Using linkography to explore novice designers' design choices during a STEM task

Nicolaas Blom
University of Pretoria, Pretoria, South Africa

Grietjie Haupt
University of Pretoria, Pretoria, South Africa

Alfred Bogaers
CSIR, Pretoria, South Africa

One of the characteristics of the 21st century is the increase in the information sources available to designers to make their design decisions. However, there is much debate about designers' choice of information that enables them to design effectively. Several studies have reported on the cognitive role played by information sources such as STEM knowledge, sketches, images, three-dimensional models, and the physical environment during the design process. However, current theoretical frameworks do not explain how internal and external information sources contribute to novice designers' moment-to-moment information processing. The purpose of this paper is to examine the use of linkography to investigate how novice designers used information sources during the early phases of the design process. In this paper, we report on a case study in which a group of Grade 8 participants completed a design task requiring them to design a heat retaining food container for street food vendors at a taxi depot. We used a mixed methods case study research design, in which Think-Aloud Protocols were used to access the cognitive processes of the participants. An extended cognition framework formed the theoretical foundations of this study. The preliminary findings indicate that the participants extensively used external information to structure and solve their design problems, with minimal use of STEM knowledge.

Key words: Design cognition, Information sources, Linkography, STEM knowledge, Technology Education

1. INTRODUCTION

This paper reports on research that is currently in progress for the completion of a PhD. While the final results are not yet available, it is worthwhile to make known the nuggets of information that have been gained in the interim.

Cognitive psychology teaches us that to understand learners' design cognition, researchers should study small increments of thought (Chinn & Sherin, 2014; Goldschmidt, 2014). This implies that the former linear, phase or spiral models of the design process becomes less appropriate for understanding the nature of designers' thinking processes in detail. The underlying assumption of these models is that the design process comprises separate phases and that designers progress from one phase to another, with iterative cycles where necessary. We now know that these models teach us little about the design reasoning processes involved in design. Although these models highlight the procedural nature of designing, they do not reveal the ontological nature of design thinking (Haupt, 2018a; Sung & Kelley, 2018). This suggests that researchers need to consider looking at smaller segments of the design process to understand how learners think and reason during designing (diSessa, Sherin, & Levin, 2016; Goldschmidt, 2014; Hall & Stevens, 2016). One way of studying learners' design processes closely is by using verbal protocols.

Verbal protocols have been used for the last 40 years to study the moment-to-moment thought processes of both individuals and teams of designers. Verbal protocols allow researchers to collect systematic evidence of

E-mail: Nicolaas Blom
nicolaas.blom@up.ac.za

designers' incremental thought processes and behaviours as they occur during a design task (Grubbs, Strimel, & Kim, 2018; Sung & Kelley, 2018). The captured verbal reports and behaviours are transcribed and coded systematically, thereafter, analysis occurs by studying the design process in small units. Although the verbal reports can never be a complete representation of designers' thought processes, they do provide some access to designers' reasoning and thinking, which would otherwise not be accessible (Goldschmidt, 2014). Allowing designers to work in design teams also enhances the validity of their verbalisations as teams naturally communicate with each other during their design task (Goldschmidt, 2014). A further strategy to enhance verbal protocols is to include the analysis of visual external representations, including sketches, 3D models and gestures.

Recently, Grubbs et al. (2018) analysed the coding frameworks used to study the verbal protocols of technology education learners engaged in design tasks. Of the seven reviewed frameworks, three frameworks emphasise the procedural nature of designing, while the other four frameworks have a cognitive science foundation and reflect an ontological approach to understanding learners' cognition. However, none of the frameworks capture the dynamics between learners' interactions with internal and external information sources. Instead, it seems that the frameworks espouse predominantly internalist cognitive science theories. To this end, this paper follows an extended cognition framework toward examining learners' cognitive processes by means of linkography.

