A Constraint-Based Understanding of Design Spaces

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ABSTRACT
This paper suggests a framework for understanding and manoeuvring design spaces based on insights from research into creativity constraints. We define the design space as a conceptual space, which in addition to being co-constituted, explored and developed by the designer encompasses the creativity constraints governing the design process. While design spaces can be highly complex, our constraint-based understanding enables us to argue for the benefits of a systematic approach to mapping and manipulating aspects of the design space. We discuss how designers by means of a simple representation, a design space schema, can identify the properties of the prospective product that s/he can form. Through a case study, we show how design space schemas can support designers in various ways, including gaining an overview of the design process, documenting it, reflecting on it, and developing design concepts. Finally, we discuss the potentials and limitations of this approach.

Author Keywords
Design space; creativity constraints, design processes; problem space; solution space

ACM Classification Keywords
H.5.m. Information interfaces and presentation: Misc.

INTRODUCTION

'Design space' is an oft-used term in the DIS community when practitioners and researchers describe and discuss the design process. Since the use of space as a metaphor is deeply embedded into our language – and as argued by e.g. Lakoff & Johnson [22], consequentially also into our ways of thinking and acting – it is not surprising that the notion of space is also prevalent in design discussions. Even so, there is no consensus as to the meaning of the term in design research. In some instances, it refers to physical spaces in which design activities are carried out, e.g. in design studios or labs [25]; in other instances, it refers to abstract, conceptual spaces in which designers navigate, as is e.g. the case with the notion of the 'third space' in the encounter between designers and users in Participatory Design [31]; and in other instances still, it refers to the discourse on design. In some cases, the ambiguity of the term can be beneficial, as it can serve as a conversational boundary object [44] in discussions between different practitioners and researchers in the field, the notion of space being open enough for each part to embed his/her own understandings into the term. Still, we argue that it is beneficial to define the notion of design space in terms of having more precise ways of addressing core issues in design research; in terms of increasing designers' awareness and overview of design processes; and in terms of making specific design moves on the basis of this understanding.

As a first delimitation, the perspective on design spaces presented here conceives design space as a *conceptual space*, and we do not directly address the notion of physical design spaces. As a second delimitation, our perspective is informed by creativity research into *constraints* (e.g. [6, 34]). Traditionally, researchers in this field have studied how constraints restrain the potential for creativity. In very recent years, attention has turned toward the ways in which constraints can simultaneously restrain and enable creative thought and action, and how practitioners through insights into constraints can manipulate them in order to further and strengthen their creative process. Thus, we focus on the components of the design space that can be manipulated. As a third delimitation, we mainly address properties of the potential future *product* of a design process, e.g. forms of interaction and intended use situations.

The *contributions* of this paper are three-fold: (1) the constraint-based articulation of the design space including a discussion of this perspective; (2) a simple format for documenting the manipulable components of the design space called a design space schema; (3) an initial discussion of ways in which practitioners can employ design space schemas productively in design. In contrast to other kinds of design representations capturing a specific design idea, the design space schema specifically encapsulates a space of opportunities.

The paper is structured as follows: We begin by offering an overview of related work in order to ground and position our work, primarily on the notion of design space, mapping and documenting design processes and, not least, the notion of constraints. We then present our constraint-based framework for design spaces, including the design space schema. In order to exemplify the framework in action, we

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introduce and analyse an interaction design case in which we have employed the framework. We discuss different ways of manipulating and manoeuvring the design space supported by this approach. Finally, we discuss the benefits and pitfalls of this way of understanding the design space.

RELATED WORK

We propose a constraint-based approach to representing central aspects of design spaces. Thus, we mainly position our work in relation to three forms of related work, namely contributions regarding the notion of design space, mapping and documenting design and, finally, constraints.

The Notion of Design Space

As said, we address design spaces understood as conceptual spaces, not physical spaces. In the past, a number of contributions to design literature have studied design space as a conceptual space although in quite diverse ways.

