resources in an embodied manner to search for potential solutions. We make use of the perspective of embodied cognition to make sense of their actions and gestures. With embodied cognition, philosophers and researchers posit the hypothesis of cognitive externalisation, that is, that the world is its own best representation (Clark, 2008; Noe, 2009); and that certain actions need to be considered as *epistemic* if, as a consequence of the action, we obtain more reliable information about reality (Kirsh & Maglio, 1994). Specifically, considering the insight and divergent idea generation phase of design, we proposed that certain actions and ways of ordering the immediate environment around oneself can serve a cognitive function to provide insight into problems, just as trajector-based cultural practices (Hutchins, 2013) reduce the cognitive load for embedding meaning by seeing the world in a particular way. We therefore set out to characterise actions taken by students as they 'tinkered' their way to solving a design prompt.

Methods

We report here on a study conducted with six pairs of students assigned to a rapid design problem solving task. The design prompt was "Within an hour, design and make a device that could signal your teacher's attention during class group work session". The students were offered a small plastic toolbox, filled with 14 pieces of littleBits, two A3 sized pieces of foam core cardboard, 10 wooden skewers, a box cutter, a steel rule, a cutting mat, a hot melt glue gun, and some paper and pencil to sketch their draft ideas on. littleBits is a system of magnetically connectable electronics components which allows students to quickly snap together electrical and electronic circuits with little consideration as to the polarity and other electrical constraints. They come in color coded modules, with the different colors representing its function as either: power supply, power/signal wire, signal input, and device output. The magnets and physical module interface ensure power, signal, and ground connections were correctly connected. Signal inputs came in the form of human adjustable modules (buttons, potentiometers), to other sensors which could receive input from physical events. Output modules included motors, lights, and speakers. Some typical modules are shown below:

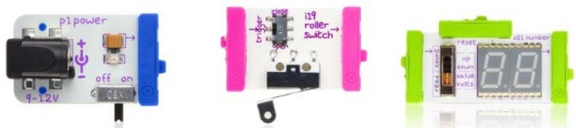

Figure 1. littleBits modules: from left to right: power, input, output.

As can be imagined, the combinatorial possibilities for connecting different modules offer a fairly wide solution space from which candidate designs may derive from. Add to this the flexibility of cutting and joining the other materials, the search space offered to students was wide indeed. As a means to constrain the design outcomes between our participants, we chose a subset of all available modules, using modules that students had familiarity with; we offered student pairs modules as shown in Table 1.

While we initially considered a stimulated recall activity as a means to get single participants to recount their intentions as they proceeded in the design task, we eventually decided to get students in pairs so that their talk events in handling the mutual coordination of design intention could be made explicit. The task was briefly explained to the students and 2 volunteers were recruited per class at each available session. Student talk and action was recorded by a pair of cameras, one in front, and another behind and above the shoulders, so that there were no blind spots. Students were instructed to spend the first half hour planning their design solution, and the next half hour implementing it. Because we were actually interested in the role tinkering played in their design problem solving approach, we did not restrict their planning phase activity, and in fact suggested that they could 'play around' with the materials as they liked.

Table 1: list of littleBits modules provided for teams

Power	Input	Output	Wire
Power (x2) 9V battery (x2)	Slide dimmer Light sensor Button Pressure sensor Pulse generator	DC motor (x2) Servo motor Buzzer Long LED	Fork wires (x2)

Students were grade eight students in an independent boy's school in Singapore. These students were of above average academic ability, and had been participants in an art course which the teacher had deliberately made use of makerspace pedagogical principles. Video data were analyzed using Transana 3.0. A coding scheme for activity segments was developed and validated through consultation with colleagues. Through joint viewing sessions, pertinent episodes were identified where phenomena of interest were discussed and competitive theory generation was used to justify an explanation that fit the observations.

