Using Linkography to investigate students' thinking and information use during a STEM task

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Abstract

One of the characteristics of the twenty-first century is the increase in the information sources available to designers to make their design decisions. However, current verbal protocol analysis methods and theoretical frameworks do not explain how internal and external information sources contribute to novice designers' moment-to-moment thought processes. The purpose of this paper is to examine the use of Linkography, a protocol analysis method, to investigate the nature of novice designers' thought processes. We also introduce the use of coloured archiographs, as a complimentary tool, to analyse how novice designers use information sources during the early phases of the design process. In order to discuss and illustrate the use of these analysis methods, 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. The findings of this study suggests that Linkography, in combination with coloured archiographs, is a novel method in technology education to analyse and visually represent how students think while they are designing.

Keywords: Design cognition; Information sources; Linkography; STEM knowledge; · Technology education

Introduction

What is a thought and how do thoughts develop into design ideas? Despite the recognition of the development and fostering of design thinking in students, relatively little research evidence exists regarding the nature of thoughts during designing. Cognitive psychology suggests that in order to understand students' design cognition, researchers should study small increments of thought (Chinn and Sherin [10]; Goldschmidt [24]). This implies that the former linear, phase, spiral or iterative design process models become obsolete for understanding the nature of students' thinking processes in detail. Goldschmidt ([24]) notes that 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. However, we now know that these models teach us little about the nature of design thinking involved in design (Goldschmidt [24]). Although these design process models highlight the procedural nature of designing, they do not reveal the ontological nature of design thinking (Haupt [31]; Sung and Kelley [54]). This suggests that researchers need to consider looking at smaller segments of the design process to understand how **students** think during designing (diSessa et al. [15]; Goldschmidt [24]; Hall and Stevens [28]). One way of studying students' 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. In technology education, verbal protocols have been used to explore students' processes of design in terms of their design procedures (Mentzer [45]; Welch and Lim [62]), their mental processes employed (Kelley and Sung [41]), the different values that they used (Trimingham [56]), and the different cognitive design styles and reasoning that students exhibited (Lammi and Becker [42]; Wells et al. [63]), to name a few. By adopting a verbal protocol methodology, researchers can collect systematic evidence of designers' incremental thought processes and behaviours as they occur during a design task (Grubbs et al. [27]; Sung and Kelley [54]). 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 students' thought processes, they do provide some access to the thinking involved in designing, which would otherwise not be accessible (Goldschmidt [24]).

Recently, Grubbs et al. ([27]) analysed eight coding frameworks used to analyse the verbal protocols of technology education students. Of the eight reviewed frameworks, four frameworks emphasise the procedural nature of designing, while the other four frameworks have a cognitive science foundation and reflect an ontological approach to analysing students' cognition. However, none of the analysed frameworks provide a way to characterise students' developing thoughts during designing. Furthermore, these frameworks do not allow researchers to investigate students' interactions within the physical and social environment, which engender their thoughts during designing. Instead, it seems as if the existing frameworks developed predominantly from internalist cognitive science theories and neglect the situated nature of students' thought processes. This paper aims to address the following research question: How can Linkography inform research with regard to the nature of students' processes of design?

In order to address this research question, we introduce Linkography, a protocol analysis method, which has previously been used in professional design studies, but not yet in technology education. This method provides both quantitative and qualitative insights (Gero and Kan [18]; Goldschmidt [24]) into the structure of technology students' thoughts during designing. In addition, we also introduce the **use** of coloured archiographs to further investigate the nature of information sources and their relation to students' thoughts. In this way, we are investigating the ways in which researchers can consider students' interactions within the physical and social environment. Howard-Jones and Jay ([37]) caution that any potential findings in research will remain inaccessible as long as the dynamic interactions amongst the social, cognitive and physical environment are ignored. With a better understanding of the social, cognitive and physical mechanisms underlying students' design thinking, teachers could be better informed about strategies to support students' processes of design.

Literature review

An overview of Linkography

Linkography is a protocol analysis method that was introduced by Goldschmidt ([22]) to analyse the verbal protocols of individual architects (Goldschmidt [23]) in order to assess their design productivity. This method has been extended by several researchers (Cai et al. [7]; Gero and Kan [18]; van der Lugt [59]) and is now an established method for studying design cognition with quantitative and qualitative applications (Gero and Kan [18]; Hatcher et al. [29]; Roozenburg [50]). Figure 1 illustrates the general structure of a Linkograph.

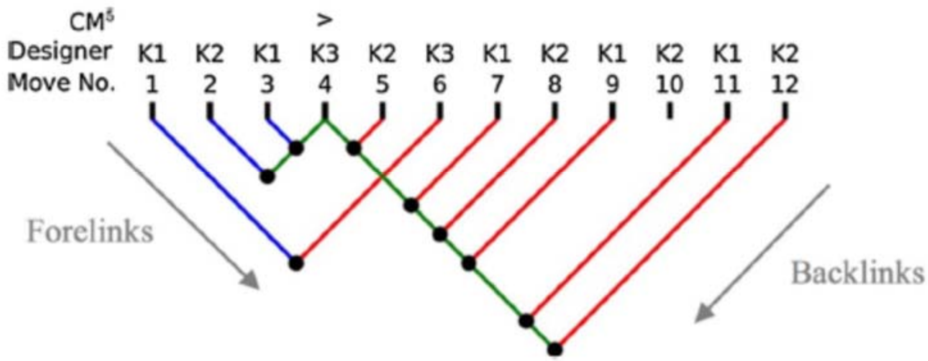

Fig. 1 General structure of a Linkograph to demonstrate the different types of design moves, with unidirectional forward (blue), unidirectional backward (red) and bidirectional moves (green).

