Using Linkography to Understand the Social, Conceptual and Physical Cognitive Mechanisms During the Design Process

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The 21st century is marked by an increase in the information sources available to designers who solve design problems. Current design thinking analysis procedures and theoretical frameworks do however not explain how designers interact with a variety of social, conceptual and physical information sources when designing. Ongoing research is required to not only understand how designers interact with these information sources; but also to find suitable methodologies with which to investigate these interactions. The purpose of this study was to examine the way in which Grade 8 technology learners interacted with social, conceptual and physical information sources during the early phases of the design process. In order to explore the cognitive mechanisms of learners when interacting with a variety of information sources, we relied on both extended design cognition and activity systems theory and implemented a mixed methods design. Three medium resourced secondary schools were conveniently selected from which nine Grade 8 participants were purposefully selected. Verbal and visual data were generated and documented by means of a think aloud protocol methodology, and analysed quantitatively and qualitatively by utilising linkography. The potential contribution of the study is twofold. Theoretically, the study adds to the existing knowledge base on learners' design cognition by shedding light on the nature of their interactions with physical, social and conceptual information sources when solving design problems during STEM tasks. Secondly, the study makes a methodological contribution by illustrating how linkography can be utilised to analyse the design cognition used by learners during design activities.

Keywords: activity systems theory, extended design cognition, internal and external information sources, integrated STEM education, linkography, think aloud protocol study

Introduction

This study stems from the need for ongoing empirical research on integrated STEM education (Fan & Yu, 2017; Hernandez et al., 2014; Greg Strimel & Grubbs, 2016). In particular, we decided to focus on the social, cognitive and physical mechanisms underlying learners' design problem solving events during integrated STEM activities in an attempt to contribute to the field in terms of theory, methodology and professional practice. By undertaking this study, we thus aimed to add to the debate between teachers and researchers about what to look for and what to support during learners' design processes. Although research on designing in school contexts has gained traction as an emerging topic of interest, research on design cognition, and practices in public school settings specifically, remains limited (Haupt, 2018; Strimel, Kim, Bartholomew, & Cantu, 2018; Sung & Kelley, 2018). Ongoing research is important to understand how learners' design cognition occurs as a result of their interactions with social, conceptual and physical structures in the learning environment.

Several scholars (Campbell & Jobling, 2014; English, King, & Smeed, 2017; Kelley & Knowles, 2016) concur that integrated STEM education is a potentially effective instructional method for fostering critical thinking, problem solving and decision-making skills. However, empirical evidence to support the cognitive benefits of integrated STEM education remains limited (Asunda, 2012; English et al., 2017; Williams, 2011). In addition, several limitations in the existing literature compromise the

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universal acceptance of integrated STEM as an appropriate framework. Examples of current limitations are impoverished descriptions of research interventions, a lack of common terminology and theoretical frameworks, and limited evidence on the benefits of interdisciplinary learning (National Academy of Engineering., 2014).

Based on a review of the implications of psychology and neuroscience for STEM learning, Howard-Jones and Jay (2014) highlight the importance of researchers developing methods for research that can combine concepts and insights at the intersection of the psychology and educational domains (Jay, 2013; Jorg, Davis, & Nickmans, 2007). According to these authors, potential research findings will remain inaccessible as long as traditional disciplinary boundaries can be observed, and the dynamic interactions between the social, cognitive and physical environment are ignored (Howard-Jones & Jay, 2014). It follows that a deeper understanding of the cognitive mechanisms underlying learners' design processes during integrated STEM activities may result in teachers being better informed about the strategies that are suitable for supporting learners' design problem solving activities. Few studies have focused on studying the social, cognitive and physical mechanisms underlying designing (Haupt, 2018). It is for this reason that we decided to focus on the combination of these mechanisms, to gain an in-depth understanding of the complexity of designing.

