Towards a model of how designers mentally categorise design information

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A B S T R A C T

This study aims to explore how designers mentally categorise design information during the early sketching performed in the generative phase. An action research approach is particularly appropriate for identifying the various sorts of design information and the cognitive operations involved in this phase. Thus, we conducted a protocol study with eight product designers based on a descriptive model derived from cognitive psychological memory theories. Subsequent protocol analysis yielded a cognitive model depicting the mental categorisation of design information processing performed by designers. This cognitive model included a structure for design information (high, middle, and low levels) and linked cognitive operations (association and transformation). Finally, this paper concludes by discussing directions for future research on the development of new computational tools for designers.

1. Introduction

Developments in science and technology dating to the industrial revolution have been of great research interest; however, historical accounts have paid relatively little attention to the role of consumers/users and designers. Since the widespread introduction of the notion of "user-centred design" during the late 1990s, research on consumers in the service of enhancing interface design, improving usability, etc. has become common. Nowadays, during the transition from a knowledge society to a creative society, research into the cognitive activities of designers, important contributors to the generation of the creative ideas that underpin efforts to meet consumers' needs and desires, has been growing and has led to a substantial increase in the value assigned to certain domains [12,39,40]. Indeed, the expertise and the cognitive and creative processes of designers during the early stages of design have been acknowledged as important research foci. At the same time, designers have developed digital design databases, which have become increasingly important parts of their work as a result of the dissemination of information technology (IT) [9,13,35,40]. However, the development of computational tools for designers has been limited to prototyping technology such as Computer Aided Design (CAD), Computer-aided Manufacturing (CAM), or Computer-aided Styling (CAS), because the activities of designers are relatively implicit and subjective and involve rich mental representations during the early stages of the design process [45].

In this context, our study was designed to develop new models and tools to be used to digitise this early design process according to the three progressive steps: (1) to identify the design knowledge, rules, and skills that underpin designers' cognitive processes [38]; (2) to translate the design rules into design algorithms; and (3) to develop computational tools for use by designers themselves and by other professionals involved in the early collaborative design process [9].

This paper focuses on the first step in particular, which involves modelling those aspects of a designer's cognitive process that are dedicated to the mental categorisation of the design information used during the generative phase. We applied an action research approach which is a form of reflexive process in encompassing both theoretical and practical concerns while contributing a scientific method or a model [32]. This approach enabled us not only to build a model of the cognitive processes used by designers, but also to rely on both theoretical and experimental approaches to elicit the specific cognitive activities used by designers (see Fig. 1). First, we reviewed the scientific literature on the cognitive processes of designers from the perspectives of both design science and cognitive psychology in Sections 2.1 and 2.2. A descriptive model of information processing involving memory theories drawn from cognitive psychology is presented in Section 2.3. This model was refined and enriched via a protocol study with eight product designers, as discussed in Sections 3 and 4. Finally, Section 5 synthesises the results of a subsequent protocol analysis within the framework of a cognitive model depicting the mental categorisation of design information processed by designers.

2. Theoretical background

2.1. Understanding the cognitive dynamics and information processing of designers during the early stages of design

The early stages of the design process have been characterised in terms of information processing and idea generation (also called

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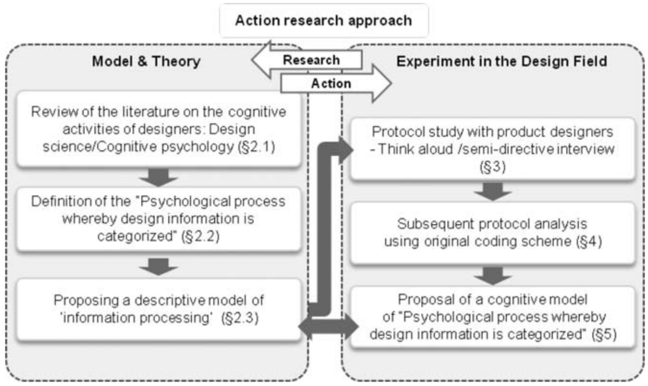


Fig. 1. Research methodology: action research approach.

"conceptualisation") [7,8,13,19]. During the early stages of the design process, designers integrate various levels of information to reduce abstraction by adding constraints [7,8]. Bouchard et al. [8] and references therein, interpreted the cognitive processes of designers during the early stages in terms of information processing. According to this view, designers engage in an informational cycle that includes informative, generative, and decision-making phases (evaluation–selection) to produce intermediate representations (IRs) that develop in an evolutionary way. Goldschmidt [25] defined IRs as mental or physical images used during the entirety of the design process. IRs can be implicit or explicit, appearing as design briefs, trend boards, 2D/3D sketches, styling models, digital geometrical models, mock-ups, prototypes, etc. They are used strategically according to the design context, design phase, design purpose, cultural context, etc.

