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# ROLES OF EXTERNALISATION ACTIVITIES IN THE DESIGN PROCESS

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**KEYWORDS:**

Design activities, External representations,  
Sketching, Physical and digital modelling.

## ABSTRACT

Designers engage in various activities, dealing with different materials and media to externalise and represent their form ideas. This paper presents a review of design research literature regarding externalisation activities in design process: sketching, building physical models and digital modelling. The aim has been to review research on the roles of media and representations in design processes, and highlight knowledge gaps and questions for future research.

## INTRODUCTION

Rather than making products, designers make representations of their design (Pye, 1978, Lawson and Dorst, 2009), which puts the activities and media that precede design representations in the spotlight. Creation of product forms involve making various decisions to embody a potential function of a design through geometrical ordering, and the way this function is to be utilised (Muller, 2001). Design representations are made before, after and during the process. They may be very detailed or partial, vague or clear. Common design representations are sketches, physical and digital models (figure 1). The ability to make representations is central to the design process. According to Menezes and Lawson (2006), skilled designers can describe sketches in

more ways than design students. Suwa and Tversky (1997) found that experienced designers think deeper in each phase of their work as they read nonvisual functional issues from the visual features of their sketches, leading to emergence of new ideas. This requires developed *imagery* abilities (e.g. the ability to transform and rotate mental images as mentioned by Kavakli and Gero, 2001). Externalisation activities involve *imagining, drawing, and seeing* (figure 2) that are constituents of visual thinking and imagery (McKim, 1980).

Design representations are considered essential for understanding the works of designers and the origins of design artefacts (te Duits, van Daalen and Beuningen, 2003). The externalisation of shape ideas freezes and represents one instance of the designer's cognition (Lawson, 2006): *“the form of representation used and the skill in using them are likely to have a huge effect on the design process.”* Sketching is considered the “heart” of the design process (Lawson and Loke, 1997), *“amplifying the mind’s eye”* (Fish and Scrivener, 1990), and supporting innovative design thinking (Tovey, 1986). Even though much of the design nowadays relies on CAD in most design disciplines, digital modelling is regarded a threat in design, especially if the designers abandon their sketching practices (Lawson, 2002).

Despite their importance and potential effects on the

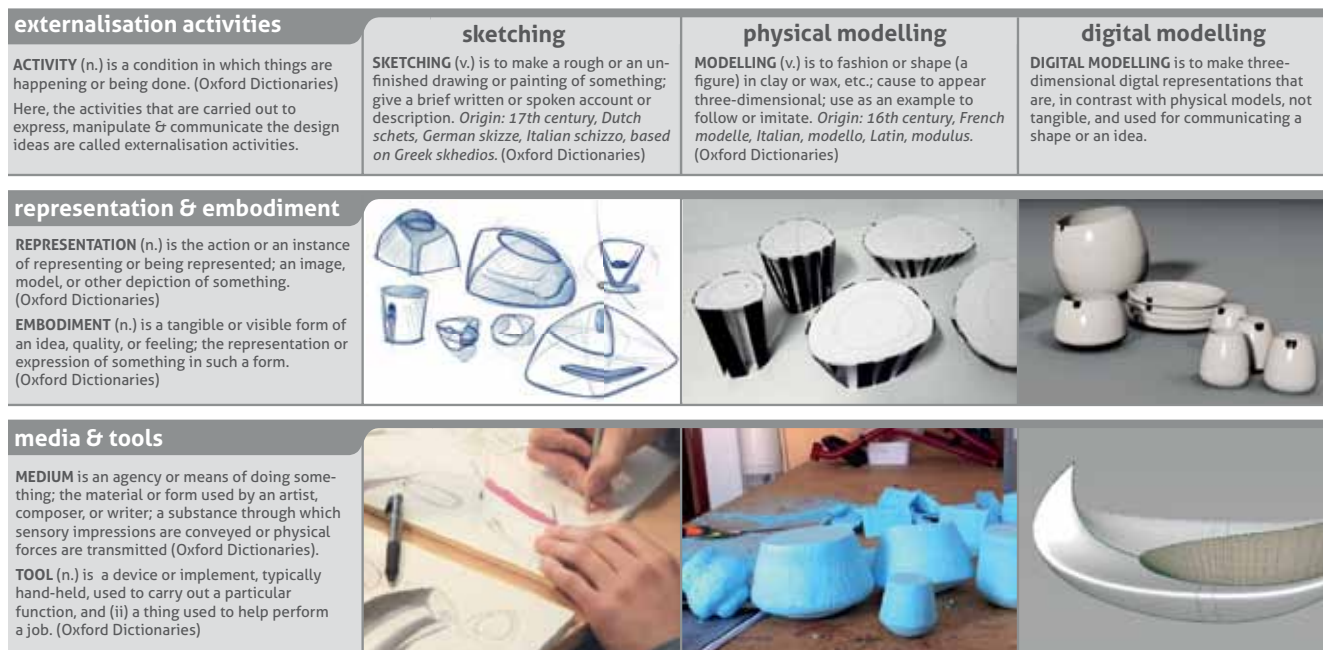


Figure 1. Externalisation activities, representations and media with examples from students works.

design process, research regarding externalisation activities and their roles in industrial and product design discipline is relatively sparse. While some literature elaborates on the role of individual activities (e.g. the review on the roles of sketching by Purcell and Gero, 1998), a broader, more holistic and systematic review of several externalisation activities, comparing and contrasting them is missing. The primary aim of this paper is to review research - across different disciplines - that has looked at the roles of different media and representations, and to examine their implications for the design process. Such a review may also provide a theoretical framework and a point of departure for future research.