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 [23], p. 195). In this study, verbal utterances were parsed based on the participants' turn-taking, which is a common segmenting principal in team designing (Gero and Kan [18]; Goldschmidt [24]; Hatcher et al. [29]). After the verbal protocols have been segmented into a sequence of design moves, a Linkograph can be constructed by identifying the links between the design moves (Goldschmidt [25]). The purpose of this is to visualise the links between the design moves. The links between design moves are visualised with nodes. 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 [25]). Hatcher et al. ([29]) explain that the density of these nodes can provide insight into the inter-connectivity of the thoughts underlying designing: too sparse indicates that the design process could be considered sporadic and poorly structured, or, a very dense Linkograph may imply design fixation (El-Khouly [16]; Gero and Kan [18]; Goldschmidt [24]).

Goldschmidt ([24]) further notes that this approach to link-coding is based on 'common sense' and an understanding of the domain in which the design process is embedded. If a link is established, it is called a backlink as it is directed back in time (Goldschmidt [25]). 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 ([25]) notes that backlinks suggest instances where convergent thinking was instantiated and forelinks suggest instances where divergent thinking was instantiated.

Different types of design moves

In a Linkograph, Goldschmidt ([24]) distinguishes between four different types of design moves, illustrated in Fig. 1: orphan moves (move 10), unidirectional moves (moves 1, 2, 3, 5, 6–9, 11–12), bidirectional moves (move 4) and critical moves (move 4). Orphan moves are isolated moves and are not related to any of the other design moves. Goldschmidt ([24]) has noted from her studies that novice designers are more likely to create orphan moves as compared to expert designers. She explains that a possible reason for the fewer orphan moves in expert design protocols is that experts are able to anticipate the implications of their moves for longer stretches of future 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 [24]), without any reference to future design moves. 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 [24]). Moves that contain both backlinks and forelinks are labelled as bidirectional moves, and are illustratively shown by design move 4 in Fig. 1, where move 4 backlinks to moves 3 and 2, but also forelinks to moves 5, 7, 8, 9, 11 and 12. Bi-directional moves suggest that the participants are planning ahead while still making sure that there is continuity between past design moves (Goldschmidt [24]). Bidirectional moves illustrate that the participants are rapidly shifting between two modes of thinking, namely, divergent and convergent thinking (Goldschmidt [25]).

Critical moves are design moves that are rich in links to other moves and can be unidirectional or bidirectional. 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 [25]). If a design move has a high number of backlinks, it means that the move referred back to a great deal of previous design moves, implying that new thoughts that were proposed were developed, explored or summarised. Similarly, a design move with a high number of forelinks suggests that the move was an important new thought that emerged during designing, and was critical in the development of the overall thought process of the designers. The criteria for determining critical moves vary depending on the context of a study, but Goldschmidt ([24]) advises that the criteria be selected such that 10–12% of the total number of moves with the highest number of links be classified as critical moves.

Theoretical framework

For the study of students' moment-to-moment designing, we adopted an extended design cognition lens (Blom et al. [4]; Haupt [32]). In contrast to classical information processing theories, extended cognition recognises that designers' cognitive processes extend beyond their bodies. As a result of this extension, designers can then perform cognitive functions, such as remembering, perceiving, understanding or learning more efficiently than if they only relied on internal information alone (Heersmink [35]; Menary and Gillet [44]; Trybulec [57]). This implies that the design task environment encompasses internal and external sources of information. Extended cognition develops as a subset of the Situated Cognition (Robbins and Aydede [49]) and Distributed Cognition Theories (Ball and Christensen [3]; Hutchins [39]), and pays equal attention to computational theories of mind and ecological psychology when studying cognition. The Extended Mind Thesis (Clark [11]; Clark and Chalmers [12]) rejects exclusive internalist and externalist theories of cognition in favour of an integrated model of cognition (Hurley [38]; Menary and Gillet [44]). This formed the backbone of our current understanding of students' thinking during designing. The theoretical framework for this study is illustrated in Fig. 2.

The theoretical framework displayed in Fig. 2, was adapted from the work of Haupt ([30]), who developed it from Goel and Pirolli's ([21]) Information Processing Theory of Designing, by integrating principles from ecological psychology (Anderson [1]). The framework can be described in terms of three components, namely: (1) the extended information processing system; (2) the design problem solving space; and (3) the extended design task environment.