Given that the early stages of design are considered to be among the most cognitively intensive in the design process [34], several studies based on interior and architectural designs have been pioneered to understand the sketching activities of designers, especially those performed during the generative phase [6,25,41,43]. Since the early 1990s, a few studies dedicated to the sketching activity of designers have emerged in mechanical engineering design; these include Ulman et al. [46], Goel [24], Purcell and Gero [37], and Yang [47]. To date, little research has addressed issues related to the inspirational sources used by designers in the informative phase [9,19,29]. Moreover, the bridge between the informative and earliest generative phases has been relatively neglected, and the specific experiences of product designers have not yet come to the fore.

2.2. Definition of the "psychological processes whereby design information is categorised"

The bridge between the informative and earliest generative phases involves the generation of new ideas and new solutions. It begins with numerous mental images, memorised design briefs, and other information derived from previous design projects [8]. This process has been recognised as an individualised experience for designers that manifests in repetitive cognitive activities [28]. During the earliest generative phase, certain parts of the mental images can be externalised in sketches. These early sketches are not mature or suitable to be shared with or interpreted or used by other people. Instead, they can serve as external representations (i.e., externalised memories that act as visual tokens during later inspection) [15,25,36,43]. External representations (e.g., early sketches) allow a reflexive conversation between the designer and the product to be created [15,43]. Previous studies have shown that external representations allow designers to identify errors that are then used to generate new ideas [1]. Similarly Crilly et al. [15] noted that designers engaged in "bi-directional conversations" with representations insofar as intentions were formed and reformed during the activities of representation (see also Schön's "Seeing–Drawing–Seeing model" [41]). External and internal information interact with each other in an evolutionary manner and are integrated and synthesised into categories contributing to design solutions via the designer's mental processing [8]. In this respect, we define this phase as involving the psychological process whereby design information is categorised during the sketching that occurs in the earliest generative phase. More precisely, our aim is to identify the kind of cognitive operations that extract design information from memory and to determine how this design information is transformed or categorised during early sketching. Towards this goal, the following section proposes an initial descriptive model of information processing that integrates memory models derived from cognitive psychology, which describe the transfer of information through memory, including those of Atkinson and Shiffrin [2], Baddeley et al. [3], and Broadbent [11].

2.3. Proposal of a descriptive model of information processing

Broadbent [11] proposed a sequence of cognitive processing stages that can be performed in bottom-up or top-down order. Bottom-up processing is considered a stimulus-driven process caused by sensory stimuli, whereas top-down processing is seen as memory-driven. In many cases, stimulus-driven processes are based on inspiration such as photos, magazines, etc., which evoke feelings or emotions. Memory-driven processes are driven by knowledge derived from past experiences. In this paper, we focus particularly on memory-driven processes, which have received relatively less attention and thus remain less understood due to their implicit nature, characterised by information stored in memory as well as cognitive operations related to such information. We adapted two theoretical models drawn from cognitive psychology to formalise our examination: the model developed by Atkinson and Shiffrin [2] and that developed by Baddeley et al. [3] (see Fig. 2).We selected cognitive operations related to six phenomena to account for overall information processing: stimuli, perceptual action, questioning, association, transformation, and judgment/decision. More specifically, operations involving questioning, associating, and transforming play roles in retrieving memorised design information from long-term memory (LTM) and moving it to working/short-term memory (WM/STM). According to the Geneplore Model defined by Finke et al. [21] in the work of Benami and Jin [5], several types of cognitive operations underpin the generative phase: retrieval of information from memory, association, mental synthesis, mental transformation, analogical transfer, and categorical reduction. Several of these, including mental synthesis and reduction, are difficult to categorically identify through verbalisations or sketches, but the remaining

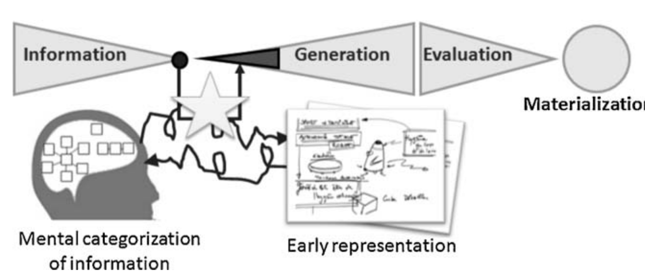


Fig. 2. Categorisation of design information during the earliest generative phase (description of an informational cycle [8]).

Table 1
Protocol coding scheme (based on verbal protocol).