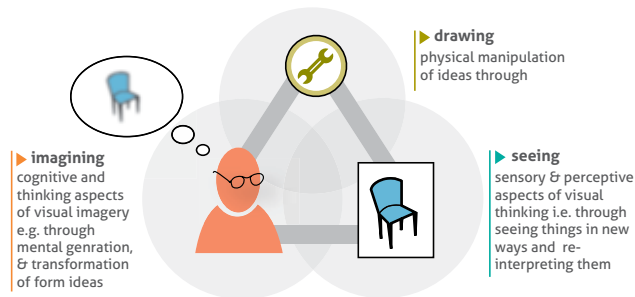


Figure 2: Visual imagery in externalisation activities (adopted from McKim, 1980).

## DATA COLLECTION AND ANALYSIS

The search for relevant scientific literature was initiated by defining several key words e.g. sketching, physical and digital modelling as well as their synonyms. This review includes research from disciplines that are concerned with design of utilitarian artefacts<sup>1</sup> (e.g. engineering and mechanical design, architecture, and communication design), since the empirical evidence regarding the interrelations between the design process and externalisation activities is dispersed

1) Artistic disciplines (e.g. sculpture and painting) with mere aesthetic dimensions are excluded from this review, as they may involve limited restrictions regarding the use of materials and media.

2) In the words of Gibson (1986): "the affordances of the environment are what it offers the animal, what it provides or furnishes". What something affords is tied up with our bodily structures, our acquired skills and our specific cultural context e.g. for a chair to afford sitting or for a mail box to afford mailing letter, we should not only have a certain bodily structure, but also the skill to sit and to mail letters and live in a culture where sitting and mailing letters are practiced (Dreyfus and Dreyfus, 1999). The concept of affordance has been used extensively in design and HCI literature to explain and predict the interaction between users and artefacts. Norman (2002) defines affordance as "the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used."

3) "Hartson's classification (2003) also includes social and communicative affordances, which falls beyond the scope of this paper.

across different disciplines. Further, the present review only includes aspects of design that concerns the designers' individual process, especially those activities that enable the designers to externalise their ideas. Apart from the academic literature, professional literature (e.g. design-related books that include anecdotal evidence on externalisation activities) was also reviewed. Further, only printed sources in English language were considered, while excluding unpublished work like magazines, or blogs.

The reviewed literature was analysed by summarising, extracting, tabulating and mapping key ideas, theories, and interpretations, as recommended by Hart (1998). To categorise the roles of externalisation activities, McKim's (1980) notion of visual imagery and its classification that pervades design activities were considered. This classification was in accord with Hartson's (2003) typology of *affordances*<sup>2</sup>: (i) *physical*, (ii) *sensory*, and (iii) *cognitive*<sup>3</sup>. In the present paper, affordances can be defined as the conditions that media provide for the designer, triggering certain types of actions or form repertoires. This classification is used here to account for the roles of media and design representations. Further, sub-themes were identified to describe these roles on a more detailed level. To explain and exemplify the identified roles, data from design diaries in an earlier study by the author (Babapour, Rehammar and Rahe, 2012) was consulted and diary entries were extracted.

## ACTIVITIES, MEDIA, AND REPRESENTATIONS

An overview of externalisation activities, media and representations considered in this paper is provided in figure 1. The reviewed literature involved overlapping and at times blurry terminologies, especially since these terms are not only used to explain an externalisation activity, but also as the media and tools by which the activity is carried out, and the resulting representation or embodiment. For example McKim (1980) uses sketching as a general term to explain generation of ideas: "*Idea sketching is a way to express visual ideas... Visual ideas can be expressed by acting them, talking about them, writing them down, constructing them directly into a three-dimensional structure, and drawing them.*" The inconsistent use of terminology also extends to the use of sketching and drawing to explain making marks on paper, or modelling and prototyping for making three-dimensional representations.

