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Synergy in Vertical Transformations of Expert Designers

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***Abstract*—**Existing literature ondesign reasoning seems to give either one sided accounts on expert design behaviour based on internal processing. In the same way ecological theoriesseem to focus one sidedly on external elementsthat result in a lack of unifying design cognition theory. Although current extended design cognition studies acknowledge the intellectual interaction between internal and external resources, there still seems to be insufficient understanding of the complexities involved in such interactive processes. As such,this paper proposes a novelmulti-directional model for design researchers tomap the complex and dynamic conduct controlling behaviour in which both the computational and ecological perspectives are integrated in a vertical manner. A clear distinction between identified intentional and emerging physical drivers, and relationships between them during the early phases of experts' design process, is demonstrated by presenting a case study in which the model was employed.

Keywords—External representation, early phases, extended design cognition, internal processes and external drivers, conduct controlling behaviour.

I. Introduction

ENGINEERS and other designers, such as architects and industrial designers, solve problems by achieving various intentions which they articulate early in the design process. To help them achieve their intentions, a process of synergetic coherence between abstract intentions and concrete decisions are needed. Arnheim [1] ascribes designers' ability to develop abstractions into concrete representations to a close coupling of abstraction and perception. This implies a synergetic interaction between complex internal processing and perception of external triggers. A systematic mapping to detect where and when directional changes take place and what served as decision drivers are therefore necessary. Top-down abstract intentions seem to drive decision making while bottom-up emerging physical elements in the design task environment both influence the control of what designers think about. The purpose of this paper is to describe empirical research on the ability of a pair of systems engineers to constantly switch between internal processes and external triggers, based on a multi-directional model. This paper will furthermore demonstrate how these switches are both represented and facilitated by the participants' external representations.

In the real world of design, productivity and effective expert decision making depend on tracking pivotal instances of changes in the direction of thought. It is therefore important to find ways to model such instances and the context in which they occur. One such way is to examine external representations of designers building on what is already known about the cognitive value of their sketches, hand-written notes, diagrams and charts, in addition to their verbal utterances. Designers' external representations not only serve as aids reducing the complexity of a problem [2], but also facilitate cognitive mechanisms such as conduct control in the transformation of intentional states to states of satisfaction[3]. Such conduct control implies that designers interactively use internal processes and stored knowledge, as well as perceived information embodied in external objects, including their sketches and physical objects which they connect with intentions of their design tasks. Satisfaction of these intentions implies gaining confidence in the fitness of purpose of the envisaged artifact [4]. Gaining such confidence takes place when control of decision making is based on the application of what designers know, what they perceive and how they connect new information with existing knowledge to intentions [5].

Researchers often use existing models to map their understanding of how experts make these connections during the early phases of the design process. However, computational researchers tend to approach the design process by focusing on internal process only. Similarly, ecological researchers tend to focus one sidedly on external factors influencing processes without providing maps accounting for the interaction between internal and external factors. Although extended cognition mapping is emerging, many interactive literature also lack in providing comprehensive models [5]. The aim of this paper is therefore to demonstrate the use of a practical model that researchers can use to empirically tracesome of the interactive problem solving processes. The advantages of the model discussed here is twofold. Firstly it enables mapping the relationship between the internal and external drivers of thoughts and secondly and visualises the moments of directional changes apparent in designers' thought processes while they concurrently talk and make sketches.

II. Literature Review

A. The Properties of Sketches

Designers typically use multiple external symbol systems when solving design problems [6]. As such, sketches play an integral role in the early phases of the design process. The

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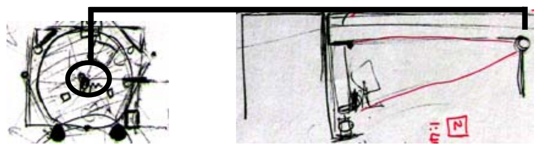
early phases entail problem structuring and preliminary design, detailing and refinement [7]. By linking these phases with the mental states of designers, it is evident that sketches not only reflect content of thoughts, but also correlate with particular mental states. Sketches thus serve as indicators of directional changes in thought processes.