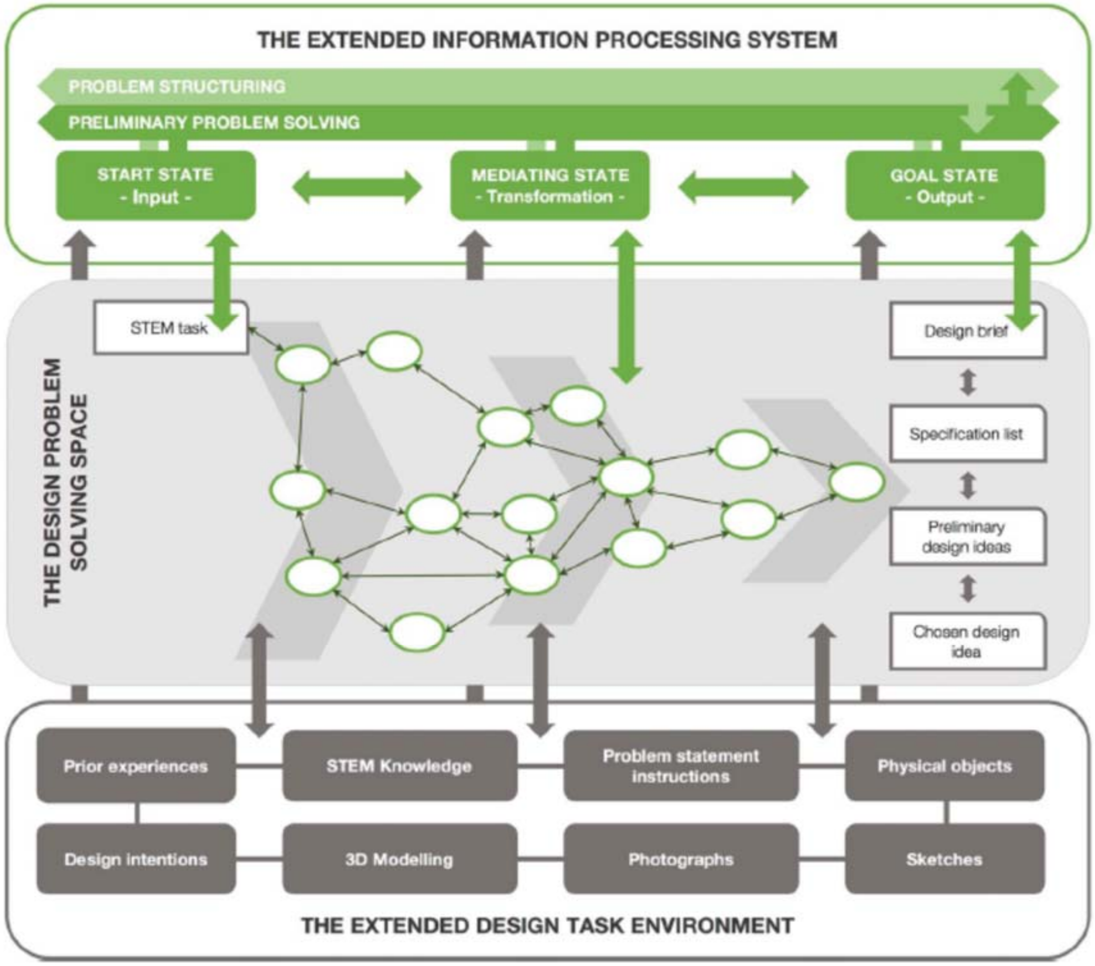

Fig. 2 An extended design cognition framework for the early phases of the design process. Adapted from Haupt ([30])

Component 1: The extended information processing system

The extended information processing system consists of three structures, including an input, process, and output. These structures are situated in the early cognitive phases of the design process, namely, problem structuring and problem solving (Goel and Pirolli [21]). One assumption underlying the extended information processing system is that problem solving is dependent on input information sources regarding a problem situation. This is systematically transformed during a transformation process into a physically embodied solution output, which might take the shape of drawings, 3D models or physical artefacts. Each of these structures in the information processing system corresponds to problem solvers' psychological states, which determines the construction and boundaries of a problem-solving space.

Component 2: The extended design problem solving space

In the problem-solving literature, the psychological states that make up the problem-solving space are distinguished as the start, mediating and goal state. Most design researchers acknowledge that all of the psychological states in design problem solving are characterised by a lack of information due to the ill-defined and ill-structured nature of design problems.

The start state represents the psychological state where students receive their STEM task for the first time (Haupt [30]; Newell and Simon [46]; Reed [48]). When they receive their STEM task**,** students will experience uncertainty due to the ill-structured and ill-defined nature of the task. Their uncertainty is caused by a lack of information about the problem and knowledge of possible solutions. This implies that students need to engage in a cognitive process to understand the problem or find solutions in the resulting mediating states.

The mediating states represent the psychological states in which the dynamics between students' understanding of their STEM task, and their choice of a suitable solution to the problem unfold (Haupt [30]; Newell and Simon [46]; Reed [48]). These dynamics are caused by the limited information contained in each state, and the students' need to know. It is during the mediating states that the students interact with internal and external information sources in order to develop suitable output solutions. Using Linkograpy, we sought to analyse the mediating states, as design moves, in which the students interacted with internal and external information sources. These design moves are produced when students apply physical and mental operators in order to move from the start state to the goal state (Goel [19]; Hay et al. [33]; Ullman [58]). Building on the work of Ward et al. ([60]), Stempfle and Badke-Schaub ([53]) propose four basic operators that are aimed at widening and narrowing the design problem space. They suggest that generation and exploration operators, which are consistent with forelink design moves, produce new thoughts about the problem and solution that widen the design problem space. Moreover, comparison and selection operators, which correspond with backlink design moves, evaluate or justify existing thoughts about the problem or possible solutions that narrow the design problem space. In this way, we aimed to trace the development of the participants' thoughts during designing.

The goal state represents the psychological state where students have solved their STEM task by choosing a suitable design solution (Haupt [30]; Newell and Simon [46]; Reed [48]). During the start and mediating states, the goal state is ill-defined. As students progress with the problem-solving task, they make design choices that result in the narrowing of the problem space. This means that in the beginning of the design process, students have a vague and abstract idea of the problem and solution. While they engage with internal and external information**,** they are enabled to explore the problem space, make design choices in order to structure their problem, process and find a solution (Goel [20]; Haupt [30]; Ullman [58]). The goal state represents the defined solution that could address the ill-structured problem in the start state. The solution might be embodied in the students**'** design briefs, specification lists, idea sketches, and 3D models.