By investigating the underlying cognitive mechanisms, the potential theoretical contribution of this study entails increased understanding of the nature and types of thoughts underlying learners' design processes, and how learners' interactions with social, conceptual and physical structures may engender these thoughts. Theoretically, the findings of this study may thus add to existing literature on the way in which learners' thinking develops during STEM activities.

Using Linkography to investigate the cognitive mechanisms of technology learners

Linkography enables researchers to visually represent and analyse individual or teams of designers' processes of designing. Essentially, each linkograph represents the chronology of connections that designers make between their thoughts, which will subsequently result in design ideas. These connections can then be analysed both qualitatively and quantitatively (Gero & Kan, 2017; Goldschmidt, 2014). Linkography has been utilised in several professional design contexts to understand the complexity of designers' thought processes during designing. Examples of existing studies include those that focus on how design ideas are conceptualised and developed (Goldschmidt, 1995) on the nature of design reasoning in the early phases of the design process (Goldschmidt, 2013), the role of sketching during idea development (van der Lugt, 2005), the role of team communication during designing (Jiang & Gero, 2017), and uncovering moments of creative discovery during designing (El-Khouly, 2015), to mention but a few.

In comparison to other methodologies used in design studies, linkography allows researchers to investigate the ontological nature of design processes rather than merely describing designing in terms of design activities or phases (Goldschmidt, 2014; Haupt, 2018). Linkography can furthermore enable researchers to uncover the basic structure of reasoning involved in designing (Goldschmidt, 2014).

In a linkograph, we can distinguish between four different types of design moves: orphan moves, uni-directional moves, bidirectional moves and critical moves. 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 forward 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). 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).

Conceptual framework

We compiled a conceptual framework by drawing on Extended Design Cognition and Activity Systems Theories, shown in Figure 1, in order to explore the participants' dynamic interactions with social, conceptual and physical structures that may have affected their design thinking.

