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Prototyping: The Dual Actions

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Reflecting upon the constructionist model "learning-by-making," prototyping (prototype making) as a product design and research approach is well recognised for assured development of innovative concepts in individual or collaborative working environments. A prototype is typically used as a tool to support experiments or interventions and to evaluate research goals. It also facilitates participatory design and user-centred design. However, it carries both coded and tacit knowledge that we, design educators and practitioners, find problematic to explain and instruct, particularly to non-designers. This paper amalgamates and argues the characteristics of prototyping including types, formats, and principles through literature review. Reflecting upon the designer's intentions and the dual coding cognitive learning process, the author proposes a descriptive model that illustrates the dual actions experienced by the designer which can enable study on the improvement of the prototyping process.

#prototyping

#constructionism

#dual coding theory

#analytical-synthetic action

Introduction

A prototype is a simplification of a product concept meant to resolve issues in product development (Otto et al. 2001). It can be considered as an ideation technique in which a physical object is built to encourage new ideas-"we build to think" (Rikke and Teo 2019). Designers and non-design practitioners recognise prototyping, or prototype making, as an essential activity for innovation, collaboration, and creativity in design (Hartmann et al. 2006). Described by Murray et al. (2010), prototyping is the design of a working model of a product or service to test out reactions of potential clients and providers. It is an informal evaluation or testing approach to test ideas in an incomplete form and move quickly into practice. Operating principles of prototyping include:

1. Speedy production processes;
2. Low cost;
3. Providing tangible experience;
4. Iterative design; and
5. Feedback from users and specialists.

Prototyping became a buzzword during the design thinking movement, elaborated by 3D printing and maker culture's emergence in the last decade (Halverson and Sheridan 2014). More people recognise that physical models support the transformation of intangible concepts or two-dimensional experiences into physical or three-dimensional objects that users can effectively understand, such as perceiving form factors or ergonomic responses (Rikke and Teo 2019). In Hong Kong, there are numerous non-academic organisations, such as the Hong Kong Design Centre and some professional societies, promoting design thinking and offering participants a glimpse into designer-ly ways of thinking or working. Target audiences include non-design professionals, such as business community leaders and civil servants. The design thinking process of the "the five-stage Design Thinking model by The Hasso Plattner Institute of Design at Stanford University" and the "double diamond model" of the British Design Council are favourable guiding principles, through which exercises numerous people have learned about the prototyping methodology.

For social innovation projects, Hillgren et al. (2011) elaborated the advantages of incorporating prototyping as a method for establishing long-term engagement with stakeholders. Prototyping can facilitate open discussion, conflict realisation, empathy development, consensus development, and conflict resolution through visualisation and collective experience. As prototyping is prior to *final* implementation, which conceptually limits freedom for further interpretation, modification, and negotiation, prototyping increases stakeholder buy-in and reduces conflict.

This approach follows the principle, "Fail earlier to succeed sooner" in the context of use (Burns et al. 2006; Brown and Wyatt 2010). Prototyping is an informal evaluation or testing approach for an idea to emerge in an incomplete form and swiftly move into practice. For bottom-up social innovation initiatives, prototypes act as catalysts and binders which help stakeholders, especially non-professionals who take part, build ownership. Prototypes allow collective involvement through iterative development: a prototype is understandable as part of an ongoing process, open to user contribution. As such, it not only supports conventional design processes, but also extends into the social economy by connecting users to professionals, resolving conflicts, and creating an agreement amongst the stakeholders with entrenched personal interests (Murray et al. 2010). Social service providers in Hong Kong have recently shown great interest in prototyping, and approached design researchers and professionals to offer training and support on the prototyping technique. A noteworthy fact is that most stakeholders perceive prototyping as a design professional skill set.

The author held discussions with stakeholders, such as design workshop facilitators and participants, to articulate what prototyping is, and how this skillset can transfer more effectively. In particular, knowledge transfer must address the time constraint of short-term design thinking workshops, lasting the duration of a few hours or days. Innovation training emphasising early prototype making, such as sketching, scenario design, mock-up or model making, is well accepted as a strategy that ensures quality design concepts and market fit. Unfortunately, the author witnessed failure cases and difficulties pushing forward effective prototyping practices with different workshop participants, particularly those without art or design training. To understand this, design educators must clarify what prototyping is, and how it may benefit the promotion of design thinking to other disciplines, as well as pedagogical development in design school.

Scope

In design education, prototyping involves material processing techniques, from hand tools to mass production methods, hand-eye coordination training through sketching and modelling, and visual-spatial thinking techniques through two- and three-dimensional visualisation practice. It is a time-consuming investment. Prototyping is discipline-specific know-how and is therefore difficult to facilitate in a short-term course. What are the factors that contribute to effective instruction of the prototyping methods other than time? To answer this, we must firstly have a detailed understanding of the prototyping experience.

Rikke and Teo (2019) provide eight common prototyping methods or types as a holistic overview of the process. They state that there are endless ways to build a prototype, but Rikke and Teo's methods include:

1. Sketches and diagrams, for visualisation of concepts;
2. Paper interfaces, such as a draft mechanism design to gain user feedback on the user experience;
3. Storyboards, like a storyline sketch to explain the user's journey;
4. LEGO prototypes, or more broadly a set of modular toys or components to facilitate quick modelling;
5. Role-playing, such as the imitation of a scene whereby potential users can anticipate experience for reflection;
6. Physical models, like a three-dimensional mock-up of a chair design for ergonomic evaluation;
7. "Wizard of Oz" prototypes, which are partial demonstrations of automated systems triggered by humans rather than by computation; and
8. User-driven prototypes, developed in forms according to users' intuition and preferences.

