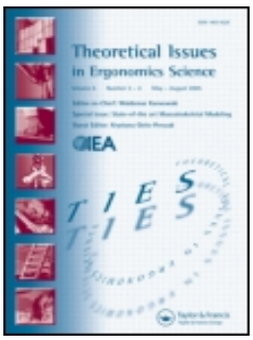

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External procedures in design problem solving by experienced engineering designers – methods and purposes

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In the creative early phases of design problem solving, several kinds of external – especially manual – procedures of thinking ('externalizations') are applied. This was mainly shown in experimental settings for tasks of architects. We analysed the kinds and the reported purposes of externalising in the everyday work of experienced engineering designers. Three field studies with different samples of engineers ($n = 55$) show: the majority of experienced designers reported the application of simple low-cost externalising (especially manual sketching and impromptu-prototyping) in their everyday work mainly for memory relief, communication and generation of ideas. Different mental processes in the early phases of engineering design require different kinds of externalising to support them. Simple low-cost externalisations offer most perceived support for communication and sophisticated ones (e.g. manufactured prototypes) for the evaluation of solutions. The results based on retrospective memory reports of engineers are confirmed by self-records of an ongoing conceptual design process and the documented frequencies of different kinds of externalising.

Keywords: design problem solving; external thinking; design education; external cognition; distributed cognition

1. Introduction

Design problem solving is a kind of creative thinking, generating new objects or artefacts, such as machines, buildings, drugs, pieces of music or poems (Guindon 1990, Smith and Brown 1993, Visser 1994, Wielinga and Schreiber 1997).

Design problem solving may be characterised by a sequence of phases. Within the early phases of design, creative processes are decisive for the innovativeness of the desired artefacts. For the purposes of this article, the term 'early phases of design' refers to the clarification and definition of the problem, the determination of the functions of the future product, and the search for solution principles.

Mainly, for the search for solution principles, several assisting procedures are recommended, for example, brain writing or systematic heuristics. A further discussed group of procedures is externalising. The most common methods of externalising are freehand sketching, drawing and 'impromptu' prototyping. The approach of 'impromptu

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prototyping' was introduced by Radcliffe (1998, p. 224): 'Impromptu prototyping refers to the use of things-at-hand to express physically a design idea, embodiment or detail... The materials at hand may be everyday work pieces, the stuff on the desk, a ruler, a disc box, a water bottle... In episodes of solitary work, individuals are seen to use impromptu prototyping presumably as a means of clarifying or testing their own thoughts... While aiding mutual understanding (in design teams) and shared appreciations they also invite ambiguity, thus ensuring potentiality in the device developed.'

The kinds, purposes and effects of externalising are analysed mainly in experimental settings with architects. Our interest is in the kinds and purposes of externalising in the everyday work of experienced engineering designers. This information could be important to planning the academic training of engineering designers.

2. Related work

Many investigations consider the design thinking of architects, others that of engineering designers. Some of these studies analyse externalising (Goldschmidt 1991, Andreasen 1994, Scaife and Rogers 1996, 2005, Tversky 1999, Sachse 2002, Sachse *et al*. 2004, Bilda and Demirkan 2003, Do 2005, Pache 2005, Bilda and Gero 2006, Tversky and Suwa 2009).

Possible purposes of externalising are discussed mainly in researching architects (Suwa and Tversky 2002, Bilda *et al*. 2006).

Externalising procedures and their results store solutions and, thus, reduce memory load (Bilda and Gero 2005). Furthermore, these visualisations may assist communication with colleagues and clients (Israel and Zacharias 2007). This point is elaborated within the approaches of Shared Visions (Pearce and Ensley 2004) and of Distributed Cognition (Hollan *et al*. 2000).

A third purpose may be the facilitation of the assessment of design results by comparing them with the list of requirements.