Component 3: The extended design task environment

The extended design task **e**nvironment is a theoretical construct used by design researchers to examine how the nature of the problem to be solved and the problem solvers' actions influence the problem-solving space (Goel and Pirolli [21]). This means that the 'extended design task environment' involves the entire problem-solving task given to students, comprising their cognitive accessing of information and acting thereupon, as well as the resultant cognitive feedback loops (Clark [11]; Heersmink [34]; Menary and Gillet [44]). This encompasses the fundamental situated cognition assumption that whenever students encounter a particular ill-structured problem, they **use** a combination of internal and external information sources to assist them in defining and solving their STEM tasks. While the Traditional Information Processing Theory only studies the internal information sources of students' problem-solving behaviour in a task environment, we agree with Haupt's ([30]) Extended Design Cognition Theory that considers any mental or physical action taken by a problem solver, and any external action or information source used during the course of the problem-solving process as potentially able to influence the cognitive process to complete a cognitive task.

The benefit of using an extended cognition framework lies in the descriptive power it provides in describing the development of students' thoughts during designing. From a Computational Theory of Mind perspective, it allows the researcher to study the sequence of thoughts that lead to design ideas. It also accounts for the dynamic nature of the students' interactions with information sources. In the professional design literature, Cash and Gonçalves ([8]) emphasise that there are limited theoretical frameworks describing the development of design procedures in conjunction with the information sources that designers access and use. As such, an extended cognition framework provides a means to study how technology students use information sources during the early phases of the design process.

Method

Research approach and design

In this study, a critical realist stance was adopted based on our commitment to understand the cognitive mechanisms underlying students' processes of design (Cash et al. [9]; Danermark et al. [14]; Wynn and Williams [65]). In order to construct the Linkographs and study what information sources the students used, we followed a concurrent mixed methods approach (Creswell [13]; Teddlie and Tashakkori [55]) in which we utilised a multiple case study research design (Yin [66]). We purposefully selected three different medium resourced secondary schools as research sites, based on their geographical proximity.

Participants and setting

In total, 18 Grade 8 students (5 girls and 13 boys) between the ages of 13–14 years old participated in the study. These students were purposefully selected by their teachers based on the following sampling criteria: (a) they should have maintained an above-average performance in science, mathematics and technology subjects, (b) they should be able to work together effectively with other participants in the group, and (c) they should be able to communicate effectively using verbal and visual representations. These criteria ensured that the participants were able to demonstrate their design abilities to a level that would make detailed analysis possible and worthwhile.

At each of the three research sites, the participants were divided into triads. As Welch ([61]) and Kelley et al. ([40]) note, this reflects the real world of designing where typically two or more people work in collaboration. Additionally, allowing **students** to work in design teams enhances the validity of their verbalisations as teams naturally communicate with each other during their design tasks (Ball and Christensen [3]; Goldschmidt [24]). For this paper, we only used one of the cases to demonstrate the application and usefulness of Linkography to explore the nature of students' thought processes.

Context and the design task

Because we followed a multiple-case study design, it was critical to ensure that each triad engaged in a common STEM task. The STEM task that we designed for this study was adapted from an existing technology textbook prescribed by the South African Department of Basic Education (Bosch et al. [5]). Although none of the participants in our study had previously seen or used this textbook as part of their Grade 8 curriculum, choosing a different task than what the participants had been exposed to was based on the notion that students can apply their prior knowledge and skills to new and similar situations (Bransford et al. [6]; Kelley et al. [40]; Kelley and Sung [41]). For our study, this implied that when we presented the participants with an existing design task from an unfamiliar textbook that was similar to their prior learning experiences in Term 2, we assumed that learning transfer could occur. We therefore carefully adapted and crafted a new task that was similar in scope to those presented in the cases during their prior learning experience. We also provided each triad with pictorial information giving information about the design context in order to trigger the participants' prior knowledge and experiences with packaging from their previous term's work. In order to elicit the thought processes of the participants, we provided them each with a copy of the following design brief:

Food vendors are situated at most of the taxi ranks in South Africa. People can buy a meal after a long day of work before catching a taxi and heading home. Food vendors usually sell food to customers in plastic polystyrene containers. However, these containers do not retain the heat of the food inside the container for the trip home. Also, these containers are not easily recyclable because it is contaminated with food and difficult to clean because it is so porous, and therefore does not support sustainable use of the country's resources.

One of the most popular dishes served by the street vendors in South Africa is 'pap and meat'. The pap is maize meal porridge, which is usually made thick enough to eat with your fingers. There are also many different meat options to choose from, including, chicken, beef, mutton or fish. The meat is served in a tasty gravy or 'chakalaka'. As a take away meal bought from the street vendors, the pap and the meat is often served separately in a polystyrene container.

Design a recyclable heat retaining food container that will ensure that the pap and meat dish placed therein would retain its heat for at least 1 h.

Requirements and constraints

- The container should be able to keep the food hot for 1 h.
- The container should be made from bio-degradable materials.
- The container should be comfortable to carry as a take away container.
- The container should hold the food so that it does not spill or leak.
- The container should be able to contain food and withstand forces in a crowded transport environment.
- The container should be able to contain 1.1 kg of food.

This STEM task was appropriate for the multiple-case studies because prior to the commencement of this study, all of the participants had already completed work in their science, technology and mathematics subjects related to this STEM task. A breakdown of their required knowledge to solve the STEM task, along with when the participants would have acquired the information within their science, technology and mathematics subjects is given in Table 1.