Typically at the beginning of a problem solving task, when designers are uncertain, the symbol systems that they use usually display vague and ambiguous properties[8].It follows that the more certain and committed designers become as the design process progresses, the less ambiguous and more specific the structural properties of the symbol system used may be.In previous studies [7], [8], [10],it was found that there is a close correlation between the structural ambiguity/clarity of designers' sketches and the meanings there of. An example of the progression from ambiguity to specificity in two different sketches by the same designer is captured in Fig.1 extracted from an empirical study by Haupt [10]. In sketch (a) an ambiguous mark resembling a dot with no detail regarding its specific meaning, was developed in a separate sketch (b) at a later stage in the design process. In (b) the initial dot was developed into the idea of a mechanical rotating device [10].



(a) (b)

Fig. 1 Ambiguous marks developed into specific shapes affording content

The implication is that the process of makinggraphic marks facilitates the process of gaining certainty and satisfaction with fitness of purpose. This is made possible by the structural properties of conceptual sketches, which are by nature rough, ambiguous and often dense. Empirical evidence shows that it is the ambiguity of sketches that triggers new ideas and associations. It has also been shown that the ambiguity of the sketches enables designers to easily manipulate them and thus transform their ideas laterally or vertically [8]. Designers seem to need the ambiguity to generate alternatives which conventional computer software does not always allow them [9].

B. Sketches as Mediator between the Inner and Outer World

Numerous design cognition studies report on sketches that mediate internal recall of knowledge [8], [13], [14], a process which is regarded as part of designers' inner world. In aforementioned research it was[10] found that designers' recall of previous cases, which they externalise in sketches proceeds through an initial internal visualisation process that often results in the generation of additional ideas which fall outside the scope of their design briefs. Through manipulation of the structure of their sketches, designers transform initial ideas. They then incrementally manipulate the structure of the sketches. Emerging shapes that develop through construction and manipulation in their sketches, often trigger new ideas [15]. Simultaneously, the act of manipulation implies the transformation of their intentional state into a state of satisfaction. As such, designers' sketches serve as external causal structures that carry content as well as facilitators of transformation [16]. The act of sketching can therefore be viewed as the convergence of bearing content and processing it [15].

C. Hierarchical Thinking– Where Intentions Meet the Physical World

The aforementioned research [10], in which verbal and visual material were used to establish typical patterns in the hierarchical way expert designers think during the early phases of the design process, providedinteresting insights.

By classifying verbal data into categories of internal content and external elements [10] it was established that designers articulate intentions in a hierarchical manner. Internal content collapsed into three subcategories of intentions: aspectual intentions, functional intentions and implementation intentions. Aspectual intentions occur early during the problem structuring phase and are typically vague and abstract. They are typically abstractions of domain specific philosophical approaches to artifacts and people's interactions with them. As such, 'aspect' relates to aspects of life experienced by people [11]. When designers make conceptual sketches, theyintentionally relate their existing knowledge with new problems as they interpret it [12]. In order to achieve this, they firstly find out what the socio-cultural aspects of the context for which artifacts are intended entail [8].

From attention to aspectual intentions,designers attend to functional intentions;designers are required to consider technical and functional intentions of the artifacts.They subsequently develop their functionality ideas around the physical elements and properties of which the required artifacts should consist ofin order to work effectively. Designers connect functionality of artifacts with external elements that emerge from sketches and physical environments. Intertwined with internal processing, designers explore conceptually related ideas. It is at the intersection of the functional and physical level that internal processes meet external elements and arefound across the entire design process.When designers reach a stage of either temporary or final satisfaction of a particular functional intention they turn to another intention.

Implementation intentions are found in the entire problem solving phase and connect with aspectual and functional intentions. 'Implementation' refers to the active plans designers make to realise the aspectual and functional intentions. This increases when designers develop and refine their designs during the problem solving phase.