A fourth purpose mentioned is the support of idea generation (Goldschmidt 1992, 1994, 2003, Suwa and Tversky 1997, Do 2005). The authors explain this purpose by an interaction between the produced external representations and the cognitive process of interpreting them as well as by an interaction between visuo-figural and conceptual arguments. Sketches may 'serve as a ''perceptual interface'' through which one can discover non-visual features' (Suwa and Tversky 1997, p. 401). In this process, a feedback cycle of externalisation (e.g. sketching), inspection and revision arises, which can be described as having a conversation with one's self or a backtalk of externalisations (Goldschmidt 2003).

- In detail, the support of idea generation by externalising may result from retrieval of stored images or concepts (i.e. knowledge retrieval).
- Recognition of solution possibilities of unanticipated features and relationships, and of conflicts between them; and
- Reinterpretation, revising and refining of ideas (Goldschmidt 2003, Do 2005).

However, the benefit of externalisation for design problem solving is not clearly evaluated. At least for expert architects, an essential benefit is disputed (Scaife and Rogers 1996, Bilda *et al*. 2006): based on blind-folding experiments, Bilda *et al*. (2006, p. 601) concluded 'that ''externalizing'' may not be essential for expert designers (1) for a satisfying and reasonable outcome, (2) for pursuing cognitive activity needed for

designing, (3) for developing a coherent network if ideas/concepts in the early phases of the conceptual designing.'

However, externalising might be useful even for experts as it 'puts much less load on the cognitive processes needed to design' and it 'would release the working memory load, allowing other tasks to be done effectively' (Bilda *et al*. 2006, p. 600).

Our questions concern the application and benefit of externalising in everyday design problem solving by experienced engineering designers. We are interested in whether at all, and if so for which purposes, experienced engineering designers use externalising in their everyday work, as well as which benefit they perceive as a result.

Specifically, we are interested in which *kinds of externalisations* may be used in the early phases of conceptual design for which *purposes*. We expect evidence whether engineering design experts perceive externalising as helpful for reinterpretation, revising and refining ideas, recognition of features and relations, knowledge retrieval, for communication or for reducing memory load.

From a practical point of view, the results may offer consequences for the role of rough low-cost externalising in engineering design education. The approach of 'Rethinking Engineering Education (CDIO-Approach)' (Crawley *et al*. 2007) criticises the neglect of training of skills such as scheduled generic problem-solving techniques of design. Externalising might be such a technique (see also Hollnagel 2001).

3. Questions and hypotheses

We analysed the following issues in the everyday work of experienced engineering designers who were engaged in the early phases of the design of new artefacts:

(1) *Do experienced engineering designers use externalising in the early phases of design at all and, if so, for which purposes?*

We assume that experts apply externalising along with their computer-aided design (CAD) work. Their reported purposes – in excess of the stressed memory relief – are the support of communication, idea generation and idea testing [hypothesis (H1)].

(2) *Which kinds of externalising do experts use?*

Based on the literature, we expect mainly the use of sketches and drawings as well as impromptu prototyping (H2).

(3) *For which purposes do experts assess what kinds of externalising as particularly efficient?*

We expect that experts assess sketches and drawings as particularly efficient in communication, and to a lesser extent in idea generation, whereas impromptu prototyping is perceived helpful mainly in idea assessment and in communication (H3).

For the generation of ideas, only a moderate reported benefit of rough externalising is expected because of the partly unconscious character of these ideas (Unconscious Thought Theory; Dijksterhuis and Nordgren 2006).

Since these questions aim at retrospective responses of designers, we add a further one:

(4) *May documented externalisations and self-records concerning the purposes, collected and documented over the course of a design process, confirm the results of the retrospective memory-records? More precisely: What externalisations and which purposes of their use are documented in the course of the design process?*

We expect that the ongoing documentation of possible externalisations and self-records on their reasons will confirm the retrospective memory-records (H4).

These questions are dealt with sequentially in three separate field studies. Field studies are applied in spite of their limitations, since it is necessary to cope with the role of externalising in the everyday work of experienced engineering designers in order to answer the questions mentioned.