### Sketching

Sketching refers to the production of visual images to

<p><b>interior designers</b> (<i>Bilda &amp; Demirkan, 2003</i>)</p> <ul style="list-style-type: none"> <li>&gt; exhibited more changes in decision-making, made more redefinitions of spatial relation, and spent more time working with the problem in traditional media.</li> <li>&gt; had shorter problem definition stage and spent more time in modification and concept evaluation phases in digital sketching media.</li> </ul>
<p><b>architects</b> (<i>Yi-Luen Do, 2005</i>)</p> <ul style="list-style-type: none"> <li>&gt; used diagrams, texts, and symbols, and constantly interpreted these symbols in pen &amp; paper sketching.</li> <li>&gt; did not use diagrams and symbols to the same extent in digital media.</li> </ul>
<p><b>graphic designers</b> (<i>Stones &amp; Cassidy, 2010, 2007</i>)</p> <ul style="list-style-type: none"> <li>&gt; generated more design alternatives and were more likely to reinterpret them for creating novel solutions when sketching with pen &amp; paper.</li> </ul>

Table 1: Comparative studies between traditional and digital media (summary of findings).

externalise the visual thinking process and assist the creation and development of visual ideas (Fish and Scrivener, 1990). Schön and Wiggins (1992) describe it as a moving, seeing, moving process where each move serves as preparation for the succeeding moves. Other words that are used to describe the sketching activity are doodling, scribbling, drafting, etc. While some scholars use the terms drawings and sketches interchangeably (e.g. Purcell and Gero, 1998), others make a distinction between them. For instance, Pei, Campbell and Evans (2011) describe sketches as rough visual representations of the main elements of design as opposed to the more structured and specified character of drawings. In the present paper, sketching includes both rough and structured representations.

Sketch as a medium – Traditional or manual sketching with pen and paper has been considered a primary medium for visual thinking (McKim, 1980). With the introduction of digital media, new considerations are brought forward in discussions of sketching in design. This includes new ways of seeing and interpreting design situations that are, according to Coyne, Park and Wiszniewski (2002), enabled through (i) introducing new practices e.g. making backups and managing files that open possibilities for investigation and retrospection, online communication that requires being more organised, experimentation and discovery as modes of working, and (ii) introducing new terms and definitions

regarding new tools (e.g. digital drawing tablet, projector) or new practices (e.g. layering, filtering, scanning). Several studies compare digital and traditional sketching media and highlight how they influence the designers' behaviour (see table 1).

Sketch as representations – Different types of sketches are made across different design disciplines (table 2). Akin and Lin (1995) highlight how the nature of design problems can influence the type of sketches made. For example, using unstructured and random drawing marks are found to stimulate finding new ideas in architectural design process (Cross, 1999) which according to Akin and Lin (1995) is due to the nature of architectural design problems generally involving a novel and rare combination of site, client, etc. The extent to which a sketch is structured may also depend on the phase of design process as well as the individual preferences of designers.

Roles of sketching – Different roles that sketching can play in design process were identified from the reviewed literature and exemplified with diary entries from an earlier study (Babapour et al., 2012) in table 3. These roles can be seen as underlying facilitators that sketching entails even though the designer does not necessarily realise or use them. Akin and Lin (1995) found some of these roles, having different compositions during the design process, e.g. more thinking (i.e. cognitive roles) in the conception phase and more drawing (i.e. physical roles) in the presentation pha

### Physical modelling

Tovey (1989) describes the design process as “*moving from one model to another*”. Physical models represent and embody design ideas and bring up otherwise hidden issues (Yang, 2005). Making physical models and mock-ups is generally associated with the conceptual phase of the design process. Building more detailed and accurately scaled physical models at later stages of the process is usually called prototyping (Veveris, 1994). Sometimes these terms are used interchangeably e.g. Yang (2005) refers to prototyping even for the earlier stages of the design process. Here, physical modelling encompasses making tangible three-dimensional models throughout the design process. To describe the modelling activities, Wiegers, Dumitrescu, Song et al. (2006) proposed a method for analysing clay modelling. Breaking down this process in chunks of *manipulation-see* (similar to Schön's description of sketching as moving – seeing), they found that preparation and modification of surfaces were the most common activities during clay modelling.

Working with physical models throughout the design

**industrial design** (Pei et al., 2011)

- > personal sketches (aka napkin sketches) to externalise and investigate ideas,
- > shared sketches to trigger group discussions,
- > persuasive sketches with high level of realism for stakeholders to evaluate the proposals,
- > handover prescriptive sketches to convey information for other members of the design team,
- > scenario and storyboards for describing the user interaction,
- > layout renderings,
- > presentation renderings to fully represent the product appearance,
- > perspective drawings.

**experience design**

(Greenberg, Carpendale, Buxton et al., 2012)

- > the vanilla sketch that integrates drawing, annotations, and symbols,
- > the collaborative sketch for brainstorming and expressing ideas as well as mediating interaction,
- > hybrid sketches that combine sketches with photos,
- > story boards & diagrams to communicate narratives,
- > animations to capture motions and sequences.

**engineering design** (Pei et al., 2011)

- > schematic diagrams for representing the operating principles & the relationships between components,
- > general arrangement drawings for showing the exterior view of the objects,
- > detail drawings for manufacturing details,
- > technical illustrations e.g. layout drawings and assembly drawings for communicating technical details in a realistic manner.

**graphic design** (Schenk, 1991)

- > sketches for accepting and passing the brief, as reminders of information, for an exchange of ideas, and to explain thoughts for clients,
- > inspirational sketches for collecting visual reference material,
- > personal sketches for analysing the problem and generating first ideas as combinations of words & rough and fluid visual notes,
- > synthesis and development sketches for combining & modifying visual elements to explore subtle variations in composition and form,
- > presentation sketches for evaluation, & revision of solutions,
- > sketches for preparing & controlling the production.