2. THEORETICAL FRAMEWORK

For the study of learners' moment-to-moment designing, we adopted an extended design cognition lens (Blom, Haupt & Fraser, 2018; Haupt, 2018b). In contrast to classical information processing theories, extended cognition recognises that designers' design task environment encompasses internal and external sources of information, irrespective of domain or level of expertise. Extended cognition developed as a subset of Situated Cognition (Robbins & Aydede, 2009) and Distributed Cognition Theories (Hutchins, 2014) and pays equal attention to computational theories of mind and ecological psychology when studying cognition. The Extended Mind Thesis (Clark, 2006, 2008; Clark & Chalmers, 1998), which rejects exclusive internalist and externalist theories of cognition in favour of an integrated model of cognition (Hurley, 2010; Menary & Gillet, 2017), formed the backbone of our current understanding of learners' cognition during designing.

The benefit of using an extended cognition framework lies in the descriptive power it provides in describing the development of learners' design activity. This is in conjunction with the information sources that they use during designing. In the professional design literature, Cash and Gonçalves (2017) emphasise that there are limited theoretical frameworks describing the development of design procedures in conjunction with information sources. As such, an extended cognition framework provides a means to study how Grade 8 technology learners use information sources during the early phases of the design process.

3. METHODOLOGY

In order to examine how Grade 8 technology learners used information sources during designing, a Think Aloud Protocol Study (TAPS) embedded in a mixed methods case study was used to collect concurrent qualitative and quantitative data (Creswell, 2014). The qualitative data included visual and verbal data, while the quantitative data included temporal data. Conducting a TAPS allowed us to microscopically study what information sources the participants used in the design process, and when they were used. The study was conducted in a low to middle socio-economic region in South Africa. Three participants were purposefully chosen by their teacher to participate in the case study based on their ability to communicate effectively, work together as a group, and proficiently solve design problems using STEM knowledge. The researchers were able to elicit the design cognition behaviour of each group of participants by providing them with a design task, which was adapted from a prescribed textbook approved by the South African Department of Basic Education (DBE). The design task was based on the participants' previous term's work, focusing on concepts of structures and processing. The group of participants was required to design a recyclable heat retaining food container to be used by street food vendors at a taxi depot. During a single two-hour session, we presented the participants with the design task. We then video recorded them as they engaged with the design task. The video recording was conducted as unobtrusively as possible, and the participants were provided with minimal guidance from

their teacher and the researchers. Stationary, tools and materials were provided to facilitate the design process. This paper reports on the first hour up to the point where the participants generated ideas and chose an appropriate design concept.

3.1 Analysis of the data using linkography

Linkography was originally introduced to analyse verbal protocols in order to assess designers' design productivity (Goldschmidt, 2014). This method has been extended by several researchers (Cai, Do & Zimring, 2010; Gero & Kan, 2017; van der Lugt, 2005) and is now an established method for studying design cognition with quantitative and qualitative applications. In order to generate the linkograph, verbal utterances are segmented into a chronology of 'design moves'. A design move is defined as "a step, an act, an operation which transforms the design situation relative to the state in which it was prior to that move" (Goldschmidt, 1995, p. 195). In this study, verbal utterances were parsed based on the participants' turn-taking, which is a common segmenting principal in team designing (Goldschmidt, 2014). After the verbal utterances have been segmented into a sequence of design moves, a linkograph can be constructed by identifying the links between these design moves (Goldschmidt, 2016).

In order to establish the links between moves, the researcher matches each move with its preceding moves to determine whether a link between them exists (Goldschmidt, 2016). If a link is established, it is called a backlink as it is directed back in time (Goldschmidt, 2016). After all the backlinks have been formed for a design session, one can retroductively speak about a forward link between an earlier move and a move made later in time. Goldschmidt (2014) claims that forelinks are manifestations of future-directed, divergent thinking, while backlinks are manifestations of past-directed and convergent thinking patterns.

Moves that have been identified as having a significant number of backlinks and forelinks are labelled as critical moves (Goldschmidt, 2016). In linkography, critical moves are significant because they are indicators of a high level of interconnectivity between moves, which is typically how synthesis in design is established (Goldschmidt, 2016). Figure 1 illustrates an example of a hypothetical linkograph that the researchers created with the Linkographer software.