These methods demonstrate tangible experiences, such as ergonomic or mechanical characteristics, and intangible experiences, such as aesthetics or symbolic characteristics, using low-fidelity or high-fidelity creations. These range from proofs-of-concept to functional manifestations. The forms of eight prototype methods are distinctive, but interplay of their functions in the design process can cause confusion.

To clarify the problem, the author differentiates these methods in the accompanying matrix (*Fig. 1*). According to a review of various design and design research projects, prototype methods present two dominant spectra of characteristics:

1. The detail level of their prototyping contexts, between low and high fidelity;
2. Dimensions of perceived user experience, for example from two-dimen-

sional visual information to animation, including the symbolic meaning and cultural practices.

Two of the prototype types, "Wizard of Oz" prototypes and "user-driven" prototypes, are not included in this matrix because they refer to the prototyping engagement strategy instead of the form of the work. The superimposed characteristics of these methods explain the reason why identification of a right or precise choice of prototyping method during design development is challenging to both designers and non-designers. The novice designer may encounter uncertainty, which hinders the effectiveness of product development or design collaboration due to ambiguity. There is no absolute prototyping method. On the contrary, an experienced designer employs prototyping methods depending on which are most handy. For instance, prototyping methods may depend on the availability of relevant materials, tools, and objects.

Dual coding in the prototyping process

Application of the matrix showing the distribution of prototyping methods supports the prototyping process. For instance, the red arrow indicates that a designer can develop a concept from a sketch to a role play prototype at the level of dimensions of representation to address the concreteness or richness of information at different levels of fidelity simultaneously. During this process, the designer makes sense of the design concept through the dialogue between the verbal concept and the visual concept.

This sense-making mechanism can be understood through *dual-coding theory* as described by Allan Paivio (1971, 1986). The theory explains dynamic associative processes in cognitive actions, a subsystem of holistic sensory cognition that connects verbal and visual stimuli and representations (Clark and Paivio 1991). The stimuli include newly experienced materials through the sensory systems, such as visual, auditory, and kinaesthetic information, and previously learned materials stored in the memory as knowledge. The theory supports students' learning experiences through adopting verbal and visual means together, and also ensures better memory and depth of the learning contexts. Paivio postulates that "visual and verbal information is encoded and decoded by separate, specialised perceptual and cognitive channels in the brain." The visual channel simultaneously manipulates mental images or non-verbal entities, called *imagens*. Verbal entities such as spoken or written words, called *logogens*, in the linguistics channel function linearly and sequentially (*Fig. 2*).

When the same information is presented to the brain in different forms, for instance verbally through written notes of a design concept, and visually through a sketch or model, this is a form of "dual coding." The use of visuals and text together can increase comprehension. This helps explain why designers apply visual means to carry out research and brainstorming with the input of verbal contexts, such as historical information, symbols, and abstract verbal theories. Visual information enhances the understanding, development, and memorisation of abstract verbal information. In design practice, this theory explains how designers articulate verbal and visual coding materials to develop purposive design artefacts, which communicate better with their audiences or users. Shifting in-between actions, the designer explores the most sensible prototyping approach, and critically reflects the constraints of a product's form development. The process can simultaneously occur in the designer's brain, on paper, and with hands-on making with physical materials and tools. The author argues that the immediate cognitive action of the prototyping process is the learning experience the designer perceives while he or she recognises and associates logogens and imagens together. This explains why there are many types of prototyping methods, and usually multiple methods are used in one design project: during the design process, the designer articulates design opportunities or appropriation, and justification/reflection.

The connections that pair logogens and imagens, called referential connections, are mechanisms that link words to images, or images to words. The movement inter-crossing different pairs can be considered an articulation process whereby designers adopt different prototyping methods and carry out the iterative process. For instance, if the designer explores an outdoor seating platform to enable intergenerational interactions amongst elderly and younger generations, at least physical models to probe appropriate ergonomics, and storyboard methods to demonstrate users' experiential sequences, should be applied to support the design hypothesis for further development.

Here follows further explanation about the implicit relationship between this cognitive movement between logogens and imagens, and the motivation of the designer which shapes and moves forward the idea generation and prototyping process. The discussion below will elaborate the situation through the distinction of science and design study, and the constructionist's perspective on the designer's experience. If we build a model to explain the cognitive experience of the designer in the prototyping process, researchers must explore the forces driving the designer to shape visual form.

Prototyping builds dialogue between analysis and synthesis

In product design practice, a prototype is a representation of an innovative concept, but it enhances understanding and enables communication at both personal and collaborative levels. One essential characteristic of prototyping is that it interweaves making and reflection, as research, iteratively. Thus, prototyping takes different forms, and their flexibilities are the reasons why those unfamiliar with prototyping practice cannot adequately describe it. Cross (2001, 2006), Rittel and Webber (1973), Simon (1969) and Alexander (1964) elaborated on the distinct characteristics of general design activities through differentiation against science/analytical and design/synthesis perspectives. We can further implement these two distinctions to discuss the differences in prototyping processes: analytical-prototyping and synthesis-prototyping.