Coding (code)	Description	Examples
Design information [10,30]		
High level (H)		
Values (Hv)	These words represent final or behavioral values	Security, well-being
Semantic descriptor (Hs)	Adjectives related to colour, form, or texture, but also impressive words in the field of Kansei Engineering	Playful, romantic, aggressive
Analogy (Ha)	Objects in other sectors with features to integrate in the reference sector	Rabbit → speed
Style (Hy)	Characterisation of all levels together through a specific style	Edge design, classic
Middle level (M)		
Sector name (Ms)	Object names describing one sector or sub sector being representative for expressing a particular trend	Sports
Context (Mc)	User social context	Leisure with family
Function (Mf)	Function, usage, component, operation	Modularity
Low level (L)		
Colour (Lc)	Chromatic properties using qualitative or quantitative	Yellow, light blue
Form (Lf)	Overall shape or component shape, size	Square, wavy
Texture (Lt)	Patterns (abstract or figurative) and texture	Plastic, metallic
Cognitive operations		
Stimuli		
Selectively concentrating on one aspect of outer/inner senses [42]	(In watching the bicycle wheel) 'I had seen the mini-sports shoes on the bicycle wheel in the show window'	
Perceptual action		
Interpretation of visual information, such as depict elements on sketches for arranging the spatial relations on sketches [43]	In profile, the screen should be this side for little more user-oriented, then a gripe on the right side	
Questioning		
An expression of inquiry about ideas and emerging issues not associating with one another	Does it feel sportive? It is a little static; I think that we want to something trendy	
Association		
Grouping ideas, finding similarity/uniformity, difference/contrast, how people interact with the design artefact and how the design artefact interacts with the environment [21]	If I start by an iPod which has a hard angles to differentiate into two components, fine plastic and bright/clean colour, ...	
Transformation		
Ideas are shifted to make interesting and useful entities such as new value and analogy [21]	There is an automated vacuum cleaner, like a robot, which can move by itself	
Judgment/decision		
Make a judgment or evaluation on ideas according to the design brief, related to design information, or designer's satisfaction	I like/dislike this form	

three (retrieval of information from memory, association, and transformation) can usually be identified. The remaining operations (those pertaining to stimuli, perceptual action, and judgment/decision) were based on the model defined by Ball and O'Callaghan [4] and Harris [26]. Consequently, these six cognitive operations have been used to develop our coding scheme, which was the foundation of our definitions of the major cognitive operations involved in the mental categorisation of design information (Table 1 and Fig. 3).

The descriptive model helps us to clarify and define what design is from a theoretical point [44]. The following section describes our protocol study to identify the actual designer's activities dedicated the mental categorisation of the design information used during the generative phase.

3. Design of protocol study

The aim of our protocol study was to determine the kind of cognitive operations used to extract mental information from memory and to examine how this mental information is transformed or categorised during early sketching. The present protocol is partially based on our previous work on design information [30]. We recently merged the previous coding scheme for design information with the new coding scheme for cognitive operations (see Table 1). The two complementary coding schemes allow us to link the extracted design information with the cognitive operations used to perform the extractions.

3.1. Methods

A comprehensive and varied research method is required for understanding information and activities related to design [16]. In many cases, these methods have been based on the explicit representations used or produced by designers; therefore, they have certain limitations insofar as many of the cognitive activities of designers during the early stages of the design process are implicit. One approach to this issue is provided by methods drawn from ethnography. Data collected using an ethnographic methodology often derives from observations, interviews, and questionnaires completed in real contexts rather than from results of laboratory experiments. Another approach to this issue is provided by the think-aloud method, which is based on observations and verbalisations occurring in real time.

Generally two types of think-aloud methods have been used: concurrent and retrospective. The concurrent protocol could point out detail sequences of information process reflecting the designer's working memory (WM); therefore it has been utilised to reveal the process-oriented aspects of designing [18,20]. The retrospective protocol has been used in experimentations which focus on the cognitive content aspect because it could retrieve the trace of the cognitive process and reveal information partially in both working memory (WM) and long-term memory (LTM) [18,23]. However, some methodological limitations still remain in both protocols: concurrent protocols may influence the natural design process and cause incompleteness in revealing the design

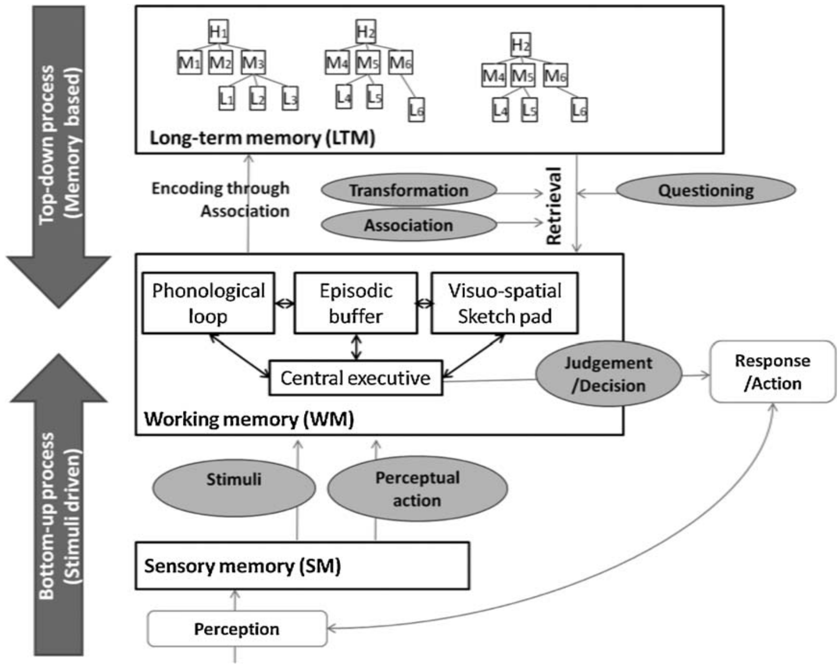


Fig. 3. Information processing model (integration of the multiple components of working memory).