Table 1. Pre-requisite knowledge needed for the **STEM task**

Subjects	Concepts	Covered in Grade ...
Science	Heat transfer	Grade 7
	Conduction	
	Convection	
	Radiation	
Technology	Shell structures	Grade 4 and 7
	Properties of materials	Grade 4, 5, 7 and 8
	Recyclable material	Grade 6, 7 and 8
	Bio-degradable material	Grade 8
	Investigating	Grade 4–8
	Designing	
	Making	
Mathematics	Measurement: length	Grade 4–6
	Measurement: mass	
	Measurement: volume	
	Measurement: perimeter, area and volume	
	Measuring surface area and volume of 3D objects	Grade 4–7
	Properties of 3D models	Grade 4–6
	Building 3D models	Grade 7

Data collection

We video recorded each of the design sessions. During the sessions, each triad was encouraged to talk normally during the session. We also set up a physical space in which the participants could engage in the STEM task. Figure 3 captures the classroom organisation in preparation for the study.

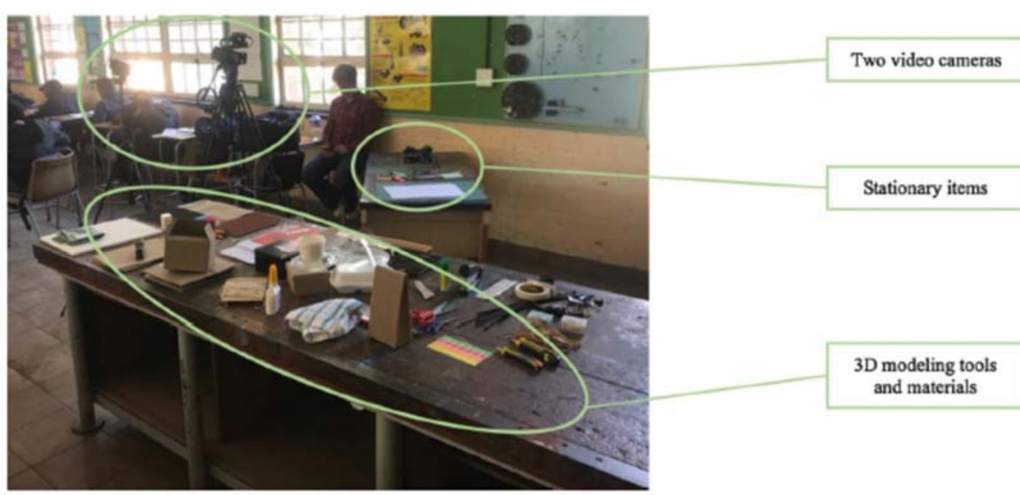

Fig. 3. Classroom organisation in preparation for the study

For their design session, the triads were provided with basic stationary items, including pens, pencils, safety rulers, post-it notes, coloured pencils, paper, paper clips, felt-tip pens and highlighters. We also provided the participants with a range of tools and materials to use during the STEM task. The participants were given time to explore the tools and materials prior to the recordings in order to familiarise themselves with these. It was necessary to pack out and display the given tools and materials for the participants to ensure easy access and to limit disturbances to their thinking processes. We recorded the sessions on two video cameras with a videographer who captured each group of participants' voices, general movements, gestures, sketching, 3D modelling and writing. The video recording was conducted as unobtrusively as possible, and the participants were provided with minimal guidance from their teacher and the researchers. The reason for this was to allow the participants to freely engage in the design task as we were interested to see how students' thinking developed without the pedagogical intervention of a teacher.

Data analysis

In this paper, we limit our discussion to the first hour of a 2-h design session of only one triad of participants. The first hour of the selected session contained the problem structuring and solving phases, just prior to the construction of the final prototype. Before the Linkograph could be created, we had to transcribe the video recorded session. Following the guidelines outlined by Goldschmidt ([24], p. 42), we did not include utterances such as "yeah," "OK," "emm," and so on since such utterances do not constitute design moves and should be removed from the analysis. In addition, instances where the discussion did not produce a design move, for example, repetition of utterances, task management or off-task discussion, were omitted from the protocol (Hatcher et al. [29]). After the design session was transcribed, conversational turn-taking was used to segment the protocol (Gero and Kan [18]; Goldschmidt [24]). This means that an utterance made by a participant was defined as one move (Gero and Kan [18]). Within the transcript, each design move was numbered sequentially and according to the participant who produced it. In this way, the design session could be analysed microscopically to trace the links between design moves.

Since determining links between the design moves is largely subjective and based on the researchers' domain knowledge (Gero and Kan [18]; Goldschmidt [24]), we ensured consistency by formulating guidelines based on the work of several researchers (Gero and Kan [18]; Goldschmidt [24]; Hatcher et al. [29]; van der Lugt [59]). As such, links were made between design moves when one or more of the following criteria were met:

- The participants related directly to earlier thoughts in the protocol,
- There were visible hand gestures, sketching, 3D modelling, or writing relating to earlier thoughts,
- There were structural, functional or behavioural similarities between thoughts, and
- Design moves occurred in serial and were within the same chain of thought.

We used inter-coding reliability to ensure coding consistency of the links between design moves at two different coding intervals. This was performed by computing the percentage of agreement between two coding intervals carried out by the same coder 2 weeks apart from the first and the second coding. We calculated an agreement percentage for the coded protocol by computing the agreement percentage of the coding between the first coding session and the second coding session. Finally, during a third coding session, two researchers compared the observed discrepancies between dissimilar codes and held a discussion to select the most reliable one. Table 2 shows the agreement percentages between the three versions:

Table 2. Coding consistency between different coding sessions

Design moves	1st and 2nd session (%)	3rd arbitrated coding (%)
1–50	81.32	91.39
51–100	80.73	88.52
101–150	78.49	86.60
151–206	72.22	90.41
Average	78.19	89.32

With the first comparison between the first and second coding sessions, the comparison between codes yielded an average agreement percentage of 78.19%. After the third session, the average agreement percentage increased to 89.32%. The findings from previous studies have also reported agreement percentages between 70 and 94% (Atman et al. [2]; Gero and Kan [18]; Salman et al. [51]).