Analytical activity in science concerns *how things are*, how to solve science problems, also called *tamed problems*, and how to identify the components of existing structures or products. Moreover, results or practices must be repeatable. Analytical-prototyping concerns recognition or understanding of the pattern or structure of the prototype through visual means. It focuses on the study of a part or a specific component through visualisation. It also clarifies the relationship of design features, and dimensions or measurement confirmation.

Synthesis activity in design concerns *how things ought to be* and how to solve design problems, sometimes called *wicked problems*, and to identify the shape of the components of new structures. Design practices may not need to be repeatable, and usually perform as a unique solution. In synthesis-prototyping, the approach emphasises pattern synthesis or hypothesis making through visualisation, such as association or combination of images, or physical construction. Synthesis-prototyping focuses on the materialisation of abstract concepts to concrete concepts. For example, prototyping converts comparatively abstract wording describing *a comfortable seat* to a concrete image of a chair with a cushion. It also enables the exploration and evaluation of unique forms.

Through prototyping, aligned with Cross' design process concepts, a designer proposes additions and changes to the artificial world which require knowledge, skills, and values entailing the techniques of the artificial. Design knowledge is inherent in the artefacts of the artificial world, and is gained through three design-related activities:

1. Designing of artefacts;
2. Usage of artefacts; and
3. Manufacturing of artefacts.

For instance, in using artefacts, designers gain knowledge connecting forms and configurations by copying from, re-using, or varying aspects of existing artefacts. In manufacturing artefacts, designers gain knowledge through making and reflecting either upon the making process or instruction. Prototyping, or designing through prototyping, is a knowledge-acquiring process in which the designer experiences both making, through shaping and pattern synthesis, and reflecting, through analysis and pattern identification.

Design involves substantial learning experiences which can be understood in the perspective of Papert's constructionism[1]–learning by making (Ackermann 2001). Thus, the designer's action of making, such as the analytical-prototyping and synthesis-prototyping, is also a learning process. The analytical process and synthesis process happen iteratively until the final prototype is settled. What aspect drives the movement back and forth between these two distinctive cognitive processes? This can be further understood through the perspective of knowledge creation.

Urging design's establishment of a stance on knowledge creation, the discussion of differences between design and research activities has emerged more formally and explicitly since the 2010s. Stappers and Giaccardi (2017) summarised various thoughts on this matter. Design activity usually connotes the production of creative work that is specific and concrete or situated. Research activity connotes the output of knowledge that is generalisable and abstract. Stappers and Giaccardi quoted Liz Sanders' identification (2005) of the similarities and differences between the traditional design research approach, which is called information-based design research such as usability test and ethnography, and the designer-ly approach to study, which is called inspiration-based design research, such as cultural probes and generative techniques. Similar concepts include both the aim to create something new, or *prospective perspective*, and building on previously known matters, through *retrospective perspective*. Hence, different prototyping methods and the intentional perspective of the designer are needed.

Making is an effective learning approach in constructionist research practice (Halverson and Sheridan 2014). Theorists can understand the design-researcher's making process as building connections back and forth from abstract to concrete. This practice immerses the design-researcher into the wicked problem space, filled with various uncertainties, to emerge with a concrete experience or prototype demonstrating distinct design functions or features.

Through a review of the prototyping cases below, the author identifies *two implicit actions* in which designers employ prototyping activities iteratively between *two zones*. At one end is the zone of retrospective action, imitating, reviewing, measuring, or correlating. At the other end is the zone of prospective action, outputting innovative or hypothetical artefacts which in turn researchers can evaluate in the retrospective zone for proof against hypotheses or theory. The analytical-synthesis action happening in the two zones is highly connected. The prospective action is a high-level cognitive activity aligned with the *constructive forethought* Sutton and Williams (2010) described. They quote the statement from Gregory (2004) who said: "design generally implies the action of intentional intelligence." Thus, this sense-making intention drives the momentum of the cognitive changes from one end in retrospective and analytical actions, to the other end in prospective and synthesis actions. The designer simultaneously develops prototypes back and forth from the abstract world to the concrete world. This momentum is illustrated in *Fig. 3*.

Typically, the designer's cognitive experience swings between the analytical and synthesis modes, indicated in *Fig. 3* as swinging to the left when the designer processes the analytical/retrospective concerns, and to the right the synthesis/prospective concerns. This movement can operate as a dialogue between the designer and the artefact, at the intrapersonal level, or in the group discussion or collaborative working environment, at the interpersonal level. Designers perceive an iterative process during the development of a prototype from abstract and uncertain concepts to concrete concepts or vice-versa.

A proposed cognitive framework for the product prototyping process

Understanding the initial stage of prototyping is useful for connecting prototyping itself with its potential outcomes. At the beginning, the designer should acquire specific design criteria, either verbal and/or visual concepts, before entering the early prototyping stage, even if the criteria are unclear or uncertain. Designers commence prototyping from a goal, whether or not clear, which could be in words and/or visual form. They map different possible factors and elements comprehensively from partial to holistic consideration.

Mapping is constructed through three primary considerations: the constraints of the product, form development, and prototyping format. Conceptual clarity itself is a relative concept, and one of designers' major intentions regardless of specific project criteria. Prototyping typically articulates this clarity later in the materialisation stage. If there is no concrete concept or image in the brain of the designer, he or she may explore, through rough sketching, a stage before prototyping. Thus, prototyping only happens when the designer is ready to engage in making or has already envisioned a potential concept in the form of a mental image, sketch, or physical artefact.