One of the early examinations of design space is found in the literature on design rationale, which seeks to document and analyse the underlying rationale for decisions made in a design process. MacLean et al. [26] define a design space as "a space of possibilities" (p. 203) and propose an approach dubbed Design Space Analysis to examine why specific possibilities were selected in the design process. McLean et al. also offer a notation technique for protocol analysis, 'QOC', focusing on the *questions* that might be posed regarding the shaping of an product (e.g. 'how wide should a scroll bar be?'), the *options* that were available (e.g. 'narrow' or 'wide'), and the *criteria* by which options were chosen in response to the question (e.g. 'size of the screen' and 'ease of hitting the scroll bar with the mouse'). Here, the design space is thus represented as discrete possibilities, and the aim of the post-hoc design space analysis is to uncover the line of reasoning behind a product. We find this an interesting approach in terms of unfolding the design process; however, we wish to move toward an approach that can be used more actively in the design process proper, and one that offers a more nuanced and broader overview of the design space. This intent resonates with that of Beaudouin-Lafon & Mackay [3], who broadly define a design space as something "which constrains design possibilities along some dimensions, while leaving others open for creative exploration" (p. 9). Beaudouin-Lafon & Mackay examine how prototyping can help designers expand and contract the design space. More recently, this understanding of design spaces is adopted by Benyon [4] in relation to other design techniques, e.g. brainstorming and the use of scenarios, but no further definition of design space is developed. The arguably most thorough treatment of the notion of design space is offered by Heape [19], who also sees the design space a conceptual space constructed by the designer, and concludes that "the design process can be described as the construction, exploration and expansion of a conceptual space; a Design Space" (p. 368). Heape builds upon the work of Schön [38, 40], among others, particularly in adopting a systemic and constructivist approach to understanding the design space as something that continuously develops in interplay (or conversation, to use Schön's terms) between the designer and the design problem. Heape analyses a range of student design projects and proposes an elaborate, if also fairly abstract, approach to diagramming design spaces in terms of point clouds [19, p. 305]. Our perspective is informed by both Beaudouin-Lafon & Mackay [3] and Heape [19]. The former suggests that the design space be understood as interplay between constraints and design possibilities; a suggestion we seek to expand and operationalize. The latter proposes a situated, systemic understanding of the design space as an evolving construct, and suggests an approach to mapping the design process as a whole. This understanding of the design space resonates with what we propose here, although we advocate a more focused way of capturing and diagramming the salient components of the design space that the designer can form. In line with Heape, our understanding of the design space is also influenced by Schön's pragmatist perspective, in which the designer plays a crucial role in constructing and developing the design space through processes of framing and inquiry.

Problem and Solution Space

In order to position our own conceptualisation of the design space, it is necessary to distinguish our use of the term from the notions of problem and solution space, which can be traced back to the seminal work by Reitman [37], Simon [43] and Simon & Newell [42]. According to Reitman, "a sequence of problem transformations may be thought of as a chain or path through a hypothetical problem space, with an initial problem as origin and the current problem as a temporary terminus" (p. 305) Thus, "each problem defines a set of constraints that must be met by subsequent transforms if they are to lead to a solution of that problem" (ibid.). Informed by Reitman's work, Simon [41] argues that "[d]esign solutions are sequences of action that lead to possible worlds satisfying specified constraints" (p. 124). According to Dorst [15], this view on problem and solution space comprises a rational problem-solving approach to design creativity, and it constitutes one of two main paradigms. As opposed to this, Dorst positions Schön's [38, 40] view on design as a reflective practice with emphasis on the unique characteristics of the individual design problem: "[I]t is clear that a 'problem space' is not given with the presentation of the design task; the designer *constructs* the design world within which he/she sets the dimensions of his/her problem space, and invents the moves by which he/she attempts to find solutions" [39, p. 11, emphasis in original]. Informed by both design creativity paradigms, but building specifically on the latter, the arguably prevailing understanding of problem and solution space is the so-called integrative systems view [2], according to which the problem space and the solution space co-evolve as argued by Maher [28], Maher & Poon [29], Maher and Tang [27] and Poon & Maher [36]. As Dorst & Cross [14] put it: "Creative design seems [...] to be a matter of developing and refining together both the formulation of a problem and ideas for a solution, with constant iteration of analysis, synthesis and evaluation processes between the two notional design 'spaces'—problem space and solution space" (p. 434). Thus, as noted by Dorst & Cross, the essential creative event in a design process is not primarily seen as a creative forward 'leap' from problem to solution. Rather, it is construed as the scaffolding of a 'bridge' that identifies a specific problem-solution pairing. This is what Schön [38] calls 'problem framing'. Recently, Wiltschnig, Christensen & Ball [49] have presented a similar argument for the problem-solution co-evolution, only in their case it is studied specifically within a collaborative setting. Here, we subscribe to their deliberately broad definition of problem space as "the required behaviour of the design" and solution space as "the potential structural combinations that constitute the design" (p. 516). In doing this, we wish to demarcate our own constraint-based understanding of the design space, as the terms 'problem space', 'solution space' and 'design space' are so closely connected (see e.g. Goel & Pirolli's [18] analyses of the 'design problem space'). Consequently, we will not explore in detail the conceptual complexity among these three terms. We deem it more fruitful to convey a specific understanding of the design space as a widely adopted, yet hitherto vaguely defined, key concept and point of reference in the design process.