4. Methods

The *first study* is a questionnaire study. Based on the cited results taken from literature, this questionnaire study investigates whether experienced engineering designers apply externalisations at all along with their real-life CAD-work and, if so, for what purposes they do so (cf. question and hypothesis 1).

Participants. Forty male design engineers, working in automotive engineering, facility engineering and mechanical precision engineering, with work experiences ranging from 2 to 25 years, took part in the questionnaire study.

Procedure. The study administered a semi-standardised questionnaire. The questions concern whether the experts apply externalising in the early phases of design and, if so, which functions they fulfil, and how these functions may be described.

Based on the literature mentioned we defined five categories of possible purposes (Table 1, left column). The answers were classified according to this system independently by two trained researchers who completely agreed on their categorisations ($K = 1.0$).

The *second study*, with another group of experienced engineering designers investigates which kinds of externalisations they use. Moreover, the engineers were asked to assess by means of rating scales how much support the different externalisations offer for the different purposes.

Participants. Eight male engineering designers of a mechanical engineering firm with 10–25 years of job experience volunteered in this study. They dealt with the conceptual design of complex units of water-power plants.

Procedure. The firm collected and registered sketches, drawings, results of impromptu prototyping, manufactured prototypes and protocols of experiments.

The designers were asked to categorise, independently, the externalisations of this collection. These 46 exemplars were developed by the participants within their individual work. Thus, they were asked to categorise own exemplars as well as those produced by their colleagues.

In a first step, the eight participants jointly developed a shared system of categories of collected externalisations (Table 2, A–G). Obviously, externalisations resulting from rough external procedures are A, B, C and D only. The categories C and D correspond with the impromptu prototyping as mentioned before.

In order to complete the categorisation of the collection, manufactured models and prototypes (E, F) and experiments (G) are also included in this study. We therefore employ the generic term ‘means’ here.

After the categorisation (step 2), the designers rated the collected means as to their perceived support for the purposes of their use in a third step. In doing so, they applied the categorisation of purposes as given in Table 1. Thus, statements were made such as ‘means

Table 1. Categorisation of the reported purposes of the application of external procedures in early phases of engineering design ($n = 70$, statements of 36 engineering designers).

Categories	Reported purposes	Share of statements (%)
Assistance of task analysis	Identification of requirements and relationships between them; detection of implicit requirements	14.3
Relief of memory load	Memory relief Information retrieval Retaining partial/provisional solutions	27.1
Assistance of individual cognition	Identification of problems to be solved/idea generation Support of concept development/refining of imagination Identification of failures, weak points Increase of transparency/control of complexity	20.0
Assistance of communication/ cooperative cognition	Means of argumentation/discussion	21.4
Assistance of assessments	Assessment of physical characteristics/functions Assessment of assembly/safety characteristics Check of manufacturing requirements/costs Check of the partial solutions concerning their fit	17.2

Table 2. Median values of reported support of different external means for different purposes of their use.

	Kinds of external means						
	Rough manual ones				Sophisticated ones		
Categories of reasons	A	B	C	D	E	F	G
Assistance of requirements analysis	3	3	4	3	3	3	3
Relief of memory load	4	4	3	3	3	4	2
Assistance of individual 'external cognition'	4	3	3	3	3	2	2
Means of communication ('cooperative cognition')	5	5	4	4	4	5	4
Assistance of assessments of solutions	2	1	3	3	4	5	4

Notes: Scale, mean x offers support for purpose y: (0) not at all; (1) hardly; (2) slightly; (3) moderately; (4) predominantly; (5) perfectly. Kinds of external means: (A) freehand sketches; (B) preliminary drawings; (C) rough low-cost physical models, produced before drawings did exist; (D) rough low-cost physical models according to drawings; (E) models true to materials; (F) manufactured prototypes; (G) experiments.

x offers support for purpose y "not at all" to "perfectly"". A median score was calculated for each means and for each category of purposes.