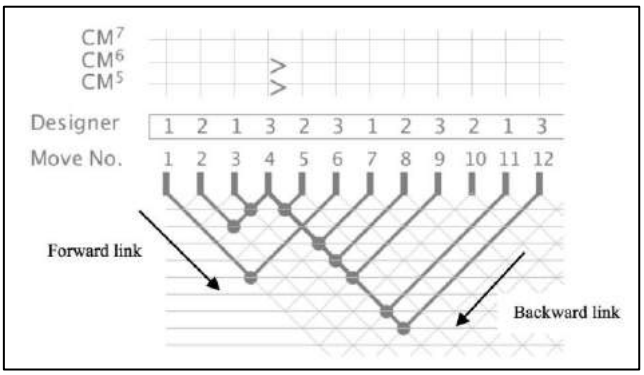


Figure 1: Hypothetical linkograph to demonstrate backlinks, forelinks and critical moves

In Figure 1, the links between design moves are illustrated. In a linkograph, we can distinguish between four different types of design moves: orphan moves (move 10), uni-directional moves (Moves 2, 3, 5, 6 – 9, 11-12), bidirectional moves (move 4) and critical moves (move 4). Orphan moves are unrelated to any previous or future design moves. Unidirectional backlink moves imply that at the moment of their instantiation, the participants were concentrating on what had transpired up to that point (Goldschmidt, 2014). Unidirectional forelink moves imply that the participants are instantiating new thoughts that leave behind what has been done thus far, but to which later moves might form links (Goldschmidt, 2014). Design move 4 is a bidirectional design move because it backlinks to move 3 and 2, but also forelinks to move 5, 7, 8, 9, 11 and 12. If a move contains both backlinks and forelinks, the move can be labelled as a bi-directional move. Bi-directional moves suggest that the participants are planning ahead while still making sure that there is continuity between past design moves (Goldschmidt, 2014). Bidirectional moves illustrate that the participants are exhibiting a rapid shift between two modes of reasoning, namely, divergent and convergent thinking (Goldschmidt, 2016). Critical moves are design moves that are rich in links to other moves and can be unidirectional or bidirectional.