Documenting and Mapping Design

We propose a simple annotation technique for capturing salient components of the design space, entitled a *design space schema*. This approach is informed by previous work on documenting and mapping design. As said, Heape [19] has proposed a notation technique for illustrating design projects as design spaces, focusing on a designer's exploration and experiments to create a composition from a myriad of potential components. This is an inspiring, if also very elaborate technique. Our approach builds more directly upon a simpler notation, namely Zwicky's [50] and Zwicky & Wilson's [51] work on morphological analysis, which concerns the identification and investigation of the possible relationships or configurations in complex problems. Morphological analysis means identifying the parameters of a problem and then finding the conditions for each parameter. By doing so, an overview of the problem can be established, and different configurations can be examined. Zwicky [50] suggests that the parameters and conditions be represented in a matrix, which informs our approach, since it offers a very straightforward mode of mapping potentially complex issues and interrelations between various parameters of a design space, e.g. a simple matrix with three parameters, each listing five conditions, can represent 125 different configurations. While Zwicky did not bring morphological analysis to bear on design, a series of more recent contributions have discussed different ways of documenting and mapping design. Dalsgaard, Halskov & Nielsen's [13] work most clearly resembles Zwicky's matrix approach in an examination of salient aspects in the design of media façades (the use of interactive technologies to enhance building façades) such as the interplay between different forms of interaction forms, content types and physical materials. Prior to that, Lanzara & Mathiassen [23] have proposed that different types of mapping design processes can improve the managing of design processes, e.g. by using diagnostic maps to identify perceived problems in the design process, or by using historical maps to outline the chronology of a project. Subsequently, Dalsgaard, Halskov & Nielsen [12] have proposed three types of maps for design reflection, i.e. overview maps for capturing the general flow of a design process, strand maps for focusing on the development of a specific concept during a design process, and focal maps for describing and reflecting upon a specific design event.

Creativity Constraints

As articulated by the said two design creativity paradigms [15], conceptualising a given design task most often entails finding an innovative solution to a creative design problem. Since the influential work by Reitman [37] and Simon [41], *constraints* have become part of not only a rational view on design as advanced problem-solving, but integral to a broadly accepted understanding of design. Chandrasekaran [10] even argues that "[formally], all design can be thought of as constraint satisfaction, and one might be tempted to propose global constraint satisfaction as a universal solution for design" (p. 65). Etymologically, the term constraint suggests a merely restraining property, i.e. constraints as "limitations on action [that] set boundaries on solutions" [48, p. 198]. Even so, a number of researchers (e.g. [16, 20, 30, 32]), have stressed how constraints play a dual role by also having an enabling character. As Boden [8] remarks, "[c]onstraints on thinking do not merely constrain, but also make certain thoughts - certain mental structures - possible" (p. 58). Constraints appear in all creative domains, but are often labelled as requirements, conditions, conventions, rules, demands, etc., depending on the specific domain. This diverseness causes a fragmented view on constraints and their salient features. In order to bridge findings from individual creative domains and design in particular, we have elsewhere argued for adopting the proposed domain-general unifying descriptor 'creativity constraints' meaning "explicit or tacit factors governing what the creative agent/s must, should, can, and cannot do; and what the creative output must, should, can, and cannot be" [33, p. 8]. In our comprehensive reviews of current contributions to research into creativity constraints [5, 6, 35], we have shown how creativity constraints in design are usually conceived as exhibiting (at least) two salient features in addition to their dual enabling and restraining character. These two features concern *mapping* and *manipulability* of creativity constraints. As for mapping, Elster [16] has offered an extensive philosophical treatment of constraints and the benefits to agency that they entail. Specifically, Elster has built various typologies, notably the distinction between *intrinsic* (i.e., material, situated, built-in), *imposed* (by external stakeholders) and *self-imposed* (by the agent him-/herself) constraints, albeit with no clear focus on creative processes. Within creativity research, Amabile [1] has established a generic typology of creativity constraints, but with no particular focus on design. In terms of design research, the argued main contribution has been offered by Lawson [24], who has devised a (three-dimensional) cube-like model of creativity constraints specifically adhering to (architectural) design problems. While the model's thirty-two boxes pin down specific design challenges and obstacles, it says less about the creativity constraints pertaining to the creative design *process* itself. Stokes [46], on the other hand, has presented a problem-solving model that not only applies to (rational) problem-solving, but also focuses on the mapping and manipulability of creativity constraints of relevance to many creative domains. From Reitman [37, see his so-called 'open constraints'], Stokes incorporates the idea that paired constraints direct and limit search in a problem space, and from Simon [41, 43] that search can only lead to novel solutions if the problem is ill-structured [47, p. 174]. This leads Stokes to assert that creativity constraints can be chosen and are indeed manipulable throughout a creative process. While Stokes [46, 47] covers a number of creative domains, she does not investigate design. In our current conceptualisation of the design space, therefore, we draw on previous and relatively disjointed contributions, which each informs our work. Specifically, we draw on our proposal of (a) creativity constraints as a domain-general unifying descriptor; the idea of (b) mapping creativity constraints in the tradition of Amabile [1] and Lawson [24]; and the emphasis on the (c) manipulability of creativity constraints as underlined by Reitman [37] and further developed by Stokes [46, 47]. Finally, in prioritising creativity constraints as integral to creative processes in general and design in particular, we bring ourselves in accord with leading creativity researchers Sternberg & Kaufman whose concluding chapter [45] in the most recent edition of *The Cambridge Handbook of Creativity* [21] stresses constraints as a pivotal growing area of analysis in creativity research in a broad sense and thus also in design.