Findings

We developed a simple three level coding scheme to distinguish between low, medium, and high levels of creative outcome via a technique resembling the consensual assessment technique (Amabile, 1982). Briefly, a low level indicated designs which were simple circuit-only, with no utilization of other materials provided. A medium level was indicated by some usage of materials in conjunction with the electronic circuits, or a complex circuit-only design. A high level was indicated by an extensive use of materials in combination with a complex circuit. A summary of the six design outcomes are as follows:

Table 2. Summary of design outcomes for six pairs of students

Group	Intended design description	Rating/Comment
1	Two LEDs connected in parallel, one on teacher's table, and another on students' desk. When button switch is pressed by student, both LEDs will light up, teacher will then look around the class for a lit box to indicate which student needed assistance.	Medium. Some intelligent use of materials in combination with circuits but design is not practical
2	In parallel, three circuits: one to light up a LED, one to a pulsed signal to cause a buzzer to ring intermittently, and a final one to cause a white board to rotate to attract attention. Activated by a button, all three circuits will turn on simultaneously.	Medium-high*. Fairly complicated circuit with the highest number of modules used. Material usage quite innovative
3.	Cockpit/dashboard style display to be mounted on a wall or on teacher's desk to indicate which team(s) needed help.	Medium. Some use of material, but circuit was straightforward.
4.	In parallel, three circuits: one servo motor circuit. Second circuit connects to LEDs, and is mechanically supported on the servo motor so that LEDs physically oscillate. Third circuit activates a buzzer. Servo motor is always on, but LED and buzzer can be selectively switched.	Medium-high*. Complicated circuit, but no materials were used.
5.	Single circuit with a slide dimmer activating a buzzer. No significant deployment of material resources.	Low*. Upon unusual prompting, student pair decided to append an LED extension.
6.	In parallel, three circuits: one buzzer, one servo motor, one LED. Single switch activates all three circuits.	Medium. Circuit is of medium complexity, but material usage is minimal and not well implemented.

We developed a coding scheme to describe participant talk and action. Due to limited space, we describe a limited selection. Of action codes, we found students 'tinkering'; exploring material possibilities for goodness of fit to design intent. Due to the availability of speech data, we were able to infer students' intention. The directions of fit could be 'top down', or 'bottom up', referring to, respectively, trying to get materials to accommodate a design plan, and manipulating materials to explore potential with no apparent design plan.

Most of the groups did not have much by way of a systematic means of exploring the circuit resources available to them. In all cases, the time spent in bottom up tinkering exceeded top down tinkering. While some groups did begin by brainstorming means by which they could obtain teachers' attention, there seemed to be a distinct lack of intention in their solution attempt. For groups 1 and 3, littleBits modules had been inadvertently laid out on their desks in a disordered manner. These groups did not further sort the modules, but instead only picked modules that they were familiar with (i.e., exploiting known resources), and left the rest on the desk.

Of note would be the contrast shown between the two higher performing groups and the low performing group. As to be expected, these two higher performing groups spent the most time exploring. Both groups 2 and 4 spent the time to get to know the circuit affordances of each of the parts, making use of the toolbox as a means to distinguish between parts that they had experimented with, and parts they had not. The systematicity in the exploration of groups 2 and 4 was displayed by sequentially connecting modules taken from the box, understanding its function, and then making mental notes (as they discussed) of what they could do with each module. When done, they would put aside useful modules distinct from modules that they did not find useful. In contrast, group 5's exploration, besides being short in duration, tended to repeat actions on modules. We could not infer that they had any order in the arrangement of modules (e.g. used/unusued), and they spent quite some time in unproductive tinkering (e.g. mechanically tapping a module not connected to power, or sliding the variable resistor faster than an effect could be observed). We did not detect any group with a deliberately explicated exploration strategy that made use of material resources as a means to reduce cognitive complexity, e.g. laying out all pieces according to color, and deciding on a strategy to sample modules. However, we cannot discount the possibility of internally organized designations of useful piles distinct from useless ones, as we did not interview students for their use of organizing routines.

Limitations, conclusions, and implications

This is a preliminary analysis presented for comments to the community; work is currently still in progress. A limitation of the data thus presented may be lack of diversity of participants. An effort currently underway is to compare the actions taken by experts provided the identical task. It appears that the top down/bottom up tinkering distinction corresponds loosely to the explore/exploit pair in search. In seeking creative solutions to design problems, it may be necessary to spend a balanced (not necessarily equal) amount of time in top down and bottom up tinkering modes. This finding presents a possible route for subsequent interventions—that learners need to distinguish between tinkering modes, to develop deliberately metacognitive strategies for the generation of creative solutions.

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