The *third study* applied self-records and documentations, since objections may arise as to the questioning results offered: they may describe retrospective reconstructions based on designers' memories, but may not necessarily provide true characteristics of the ongoing design process. To overcome this deficit, a design process was documented

concerning the application of externalisations and their purposes from the very beginning until the production of a final prototype for a period of 14 weeks.

Participants, procedure and task. In this case study, seven other experienced male engineering designers (job experience: 5 years) were asked to document the use of external means and procedures and to note down the purposes of the use. In case of missing or unclear documentations, the researchers discussed these gaps with the designers once every day.

The participants developed a computer input device which combines the functions of a conventional computer mouse with functions of the control of 3D-objects.

Data analysis. The means produced and purposes noted down were assigned to the categories of purposes and of means (Tables 1 and 2) by the researchers (successive alignment of judgements approached complete inter-rater agreement). The participants produced no preliminary design drawings (B). Low-cost models before and according to drawings (C, D) were combined into one group, likewise the two kinds of prototypes (E, F).

5. Results

5.1. *Application of externalising in engineering design and its purposes*

Ninety percent of the designers reported the use of externalising in their everyday work. Table 1 offers the categorisation of the total of 70 statements of the 36 engineers who reported the use of externalisations. All statements may be integrated into the defined categories.

The reported purposes address the assistance of mental operations, especially the development of a mental model of the intended physical product ('support of concept development/refining imagination'), or reasoning ('Identification of requirements' including their 'relationships'), or components of decision making within the assessment of a design concept (cf. the items of the category 'assistance of assessment'). Moreover, an essential share of statements addresses the relief of memory as well as the support of communication. The distribution of the reported purposes on the five categories does not differ significantly from an equal frequencies distribution ($\chi^2_{(4)} = 2.9$, $p > 0.05$).

Hypothesis 1 can be verified: experienced engineering designers use externalising in their everyday conceptual design tasks. Corresponding with results based on the mentioned experimental laboratory research with architects, they report on externalising in order to support concept development and imagination, and to assist the identification of requirements and their relationships, in order to support the assessment of ideas and solutions as well as to assist communication. Most frequently, the engineering designers report on the relief of memory by externalising.

5.2. *Kinds of externalisations; relationships of kinds and purposes*

Table 2 offers the medians of the rated degree of support by the several means for the categories of purposes.

Again, experienced engineering designers use freehand sketching, drawing and impromptu prototyping in their everyday designing along with CAD-work. Hypothesis 2 is supported. However, in addition, they initiate manufacturing of models true to materials, of prototypes and running of experiments.

The highest perceived support by external means and procedures is reported for communication. This holds for both, rough low-cost externalising and more expensive prototyping and experimentation.

Not surprisingly, the sophisticated representations such as prototypes offer support when detailed assessments are needed, whereas quick and rough ones – especially sketches and drawings – are helpful where speed is more important than detail, that is, for the release of (short-term) memory and – to a minor extent – in the identification of requirements and in idea generation.

Hypothesis 3 is verified only partially: Impromptu prototyping (categories C, D) is only moderately helpful in the assessment of solutions for the given complex engineering design tasks. Moreover, we did not expect the high perceived importance of all kinds of means for the support of communication.

5.3. *Documentations and self-records of externalisations and their purposes*

In this study, another group of experienced engineering designers, too, produced several kinds of quick and rough as well as sophisticated externalisations in their everyday design problem solving. The main kinds of externalisations reported in the first questionnaire study and collected in the second one are identified again. The documented frequencies of the application of the externalisations are given in Table 3.

In the design task given here, rough low-cost externalisations and more sophisticated ones were used with similar frequencies (Table 3, last row).