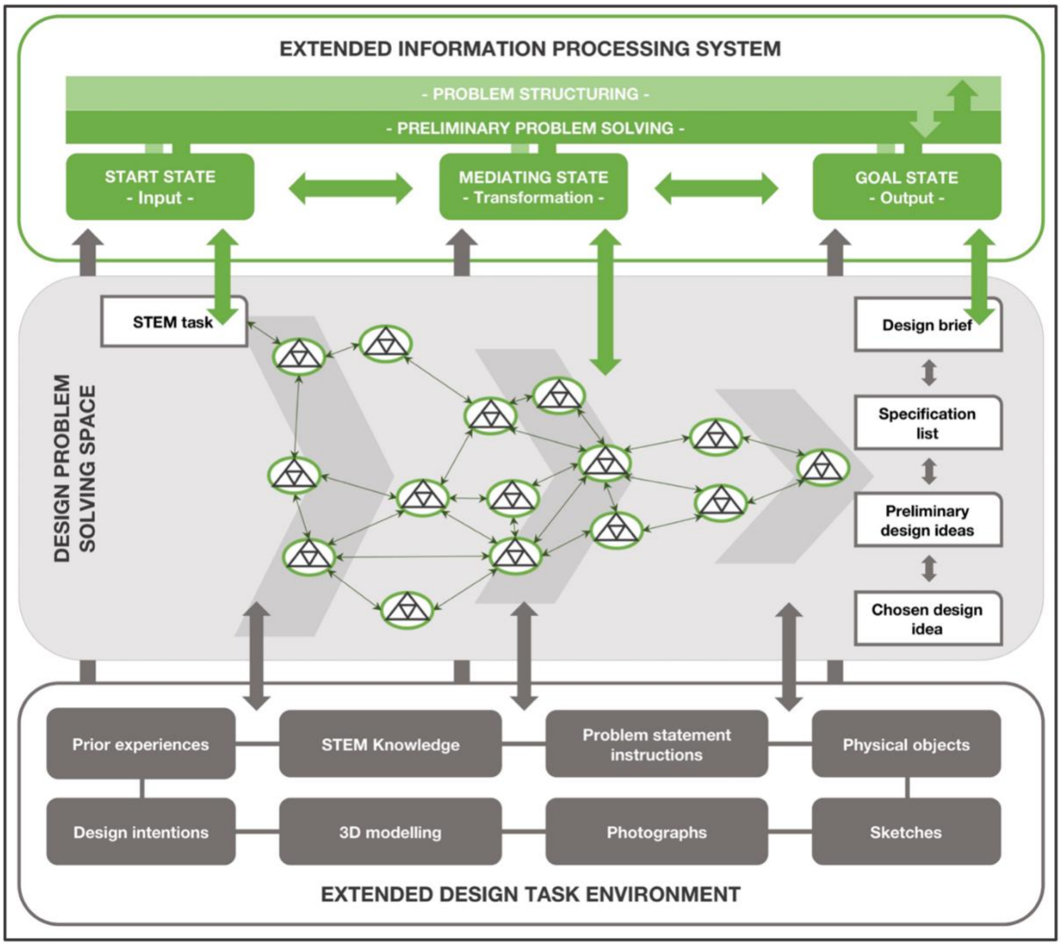

Figure 1. Conceptual framework (adapted from Haupt [2015] and Engeström, [2015])

We primarily relied on the Extended Design Cognition Theory of Haupt (2015), which is rooted in the integration of Information Processing Theories of designing (Goel & Pirolli, 1992; Newell & Simon, 1972) and embodiment principles (Anderson, 2003). This theory rests on three theoretical constructs, namely, the extended information processing system, the extended design task environment, and the design problem solving space. For this study, we viewed a triad of learners engaging in designing as an extended information processing system embedded in an extended design task environment. The result of their interactions in the design task environment gave rise to the design problem solving space. The design problem solving space consisted of various design moves where the groups of participants interacted with social, conceptual and physical sources of information.

We also integrated Activity Systems Theory (Engeström, 2015) in order to understand the underlying structures with which the participants interacted in each design move. These interactions can be seen in the context of the members of a design community, the physical and conceptual tools available to mediate a community's design objects, and the rules and division of labour that may affect the mediating tools in a community's design objects. In essence, we used Haupt's (2015) Extended Design Cognition Theory as an organising structure and its constructs as a-priori criteria for examining learners' design cognition. This was then informed by Engeström's (2015) Activity Systems Theory in identifying participants' interactions with social, conceptual and physical structures.

Methodology

To study the cognitive mechanisms of Grade 8 technology learners during an integrative STEM task, we implemented a mixed methods design, following a multiple case study design. We conveniently sampled three medium-resourced schools and purposefully selected nine participants, between the ages of 14 and 15. Learner participants were selected based on the following criteria: 1) The participants had to be top performers in Science, Mathematics and Technology subjects; 2) The participants had to be able to work together effectively with other participants in the group; 3) The participants had to be able to communicate effectively with verbal and visual representations, either in English or Afrikaans. Verbal (spoken and written) and visual (sketches, 3D models and gestures) data were generated and documented by means of Think Aloud Protocol methodology, and analysed quantitatively and qualitatively, utilising linkography. The researchers were able to elicit the design cognition behaviour of each group of participants by providing them with a single 2 hour 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. 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.

Results and findings

Social interactions

In order to understand the nature of the social interactions that occurred, we analysed the links related to the intrapersonal and interpersonal communication that transpired during the protocol (Jiang & Gero, 2017), as indicated in Table 1.