process; retrospective protocols may also cause insufficient and reinterpreted information due to the decay of LTM [6,16,17,20,33]. More recently, Gero and Tang [23] showed that concurrent and retrospective verbalisation protocols have very similar outcome in case of the process-oriented aspects of designing. However, the debate on the validity of think-aloud protocols is still ongoing.

Given the difficulties related to data collection, we used an activity-based approach, which represents a combination of these methods. Indeed, concurrent protocols are considered better suited to our study in that we focus on design information and related to cognitive operations. Semi-directive interviews [31] were also conducted at the end of the experiment to compensate for the deficiencies of the concurrent methodology.

3.2. Participants

We recruited two third-year undergraduate design students and six expert product designers (one female and seven males). The six expert designers had a mean of 9 years of experience. If one designer who had worked in product design for 28 years is excluded, the mean number of years of professional experience decreases to 5.2 years.

3.3. Procedure and equipment

The experiment was conducted at the design agencies of the participants to collect data in their natural working environments. As shown in Fig. 4, we used two video cameras and one voice recorder to collect verbalisations. One video camera captured the movements of the hands of each designer and recorded close-ups of the sketches, and the second recorded the entire body of the designer.

The protocol involved three phases:

(1) *Warm-up phase*, in which we explained the procedure of the experiment and participants became accustomed to the practice of concurrent verbalisation (∼15 min).
(2) *Concurrent verbalisation*, in which participants were asked to work on the design brief: *Designing a Nike vacuum cleaner*. During this phase, they started to generate early sketches using traditional tools and simultaneously verbalised their thoughts (∼60 min).
(3) *Semi-directive interview* about the mental images, semantic descriptors, and forms generated as well as about the relationships among those three types of data (∼15 min).

3.4. Analysis: coding

Using the principles of protocol analysis recommended by Suwa and Tversky [43] and Gero and McNeill [22], the entire verbal protocols were transcribed and segmented for coding according to our dual coding scheme (Table 1). Next, written transcripts were attached to corresponding video clips. The video analysis software INTERACT [27] was used to reduce the time involved in this process and to produce reliable quantitative results. The coding process

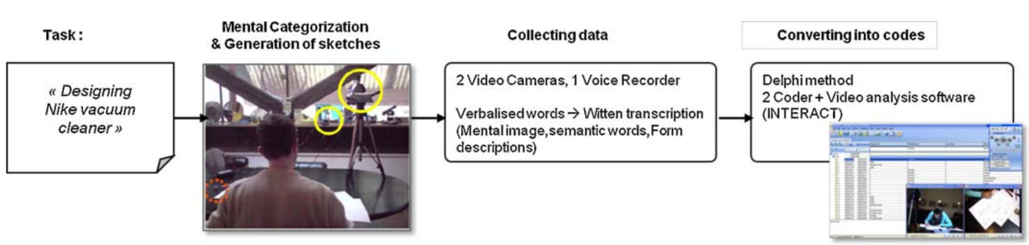


Fig. 4. Design of protocol study.

used the Delphi method [22] involving two coders. The reliability of the coding process was measured by calculating the percentages of inter-coder agreement. This figure was higher than 82%, which indicated that the coding process was reliable. Videotaped sketches were also used to complete and verify verbalised content. Our coding scheme, presented in Table 1, includes two categories: design information and cognitive operations. As noted above, the coding scheme for design information was based primarily on our previous work on Kansei words [10]. The level of an item of information can be understood in terms of its position on an axis from abstract (high-level information) to concrete (low-level information). The scheme includes 10 categories of design information. The coding scheme for cognitive operations was based on our descriptive model presented in Section 2.3. This framework includes stimuli, perceptual action, questioning*, association*, transformation*, and judgment/decision and is based primarily on the Geneplore Model [21] (the cognitive operations marked with asterisks, which are related to the process whereby information is retrieved from long-term memory and stored in short-term memory, are of particular interest). The complete coding scheme enables understanding of connections between mental representation during retrieval and external information during sketching and also yields an encompassing depiction of the cognitive processes involved in categorising design information.