A CONSTRAINT-BASED UNDERSTANDING OF DESIGN SPACES

On the theoretical foundation presented above, *we define a design space as a conceptual space, which encompasses the creativity constraints that govern what the outcome of the design process might (and might not) be.* A design space is thus a construct, developed by the designer on the basis of his/her knowledge and experience (or repertoire, in Schön's terms) in response to external conditions such as the terms of a contract, a design brief or the materials at disposal. Since a design space is co-constituted by the designer and the conditions of the design project, it changes not only according to these conditions, but also when designers learn more about the situation they as designers address, and examine new approaches while discarding old ones.

Via the designers' mapping and evolving understanding of manipulable, salient components of the design space, it may come to be interpreted in new ways. Sometimes, this may lead to interesting new combinations of existing parts; at other times, it may show the limitations of what was previously deemed a promising path for the project.

In addition to our constraint-based definition of the design space, we propose a notation technique for capturing salient components of a design space in a so-called *design space schema*, which is based on previous research [12, 50, 51]. A design space schema is basically a table consisting of *aspects* (similar to what Zwicky denotes parameters) listed in the top row and a number of *options* (or conditions, in Zwicky's terminology) for each aspect in the columns below. As an example, consider the design space schema in Table 1 representing the design space for the initial part of a media architecture design project that our research group has previously undertaken [13]. This design space schema offers a systematic overview of key aspects of the media façades at a given point in time: Display, Location, Situation, Interaction, Content, Purpose and Experience. For each of the aspects, the options in a specific column represent a list of alternatives considered in the design process, e.g. the display technology may either be LED panels or projections. A particular use scenario or design concept may be construed as a path through the design space, e.g. 'a *bodily interaction façade* using *projection* technology communicating *information* in a *playful* manner when people *arrive* at the *entrance* of the building'.

As indicated by the '….' in the far right-hand side column, more aspects may be added during the design process. Also, an aspect may be eliminated or ignored. As regards a specific aspect, options may similarly be added or removed as the design process unfolds. Informed by creativity constraint research, we consider the aspects and options to be both *restraining* and *enabling*. On a concrete level, an option represents a possible component in a design solution, but at the same time, it can also rule out other components, e.g. deciding on content for guidance may rule out considering subtle experience. On a more abstract level, a set of options can lead the designer to think in distinct ways

Display	Location	Situation	Interaction	Content	Purpose	Experience	…
LED	Entrance	Arrival	Touch	Guidance	Information	Playful	…
Projection	Wall	Exploration	Gesture	Ornaments	Branding	Subtle	…
…	Façade	…	Bodily	…	…	…	…

Table 1. The design space schema for a media architecture project.

about how to solve the problem at hand, while at the same time function as blinkers that obfuscate alternatives. And going further still, the act of physically noting down certain parameters while leaving out others creates a tangible design artefact, which can become a nexus for design discussions and decisions. Using the terminology of Actor Network Theory, the act of creating a design space schema can be seen as a process of inscription: "An inscription is the result of the translation of one's interest into material form" [9, p. 143]. This, says Callon (ibid.), can result in the design space schema prescribing certain programs of action, i.e. prompting designers to act in certain ways. This is not necessarily a negative since design is as much about ruling out undesired options as it is about selecting desired ones. Still, it is an inherent part of creating a design space schema that designers must consider.

A design space schema cannot capture all aspects of a design process, nor is it meant to. It is developed to give an overview of a complex situation in a straightforward and accessible form. We propose it as a means for designers to consider and map the aspects of the process that they find most salient. As design spaces are dynamic and evolve over time, a design space schema represents a moment in time, and it also changes over the course of time. In the following case study, we show how a design space schema transforms in a design project, and in the discussion, we suggest strategies for working with the schema, which designers can employ to manipulate and manoeuvre the design space.