Results and discussion

Figure 4 illustrates a Linkograph that was generated based on the 1-h design session. At first glance, the Linkograph allows us to see the interconnectedness between the students' thoughts as they progressed in their design process. Of importance to us was distinguishing between different types of design moves, which is summarised in Table 3.

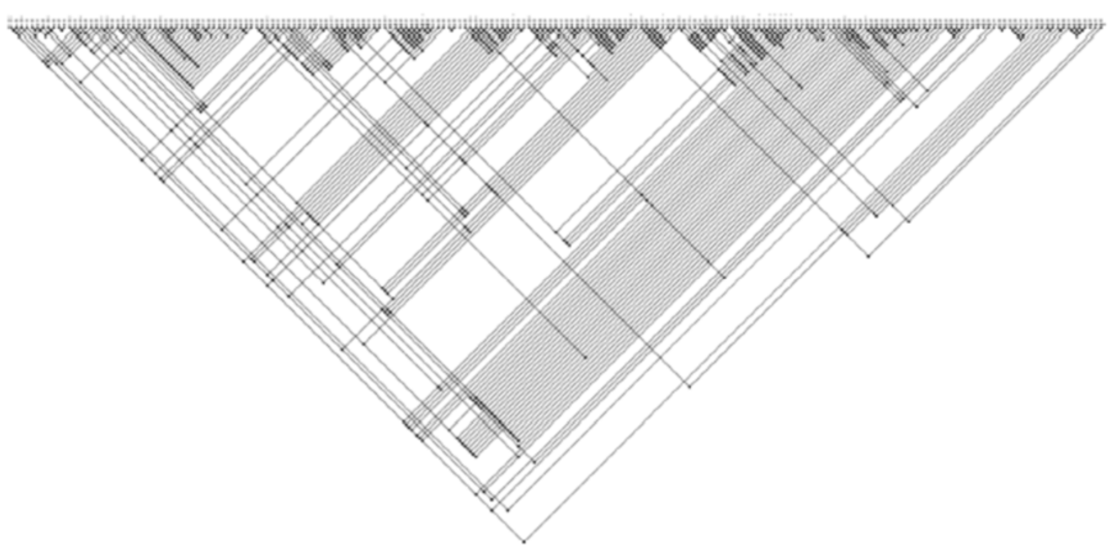

Fig. 4. The Linkograph generated for the 1-h design session, illustrating the interconnectedness of the participants' thoughts

Table 3. Comparison of the number of the types of design move

	Orphan moves	Unidirectional backward moves	Unidirectional forward moves	Bi-directional moves
Total	6	63	15	121 (59%)
Total design moves	206			

Our quantitative analysis revealed that 59% of the total 206 design moves were bidirectional design moves. This finding supports Goldschmidt's ([24]) findings, which show that the proportion of bidirectional moves, close to two-thirds, is typical of novice professional designer and warrants further investigations to refute previous opinions that "novice designers are not capable of switching their modes of thinking between convergent and divergent thinking as frequently as practising designers" (Wong and Siu [64], p. 447). Although previous research (Howard-Jones [36]; Pringle and Snowden [47]; Wong and Siu [64]) has echoed the importance of concurrent generative and evaluative thoughts during designing, there are few studies that have empirically investigated when or how these thoughts occur (Goldschmidt [25]). In fact, current methods analysing the shifts between generative and evaluative thinking processes tend to focus only on generative, divergent processes, but neglect its dynamic nature with concurrent convergent and evaluative processes (Goldschmidt [25]; Sowden et al. [52]; Wong and Siu [64]).

To further investigate how the participants' bidirectional design moves were instantiated, we dissected them in terms of the information sources that were used. Table 4 shows the information sources that the participants used during the instantiation of the bidirectional design moves.

Table 4. Information sources underlying bidirectional thoughts

Information source	Number of bidirectional moves
Internal sources	37 (31%)
Pictorial information	33 (27%)
Sketch	26 (22%)
Design problem statement	17 (14%)
Physical objects	5 (4%)
Specification list	3 (2%)
Total	121 (100%)

From the findings presented in Table 4, the participants' **use** of internal sources was the most prominent information source that was present during the instantiation of bidirectional thoughts. These internal sources included STEM knowledge, previous experiences, and their design intentions, which developed during designing. In addition, pictorial information sources (27%) and sketching (22%) played a significant role in generating bidirectional thoughts. The use of the design problem statement only generated 17 (14%) of the bidirectional design moves, which seems to indicate that the participants rarely revisited the problem that they were addressing during designing. The generated Linkograph allowed us to dissect what mechanisms underlie the instantiation of bidirectional moves. For this study, we focused on the various internal and external sources, in line with our theoretical lens of extended design cognition. However, since the focus of this study was on the usefulness of Linkography as an analysis method and not on the role of the information sources during designing, future studies could investigate (1) What internal–external information patterns arise during designing by **using** sequential analyses such as Markov chains (Gero and Kan [18]), and (2) How the qualitative nature of information sources might underlie students' bidirectional thoughts.

Lawson ([43]) notes that findings about the way in which designers switch between different modes of thought is confusing and begs the question: is it an instinctive reaction that allows designers to shift between generating and evaluation with fluidity? Or, is switching between modes of thought inculcated across years of design thinking during their design programmes? Linkography provides a useful analysis framework through which these questions may be answered. With its focus on bidirectional design moves, it reveals when **students** are instantiating thoughts that are both generative and evaluative at the same time, which lies at the heart of design thinking (Goldschmidt [25]; Howard-Jones [36]; Wong and Siu [64]). If the control and combination of generative and evaluative thought is one of the designer's most important skills (Lawson [43], p. 138), it seems necessary to have a better understanding of how students instantiate bidirectional design moves in order to develop interventions to enhance students' processes of design.