Table 2: Different types of sketch representations across design disciplines.

process and especially at earlier stages is often considered to be important for achieving successful outcomes (Yang, 2005). A remarkable example is the 5,127 numbers of physical models in cardboard, foam, plastic and metal which were made during the design and development of James Dyson's first vacuum cleaner (te Duits et al., 2003). Although scholars have highlighted the importance of modelling, the results from some studies show that modelling was the least frequent ideation activity (e.g. Jonson, 2005), which might be due to the effort and resources it requires.

Physical modelling media – Model making can include both conventional and digital media. Foam, paper, and clay models are common media used in industrial design at early stages while digital and rapid prototyping is often used at later stages. For making interactive devices, there is a wide range of modelling media e.g. Phidgets (Greenberg and Fitchett, 2001), or the Calder toolkit (Lee, Avrahami, Hudson et al., 2004). Apart from conventional approaches, designers take up experimental approaches when working with physical models (figure 3). Individual preferences and the designer's skill set may influence the choice and the extent to which materials and modelling media are used during design process.

Physical models as representations – Different types of models are made for various purposes across design disciplines (table 4). Industrial design models are mostly concerned with aesthetics of the products while engineering design models relate to the functional principles of the product (Veveris, 1994). A more general way of categorising physical models, according to Houde and Hill (1997), is by the aspects of a product they represent: the product's role in relation to its user, its look and feel, and its implementation through material, technology and components of a product. Further, they consider a fourth category that integrates all the three dimensions. The choice of physical models depends on the stage of design process and the dimension of product that designer is working on.

Roles of physical modelling – Table 5 provides a list of roles attributed to physical modelling in the reviewed literature (together with diary excerpts for exemplification). In contrast to sketches, which can only be read through vision, the tangible nature of physical models enable the designer with multimodal interaction. A recurring theme in the reviewed literature is how physical modelling aids designers in learning through identifying problems and debugging (see e.g. Brereton, 2004), which according to Viswanathan and Linsey (2009) results in rectifying designers' mental models in relation to materials.

Table 3:  
Left: roles of sketching in design process (based on the literature review), right: manifestation of the identified roles (based on design diaries).

Physical roles	<b>embodiment &amp; materialisation</b>	Embodying the content of mental images in sketch representations on paper or on screen.	“ I wanted to do a stem that had ridges, and maybe erosion and asymmetry as well... I also had some pictures of a table in mind, which had these kinds of forms. [JM]
	<b>radical transformation</b>	Generating solution alternatives through making radical changes e.g. in rough sketches.	Easy to get many shapes quickly, and easy to develop and go back. [AM] Small simple sketches were a good way of exploring the overall composition. [VS]
	<b>incremental transformation</b>	Generating solution alternatives through making incremental changes e.g. in detailed sketches.	Easy to see what works/doesn't work without having destroyed the material by taking something too far. Using paper, one can simply make an overlay and make one more iteration of the form. [...] Sketching in multiple angles and with slight variations allows one to develop form in a very quick manner. [AM]
	<b>shape determining systems</b>	Encouraging certain shapes and ways of working.	It was difficult to sketch some of the forms, especially the ones with thin walls, double-curved surfaces and holes. [JM] The soft indentions are difficult to communicate on paper. [VS]
	<b>integration of visual &amp; verbal data</b>	Integrating both visual & verbal modes of representing ideas.	The sketches [referring to a sketch representation including explanatory notes] illustrates my thoughts of the basic idea for which the form now has to be developed. [AV]
	<b>integration of 2-&amp;3d perspectives</b>	Integrating two and three dimensional perspectives and different views in sketch representations.	[Sketching] allows me to define the shape for myself, i.e. if I sketch this in different views, what will the back look like, it forces me to think in 3D in a 2D setting. [AM]
	<b>immediacy</b>	Enabling the designer with a direct and instant involvement and interaction.	Quick way to develop form. Easy to see what works/doesn't work without having destroyed the material by taking something too far. Using paper, one can simply make an overlay and make one more iteration of the form. [AM]
Sensory roles	<b>visual aid</b>	Displaying visual representations enables the designer to inspect their work.	In order to see how a given shape would be perceived had it been made with a smoother surface, sketching was utilized. [AM] [...] to be able to see how they would be affected by changes in smaller details. [...] Trying to see how different surface curvature would affect the expression. [VS]
	<b>thinking aid</b>	Aiding the designer in thinking about different issues and aspects of design.	I sat with a paper and started to draw some lines. [...] I often sketch when I am thinking. [JM] I found sketching to be a suitable first method of form development because that is what I found easiest and the fastest way to explore thoughts and try forms. To think with the pen. [AV]
Cognitive roles	<b>memory &amp; retrieval aid</b>	Monitoring thoughts by providing an environment of short-term memory in sequences of sketches.	Using the pen as a sketching tool to record ideas for later use. [JN] Sketching was used as a complement to the other methods, when ideas came up they were sketched down so they would not be forgotten and then they were further developed with CAD later. [IK]
	<b>support imagery</b>	Provoking imagery & the ability to restructure visual components through vagueness inherent in sketches.	The lines become some kind of form, and I changed it with some more lines. In that way I get a form in which I saw a possible 3D form. I draw it in 3D. I wanted to see what happened if I changed the form. That gave me a new shape. [JM]
	<b>selective attention</b>	Attending to a limited part of a task by containing selective & fragmentary information sketches.	Made some sketches of ways to integrate the handle with the shape of the cup... To see how the negative space between the handle and the cup could affect the expression. [VS]
	<b>interpretation &amp; emergence</b>	Provoking emergence of new ideas, seeing things in new ways, & recognising unintended consequences.	I wanted to see the relationship between the ridges, and how that affected the overall impression. [AM]