LEGO PROJECTED PLAY

We have applied the design space schema as a tool to support design in several cases, and as our main case, we here present and discuss Projected Play, an instance of tangible 3D tabletops based on 3D projection. In this case, we have primarily used the design space schema as a tool for documenting and analysing the design process. We have chosen this case due to its explanatory power in that it is a concise example that enables us to show the constraint-based approach and the design space schema within the scope of the paper.

As described in [11], 3D projection on physical objects is a particular kind of augmented reality that augments a physical object by projecting digital content directly onto it. Three-dimensional projection installations are based on having an accurate 3D model of the physical part of the augmented reality installation. In the digital 3D world, one can produce digital content corresponding to the shape of a physical object. By positioning and calibrating the projection system so that the relationship of the projection to the physical object corresponds to the virtual camera's relation to the 3D model, one can project the digital model onto the physical elements of the installation, thereby augmenting the physical object. The tangible 3D Tabletop platform developed by our research laboratory, CAVI, consists of a translucent table surface under which are mounted two projectors and two cameras, see Figure 1.

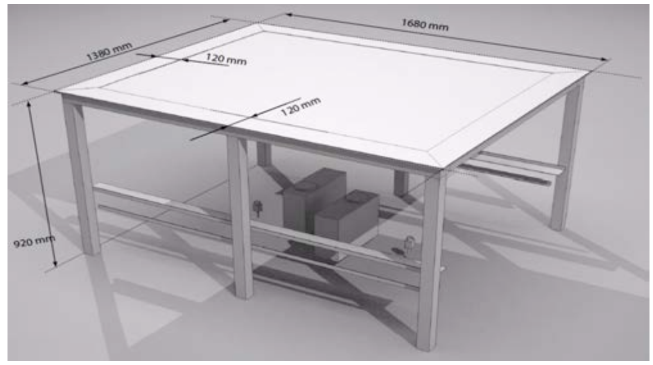

Figure 1. The Tabletop.

Above the table, two additional projectors are mounted (not shown in Figure 1). The projectors underneath the table display visuals on the table, while the projectors mounted around the table project content onto tangibles on the table surface, which are fitted with visual markers beneath their bases. The visual markers and tracking software have been custom-developed by our research laboratory.

Projected Play is a series of experimental prototypes developed in collaboration with the LEGO Group. A recent implementation was tested at LEGO World in Copenhagen, Denmark, in 2013, a four-day event offering visiting families the opportunity to play with LEGO. In this case, we operate with two kinds of tangibles: cubes and stylised buildings as featured on Figure 2.

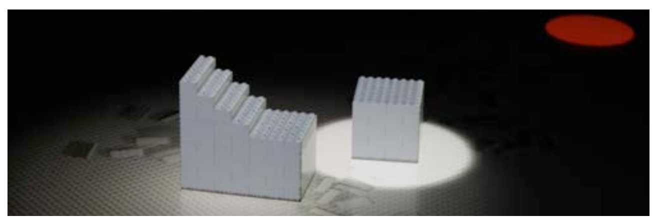

Figure 2. Cubes and stylised buildings.

On the table surface, we have set coloured circles along the edge of the table surface. When introduced onto the table, all tangibles are white. The cubes produce virtual bricks that are sprayed onto the table. When a cube is moved over one of the circles, the cube is 'filled up' or 'painted' with the colour of the circle, Figure 3, and the bricks sprayed from it now match that colour.

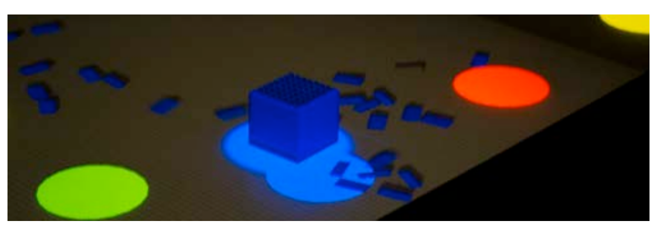

Figure 3. Painting a cube.

All cubes can push away the virtual bricks on the table, which have 3D physics properties. When two coloured cubes are close to each other, they flicker and exchange colour. When a cube touches a building, a layer of bricks gets filled with the colour of the cube, thereby enabling users to paint buildings in different layers of colour, see Figure 4. When a building is coloured from bottom to top, it emits a large flash and blows away the virtual bricks.