Compared to rough means, sophisticated means and procedures are used significantly more often for the assessment of solutions than rough ones ($\chi^2_{(1)} = 8.4$, $p < 0.1$). Rough externalising, especially freehand sketching, is used more frequently for the relief of memory than sophisticated means are applied for this reason ($\chi^2_{(1)} = 4.6$, $p < 0.5$). Analogously, rough externalising is more frequently used for the support of external cognition, especially idea-generation than more sophisticated means ($\chi^2_{(1)} = 6.8$, $p < 0.1$). The communication is supported more frequently by sketching and prototyping.

Thus, the results based on designers' retrospective memory reports on the whole are confirmed by self-records of an ongoing conceptual design process concerning the purposes and frequencies of the development and application of external means. Hypothesis 4 is confirmed.

6. Discussion

For expert architects, results of experimental research show that conceptual design may succeed without freehand sketching and drawing (Bilda *et al.* 2006). This does neither mean, however, that experienced engineering designers do not use externalising in their everyday work, nor that they may perceive no benefits in the result.

The present field studies with three groups of experienced engineering designers provide evidence that the majority of them in conceptual design spontaneously are used to apply several kinds of externalising for several purposes.

First, this replicates former results on the working methods of experienced engineers (Pache 2005): Experts – not only students or novices – use low-cost externalising of thinking processes along with CAD-work in their everyday conceptual design. In terms of the Task-Episode-Accumulation-model of design thinking (Ullman *et al.* 1988),

Table 3. Frequencies of the use of different externalisations (for different purposes) by a design team ($n = 7$ engineering designers).

	Kinds of externalisations												
	Rough and quick ones						Sophisticated ones						
Categories	A		C/D		Sum		E/F		G		Sum		Total sum
Assistance of analysis	6		31		37		29		10		39		76
	7.9%		40.8%		48.6%		38.1%		13.1%		51.3%		100%
		4.6%		41.9%		18.1%		18.5%		21.7%		19.3%	
Relief of memory load	40		0		40		17		6		23		63
	63.5%		0%		63.5%		27.0%		9.5%		36.5%		100%
		30.8%		0%		19.6%		10.9%		13.0%		11.4%	
Assistance of individual 'external cognition'	38		16		54		20		10		30		84
	45.2%		19.0%		64.3%		23.8%		11.5%		35.7%		100%
		29.2%		21.6%		26.5%		12.8%		21.7%		14.8%	
Means of communication ('co-operative cognition')	27		13		40		43		6		49		89
	30.3%		14.6%		44.9%		48.3%		6.7%		55.0%		100%
		20.8%		17.6%		19.6%		27.6%		13.0%		24.3%	
Assistance of assessment of solution	19		14		33		47		14		61		94
	20.2%		14.9%		35.1%		50.0%		14.8%		64.9%		100%
		14.6%		18.9%		16.2%		30.1%		30.4%		30.2%	
Sum	130	100%	74	100%	204	100%	156	100%	46	100%	202	100%	406

Notes: The first row of each box shows the frequencies, the second one the percentage points for the respective row and the third one those for the respective column; A, freehand sketches; C/D, low-cost (impromptu) models; E/F, prototypes (self-made and manufactured ones); G, experiments.

externalising concerns the main components of this model, intuitive idea generation as well as rational idea assessment.

Second, in literature, several purposes of the use of externalising are discussed, mainly based on experimental research on tasks of architects (Suwa and Tversky 1997, Goldschmidt 2003, Bilda and Gero 2005, Do 2005, Israel and Zacharias 2007). Unlike this laboratory approach, we are interested in possible purposes of the use of externalising in everyday conceptual design of engineering experts. Astonishingly, engineers apply low-cost externalising in their more formal tasks for purposes which are discussed for experimental research with architects, too: These are – in order of their quantitative shares – (working) memory relief, the support of communication and discussion, the assistance of cognitive procedures in idea generation, the assistance of idea assessment, and the identification of task requirements. The shares of these purposes do not differ significantly. Although the relief of memory was not elaborated on by the participants, we suppose this relief mainly concerns working memory, the well-known bottle-neck of information processing. Thus, mental capacity might be saved for design thinking, as was argued by Bilda and Gero (2005).