Note that we coded ‘‘silence’’, which is not a cognitive operation, when designers did not verbalise their thoughts and remained silent. We did so because we believe that this code facilitates the anticipation of certain internal cognitive processes that are rarely verbalised but that may enrich our model. In addition, responses consisting of replicas of a given design brief, expressions of needs/difficulties, jokes, etc. were coded as ‘‘other’’ and set aside for further study (the percentage of the ‘‘other’’ response was negligible compared with those of other responses).

4. Results and discussion

In this section, based on the video and audio protocols, we intended to identify the kind of cognitive operations that extract design information from memory and to determine how this design information is transformed or categorised during early sketching. We subsequently applied our dual coding scheme including design information and cognitive operations (Table 1). Finally, both quantitative and qualitative approaches were integrated to produce a cognitive model depicting the mental categorisation of design information processing performed by designers in Section 5.

4.1. What types of design information were verbalised during early sketching?

The substance of the comments made by the designers was very dependent on the design brief: Designing a Nike vacuum cleaner. For example, representative words in value categories included ‘dynamism’ and ‘aesthetics’, and the most common semantic descriptors included sporty, dynamic, fluid, classic, technical, fun, friendly, etc. The designers also employed 12 analogical words referring to, for example, sports (using a harness or scooter, lifting weights, using flippers, cycling, dancing, etc.), biomorphism (animals: shark fin, humans: mouth, and vegetables), and shoes and luggage (backpacks, accessories, etc.). These references draw heavily on semantic and conceptual associations with the Nike brand (e.g., shoes for sports). Other sectors (e.g., industrial products, household electrical appliances used for protection and air conditioning, robots, containers, and real estate) were also mentioned. The category encompassing the function of the target product consisted of responses related to its internal mechanics, units, and uses and operations such as ‘‘fan’’, ‘‘dust bag’’, ‘‘air cushion’’, etc.

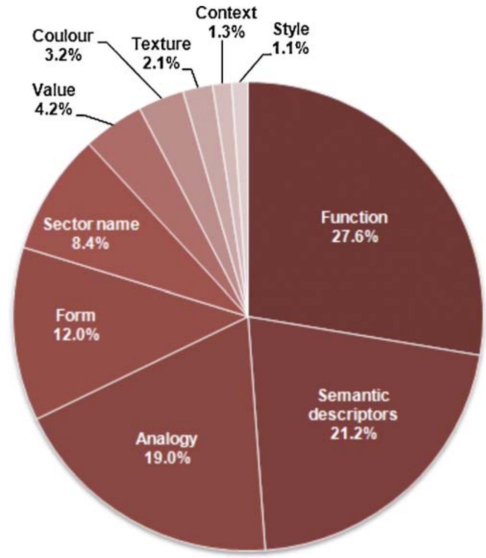


Fig. 5. Frequencies of types of design information.

Consistent with the quantitative results of a study on design information reported by Kim et al. [30], high-level information was used most frequently (47.7%), followed by middle-level (36.7%) and low-level (15.6%) information. Thus, high- and mid-level information accounted for 84.39% of the words verbalised during early sketching. Low-level information tended to be represented in sketches rather than verbalised. The detailed frequencies of each category are presented in Fig. 5. The most frequently verbalised content was related to function (27.6%); this was followed by semantic descriptors (21.2%). The remaining six categories were mentioned relatively less frequently.

4.2. Cognitive operations during the categorisation of information

Fig. 6 shows the frequencies for different cognitive operations. On average, association accounted for 44.9% of all cognitive operations, judgment/decision accounted for 18.0%, perceptual action accounted for 12.9%, transformation accounted for 12.1%, questioning accounted for 9.7%, and stimuli accounted for 2.4%. During the earliest generative phase, designers exerted relatively more effort to generate ideas by retrieving design information from memory; retrieval processes of all sorts (association/transformation/questioning) accounted for 66.7% of all cognitive operations. Thus, judgment was used less frequently than association. In addition, stimuli rarely inspired responses; because our study focussed on memory-driven processes, we tried to eliminate external stimulation and encouraged designers to rely solely on their mind/memory during the task.

Moreover, because the cognitive operations related to retrieval processes were of great interest, we intend to recode association and transformation responses in terms of the subcategories of design information (cited in Table 1). According to the three levels of information, design information can be associated in three ways: descending association (from concrete to abstract), ascending association (from abstract to concrete), or same-level association.A more detailed analysis of the results showed that a plurality of the 44.9% of the responses accounted for by association was same-level associations (22.2%), i.e., links between functions (Mf–Mf), semantic descriptors (Hs–Hs), or sectors (Ms–Ms); this was followed by ascending associations (12.0%) and descending associations (10.7%). Fig. 7a shows the frequencies of each