Intention satisfaction depends on the connection between all three categories as well as on its appropriate connection with physical elements.

D. Decision DriversinLoose Conduct Controlling Behaviour

Loose conduct control refers to designers' tendency to delay decision making and their openness to changing the content and direction of their thoughts [17], [18]. Traditionally computational researchers associated conduct controlling behaviour with internal processesonly, which implies causality [19]. Such internal processes assume that designers apply personal stopping rules and evaluation functions. In empirical design research this approach has, however, not yet offered convincingexplanations of how the typified loose control structures [20] of designers interact with embodiment theories.

By linking internal processing (recall, abstraction, pattern recognition and application of knowledge) withexternalised perception-action cycles previously mentioned research [10], provide plausible explanations for such slack control of expert designers. Itwas found that both internal and external drivers of designers' influenced their conduct control when they react on what they see. Internal drivers are aspectual and functional intentions that originate from knowledge. Aspectual intentions found were economics, aesthetics, spatial relationships, physics, lingual and formative, as labeled by Dooyeweerdt[11]. Aspectual drivers seemed to contribute to a delay in decision making due to their abstract nature. In the process of concretising them, considering design aspects provides multiple alternative combinations of physical elements. Designers' thoughts furthermore seemed to be primarily driven by two or three aspectual intentions during their entire protocol, based on personal preference or professional training [10]. Functional intentions also seemingly serve as internal driver, whereas implementation intentions result from the synthesis between aspectual, functional and physical considerations and thus do not count as a driver.

Empirical evidence [10] point to external drivers emerging from perceivable primitives and include shape, size, texture, space and colour emerging from the environment. The things that designers perceive primarily involve the external structures of their sketches and objects, and its elements and properties in their task environments. In both cases, designers pay prolonged attention to perceivable information when they are able to conceptually connect it with their aspectual and functional intentions [10], [13].

It was furthermore demonstrated [10] that once designers make such connections, they engage in repetitive and iterative cycles that consist of four possible configurations: intention-perception-action, perception-intention-action, perception-action-intention and intention-action-perception. Designers' cycles seem to be dependent on the source of the particular thought.Intertwined with the cycles was designers' normative judgment regarding the fitness of physical elements to satisfy particular intentions.There is a close association between the number of iterations and repetitive use of aspectual and functional intentions, both of which designers tend to connected with perceivable objects elements and the increase in specificity and commitment to ideas [10].

E. Reversing the Direction of Transformation

Designers are known to analyse their design briefs and interpret design problems in terms of their own professional and personal bias [21]. Existing studies[8], [10] point to the pivotal role such personal stopping rules play in the conduct controlling behaviour of designers. It is through the lens of their beliefs (derived from domain specific knowledge and general experience)and bias that designers interpret design problems, intentions and solutions. When they do this, they tend to question the appropriateness of a suggested solution or requirement by a client. They subsequently formulate their own intentions which they believe are better aligned to the 'real' problem. This behaviour is known as the 'reversal of the direction of transformation' [5], [8]. The aforementioned study[10] demonstrated strong association between the reversal of direction of transformation and the explicit and implicit representations of aspectual intentions of experts. The implication is that experts seek alignment between their interpretation of the problem and their preference of particular aspectual intentions [10].

Reversal is also strongly connected to expert professional knowledge, generic design knowledge and implementation intentions. Such connections allude to the driving role of reversal, which is primarily an interactive process of expressing intent. Empirical evidence exist [10], which demonstrate that reversal occurs right through the entire early design process. It is typically triggered by the design brief and perception of the external task environment and mechanised by normative judgment and superior domain related knowledge.

The question arising from decisions that designers makeon the basis of their personal preferences and beliefs is 'what is the relationship between such beliefs, their attempt to achieve coherencebetween connecting aspects, intentions and physical objects, and the psychological phenomenon of contesting clients' interpretation of an existing problem and their intentions articulated in design briefs.In order to answer this question, the sources of thoughts need to be mapped, as will be demonstrated further on.