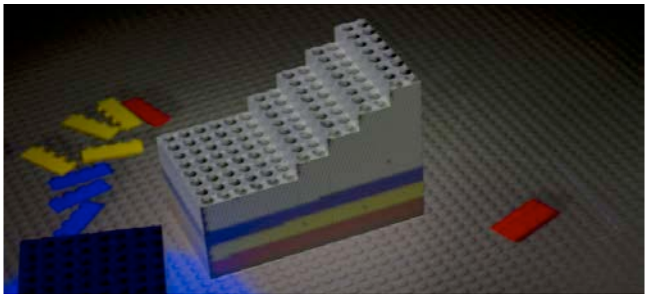

Figure 4. Painting layers of a building.

THE LEGO PROJECTED PLAY DESIGN PROCESS

Here, we discuss how the design of the Projected Play installation emerged through a series of design explorations and design experiments. For the analysis, we apply the design space schema as a framework for understanding and manoeuvring design spaces at particular points in time of the design process. First, we look into the design of the Tabletop platform on which Projected Play is built.

The Tabletop Platform

Our research laboratory has previously built two interactive tabletops; however, the tabletop surface of each of these was considered too small for an event as big as LEGO World, which attracts thousands of visitors.

Table 2 below represents an early version of the initial design space as perceived by our team of engineers and designers, and it captures the main aspects considered. The design space at this point in time is of an engineering kind consisting mainly of quantitative or measurable properties such as the dimensions of the table (Height and Surface Size). For some of the aspects, we consider sub-aspects, like in the case of the projectors where we for each of them consider aspects such as Lumens, Resolution, Number of Projectors, and Throw (distance to the projection surface). We could have represented it differently with four separate design aspects for projectors, e.g. Top Projector Lumens, Top Projector Resolution, with a separate column for each, but for reasons of simplicity, we have chosen to gather these aspects in a single aspect of the design space schema. It should be noted that the projectors are a special part of the design space, because our design team does not design the projectors, but select them from a pool of commercially available projectors. In order to simplify our presentation here, the camera used for tracking objects together with light sources under the table surface and aspect ratios of projectors are design aspects not included in the design space schema in Table 2.

Height	Surface Size	Top Projectors	Bottom Projectors
60 cm – 100 cm	Length: 1.5 m – 2 m Width: 0.8 m – 1.5 m	Lumens: 1400 + 3000 Resolution: High Numbers: 1-4 Throw: Standard	Lumens: 2 x 2600 Resolution: Standard Numbers: 1-2 Throw: Short

Table 2. Initial design space for the Tabletop platform.

A crucial part of the context for testing the first prototype was the fact that it first of all was a busy venue with more that 40,000 visitors over a four-day period including many children of all ages. Therefore, it was important that the table surface was of a size that could accommodate more than just three or four people at a time, but also that the height of the table would still allow smaller children to reach the tangible object to be added to the set. In this sense, a Height of no more than 80 cm – 90 cm was a crucial constraint together with a Surface Size of the table of around 1.2 m (width) by 1.8 m (length). Once settled on these aspects, next to consider were the Bottom Projectors. The tentative decision with respect to the size of the table surface meant that two projectors were needed, each having to cover at least half of the tabletop surface. In order to respect the low height of the table, finding the proper short-throw projector was a challenge. Looking into standard projectors on the market led the designers to reconsider the height of the table, which was increased slightly to fit with the projectors with the lowest available short-flow distance.

The Top Projectors were selected based on experiences from past 3D projection projects, which had made it evident that high-resolution was crucial due to the acute projection angle onto the tangible to be added later in the process. Realising the next step in the process, it was also decided to use two Top Projectors in order to cover projection on all sides of the tangibles. Another aspect of the intended context of use was the highly illuminated light condition at the LEGO World site. This led to choosing Top Projectors with high lumens specification available – with an eye toward Cost. The number of projectors could have been a potentially critical constraint, but the software infrastructure previously developed in our lab was designed to manage, in principle, an unlimited number of projectors.

The physical design, not least ease of transportation, was another critical constraint. The cost of producing the table was balanced out against the cost of transporting and setting up the tabletop on-site outside our laboratory, which was expected to occur on multiple occasions leading to the physical design of producing the table in a collapsible form made out of light-weight materials. The design decision with regard to this aspect of the design space affected previous decisions concerning another aspect, Surface Size, which was adjusted slightly to a smaller size. Table 3 shows the eventual design mapped onto the design space schema.

Height	Surface Size	Top Projectors	Bottom Projectors
93 cm	Length: 1.44m Width: 1.14m	Lumens: 1400 + 3000 Resolution: 2 x 1920 x 1080 Numbers: 2 Throw: Standard, 1.50 – 1.80:1 1.60 – 2.21:1	Lumens: 2 x 2600 Resolution: 1280 x 800 Numbers: 2 Throw: Short, 0.53:1

Table 3. Eventual design space for the Tabletop platform.