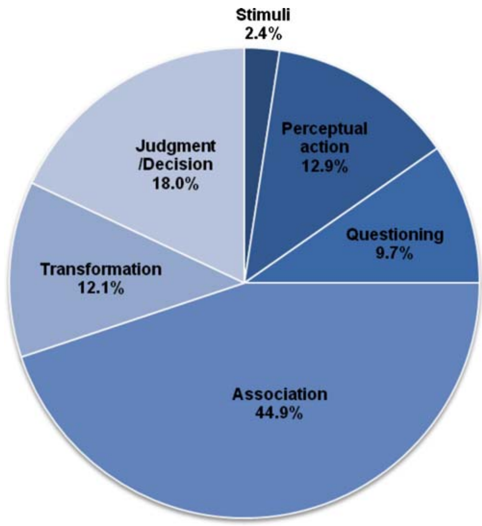


Fig. 6. Frequencies of cognitive operations.

subcategory of association. Most ascending associations involved the middle to the high level (M → H), referring to links between functions and semantic descriptors (Mf–Hs); or the low to high level (L → H), referring to links between descriptions of forms and semantic descriptors (Lf–Hs). Representative descending associations included the link between functions and descriptions of forms (Mf–Lf) or the use of words to form descriptions (Hs–Lf). Using the cognitive operation of transformation, designers created new and interesting ideas or concepts by forming analogies with functions (Mf–Ha, 43.8%) or by exploiting the meanings of words (Lf–Ha, 36.3%) (see Fig. 7b). In Section 5, the links between association and transformation will be discussed in greater depth and presented as a cognitive model for the mental categorisation of information.

4.3. Changes in cognitive operations over time

To compare changes in the six cognitive operations over time, we summed the number of cognitive operations in each 10-min interval. The normalised frequencies of cognitive operations were calculated as follows: (normalised $A = (A - \text{mean})/\text{standard deviation}$) [6]. Thus, if a cognitive operation increases in frequency, the normalised frequency will have a positive value, and if the cognitive operation decreases in frequency, the normalised frequency will have a negative value (Fig. 8).

We observed two different groups of cognitive operations that shared a similar tendency. One group consisted of association, transformation, questioning, and stimuli, and the other group consisted of perpetual action and judgment/decision. During the first 40 min, the only negative variance was observed for perceptual action during the first 10 min; this may be attributable to the tendency of designers to rely more heavily on memories for categorised mental information at the beginning of the design process. After a brief interval, the designers started to generate early sketches to represent their ideas and/or identify errors. For this reason, the operation of judgment/decision resembles that of perceptual action. During the remainder of the observation, all variances tended toward negative, indicating that the designers'

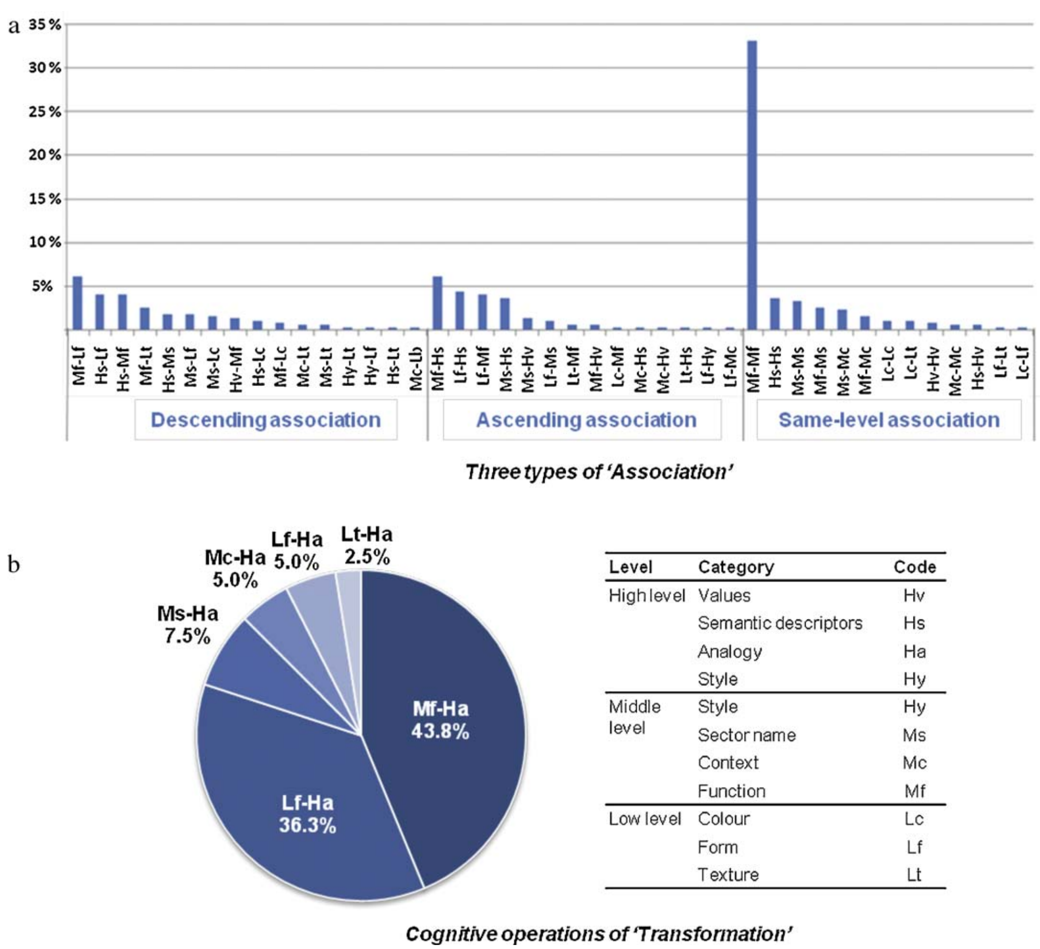
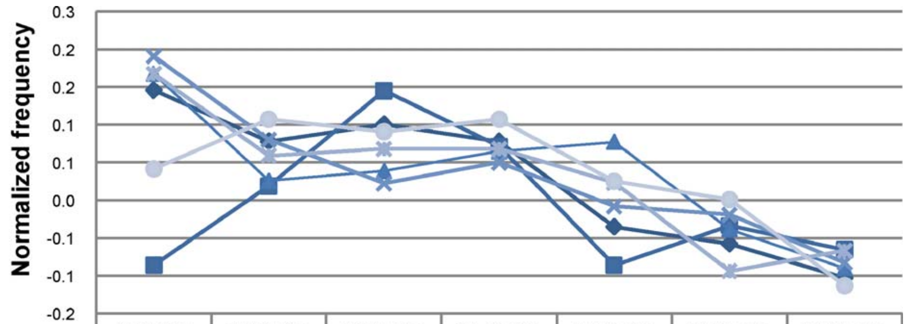