A second finding is that 20 critical forward linked design moves were observed in contrast to only five critical backward linked design moves. This translates to an 80:20 ratio of critical forward moves to critical backward moves. This is different from Goldschmidt's ([25]) 60:40 norm in early phase professional design protocols. Although the participants were engaged in the early phases of the design process, which is known for idea generation, it appears that this group of participants paid less attention to developing and evaluating their previous design moves. While the 184 moves with backlinks (unidirectional and bidirectional included) in the Linkograph demonstrate that evaluation was integral to the participants' design process, only five were critical backward design moves. This suggests that the participants proposed new thoughts and ideas, but did not necessarily develop, evaluate, or summarise them. As a research tool, Linkography provided the visual means to indicate which design moves were critical moves. This might be significant for design researchers as, amongst the plethora of design moves, it can be problematic to identify and isolate those that are critical moves. The Linkograph simplifies this identification.

A third finding related to the participants' information use, which revealed that the participants leaned more heavily on external information sources (74% of design moves) than on internal information sources (26% of design moves). It should be noted that although it seemed as if internal information was the most prominent information source used by the participants, as shown in Table 4, this only accounted for the bidirectional thoughts. Instead, when accounting for unidirectional design moves as well, the participants mostly used external information sources. These external information sources consisted of the design problem statement, pictorial information (photographs and diagrams, which were provided as part of the problem statement), physical objects, and the tangible external representations made by the participants. Internal information is defined, as before, as 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 had limited interactions with knowledge about design strategies, structures and processing of materials (technology knowledge), heat transfer (science) and measurement, and 3D objects (mathematics) (9% of design moves). In Fig. 5, the participants' information use is visually represented with an archiograph on top of the Linkograph.

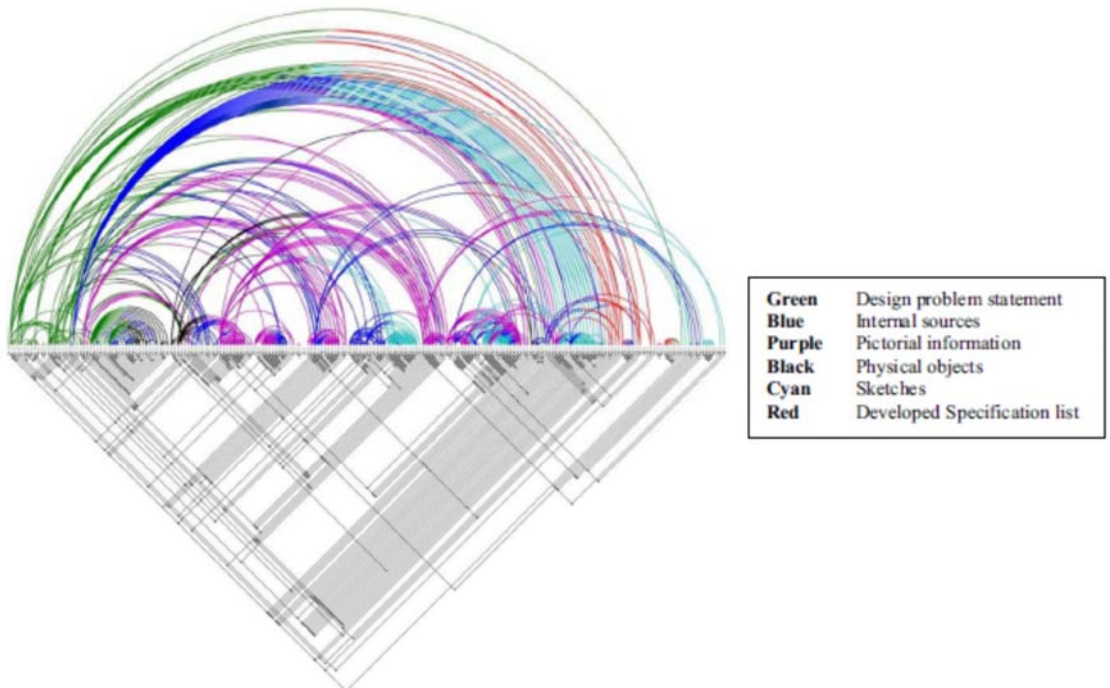

Fig. 5. The participants' information use during the design process, illustrated with a Linkograph and an Archiograph

At first glance, Fig. 5 reveals how different information sources were, perhaps, mechanisms for generating the participants' design moves and making connections between previous thoughts. We used an archiograph as an additional tool to the Linkograph (El-Khouly and Penn [17]) to illustrate the links between the information sources in a clearer way. We could, for instance, show how, on the left hand side of the arch, a thought might have originated through interaction with one type of source, and then on the right side of the arch, how this thought is referred to, elaborated or evaluated during a subsequent design move. For example, the participants might start with proposing a design requirement by reading the problem statement (green), but would modify the requirement in a later design move during a sketching activity (cyan). In order to quantitatively explore these interconnections, Goldschmidt ([24]) **uses** a Link Index (L.I.). A L.I. is a quantitative measure used in Linkography to indicate the interconnectedness of thoughts. The L.I. is calculated by dividing the number of links by the number of design moves. This means that the link index is the ratio between the number of links and the number of moves that form them. Goldschmidt ([24]) explains that a link index is a fast indication of the amount of linking activity in a design episode, which in turn hints at the designer's effort to achieve synthesis. Furthermore, she notes that productive designers only elicit design moves that have a high potential for connectivity to other moves, which is represented in a high link index, as opposed to less productive designers who elicit unconnected ideas at random, which will form fewer links. However, it should be noted that a high L.I is not necessarily an indicator of design quality, as has been found by Goldschmidt and Tatsa ([26]) and El-Khouly ([16]). Table 5 shows the link index values and the design moves generated by the different information sources.