F. Sources of Thoughts and Their Content

Sources of thoughts are considered the 'things' or 'activities' that trigger a process of transformation, but do not necessarily serve as cognitive drivers. However, cognitive drivers necessarily also act as triggers. Empirical exploration of the sources of designers' thoughts[10] resulted in two primary findings. The first relates to the nature of the triggers that influence the content and direction of designers' thoughts. Two types of triggers were found. The first trigger was internal and the second external in nature. The internal triggers fell into three subcategories: content of aspectual intentions, internal process of reversing the direction of transformation (to be discussed), and knowledge types stored in the long term memory. There were four external triggers, namely the design brief specifying the client's intentions, designers' sketches, 3-D objects, and partners. When external, triggers are invariably physical objects, whereas internal triggers can be intentional states or psychological processes represented in verbal and visual articulation, such as design briefs and recall of knowledge from long term memory (LTM).

G. Direction of Transformation of Thoughts

Three directions in design thinking are reported on in design studies [8, 10]. The first direction of transformation is a holistic vertical development of thoughts, and does not refer to individual ideas, but rather to amacro dynamic process in the thought process as a whole.These connections are found by tracing the source of a particular thought. The second direction is known as lateral transformation, taken from De Bono's creative thinking literature, but operates on a micro level of individual ideas [8]. The third direction is also known as vertical transformation [8], but involves individual thoughts on a micro level.

Empirical evidence was foundin the aforementioned study [10],of vertical coupling among intention-driven events on multiple timescales that allowed for establishing chunks, a phenomenon coined by Suwa, Purcell and Gero[22] with links between previous and subsequent changes to become apparent[23]. By creating nodes, it wasestablished [10] where internal and external sources and processes intersected.

Vertical connections imply top-down and bottom-up processes in the way designers process information and make commitments, to be discussed in more detail in the following section. Top-down processes are triggered and driven by internal sources; intentions (embodied in design briefs of clients as well as in the reversal of direction of transformation by designers), and knowledge of designers. When designers' attention to physical elements is intentional or knowledge driven, a top-down process is involved. This implies that external objects are dependent on higher order intentions. When designers' ideas originate opportunistically from perceiving an in-the-moment emerging physical property or element of an object, its direction isbottom-up. This implies that subsequent continuing cognitive activities, including forming new intentions (goal and implementation) and transforming ideasare dependent upon lower order emerging triggers.

The second direction identified in the said study [10] namely lateral, which can be traced in the sketches of designers. 'Lateral' transformation refers to movement from one idea to a slightly different idea [8]. Designers typically use lateral transformation during the preliminary problem solving phase when theyexperiment with different possibilities. The third direction, 'vertical' transformation on a micro level, entails that designers conceptually move from one idea to a more detailed and specific version of the same idea. They typically use vertical transformations tovisually clarify and develop existing ideas in greater detail when they develop their solutions [10].

From the literature discussed here, an understanding of the dependence of transformation of ideas by expert designers on constantly moving between internal intentional states and perceiving and processing the visually perceived external world. In the case study discussed in the following section, this process is explained in more detail, referring to a case study conducted on expert systems engineers en which the proposed model for mapping vertical transformation of thoughts were employed [10].

IV. Case Study

One sign of expertise in designing is designers'automatic switching of attention between information they have and what they do not have [25]. Another sign of their expertise is their ability to continuously search for holistic coherence [1]. The question begged is thus: how are expert designers able to move synergistically between top-down and bottom-up strategies of thinking and yet manage to maintain coherence? This question is addressed in this section, reducing it to two sub-questions. First, what are the driving forces that allow them to make these switches? Second, how do they use their sketches to facilitate maintenance of coherence? To address these questions, the types of cognitive activities of two systems engineers involved in an experimental design protocol are described integratively. It is argued that coherence is maintained through a constant revisiting of intentions by associating internal and external sources of thoughts withverticallines of thinking asmapped on a proposed model of multi-directional transformation of ideas (Fig. 4).