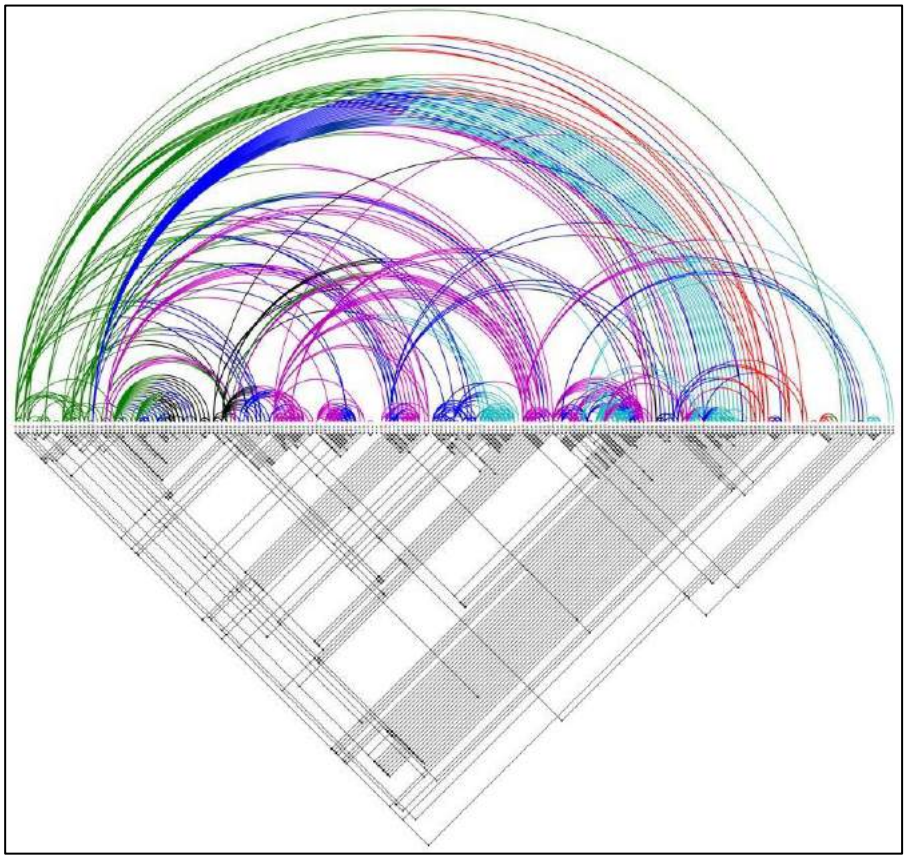
4. RESULTS

Figure 2: A Linkograph of the participants' design session

The preliminary results of this study can best be presented in visual form. The linkograph, shown in Figure 2 not only allowed us to see at a glance at which points the participants continuously referred back to their previous thoughts or discussions during designing, but also where new thoughts were instantiated throughout the design process. A preliminary quantitative analysis of the types of design moves revealed that 59% of the total 206 design moves were bidirectional design moves. This supports Goldschmidt's (2014) findings, which show that the proportion of bidirectional moves, close to two-thirds, is typical of novice designers. This begs the question: is it an instinctive reaction within the design process, uninfluenced by the level of expertise, that allows the designer to move with fluidity between the past and the future? Further research is necessary to establish whether this trait is commonly to be found in the design process of novice designers, or if this has been inculcated across years of unintentional design thinking during their school programme.

A further finding revealed that there were 20 critical forward linked design moves that emerged during designing, in contrast to only two critical backward linked design moves. This suggests that the participants engaged in more divergent thinking, with minimal convergence taking place. According to Goldschmidt's (2016) findings on professional design protocols, typical ratios of critical forward moves to critical backward moves should be 60:40. Although the participants were engaged in the early phases of the design process, which is known for idea generation phases, it appears that this group of participants paid less attention to taking stock of their previous design moves. Although there were a total of 184 moves with backlinks (unidirectional and bidirectional included) in the linkograph, only two were critical design moves. This suggests that the participants generated ideas but did not necessarily develop, evaluate, or summarise them.

A final preliminary finding related to the participants' information use revealed that the participants leaned more heavily on external information sources (74% of design moves) than on internal information sources (26% of design moves). External information sources comprised a design problem statement, pictorial information (photographs and diagrams), physical objects, and the tangible external representations that they made. Internal information comprised their STEM knowledge, previous experiences, and their design intentions. Although the participants used their prior experiences with food containers extensively (17% of design moves), they made limited interactions with STEM knowledge to make design choices (9% of design moves). In Figure 3, the participants' information use is visually represented with an archiograph on top of the linkograph.



Green	Design problem statement
Blue	Internal sources
Purple	Pictorial information
Black	Physical objects
Cyan	Sketches
Red	Developed Specification list

Figure 3: The participants' information use during the design process, illustrated with a Linkograph and an Archiograph

At first glance, Figure 3 reveals how different information sources were, perhaps, mechanisms for generating the participants' design moves. Future studies might want to investigate the nature of information sources in the design task environment, and what role they play in learners' reasoning processes.

5. DISCUSSION AND CONCLUSION

This paper has shown that what may be seen as a design activity by school children is, in fact, a complex process that involves various backward and forward connection making. It is worth considering that the deliberate enhancement of these processes through pedagogical expertise may deliver more expert results than is generally expected of secondary school learners. This speaks to tertiary training and the design processes of teachers as they create lesson plans structuring design activities and preparing information sources.

In this regard, this study has shown that external information sources are used extensively in the design process. Therefore, it seems necessary that teachers should pay careful attention to the nature and quality of the information sources that they provide for learners, as these sources facilitate learners' thinking about their design problem and solutions. The sources should not be the product of hasty lesson planning, but deserve to be carefully thought through and judiciously selected based on their cognitive affordances in the design process. In conclusion, the linkograph has been found to be a revolutionary tool in the analysis of the design process as it accurately and efficiently represents the structure of learners' reasoning during designing.

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