To realise the relationships between the actions, conditions, and considerations, *Fig. 4* explains the designer's cognitive processes while perceiving the verbal and visual stimuli during early prototyping stages with the dual coding system as the first action, shown as vertical movement on the diagram. During the stage when logogens and imagens connect, the second action, shown as horizontal movement on the diagram, happens in two distinctive mindsets. The six constraints on product form development drive analytical/retrospective processes. The five prototyping principles and eight appropriated prototyping formats drive the synthesis/prospective processes. To initiate the dual actions mechanism, one of three common conditions for a product's form development steps in. Lastly, the prototype or test deliverable induces iterative development.

Knowing the requirements and constraints of product form development cannot explain a designer's motivation during the appropriation process, while the designer chooses prototyping methods. The driving force for prototyping method selection is the availability of actionable resources to the maker. Camburn et al. (2015) proposed five design oriented and actionable principles which aid designers to meet the objectives of a prototyping task. Designers incorporate the five principles below into the prototyping process to develop specific prototyping methods. Appropriateness to the project brief and the designers' situation motivates choice between one or more of these five principles. These work as subsets to the eight prototyping methods, and consideration of the six constraints:

1. Hack commercial products;
2. Employ basic crafting;
3. Prepare fabrication blueprints;
4. Repeat fabrication processes; and
5. Include structural voids.

The author proposes a framework to explain the considerations of the designer's experience in prototyping approach selection and development of prototypes driven by the proposed dual actions. In this framework, vertical movement demonstrates the dual coding path, and horizontal movement the ambivalent intentions of the designer shifting between analysis and synthesis processes. The processes involve iterative consideration of constraints and opportunities through various prototype methods.

Prototyping is a learning process across retrospective and prospective zones

Through learning by making, the author identified several characteristics of prototyping in its role to further substantiate the above-proposed framework of prototyping process through the elaboration of five first-hand cases. Sketching case studies describe the significance of cognitive movement back and forth between the analytical/retrospective zone and the synthesis/prospective zone during the prototyping process.

As mentioned earlier, the designer conducts analytical activities to imitate, review, measure, and correlate concepts through prototyping in the retrospective zone. The first case researched indigenous handicrafts and sought ways for prototyping and design thinking to support revitalisation. This paper selects a sketch-prototype (*Fig.* 5) from this project for discussion. It is a common practice to sketch to explore new ideas. However, sketching to facilitate learning or enhance memory plays a vital role in design, such as solving complicated assembly problems.

This sketch helped the author to build a mental model, describing the relationships of different components of the wooden cart and fabrication method in the mind's eye. This example illustrates that design researchers can adopt sketching to investigate the form of an artefact, as it can be directly carried out by visual or physical examination, and by reverse engineering the fabrication process. This kind of reverse engineering is indirect learning through a dry run in the brain, at a lower risk of resources. Designers can also review the constraints of form development such as functional, aesthetic and production considerations for their impact on product effectiveness (Bloch 1995 as cited in Crilly et al. 2009).

Sketches accompany verbal descriptions of visual thinking, during which designers can memorise and manipulate visual images (Reed 2013). Thus, sketching is a common tool used at the early concept and other phases of the development process. Sketching as a type of prototyping works not only for envisioning the hypothetical design but also applies to the analysis of the artefacts or scenarios whereby the design researcher can explore the contexts in detail through visual means.
Visual contexts usually refer to affective responses that users experience in human-product interaction, in which sense stimulation can be triggered. A recognised framework to

elicit the experiential impact of new designs is the three components or levels of product experience proposed by Desmet and Hekkert (2007). As defined by Hekkert (2006, 160), product experience is:

> *…the entire set of effects that is elicited by the interaction between a user and a product, including the degree to which all our senses are gratified (Level I: aesthetic experience - visual aesthetics, and tactile and kinaesthetic), the meanings we attach to the product (Level II: experience of meaning – semantic interpretation, symbolic association, linguistic expressions, and figurative expressions) and the feelings and emotions that are elicited (Level III: emotional experience – personal evaluation (appraisal) of an event or situation with beneficial or harmful impact).*

In practice, designers and researchers can use this framework to explain phenomena of iterative processes based on the evaluation of the three types of product experience induced while sketching or making a prototype.

Compared to written concepts, sketching or prototyping can provide visual information to the creator or interpreter. The designer can then associate aesthetic experiences and the experiences of meaning, and also tacit or intangible product experiences that verbal tools cannot support. For instance, aesthetic experiences, such as line quality of a sketch, help the creator to experience the abstract qualities of a sketch/prototype such as softness/hardness or gentleness/robustness in a design. The creator can also perceive additional information, such as emotional experience induced by touching the material, while fabricating an artefact. Furthermore, people can understand implicit know-how either by fabricating a design or drawing it on paper. This experience involves visual and spatial relationships correlating with various design components which cannot be communicated easily through words. Thus, sketching or drawing is a popular method to collect people's perceptions or express individual understanding.

On the other hand, if articulation in oral language of a participant or informant is an issue, for instance when researchers interview people who are deficient in verbal communication, verbal thinking and expression is less successful compared to a sketch-prototype. Building a physical model to make a direct copy of an existing design can also support the builder or maker to learn the unique structure and production method, which cannot be explicitly and comprehensively described through a verbal description alone.

Case two demonstrates prototyping as a synthesis process in a prospective manner. In this case, the author carried out an ergonomic chair design proposing an adjustable backrest. Before exploring a new backrest, the author examined several backrest designs of different ergonomic chairs through desktop research and sketching. Using a quick paper mock-up (*Fig. 6*) helped the visualisation of the three-dimensional structure and mechanical movement that cannot be quickly evaluated and shared by sketching alone.