The reported support of externalising for communication may be explained by the approaches of Shared Vision (Clark and Brennan 1993, Pearce and Ensley 2004) and of distributed cognition (Hollan *et al*. 2000). A deficit of our studies concerning communication may be the neglect of verbal dialogues between designers, which also externalise mental processes like freehand sketches or drawings, without, however, relieving memory.

The perceived support of cognitive processes in idea generation and idea assessment may be explained by the approach of external thinking, first proposed by Vygotski (1964) and Galperin (1966).

Third, the engineering experts apply several kinds of externalising. Along with quick and simple ones, the engineers used sophisticated external representations and procedures in certain design tasks, too. The first group included freehand sketching, drawing and impromptu prototyping, the second one manufactured models or prototypes, and experiments.

Fourth, there are specific relationships between the purposes of externalising and their kinds used. Not surprisingly, sophisticated externalisations such as prototypes offer perceived support where detailed assessments are needed. Quick and rough ones – especially sketches and drawings – are perceived to be helpful where speed is more important than detail, that is, for the relief of (working) memory and to a minor extent for the identification of requirements and for idea generation.

The moderate support of intentionally and, thus, consciously produced externalisations in idea generation may be explained hypothetically by the less conscious, intuitive character of creative thinking, as elaborated in the Unconscious Thought Theory (Dijksterhuis and Nordgren 2006).

For purposes of communication, no significant differences are shown as to the perceived support by different kinds of externalising. Both, rough low-cost means as well as the more expensive prototyping and experimentation offer high perceived support.

Finally, the results based on retrospective memory reports of designers are confirmed by self-records of an ongoing conceptual design process concerning the purposes and frequencies of application of externalising. The documented frequencies of use are in accordance with the extent of perceived support identified in our second study with another sample of engineers and other design tasks. More often used, externalising may offer higher perceived support.

Thus, the results may advance the knowledge on categories of purposes of externalising in everyday engineering design thinking, on the kinds of externalising used in the early phases of design and on the allocation between these purposes and the kinds of externalisations. Therefore, the concept of externalising cognitive processes, from a theoretical point of view advocated by Vygotski (1964), proves to be a necessary aspect of engineering design thinking. Different cognitive processes in the early phases seem to require different kinds of externalising to assist them – as was proposed for the tasks of architects, too (Bilda *et al*. 2006).

Several limitations of this research warrant note. First, the relatively small sample sizes of the second and the last study suggest caution in generalising results prior to further replication. Second, the dependency of the use of externalising on different engineering tasks with different requirements needs further research. Third, the impact of externalising on engineering design results was verified so far for advanced engineering students in the laboratory only (Römer *et al*. 2000, Sachse *et al*. 2004, Englisch *et al*. 2008). Whether, however, the perceived support of externalising discussed here will actually coincide with the quality of the technical results and with some limitations of workload requires further research.

Fourth, the dependency of externalising on work experience of the engineering designers was not considered thoroughly so far. Although a rough comparison in the first study does not hint at severe differences in the application of externalising depending on work experience, their point needs systematic investigation. For this reason, essential covariables should be taken into account. These are the possible effects of different engineering tasks of designers with differing work experience, as well as changes in academic training within the last decades (especially concerning the shares of training in freehand sketching vs. in CAX- and virtual reality techniques). In our presented studies, this information was not available.

However, the methodology tested and proposed here would be useful for further investigations with greater sample sizes. Since the results of the interview studies concerning retrospective memory reports of the designers were confirmed by the self-record and documentation study (study 3), economic questionnaire studies are suitable to increase sample sizes. Thus, it becomes possible to study efficiently the essential issues of the dependency of externalising on different types of engineering tasks and on the work experience of the designers, as well as the effects of externalising on engineering design results of experienced designers in their everyday work settings.

If replications and extensions of the results are possible, these might contribute to the rethinking of engineering design education concerning the role of generic skills in design problem solving (Crawley *et al*. 2007).

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