Projected Play

For the initial part of the design process, multiple ideas were proposed and in order to structure design discussion, the design space considered was represented as the schema shown in Table 4. The design space schema conveys how certain aspects of the design space are more concretely considered than others. At this point, Content on Table Surface was not addressed except for the consideration that it most likely was going to be 'LEGO-related' whereas, which we return to, the main focus was on the Basic Idea. But first, it is important to note that Tangible Shape was a particular concern, since we have previously implemented a couple of other Tangible 3D Tabletop installations using tangibles with very simple geometrical shapes, e.g. cubes and boxes. However, for the current project, we wanted to challenge our technical 3D projection setup, which we believed could accommodate more complex shapes. Based on past design experiments, we were very much aware of how the 3D projection set-up constituted a constraint with regard to how complex the Content on the Tangibles could be. Due to the resolution of the visual material projected onto the tangible, content could only be simple graphical material, not text. Also, if we opted for tangibles of a more complex form than before, this would be an even stronger constraint on the content projected onto the tangibles.

Since we also had a research interest in experience design, we included Experience as a separate design aspect to capture our interest in designing for and studying emergent and exploratory use. This design aspect thus constituted a self-imposed creativity constraint. Use Situation as such is not part of the actual design, but is intended to capture that we were considering whether to design a single-user system or a multi-user system. By addressing this aspect explicitly, we later realised that we wanted to design for multiple user groups at the same time. The pivotal aspect of the design space was the Basic Idea for which we brainstormed many candidates, including a game and a learning platform. The brainstorming was guided, informed, and constrained by many of the other aspects, but in different ways. The fact that we had early on chosen a particular kind of experience (emergent and exploratory) was a decisive constraint (a concept presented in detail in [5]) having a profound impact on the kind of Basic Ideas we considered and, not least, chose to exclude, e.g. we did not explore in detail any learning applications. Another insight was that the tangible tabletop with multiple tangibles could potentially smoothly accommodate two or more groups playing at the same time. Likewise, the goal of pursuing design for exploratory experience seemed to go hand-in-hand with the right content on the tangibles. Also, the fact that the design and implementation had to be completed within five weeks constituted a process-oriented constraint.

The most significant design decision made was going for designing not a game with specific rules or gameplay, but an interactive installation with colour-changing tangible objects. This decision led to modifications of the design space considered, see Table 5. Some aspects were narrowed down to a single option, e.g. the Basic Idea; other aspects were expanded or elaborated in more detail, while some remained fixed constraints, e.g. emergent and exploratory Experience. Deciding on the Basic Idea directed focus on other aspects, especially the two aspects related to the tangibles. As first choice, it was decided to work with cubes built from white LEGO bricks; a decision the designers felt confident about when it came to adding visual material by means of projection. Having decided on one of the options concerning Tangible Shape, the designers turned to the related aspect of Content on Tangible. Thus, the design space schema was both a driver of the process and used as a way of capturing (perhaps only tentative) decisions.

The choice of creating the tangibles out of LEGO bricks enforced an inherent constraint on the complexity of the tangibles. However, as it was a research goal of the project to explore the boundaries with regard to the complexity of the tangibles projected onto, it was decided to expand that particular aspect of the design space. Building a car out of white LEGO bricks was considered, but the decision was soon made to go for something more basic, namely an Asian-style tower and a simple stairway.

Content on Table Surface	Content on Tangible	Tangible Shape	Experience	Basic Idea	Use Situation
	Simple and graphical LEGO style	Slightly complex Cubes Stairs Asian-style tower	Emergent Exploratory	Game Tetris game Learning	Individual Social Multiple groups Walk-up and use

Table 4. Initial design space for Projected Play.

Content on Table Surface	Content on Tangible	Tangible Shape	Experience	Basic Idea	Use Situation	Interaction
Coloured spots in LEGO primary colours A sea of LEGO bricks	Mono-chrome LEGO primary colours (red, blue, green, yellow)	Cubes LEGO car Asian-style tower Stairway	Emergent Exploratory	Playing with colour-changing LEGO objects	Individual Social Multiple groups Walk-up and use	Colouring of cubes Objects exchanging colours Cubes colouring the other objects

Table 5. Eventual design space for Projected Play.

Hitherto, Interaction as well as Content on Table Surface had not been considered and constituted an empty corner of the design space. Coloured spots for each of four primary colours were added along the edges of the table, and moving a white cube onto one of the coloured spots would paint the cube in the corresponding colour. The Interaction aspect of the design space was further expanded by adding two more elements: (1) bringing two cubes close to each others would trigger an exchange of colour between the two visualised by a checkered animation; (2) moving a cube close to a tower tangible or the stairway object would add a coloured layer to the tangible. All design decisions were guided by the constraints settled by the Experience aspect and the concern for the Use Situation.