A. The Experiment

The experiment consisted of three design protocols. Two practicing architects and two engineers participated in pairs and worked for two hours. Three industrial designers participated as a small team and worked for three hours;the protocols were conducted separately. Each pair/team was considered as a unit and not as individuals. The architects were expected to work on designing an open air theatre on a university campus that should be intimate and convey a feeling of 'playful, creativity and growth'. The engineers worked on designing a rotating platform for an open air circular theatre with a total diameter of forty meters, on a university campus. The industrial designers worked on designing a system/device that could assist teachers with counting, organising and storing Lego™ used in week-end technology workshops at off-campus venues. They all received written briefs at the start of the sessions. I gave them basic standard instructions for protocol studies to think-aloud and sketch while they talked. The entire protocols and sketches were video-recorded.

At the request of the participants the researcher acted as client. Information was provided when the participants required it, but they were not interruptedor influenced in their decision making. The content of their verbal utterances as well as their sketches were used for thedata analysis. For practical purposes,only the engineers' case is discussed to demonstrate the implementation of the model that was devised to map their vertical thought process.

B. *Structuring the Model*

Partners were not considered as sources of input; combined pairs' or team knowledge, with which they entered the problem space, was considered as a unit. The 'brief' was viewed as internal to the design task environment. The content of participants' thoughts wascategorised, based on empirical and theoretical considerations [10].

The content of participants' verbal protocols was encoded into vertical levels of activities, categories and subcategories. It was further coded (Fig. 3) to map detail in the model, for which the key in Table I was used.

TABLE I
KEY FOR CODING VERTICAL TRANSFORMATION MAPS

Level	**Code interpretation**
Level 1:	INPUT
RE-E	Resource External Environment (Site)
RE-PH	Resource External Photograph
RI-B	Resource Internal Brief
RE-S	Resource External Sketch
RE-RB	Resource External Reference Book
RE-PSK	Resource External Previous Sketch
RE-L	Resource External Lego (in existing bags and boxes)
RI-LTM	Resource Internal Long Term Memory
Level 2:	ORIGIN OF GOAL INTENTIONS
I-1	Internal: Client Intentions
I-2	Internal: Reversal of client Intentions by participants
I-3	Internal: Additional own Intentions
	Link intentions with Levels 3 and 4 to indicate vertical connections between levels
Level 3: (sketches and writing coinciding with talking)	VISUAL OUTPUT
NS	New Sketch
R	Reinterpretation (of previous sketch)
LT	Lateral Transformation
VT	Vertical Transformation
IS	Identical Sketch
W	Writing
Nodes and loops	Link sketches horisontally to indicate conceptual links between sketches
Level 4:	PHYSICAL ELEMENTS meeting with FUNCTIONAL INTENTIONS
Ph-F	Physical elements
Level 5:	EMERGING PHYSICAL ELEMENTS
Ph-Ob	Physical Object (including sketches)
Ph-Ob-Pe	Physical Object-People interaction
Ph-El-Pr	Physical Element Properties
Background graphics	
Levels are graphically separated with various grey tones, which bear no conceptual interpretation apart from visually separating the various levels.	
Within the context of the Levels 1-5,vertical arrows indicate approximate time of origin, horisontal duration of vertical direction of thoughts	

The basic structure of the model adapts the well-known cognition concept of top-down and bottom-up vertical processing [26]. Starting from the top, the problem space was divided into levels: Level 1 – Input, Level 2 – Origin of goal intentions, Level 3 – Visual output, Level 4 - Physical elements meeting with functional intentions, Level 5 – Physical elements (including sketches). Level 1, input, included external and internal resources that the participants had access to. Level 2, goal intentions that encompass aspectual and functional intentions, falls into three categories: requirements of the client, reversal of the direction of transformation and additional intentions that the participants added. Functional intentions are identified by operators that imply behaviour of objects and human interaction with objects. Based on the empirical findings [10], the subcategory'conceptual knowledge' was developed into sub-sub-categories that indicate conceptual thoughts about objects and object-people-interactions.