Fig. 7. Frequencies of association and transformation operations by subcategory.



	0-10 mins	10-20 mins	20-30 mins	30-40 mins	40-50 mins	50-60 mins	60-70 mins
Stimuli	0.1	0.1	0.1	0.1	0.0	-0.1	-0.1
Perceptual action	-0.1	0.0	0.1	0.1	-0.1	0.0	-0.1
Questioning	0.2	0.0	0.0	0.1	0.1	0.0	-0.1
Association	0.2	0.1	0.0	0.0	0.0	0.0	-0.1
Transformation	0.2	0.1	0.1	0.1	0.0	-0.1	-0.1
Judgment/ Decision	0.0	0.1	0.1	0.1	0.0	0.0	-0.1

Fig. 8. Normalised frequencies of each cognitive operation every 10 min.

cognitive operations slowed after 40 min. However the variance was higher for perceptual action than for the other cognitive operations; that is, designers continued to improve their ideas by sketching or retouching the features of forms until they were satisfied with the outcomes.

4.4. Limitations of the current methodology

One might question whether a designer's mental processes can be inferred from concurrent verbalisation and/or whether sketching may be inhibited by the pressure of thinking aloud. In our specific study, designers verbalised their thoughts during 81.9% of the session and remained silent for 18.1%. During more than half of the time (57.1%), designers simultaneously verbalised and generated sketches; designers sketched without verbalising during only 9.3% of the session. Additionally, a pilot test showed no significant differences in the production of sketches during concurrent verbalisation and during silence.

However, as Coley et al. [14] reported, the think-aloud method may result in interference. For example, some thoughts cannot be verbalised without causing a distortion in thinking. In addition, we assumed that inter-individual differences due to age, sex, and working experience (novice, expert) occurred. Moreover, as our participants were all French and worked in the same design agency, cultural and status differences may not have been taken into account; indeed, analysis of these variables may prove interesting with a larger panel of designers.

5. Cognitive model of the mental categorisation of design information processing performed by designers

In this section, we present a cognitive model of the mental categorisation of design information processing performed by designers. This model is focussed specifically on the structure of design information and two cognitive operations, association and transformation, which are representative of the cognitive operations related to long-term and working memory. These provide clues to help us identify how designers encode and store information in long-term memory.

As Fig. 9 illustrates, the solid lines represent the direction of association, and the dotted lines represent the direction of transformation. The width of the line indicates the frequency with which cognitive operations were performed on design information. The structure of design information is represented