Table 1. Intrapersonal and interpersonal communication links for the various groups

		Intrapersonal # links	**% links**	**Interpersonal # links**	**% links**
Group A	P1	95	35	180	65
	P2	172	39	267	61
	P3	48	27	129	73
	Teacher	0	0	3	100
	Total	**315**	**35**	**579**	**65**
Group B	P1	34	38	55	62
	P2	10	22	35	78
	P3	57	50	56	50
	Teacher	0	0	0	0
	Total	**101**	**41**	**146**	**59**
Group C	P1	161	59	112	41
	P2	86	44	111	56
	P3	16	28	41	72
	Teacher	0	0	0	0
	Total	**263**	**50**	**264**	**50**

The data in Table 1 indicate that Groups A and B generated the majority of the links from each other's design moves, thereby implying a high percentage of interpersonal communication, while Group C maintained a balance between generated interpersonal and intrapersonal links. Group A and B's high percentage of interpersonal links indicates that the participants relied on each other's design moves, which in turn resulted in interchanges of ideas and opinions during collaborative designing. In Group C, the balance between intrapersonal and interpersonal links indicates that the participants were equally involved in collaborative and individual designing. In this way, the 50% intrapersonal links indicate less successful team efforts as each participant tended to concentrate on their own ideas instead of considering other participants' contributions.

In relating these findings to the existing literature, it seems clear that, while unguided in their endeavour to understand and solve design problems, learner designers are generally able to take an active role in developing an understanding of the design problem and generate possible solutions when communicating their thoughts to their peers (Fox-Turnbull, 2015). In the current study, the participants' verbal interactions in the STEM task context included the actions of giving each other information, proposing ideas, evaluating each other's suggestions, making judgements, and responding to their peers' questioning, which all seemed to contribute to the synthesis of their problem understanding of the problem or to generating design ideas. Not only did learners view each other as a source of information; they also used external information, including physical materials, as well as their teacher to gain a better understanding of the design task or clarify their design ideas. In this regard, these results echo previous findings that the quality of learners' thoughts in peer groups can be associated with the nature of their social and physical interactions (Marra, Steege, Tsai, & Tang, 2016; Murphy & Hennessy, 2001; Rowell, 2002). However, existing literature remains silent regarding the manner in which social and physical interactions constitute learners' thought processes.

Conceptual interactions

Tables 2-5 summarises the different design moves that were generated as a result of learners' interactions with scientific, technological and mathematical knowledge, as well as their recall of prior experiences.

Table 2. Directionality of thoughts when interacting with scientific knowledge

Scientific knowledge interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	0	0	0
Unidirectional backward	0	0	1 (1%)
Bidirectional design moves	1 (0.5%)	1 (1.2%)	6 (5.9%)
Orphan moves	0	0	0

Table 3. Directionality of thoughts when interacting with technological knowledge

Technological knowledge interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	3 (1.6%)	4 (4.7%)	3 (3%)
Unidirectional backward	9 (4.9%)	12 (14.1%)	7 (6.9%)
Bidirectional design moves	29 (15.8%)	27 (31.8%)	10 (9.9%)
Orphan moves	1 (0.5%)	0	0

Table 4. Directionality of thoughts when interacting with mathematical knowledge

Mathematical knowledge interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	0	1 (1.2%)	0
Unidirectional backward	20 (10.9%)	7 (8.2)	1 (1%)
Bidirectional design moves	82 (44.8%)	4 (4.7%)	3 (3%)
Orphan moves	0	0	0

Table 5. Directionality of thoughts when interacting with prior experiences

Prior experience interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	0	0	5 (5%)
Unidirectional backward	2 (1.1%)	10 (11.8)	15 (14.9%)
Bidirectional design moves	5 (2.7%)	17 (19.6%)	44 (43.6%)
Orphan moves	0	0	1 (1%)

In this study, 'conceptual structures' referred to the participants' recall of STEM knowledge and prior experiences. Tables 2-5 show that the participants had the least interactions with scientific knowledge in general, while having the most interactions with technological knowledge. Furthermore, only one group extensively interacted with mathematical knowledge, while most groups had fair interactions with recalling prior experiences during designing. In terms of the directionality of design moves, the participants did not use their scientific knowledge to generate ideas, as no group generated unidirectional forward design moves. Instead, all three groups used scientific knowledge only after generating initial thoughts. All three groups used technological knowledge to generate new thoughts, as shown in the unidirectional forward moves. The participants also used technological knowledge solely for the purpose of reflection or evaluation, as indicated by the number of unidirectional backward moves. The majority of the moves were bidirectional, meaning that the learners were able to reflect back on previously generated thoughts, while generating new thoughts and ideas about their understanding of the problem or their design solutions. In terms of mathematical knowledge and prior experiences, when the participants interacted with these conceptual structures, they were able to generate bidirectional design moves, which demonstrate the participant's ability to evaluate previously instantiated thoughts, but also to generate new avenues for thinking.