Hands-on work and manipulation of tools support the proving of a design hypothesis, such as the identification of novel design pattern. Case three is another example that showcases the back and forth between retrospective learning and prospective learning. The project is an upcycling lampshade design and production project which the author and a project team facilitated for a group of secondary school students. The students learned about the properties of polyethylene terephthalate (PET) bottles by exploring their physical patterns and structural performance, cutting, bending, and punching the material. They experienced and identified material characteristics during the making process. After identifying a potential module or unit, the student integrated the components or units into a bigger piece of meaningful structure that functioned as a lampshade (*Fig. 7*).

Case four illustrates a fully functional prototype (*Fig. 8*). A revamp of an old tram for the event called deTour 2013 funded by CreateHK provided a chance to develop a full-scale, functioning design prototype. The project created an alternative urban experience by transforming a street tram, and the project team proposed a transparent envelope to allow people to understand the internal structure of daily transportation design. Researchers studied the workings of the tram windows, the linkage system that opens and closes the window, and the traditional wooden structures of the tram's framework, which became the primary feature. Transforming the tram to be entirely transparent was the experimental goal of the prototype.

This working prototype generated a new transportation experience for real users and demonstrated an innovative, feasible approach to the management of the tram company, and the Electrical and Mechanical Services Department of the Hong Kong Government, which took on the project risk. As mentioned above (Murray et al. 2010), prototypes help build coalitions amongst stakeholders, and in this case may assist future policy development. This example portrays how a functional prototype can benefit evaluation at the community level. Synthesis is essential in the prototyping process but evaluation and feedback through public engagement could be a more important project goal.

The final case is a qualitative research project about elderly people's' perceptions of home furniture and spatial needs through scale modelling (*Fig. 9*). The author's team developed the model to facilitate a participatory design activity for engaging elderly residents. The preparation of the models, including the selection, measurement, and making of the proper apartment and furniture, provided plenty of background information and encouraged project team reflection. The team implemented a two-step prospective and retrospective prototyping approach, with a model prototype allowing retrospection on the apartment's current state. Users guided most of the prospective phase as experts of their own experience (Sanders and Stappers 2008). The team visited the home of local elders who were instructed to build their current home furniture layouts. The team asked questions about relevant living problems such as, "does the bed meet your current needs?" Afterward, prospective questions like, "how does this arrangement meet your foreseeable future needs?" were easier to ask using the prototype. Elders designed and made their preferable furniture layout, and told the team reasons for changes or an unchanged design. This sample illustrates that a modular-type prototyping tool can engage non-professionals to express creative ideas and needs with more accuracy and accessibility than a questionnaire alone. It also supports a designer who can collect more genuine user needs through interaction between informants and prototypes. Especially, since participants know their personal needs well, prototyping with the two-step approach is more effective.

Conclusion

The above integration of various theories maps the designer's overall cognitive experience in the product design prototyping process. The core cognitive activity is the recognition of verbal and visual stimuli whereby analytical, constructive, and creative associations between verbal and visual materials can lead to comprehensive learning as well as the development of new meaning or knowledge. It is illustrated as the vertical axis in *Fig. 4* and represents the first dimension of cognitive action.

The five design-oriented, actionable principles, the six constraints of product form development, and the eight prototyping formats are the major elements that guide the prototyping process. Designers employ all of these factors in the second dimension amongst two distinct zones– a retrospective/analytical and prospective/ synthesis at the horizontal axis. The description of this dual-action prototyping process framework and the correlated cognitive learning activities are expected to shed light on the future studies of prototyping strategy and pedagogy in design education.