**industrial design** (Pei et al., 2011)

- > sketch models aka foam models or 3d sketches,
- > design development models for exploring the relationship between different components,
- > operational models for ergonomic evaluation,
- > appearance models for capturing precise appearance of the product.

**engineering design** (Ulrich & Eppinger, 2008)

- > soft models e.g. from foam for defining the outlines,
- > rough models from wood, plastic or metal for selecting the final concept.

**mechanical design** (Ullman 2003)

- > proof of concept at the initial stages,
- > proof of product for evaluating feasibility,
- > proof of process to address production methods and material properties,
- > proof of production that involves complete manufacturing process.

Table 4: Different types of physical models as representations across design disciplines.

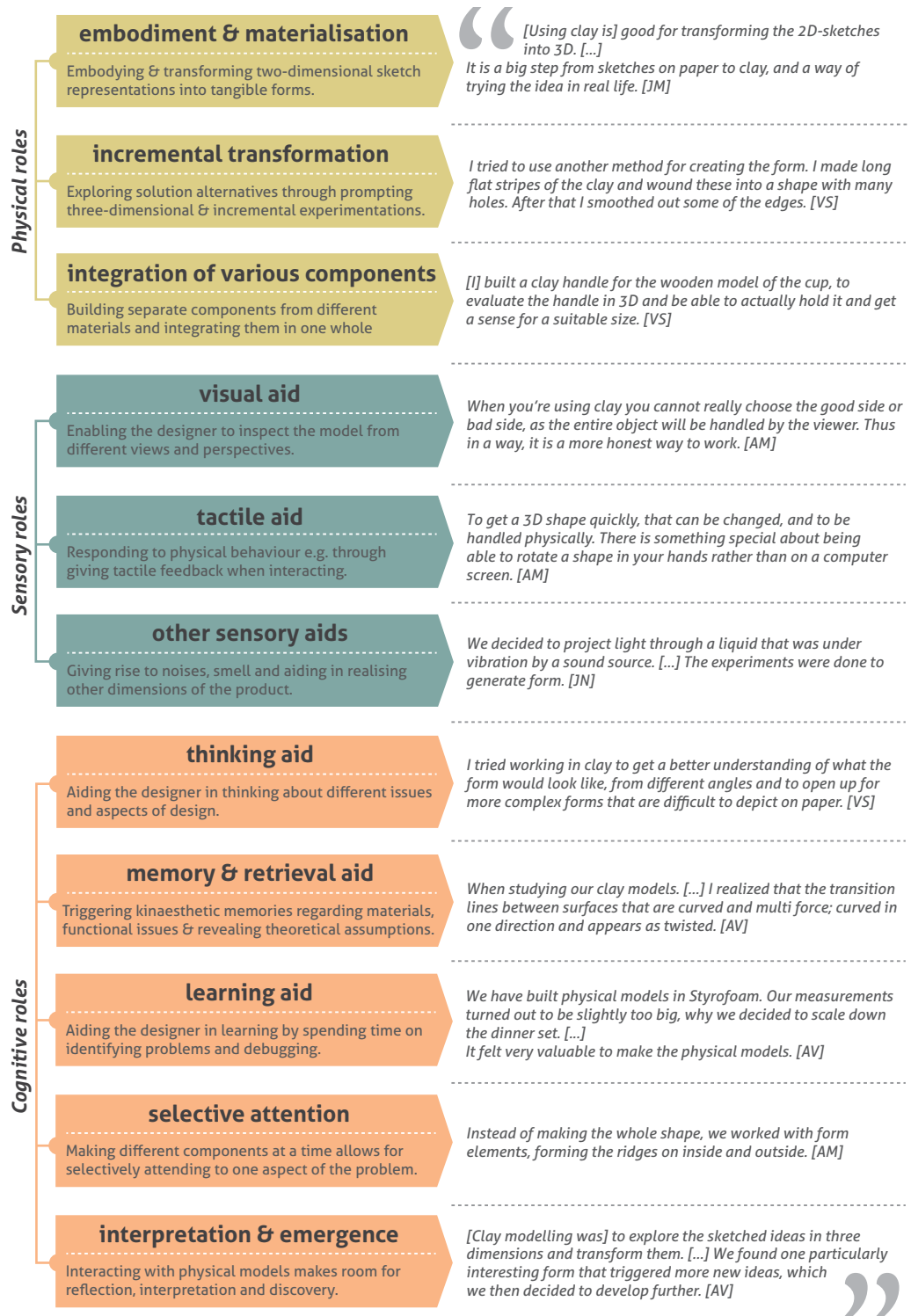
Figure 3: Examples of experimental physical modelling for exploring form ideas for a dinnerware project (student works), from left to right: (i) transmitting soundwaves through a liquid, (ii) using balloons & flour, and (iii) using plaster & cotton.