Table 5. Link index values and design moves generated by the different information sources

Information source	# design moves	L.I
Design problem statement	31	4.58
Pictorial information	53	3.71
Sketch	38	2.92
Physical object	13	2.46
Internal sources	54	2.37
Specification list	17	0.59
Total	206	3.00

According to Table 5, the link index value (4.58) is the highest for the design problem statement. This means that for every move that was instantiated with the use of the problem statement, an average of 4.58 links, or connections, were generated to previous or subsequent design moves. This makes sense as the problem statement served as input information for problem structuring and problem solving to occur. Other information sources, including pictorial information, sketches, internal information, and physical objects also had moderate link index values, which highlights the role of the different sources in designing. This points to the pivotal role that information sources can play during designing in facilitating connection-making between thoughts, which is currently under-emphasised in the design cognition literature (Cash and Gonçalves [8]). Although several studies have investigated cognitive processes by using verbal protocols in technology education (Grubbs et al. [27]), none of these studies have looked at the role of information sources in facilitating design synthesis.

In this paper, we identified the two information sources with the highest link indexes for discussion, namely, the design problem statement and pictorial information. These are shown in Figs. 6 and 7.

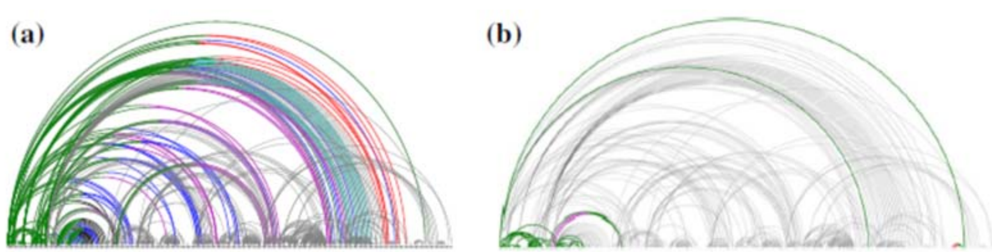

Fig. 6. The role of the design problem statement as an information source. a The role of the problem statement in generating forelinks. b The role of the problem statement in generating backlinks

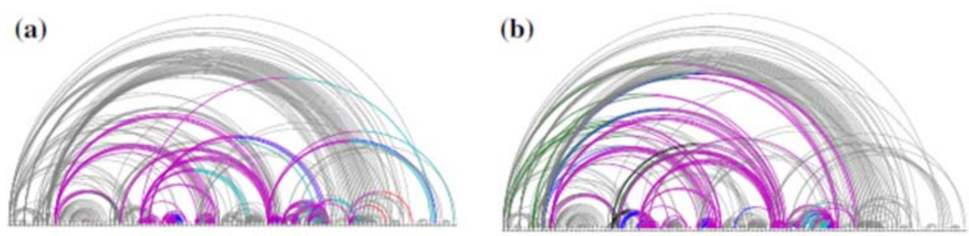

Fig. 7. The role of the pictorial information as an information source. a The role of pictorial information in generating forelinks. b The role of pictorial information in generating backlinks

In Fig. 6a, b, the role that the design problem statement plays is illustrated in green. The thoughts that were instantiated from reading, elaborating and questioning the given problem statement occurred mainly at the beginning of the design session (in green on the left). This makes sense as the participants were trying to understand and structure the design problem. These thoughts were then later referred to, explored or evaluated in subsequent design moves during the 3D modelling (black), knowledge and experience recall (blue), interactions with pictorial information (purple), sketching activities (cyan) and writing specifications (red). Figure 6b, however, shows a different picture in that the participants rarely made connections to previous thoughts using the problem statement during the middle and end of their design session. Therefore, while the problem statement played an integral role in generating ideas and moving the design session along, the participants did not use the provided problem statement as a tool to reflect back on the requirements, goals and constraints of the design solution.

In Fig. 7a, b, the role that pictorial information played is shown in purple. By examining Fig. 7a it appears as if the majority of the thoughts that were generated by investigating and discussing pictorial information were referred to, explored, evaluated or summarised during sketching (cyan) and recall of internal information (blue). In Fig. 7b, it appears that when using pictorial information**,** students**'** thoughts made backlinks to the problem statement (green), internal information (blue), and their sketches. This might show that the pictorial information triggered thoughts related to information discussed during earlier thoughts when they analysed their problem statement. This implies that the pictorial information might have served as a mechanism to evaluate, refer to, or summarise previously discussed information**.**

Conclusion

In this paper we have attempted to demonstrate how Linkography can be used to better understand the nature of students' thought processes during designing. Linkography afforded us a way to study students**'** thoughts by looking at the moment-to-moment development of their thinking as they structured and solved a design problem during the early phases of a STEM task. This paper has shown that by using Linkography to study how students think during designing, we were able to illustrate the complex nature of students**'** design cognition, which involves various backward and forward connection-making during designing. Furthermore, we illustrated how coloured archiographs can be used in combination with Linkography to visually highlight previously obscure mechanisms of thought, especially the inter-relatedness between thoughts and the various information sources. This paper foregrounds the umbilical link between the information sources and the design moves produced during designing. Further research is necessary to establish the value of other factors that influence the development of thoughts during designing.

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