Acknowledgements

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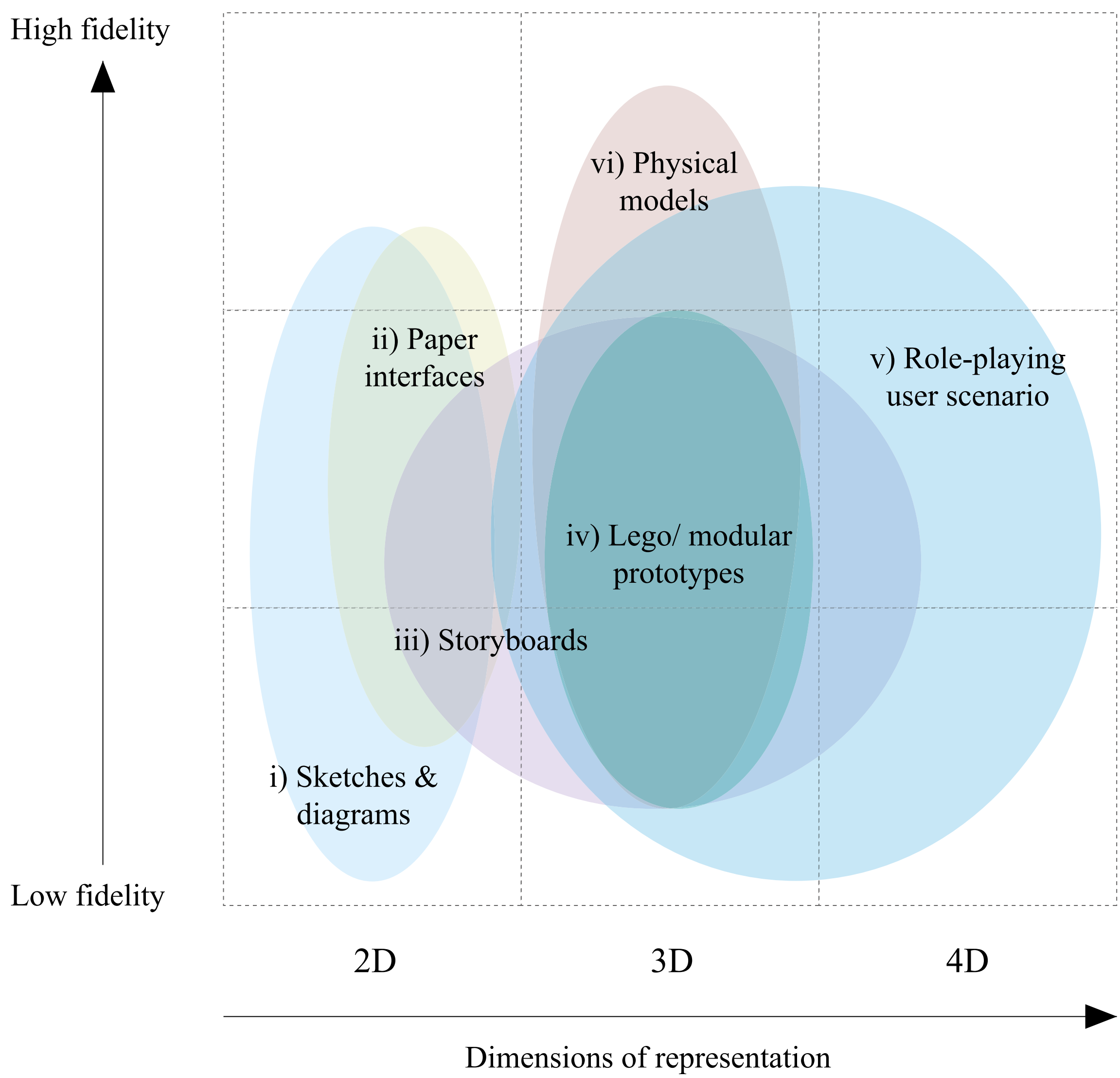


Figure 1: A matrix of prototyping methods illustrates two significant spectra of a prototype's characteristics. Designers may quickly visualise the most appropriate method according to current resources on hand during the prototype planning process. The paths of red arrows illustrate the designer's identification of the most reasonable type of prototype across different characteristics as shown in the two dimensions. Source: *author.*