**Digital modelling**

In digital modelling a CAD (computer-aided design) system is used to assist in defining the geometry and visual appearance of a design. There is an on-going debate regarding the nature of digital models, and if they can be considered as models or merely drawings (Coyne et al., 2002). Here, digital models are three-dimensional representations created in digital media. In general, digital modelling belongs to the later phases of the design process. Handing over final sketches to a modeller, who interprets and translates them into a digital model, is a common practice in most design firms. CAD systems are driven more by production needs i.e. accuracy and efficiency rather than creativity (Jonson, 2005), and encourage working with precision and details while allowing little room for vagueness and indeterminacies that trigger creativity in the ideation phase. Many scholars hold that digital modelling in ideation phase inhibits designers' thinking and creativity (see e.g. Séquin, 2005). Findings from a case study and an extensive survey with 255 designers suggest that the intensive visualisation in digital media discouraged the designers to modify their ideas resulting in *premature fixation*. Some studies however challenge this view. In a study with two designers, Won (2001) found that digital modelling demands a more complex cognitive behaviour than traditional sketching, since the designer has to deal with enhanced visualization, thus supporting better reinterpretation and frequent shifting from the whole design to details in the

Table 5:  
Left: roles of physical modelling in design process (based on the literature review).  
Right: manifestation of the identified roles (based on design diaries).





ideation phase. One of the four participants in another study (Salman, Laing and Conniff, in press) had a moment of discovery when conceptualising in a digital medium that was enabled by the systems' immediate visual feedback provided. However, all the participants in this study showed signs of distraction during the ideation phase, moving their attention to manipulating the system and focusing on a lower level of detail in the concept. Some researchers propose recommendations for enhancing digital systems or new ways of working with them in order to overcome the mentioned shortcoming. For example, Séquin (2005) showed how digital media could allow designers to explore a wide range of design alternatives through computation and programming. In another study, a digital sculpting medium was found suitable for the ideation phase, due to its restricted precision, which enabled the designers to carry out activities similar to that of sketching in terms of the number of ideas and reinterpretations (Alcaide-Marzal, Diego-Más, Asensio-Cuesta et al., 2012).

**Digital modelling media** – Computer-aided media differ in the particular approaches that they allow for working with digital models (e.g. through surface and solid modelling or deforming three-dimensional meshes like that of digital clay). A recurring theme in the reviewed literature concerns technical problems of CAD systems, distracting designers from ideation process, causing resistance for making major changes in the representations, and limiting the solutions to what is easiest and most available (Robertson and Radcliffe, 2009). Some researchers have suggested making CAD systems more sympathetic and responding by allowing more feedback and conversation in order to help designers express their ideas in a natural manner (Lawson and Loke, 1997).

**Digital models as representations** – The representation types that were mentioned for sketching and physical modelling may also apply to digital modelling, since designers tend to create digital representations that resemble their sketches and physical models. However, digital media also come with specific potentials e.g. the ability to create interactive representations by including movement and animation as well as photorealistic renderings.

**Roles of digital modelling** – Different roles of digital modelling in the design process are listed and exemplified with diary excerpts in table 6. Among these roles, introduction of new practices is frequently discussed, especially the ability to make photorealistic renderings in a short time. This is while cognitive roles were not a recurring theme for digital media. In fact, they were mostly considered to inhibit designers' thinking and creativity.

## DISCUSSIONS AND CONCLUSIONS

### Comparing externalisation activities and their roles

This review has presented a tentative overview on the roles of externalisation activities, as a starting point for future research. Figure 4 shows roles that different externalisation activities have in common, as well as those that are unique to each activity. While the presence of these roles in the reviewed literature illustrates the ways in which different activities contribute to designers' progress in design process, their absence may be merely due to sparse empirical evidence. Moreover, some roles are more prominent in one activity than others. For instance, the learning role that is uniquely discussed in relation to physical modelling might also apply to sketching and digital modelling possibly to a different extent. On the other hand, learning can be regarded as a latent role of sketching and digital modelling. This is however not applicable to all of the roles; e.g. the tactile inspection of representations is solely offered by physical modelling and there is no varying degree of this role in sketching or digital modelling. Further, the roles that different activities have in common may also vary in nature e.g. visual inspection is enabled in various perspectives in physical and digital modelling while sketching only offers a specific view of the representation. To account for the validity of these roles, future research should consider crosschecking the extent to which they occur across different media used in product design practice.

Comparing externalisation activities based on their roles reveals why sketching is considered an intelligence amplifier, while digital modelling is regarded as a creativity inhibitor. More cognitive roles are associated with sketching in the reviewed literature, in comparison with physical and digital modelling. Among these roles, *supporting visual imagery* was solely attributed to sketching which, according to Kosslyn, Thompson and Ganis (2006), concerns mental generation, inspection and transformation of forms. For example, Verstijnen, van Leeuwen, Goldschmidt et al. (1998) found that sketching facilitates restructuring of forms which is otherwise difficult to perform mentally.