Level 3, visual output, denotes the sketches and written notes of participants. This level is central to mapping the direction of participants' thoughts asit allows for semantic and syntactic evidence of directional change and therefore served as nodes from where conceptual connections could be drawn. The three subclasses of the sketches are 'new', 'reinterpretation', 'lateral transformation' and 'vertical transformation'. Level 4, where physical elements meet with functional intentions, refer to instances where emerging physical elements connect with structural components and surface properties in local objects or sketches. Level 5, emerging physical elements, refer to visual triggers provided by objects, primary elements and properties of objects.

C. *Encoding of Verbal Protocols*

Due to the emphasis on context of protocol studies, determining sequence and distribution of events were the underlying principles of all coding and decoding processes in this case study. The entire protocol of the engineers was dividedinto temporal instances and modules. 'Instance' refers to a particular occurrence of an observable or implicit psychological activity (Table I). Instances was analysed by using operators included 'commenting', 'qualifying', 'elaborating', 'justifying', 'evaluating', 'proposing' 'commenting' and 'repeating'. 'Module' refers to distinguishable themes emerging from the content of the verbal protocols. In some instances a module consisted of one theme only, while some modules developed into submodules. The modules were analysed by using two subcategories;the first was the conceptual knowledge subcategory, and individuated 'objects', 'people', and 'object-people-interaction'. The second was the ecology subcategory intention-attention that revealed the various intentions and their content. As a result of this individuation, the entire protocol could be clusteredinto short and continued chunks [21]. 'Short chunks' refers to themes that the engineers considered once or twice during their protocol, whereas 'continued chunks' refers to recurring and iterative consideration of the same theme throughout their protocol. Based on the temporal indicators on the video material the verbal themes could be matchedwith those in the sketches.

Input (Level 1) was identified through close observation of the video material. Input was subsequently connected with the content of verbal protocols to determine the origin and type of intentions on Level 2. It was then combined with the coding schedules of the participants' sketches in order to code Level 3.

Information to code Levels 4 and 5, indicators of thoughts about functional intentions and physical elementswere identified and applied. These indicators resulted in positioning nodes on relevant sketches in Level 3. Connecting loops between the sketches which shared the same content were

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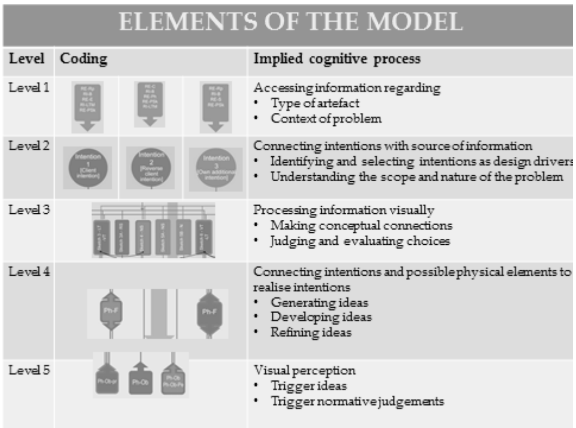
drawn. As such, the nodes and loops represent iteration and development of particular ideas.

The codes for Level 5 originated from 'knowledge' subcategories [10]. When thoughts originated on Level 3, the sketch/writing was consideredas a physical object embodying knowledge and wasthen also reflected on Level 5. Level 4was not considered as representative of individual sources of thoughts, but rather as a synthesis of processing thoughts.Physical objects meeting functional thoughts could therefore connect with ideas represented in Level 4 (sketches) with physical elements (Level 5). Similarly, they could connect to Level 3 and Level 2 (intentions) through perceptual stimuli from Level 5.