Physical interactions

Tables 6-9 summarise the different design moves that were generated as a result of learners' interactions with the problem statement, figures, drawings and physical objects.

Table 6. Directionality of thoughts when interacting with the problem statement

Problem statement interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	11 (3%)	11 (9.3%)	3 (1.7%)
Unidirectional backward	8 (2.2%)	13 (11%)	6 (3.5%)
Bidirectional design moves	23 (6.3%)	7 (6.7 %)	8 (4.6%)
Orphan moves	1	0	0

Table 7. Directionality of thoughts when interacting with figures

Figure interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	6 (1.6%)	1 (0.8%)	7 (4%)
Unidirectional backward	21 (5.8%)	3 (2.5%)	15 (8.7%)
Bidirectional design moves	94 (25.8%)	11 (9.3%)	49 (28.3%)
Orphan moves	0	1 (0.8%)	0

Table 8. Directionality of thoughts when interacting with drawings

Drawing interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	0	2 (1.7%)	2 (1.2%)
Unidirectional backward	19 (5.2%)	8 (6.8%)	12 (6.9%)
Bidirectional design moves	42 (11.3%)	4 (3.4%)	46 (26.6%)
Orphan moves	0	0	0

Table 9. Directionality of thoughts when interacting with physical objects

Physical object interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	0	7 (5.9%)	2 (1.2%)
Unidirectional backward	3 (0.8%)	18 (15.3%)	3 (1.7%)
Bidirectional design moves	12 (3.3%)	18 (15.3%)	6 (3.5%)
Orphan moves	0	2 (1.7%)	0

In this study, we regarded ‘physical structures’ as any material object that the participants interacted with during design problem structuring and solving. In this paper, we will be discussing the participants’ interactions with the problem statement, figures, drawings and physical objects. In terms of the participants’ interactions with their problem statements, the directionality of the design moves show that they seldom generated bidirectional moves. Furthermore, the participants rarely used the problem statement as a starting point for generating new thoughts, as a limited number of unidirectional forward moves occurred. In the same manner, they did not utilise the problem statement as a tool for evaluating and reflecting on already instantiated ideas. The participants’ interactions with figures in Groups A and C seemed to reflect productive thought processes as many bidirectional design moves were generated in these cases. In contrast, Group B seemed to have preferred working with physical objects during designing rather than using figures, as reflected in Table 9.

Discussion and conclusion

Children’s thought processes are embedded in environments that contain a variety of information sources that will inevitably influence how they think and what they do. For STEM teachers, it is important to understand the way in which learners interact within the classroom environment, especially in terms of the way that learners access information in social, conceptual and physical environments.

The results of the various groups’ interactive use of conceptual and physical structures relates to the theoretical assumptions of Extended Design Cognition Theory, which states that external information sources will function as scaffolds and constituents of internal cognitive processes (Haupt, 2015). Internal cognitive processes will in turn extend into the environment from which they can be manipulated (Menary & Gillet, 2017).

The idea that learners think by way of forward and backward design moves is vital to keep in mind because it shows how learners synthesise understanding and design ideas from nothing into something. To this end, the use of linkography implies a novel approach that successfully demonstrates how this method can be applied with STEM learners. More importantly, in this study linkography showed the connection between the different types of thoughts, including unidirectional, bidirectional and critical thoughts, as well as how these types of thoughts arose from learners’ interaction within their social, conceptual and physical environments.

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