Tangible qualities of physical modelling enable sensory roles e.g. triggering kinaesthetic memory, and learning. The latter, according to Brereton (2004), is enabled through experimentation, identification of problems and debugging. There is a need to understand the underlying relations between the haptic experience from manipulating materials in physical modelling and learning.

Digital modelling introduces a range of new practices that allow manipulation of forms in ways not possible in

Table 6:  
Left: roles of digital modelling in design process (based on the literature review), right: manifestation of the identified roles (based on design diaries).

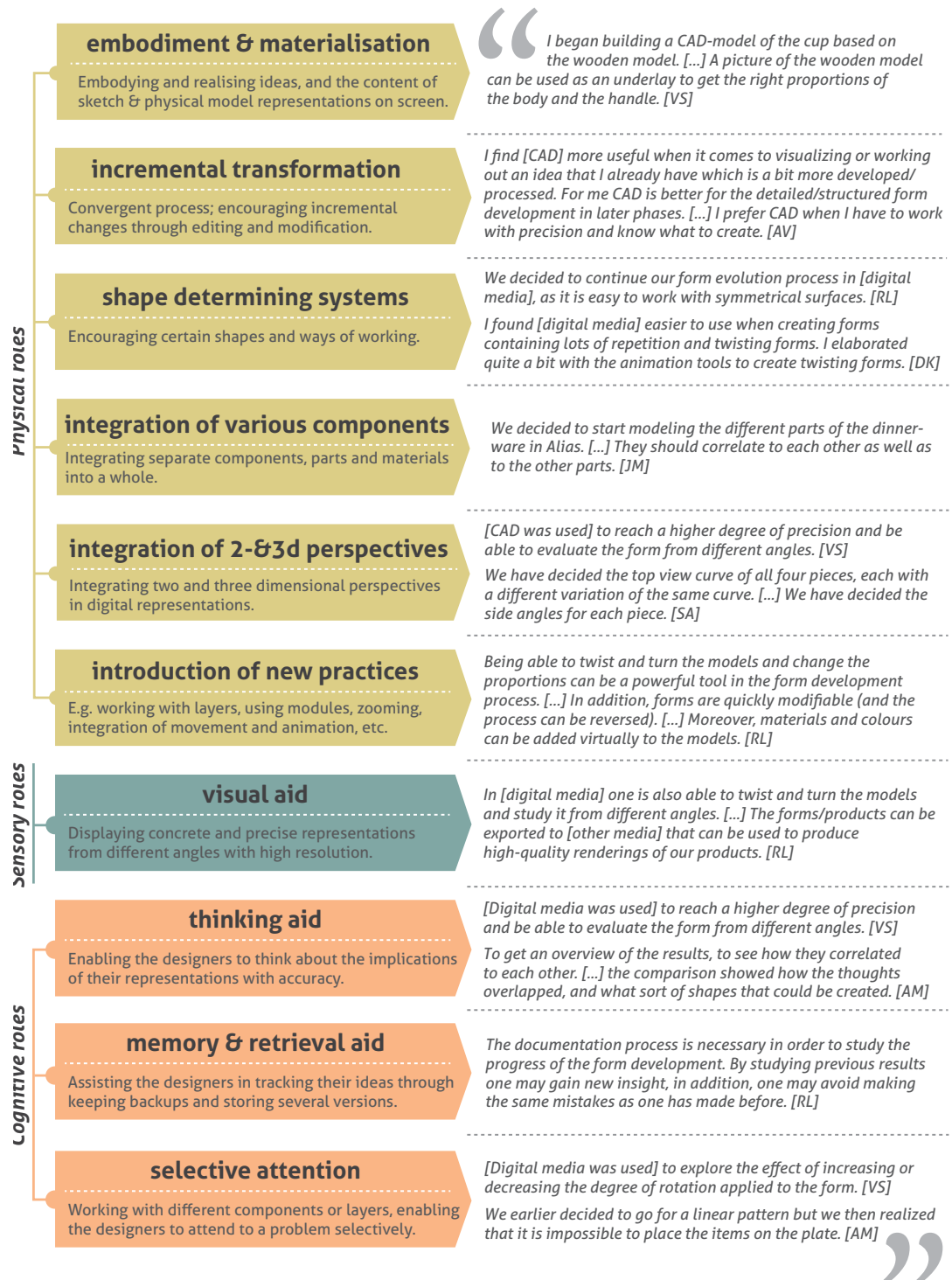
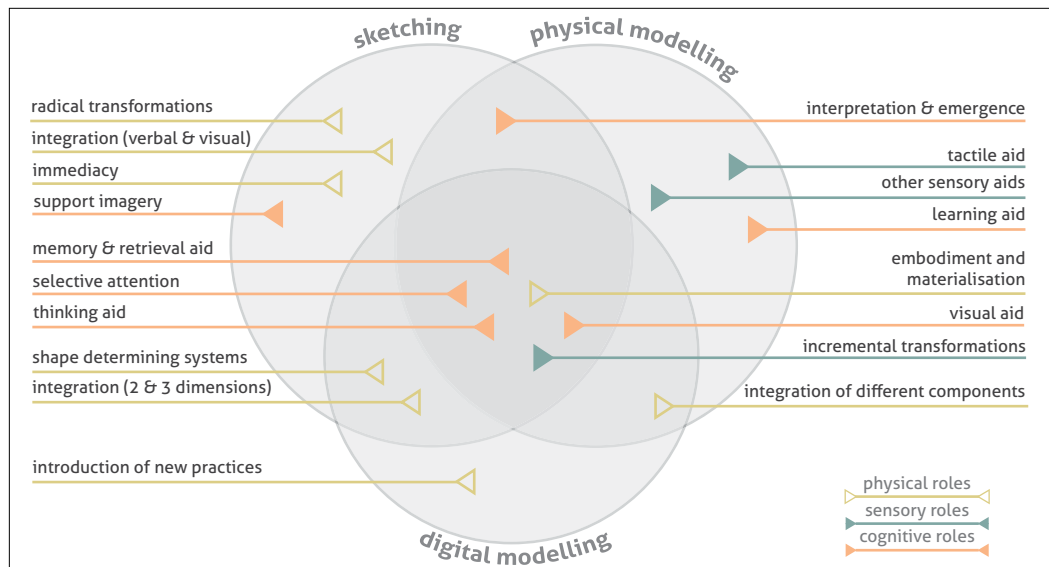