Thepositions of the large grey arrows in the background(Fig. 4) were determined temporally whenthe switch of triggers co-occurred with a change in vertical direction. When these arrows originate from the top, it means that the physical elements at the bottom merely interacted at those points in time. In contrast, when the arrows originate from the bottom, the physical elements in its vicinity serve as the source of the sketches that connect to the physical elements. Fig. 3 summarises the elements of the model (Fig.4) and the implied cognitive processes involved on each level.



ELEMENTS OF THE MODEL

Level	Coding	Implied cognitive process
Level 1		Accessing information regarding • Type of artefact • Context of problem
Level 2		Connecting intentions with source of information • Identifying and selecting intentions as design drivers • Understanding the scope and nature of the problem
Level 3		Processing information visually • Making conceptual connections • Judging and evaluating choices
Level 4		Connecting intentions and possible physical elements to realise intentions • Generating ideas • Developing ideas • Refining ideas
Level 5		Visual perception • Trigger ideas • Trigger normative judgements

Fig. 3 Elements of vertical model of transformation

D. Results

The engineers made a total of sixteen sketches that encompassed their entire design process (Level 3). They made ten new sketches while they reinterpreted two sketches. In turn they made two lateral and three vertical sketches. The semantic connections between these different sketches implied a linear progression in their consideration of the requirements of their brief. In spite of the fact that the majority of their sketches represented physical things (Level 5) that they thought about, their primary drive was the requirements of their brief (Level 1 and Level 2), which offset a predominantly top-down process, as is visualised in Fig. 4 by the large grey arrows in the foreground.

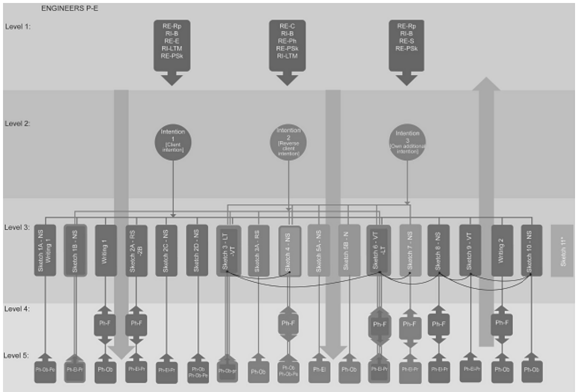


Fig. 4 Vertical transformation mapping of engineers' thoughts encompassing the entire protocol

The engineers' sketches (Level 3) contributedtolong chunks, a phenomenon supported by empirical research by Suwa and Tversky [26]. This could be attributed to sketches' ability to carry information [14] that fed intoparticipants' decision making processes. The correlation between the content of their sketches and co-occurring verbal utterances indicated that, when the engineers captured an idea in a sketch for the first time, the instance was triggered by the brief. They seemingly registered their own knowledge of the physical properties of the concept 'theatre' and domain specific knowledge 'rotation' and used this sketch to confirm their interpretation of the brief.

They subsequently progressed to generating ideas in their sketch 6 (see Fig. 5 below) which included provision for functional elements that are required to provide the expected performance from the platform. Fig. 5 demonstrates how the engineers used vague and ambiguous marks in their sketch that represented their initial vague thoughts about functional intentions meeting with physical elements, namely lighting, sound systems, modular canopies and rotational objects.

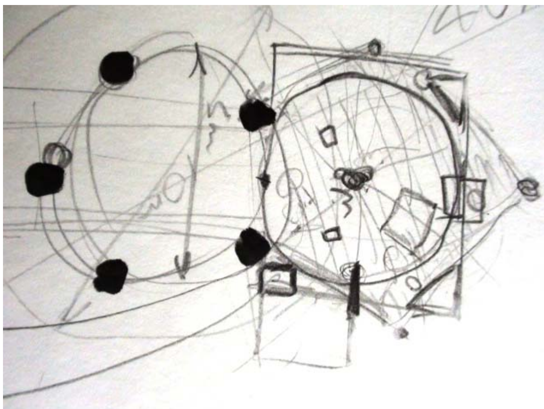


Fig. 5 Development sketch of engineers demonstrating the power of vague and ambiguous marks to represent specific physical elements with functional intentions