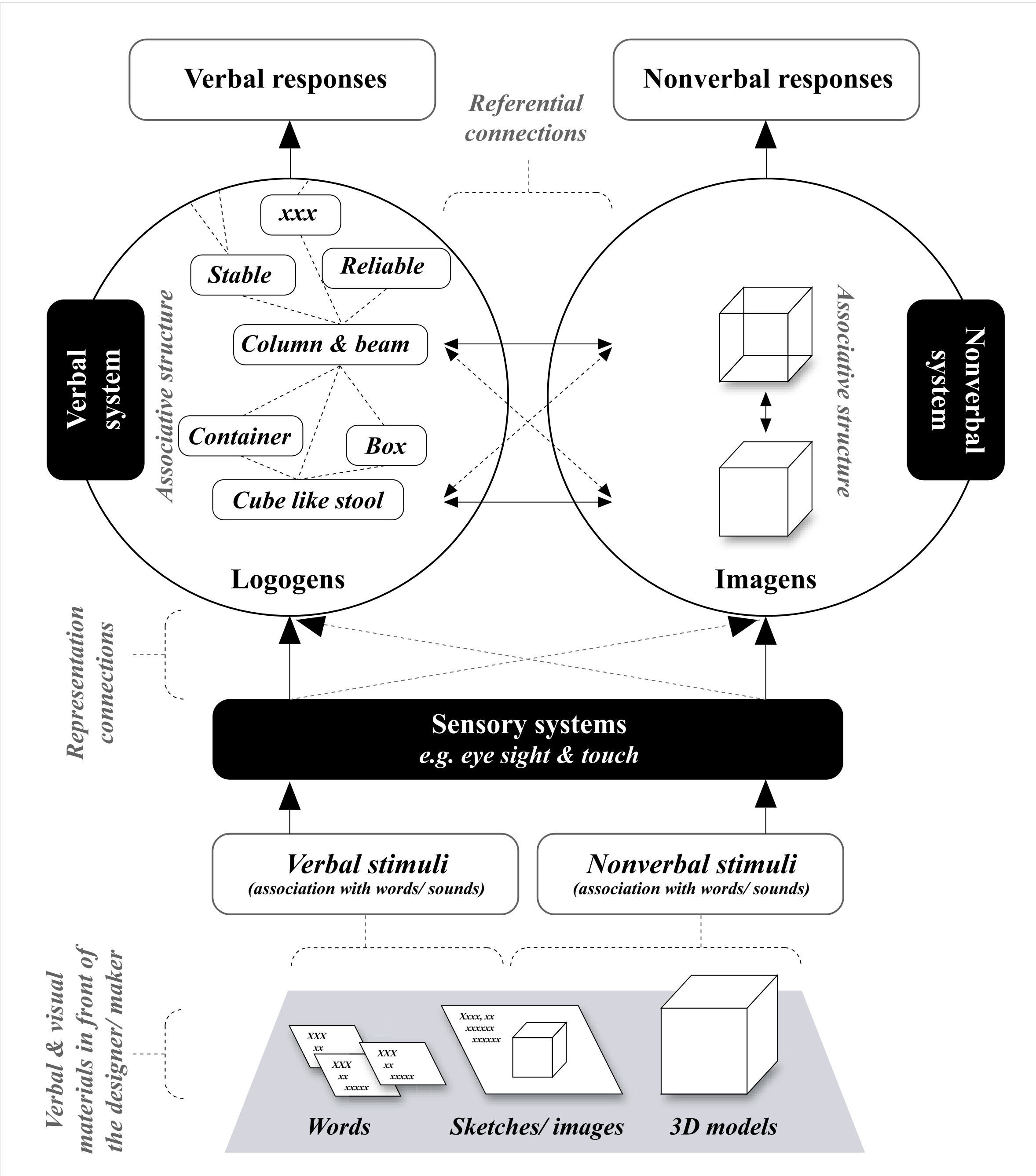
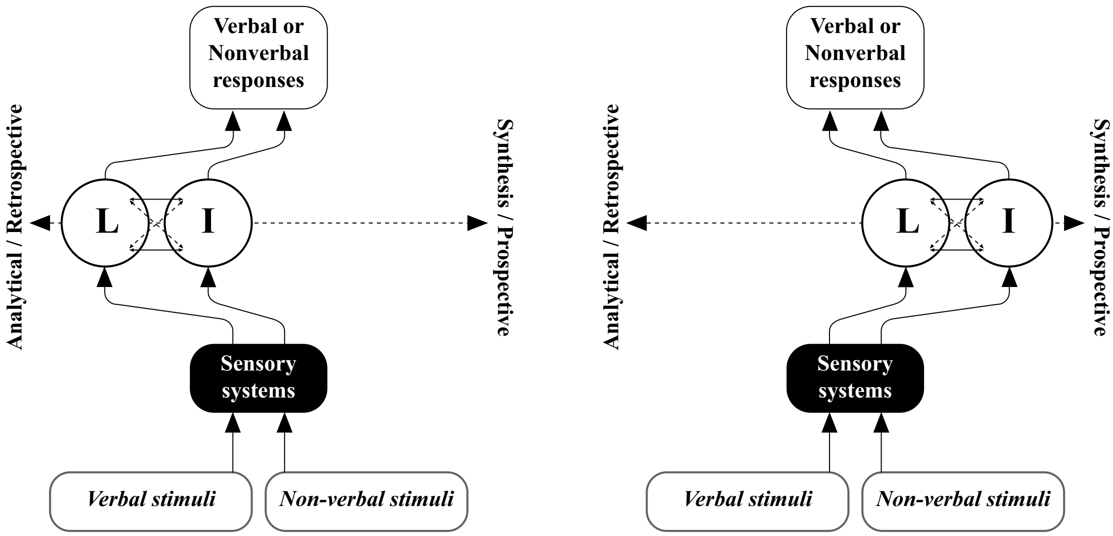


Figure 2: This diagram illustrates the dual coding mechanism modified from Allan Paivio's theory (Paivio 1986). This indicates two cognitive subsystems sensing verbal and visual materials respectively. Verbal coding interprets lologens associations and hierarchies. Visual coding interprets part-to-whole relationships within imagens. Source: *author.*