Figure 4: Roles unique to – and in common between different activities, identified from the literature review.



other activities, while having fewer cognitive roles. This may explain why digital modelling is regarded a threat in design. Several reasons are given to explain why CAD systems inhibit thinking and creativity in the design process. First, the high resolution of CAD representations distract the designers' attention from whole to detail and limit their ability to see and interpret things in new ways (Lawson, 2002). In contrast, the ambiguous character of sketches support imagery and encourage reinterpretation (e.g. Goldschmidt, 2003, Fish, 2004, Goel, 1995). This makes digital media more appropriate for incremental development, evaluation and integration in the concrete phases. Second, CAD systems are considered unsympathetic and not responding (Lawson and Loke, 1997). Since these systems introduce new ways of working and talking about design (Coyne et al., 2002), a gap between the new terminology and the designer's mental model is created that may inhibit the designer to engage in a conversation with these media. This is while some researchers emphasise that the main modality in the conceptual phase of design is verbalisation (Jonson, 2005, Lawson and Loke, 1997). The terminologies, however, vary considerably across different digital media. Third, "designers adopt their style to the computer software's capability and accept its limitations" (Fish, 2004). A possible compromising behaviour would be to adopt the visual appearance of products to what the system allows for. This has briefly been mentioned in a few publications regarding architectural CAD systems. Lawson (2002) highlights the more frequent appearance of parabolic rotated forms, or shell form with elliptical sections as a result of using digital media. Specific and explicit visual cues that dif-

ferent digital media impose on the appearances of products are not addressed in the reviewed literature, which might partly be due to the difficult nature of this topic. Systematic studies for identifying these compromising behaviours are yet to be initiated. Finally, learning and using CAD with its large array of functions is considered to be labour intensive and time demanding (e.g. Ullman, 2003, Lawson and Loke, 1997) and can limit the design possibilities (Jonson, 2005, Bilda and Demirkan, 2003, Coyne et al., 2002).

#### Interplay between different media and representations

In this paper, the externalisation activities and their roles were addressed separately, to allow for comparison. However, designers undertake a combination of these activities in the design process. Reframing prior ideas using a new medium facilitates interpretation and leads to finding geometric relations that would otherwise be hidden in one representation. Some studies suggest that working in one medium might limit design possibilities (Jonson, 2005), while use of different media and an interaction between two – and three-dimensional representations facilitate a creative approach and assist the designer to identify otherwise hidden issues (Tovey, 1989). For example, Capjon (2004) recommends using a combination of Rapid Prototyping and scanning techniques for translating digital representations to physical models, helping the designers to discover and correct shortcomings of their precedent solutions. A combination of media and activities may therefore result in different roles merging, eliminating the potential hindrances of a single activity. Empirical evidence regarding

the interplay between different activities and how they may complement each other in the design process is however relatively sparse.

### Future work

Greater research efforts are required to explore the differences between various media and the extents to which they facilitate or inhibit the design process. This could be achieved by contrasting them against each other and also traditional media. Several comparative studies between digital and manual sketching were reviewed in this paper, but no research was found comparing three-dimensional physical and digital models or different digital media.

The designers' feel for media enables them to engage in a conversation with the design situation (Schön, 1983). Underdeveloped skills in externalising ideas considered a handicap to design particularly in the ideation phase (Muller, 2001). Several studies show hints of developed mental imagery abilities among skilled design practitioners when sketching, especially the ability to reinterpret their sketches (e.g. Menezes and Lawson, 2006, Suwa, 1997). Greater research efforts are required for understanding the mechanisms behind imagery, and whether using different media support or inhibit (i) designers' ability to reinterpret the design situation, (ii) their mental imagery processes and (iii) and the development of their skills.

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