Their dialogue suggested that they reacted toperceptual stimuli from the external environment, while the video material impliedthat much interaction emerged from their sketches (Level 3 and 5). In addition,the engineers' repeated references to their brief's requirements seemed to take precedence over their own emerging ideas.Nonetheless, they reversed the directions of transformation (Level 2) by questioning the client'sintention regarding the required size of the theatre's stage articulated in their brief. They constructed a sketch to judge the size of the theatre (Level 3).

Evaluating it as excessively large, they adapted the size of the platform to dimensions of their own subjective choice. This means that their sketches served as an external mechanism that activated their evaluation functions and contributed to their commitment and decision to change the size of the stage to a size they believed appropriate.

No clear indication that the engineers generated this decision by applying domain specific knowledge (Level 2) could be found. It was thus inferred that it originated in their personal experience. The participants pursued this decision throughout their entire protocol, resulting in a long chunk.

The engineers had four other particular instances in which they reversed the transformation direction (Level 2). These instances were distributed close to one another and occurred during a leaky phase, while on site. Although perceiving physical elements on the site seemed to strongly influence their generation of additional ideas about the inclusion of an existing sculpture in their design of the mechanical objects, they later disregarded this idea on the basis that it fell outside their domain as well as their brief. This is confirmation of their dominant top-down approach (Level 1) to solving the problem in their aspectual intentions (Level 2).

Visual evidence of instances where the engineers considered aspect intentions in their dialogue could not easily be found in their sketches (Level 3). Their seeming preference for economic design and efficiency, which they explicitly stated and implied in their multiple references to 'simple' design, was not equally explicit in their sketches. However, coupled with their multiple sketches that consisted of physical elements, there was evidence of seven functional intentions by coupling their sketches with their dialogue. Two of these instances occurred during their problem structuring phase when they made sketches that were based on their pattern recognition evident in their recall of cases in which similar theatres were designed.

This implied that the engineers used their sketches as external scaffolds to understand the intentions of their design task set out insufficiently in their brief. Sketches 3 and 6 (Level 3) (see Fig. 5) were interesting as they represented complex thought processes. Input sources (Level 1) of these two sketches, as well as physical elements (Level 5) that the engineers included in all three sources of intentions (connection between Level 1 and 2), could be mapped. This indicated a seemingly simultaneous drive from their internal and external resources. In turn, it suggested the engineers' alignment of their aspectual intentions, functional intentions and physical elements to find holistic coherence [1] and fit for the purpose. This furthermore implied that the engineers considered physical properties of elements from various points of view and found multiple reasons to include a particular element and assisted them to generate both lateral and vertical development of ideas (Level 3).

V. Conclusion

This paper proposes a novel vertical transformation model based on theory and empirical evidence of primary design drivers and extended cognitive processes. As was shown in the analysis of systems engineers' verbal protocols and their co-occurring sketches, external visualisation serves a central facilitating role in connecting designers' inner and outer worlds. Sketches are not only the result of intentional acts of sketches, but they also serve as objects externally affording emerging perceivable information that trigger the generation of new ideas. Sketches furthermore assist designers in connecting new information with internal knowledge that is stored in their long term memories through pattern recognition. This paper thereby contributes to existing theory on three levels. Firstly, on the level of the cognitive role that sketches play during the early phases of the design process. Secondly it adds to existing theory on vertical reasoning processes. This demonstrates that sketches contribute to designers' ability to swiftly change their direction of thought processes from top-down to bottom-up. Finally, it wasshown that the proposedvertical transformation model is able to implicitly map rich information about the dynamics of designers' thoughts in a condensed form. However, it is limited in the information it provides regarding the distinction between aspectual and functional intentions on Level 2. The refinement of the model at this level could be considered in a study in which this level is developed further.

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