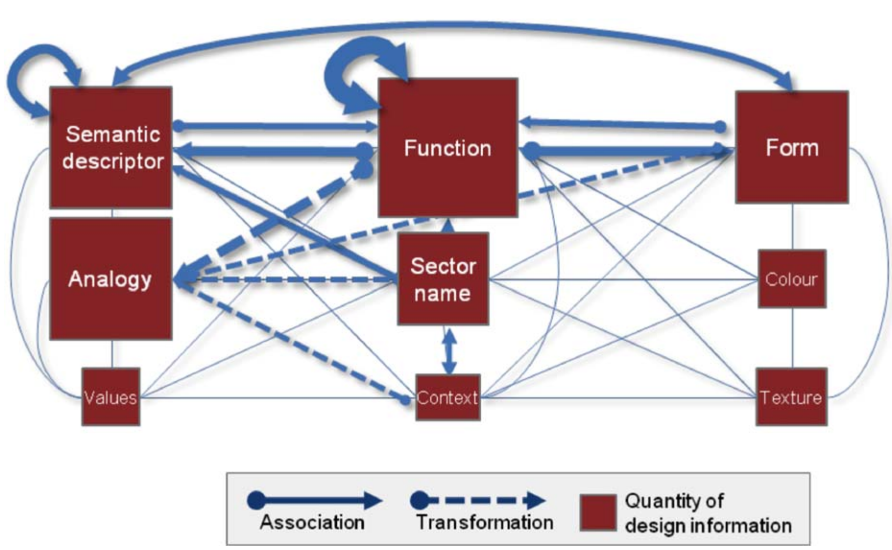


Fig. 9. Cognitive model of the mental categorisation of design information processing performed by designers.

in the red boxes. The size of boxes reflects the frequencies of particular types of as percentages of all verbal responses on the protocol.

The predominant forms of design information involved functions, semantic descriptors, analogies, and descriptions of forms. Designers tended to use same-level associations among elements of design information (horizontal), especially between functions, pieces of semantic descriptors, functions and sectors, and sectors and their contexts. Some excerpts from the verbalisations are given as follows:

"*I'll try a backpack type of vacuum cleaners*. This model should provide enough power, but it should not be too heavy to carry on his shoulder. Also, I would guess that a potable battery-powered model will still be a problem. It is due that a wrong position of air evacuation could cause a person to heat up"; or "I would like to start with an automatic vacuum cleaner, ah yes, like a robot, which has a technical aspect, *like* '*hi-tech*'; and has a look more masculine, seductive, and aerodynamic".

Remarkably, designers also tended to associate information across different levels (vertical) including between functions and descriptions of forms functions and semantic descriptors, and semantic descriptors and descriptions of forms (and vice versa). Here are a few excerpts from the verbalisation: "*Nike vacuunm cleaner, Nike makes me imagine a form like a Capricornus's horn which might be more rounded*..."; or "*regarding colour ranges, sport colours in my head are very flashy, vivid, and dynamic. So I could use primary colours: red, green, blue, or yellow with a black accessory; and it could be better if I use glossy materials such as plastics, metal*".

This model also confirmed that designers tend to associate design information according to rules that span different levels of information and relate colours, textures, and shapes. In addition to transformation, high-level descriptors (values, semantic descriptors, etc.) may serve as sources of creativity in designing insofar as these descriptors reflect the designers' personal sensibilities and tendency to create designs based on divergent ideas. Thus, the bi-directional associative links between high- and low-level information constitute very interesting foci for research on the generative phase of designers' work.

6. Conclusions

In this paper, we explored how designers mentally categorise design information during early sketching performed in the generative phase of the creative process. Our research question was what kind of the mental information is extracted and how this can be transformed or categorised during early sketching. By employing action research approach, we initially proposed a descriptive model of information processing involving memory theories drawn from cognitive psychology. To enrich and validate this model, we then used a think-aloud method to conduct a protocol study with product designers. We subsequently applied our dual coding scheme, derived from video and audio protocols, to identify deign information and cognitive operations relevant to this specific phase. Finally, both qualitative and quantitative approaches were integrated to produce a rich cognitive model of the mental categorisation of design information (see Fig. 9).

Three types of results (qualitative, quantitative, and integrated) showed: (1) two representative cognitive operations, association and transformation, were particularly related to retrieval processes of mental information. The finding explains a cognitive mechanism about how mental information is encoded and stored in long-term memory (LTM) and moved to working/short-term memory (WM/STM) during the early sketching in the generative phase. In addition, we have confirmed a strong correlation between the perception and the judgment/decision and (2) regarding a structure for design information, functional and structural analogies as well as links among functions, semantic descriptors, and descriptions of forms have emerged as an area of great interest. Particularly, a significant use of high-level information (semantic descriptors and analogy) would be interesting to investigate because it could influence the creativity and emotional aspect of design.

Therefore, we need to introduce additional coding schemes related to the emotional aspects of perceptual and generative processes to refine and enrich our cognitive model. In addition, we plan to validate our cognitive model with a large panel of designers and compare the possible differences between the novice and expert designers in the rate of cognitive operations and a structure of design information. Furthermore, given that the notion of information level was initially derived from the field of artificial intelligence, where it is used to develop specific algorithms, the findings suggest that our model may be helpful in developing a list of specifications for the design and development of computational tools. The development of design specification is under way; it involves a construction of database (semantic descriptors, archetypes, divers analogy issues from different sectors), an association between design information, transformation of forms (morphing in terms of semantic descriptors, or analogy), a support of the memorising process of design precedent, etc.

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