For the last part of the design process, a little more attention was paid to the content of the tabletop by adding a sea of floating LEGO bricks, which opened up an opportunity in another part of the design space, Interaction. This led to the additional feature that when the tower or the stairway-tangible had been coloured by cubes, an explosion occurred repelling the nearby bricks in the sea of LEGO bricks.

DISCUSSION

The issue of how design projects unfold and why design concepts end up the way they do is integral to design research. Here, we have defined the *design space* as a conceptual space, which (a) encompasses the *creativity constraints* that govern what the outcome of the design process might (and might not) be; and which (b) is co-constituted, explored and shaped by the *designer* during the design process. Also, in order to study how design spaces are established and transformed throughout a design process, we have proposed a particular form of (c) *schema* as a concrete means to represent the design space.

Using a specific design process as our object of study enables us to identify a number of strategies that designers apply when manipulating and manoeuvring the design space. The *design space schema* enables the designer to work both globally and locally in the sense of identifying and addressing several aspects at a time versus working with a single aspect at a time. This way of working is much similar to creating horizontal and vertical prototypes [17].

Decisions about what to include in the design space schema reflect what the designer perceives as pivotal aspects of the design, thereby bringing to the foreground the most crucial – and critical – aspects. Our present initial and limited study of the use of the design space schema clearly suggests the use of several *strategies*: (1) Dynamically removing and adding aspects; (2) Dynamically removing and adding options; (3) Brainstorming with regard to options within one aspect; (4) Temporarily ignoring aspects; and (5) Deciding (perhaps only temporarily) on one aspect to consider the implication with respect to another aspect. In our previous use of the design space schema, we have applied the strategy of systematically combining all options with regard to two or more aspects; however, we have not observed this strategy in the current case.

In addition to (a) providing an overview of the design space, the design space schema (b) directly supports ideation; (c) serves as documentation; (d) supports internal as well as external communication; (e) establishes a shared understanding among design team members; and (f) serves as a resource for reflection on a given design process.

The design space schema shares many similarities with various kinds of design representations, but in contrast to these, the design schema encapsulates not a specific design idea but rather, as the term suggests, a *space of opportunities*. Moreover, the design space schema thinking offers a way of capturing how a design concept has evolved over time, including decisions made and alternatives considered. The design space schema helped us keep track of aspects considered and which of those aspects that were deemed the most important ones to consider. At the same time, making parts of a design space explicit in a design space schema may actually help in finding blind spots in the design, e.g. the relation between tangible and tabletop content in the specific case considered.

The design space thinking strategy may seem to potentially encompass most aspects of the design process; however, as we have briefly touched upon, focus is on the design itself, not process-related aspects such as stakeholders, methods, deadlines, money, skills of the design team members, market considerations and more. In the case discussed, we have included a single of the non-product oriented aspects, namely context of use, since choosing LEGO World as the venue for testing a tangible tabletop installation constituted a crucial self-imposed creativity constraint that governed the entire design process.

The research in this paper is limited by building mainly on a single case, which raises the obvious question whether our approach is worthwhile in other situations, e.g. in much less open-ended design tasks like the design of an e-commerce website, to give a more industry-oriented example.

We have argued for a constraint-based understanding of the design space as a conceptual space, which (a) encompasses the *creativity constraints* that govern what the outcome of the design process might (and might not) be; and which (b) is co-constituted, explored and shaped by the *designer* throughout the design process. Also, we have argued that the design space may profitably be represented in the form of (c) a *design space schema* organised around *options* subsumed under various *aspects*. This approach to a design process enables and supports one particular kind of design thinking for designers, and for researchers, the approach provides a useful platform for conducting design research. Compared to some of the other ways of conceptualising and representing design, we argue that the creativity constraint-based understanding of the design space we have presented entails (at least) three advantages: (1) it is straightforward in terms of mapping and visualisation; (2) it can be as sketchy and simple or as comprehensive and detailed as the situation requires; and, given the manipulability of the design space schemas, (3) it is easy to use as a means to manoeuvre and transform the design space.

We plan on advancing this research in several ways. As regards the technical aspects, an obvious next step is to examine the possibilities for implementing a tool for capturing the design space, thereby making it less costly to capture the design space at specific points in the design process as well as help keep track of how the design space is transformed throughout the process. As for the practical use aspects, we plan on documenting and studying the design space schema in use in a number of design cases in which we will also introduce other representation and documentation resources and tools in order to get a richer understanding of the benefits and limitations of different design representation tools, as well as the underlying assumptions that such tools embody.

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