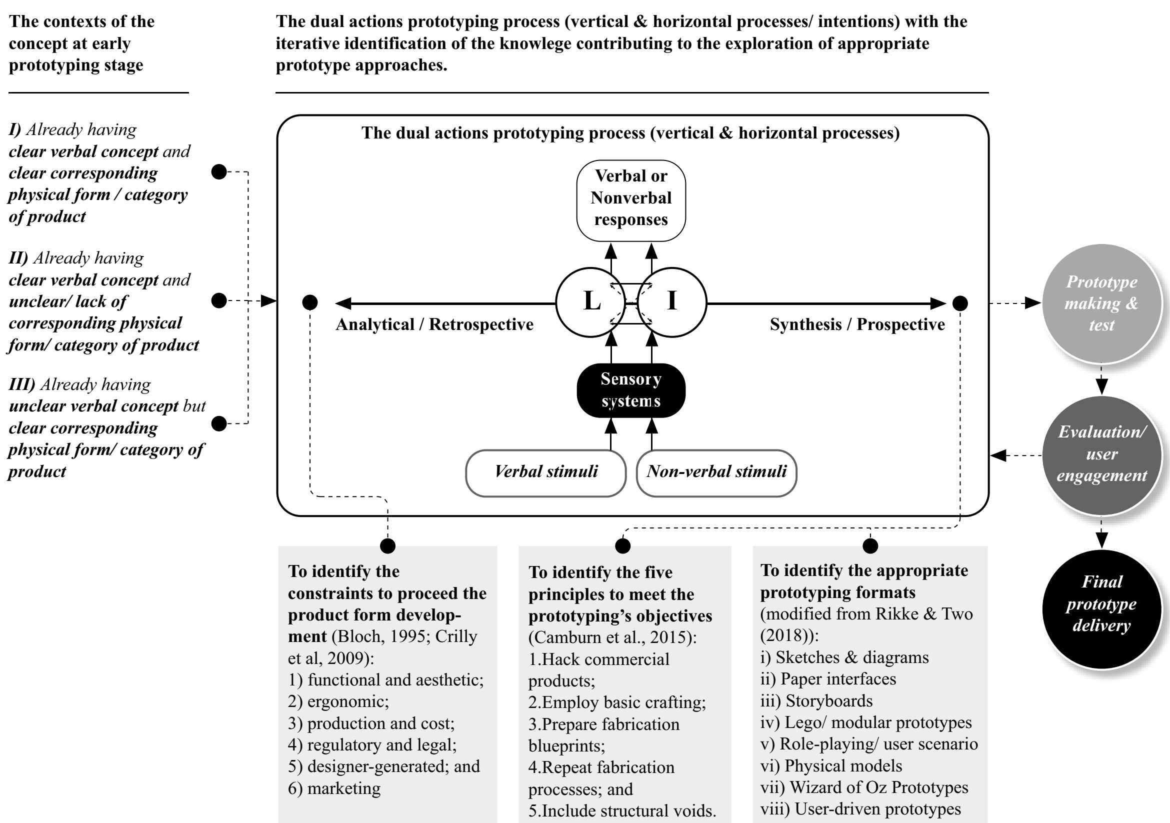


Figure 3 (top): The analytical/retrospective and synthesis/ prospective swinging action diagram. The vertical path indicates the dual coding system from sensory stimulus to the responses of a designer. The horizontal dimension with two ends indicates the intentions of the designer who either operates the analytical-prototyping or synthesis-prototyping. Source: *author.*

Figure 4 (bottom): The dual actions prototyping processes framework. It demonstrates how consideration of constraints and opportunities of product form development, and various prototyping objectives and formats are connected and driven by the dual actions. Source: *author.*

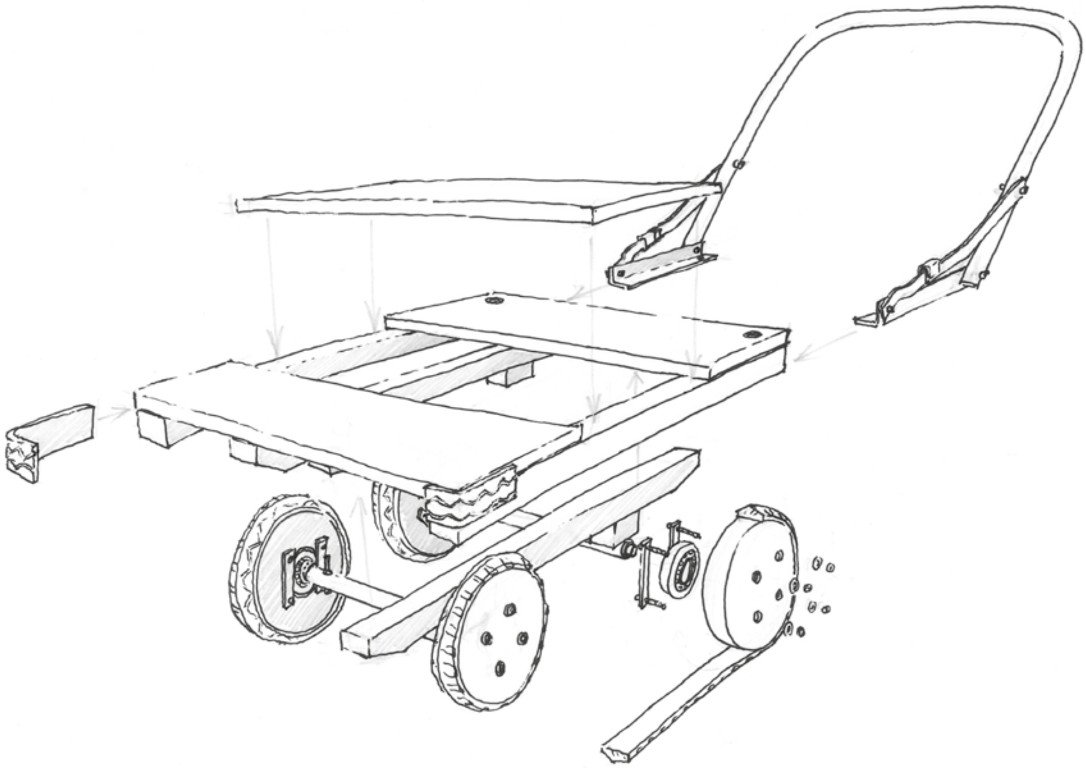


Figure 5 (top): Sketch as a visualisation tool to facilitate visual thinking that enables investigation of, in this case, craftsmanship techniques including the logic of structural form, selection criteria of materials, and fabrication methods. The drawing also facilitates visual driven communication amongst researcher, designer and the producer. Source: *author.*

Figure 6 (bottom): The paper model demonstrates the relationship of movable parts of the design hypothesis. The animated structural feature of the design supports simulation and evaluation through sequential movement and tactile experience. Source: *author.*

Figure 7 (page 69): Searching design patterns, or meaningful visual structure, is a significant learning experience and creative outcome of prototyping. This image is the result of a group of secondary school students after they explored PET bottles' material properties through trial and error, and explored pattern recognition by organising the material. Source: *author.*

Figure 8 (opposite page): The tram with a transparent envelope run on Hong Kong Island served people for more than a week during the end of 2013. LED lighting was installed to highlight the internal mechanism of the tram. Source: *author.*

Figure 9: The participatory design activity conducted during a home visit of a local elder who was asked to prototype his preferable home furniture layout with the modular components and models. Source: *author.*

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Bio

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