Res Eng Design (2016) 27:265–289
DOI 10.1007/s00163-016-0218-3

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ORIGINAL PAPER

Beyond the concept: characterisations of later-stage creative behaviour in design

Chris Snider[1] · **Elies Dekoninck**[2] · **Steve Culley**[2]

Received: 7 January 2015 / Revised: 24 January 2016 / Accepted: 26 January 2016 / Published online: 24 February 2016

Abstract As a mechanism through which better solutions are developed, creativity is well-recognised as an important part of the engineering design process, but has to date largely only been studied in general or in early design process stages. This paper aims to study the occurrence of creative behaviour in engineering design with a particular focus on the later design process stages. Through the application of a detailed coding scheme to two studies of engineers' work, this paper identifies patterns in creative behaviour through the design process stages, creative approaches employed by engineers, typical types of creative task, and fundamental differences within creative behaviour between early- and late-stage design. This understanding is then used to form ten characterisations of engineer behaviour within late-stage design, early-stage design, and throughout the design process. These characterisations can be used to direct future research and to improve the design process and output through development of specific, effective design support methods, selected to be appropriate to the design stage and type of creative behaviour that occurs within.

Keywords Creativity · Design behaviour · Embodiment · Detail · Creative behaviour

✉ Chris Snider
chris.snider@bristol.ac.uk

[1] Department of Mechanical Engineering, University of Bristol, Bristol, UK

[2] Department of Mechanical Engineering, University of Bath, Bath, UK

1 Introduction

The study of creativity has over the past half century become a highly important, multi-disciplinary field of research, with dedicated work completed in fields from psychology (see Boden 1994; Amabile 1996), to architecture (see Akin and Akin 1996; Schon 1983; Lawson 2006), computer-science (see Shneiderman et al. 2006; Wiggins 2006; Brown 2010), and engineering design (see Gero 1996; Dorst and Cross 2001; Howard et al. 2008). Creativity is recognised broadly as a complex and multi-faceted research subject, and while often defined in terms of the creative product [as *original*, *appropriate*, and *unexpected* (Chakrabarti 2006; Howard et al. 2008; Brown 2012)], it is important to consider the wider breadth of areas in which it may appear.

In particular, within engineering design, the study of creativity must be understood through the lens of engineering design itself—to produce an output as a solution to a specific problem. As a creative solution is by definition better in some way than a non-creative alternative (Howard et al. 2008), the study of creative behaviour is therefore the study of those elements within a process that may lead to a better solution—the sequence of activities that lead to the result, and the patterns of behaviour through which these activities are completed.

This understanding of creativity as in a sequence of actions is, however, only a single part of a larger whole. One manner in which creativity can be studied and understood is through the *Four Pillars of Creativity* (Rhodes 1961), including not only the *Product*, but also the *Person* who is creative (Kirton 1976; Feist 1999; Helson and Pals 2000), the *Process* they are following (Hayes 1989; Lubart 2001; Dorst and Cross 2001; Sosa and Gero 2003), and the *Press* (or context) in which they are working

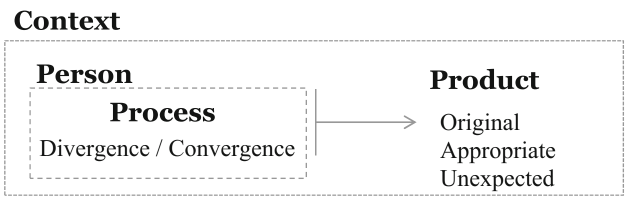


Fig. 1 The structure of the four pillars of creativity

Table 1 Papers relating to later-stage design behaviour

Author references relating directly to later-stage design behaviour	
Bender and Blessing (2004)	Matthiesen (2011)
Eckert et al. (2012)	Motte and Bjärnemo (2004), Motte et al. (2004a, b)
Eisentraut (1997)	Scaravetti et al. (2006)
Feng et al. (1996)	

(Amabile et al. 1996; Lubart 1999; Csikszentmihalyi 1999). These four pillars are co-dependent in contributing to understanding to creativity—through any one alone it is not possible to gain a full understanding of the circumstances by which a creative product comes to exist, or creative behaviour comes to occur.

For the purposes of this work, the relationships between the four pillars can be understood as in Fig. 1. While variations in such a structure are proposed by others [see Samuel and Jablokow (2011)], such a form draws attention to the active nature of creative behaviour. Given that the product is an output, it is vital to consider the process followed in its creation, the person or entity governing the process, and the context in which that person is working.

The process, person, and context all may influence whether a product will be produced that is judged creative. Each of these can be seen as a lens for study, and the nature of these elements in a given design process influences the potential for an output to be judged as creative. Taking the traditional four-stage model of the creative process of Wallas (1926) (preparation, incubation, illumination, verification), a creative product will only be produced through allowing time for an idea to slowly and organically form, at a near subconscious level. In the divergence/convergence model of Guilford (1956), a process of exploration and evaluation is required. More recent models such as co-evolution (see Nidamarthi et al. 1997; Dorst and Cross 2001; Maher and de Silva Garza 2006) propose iteration and re-evaluation as key components in the formation of a potentially creative solution. The process followed by any designer is in turn governed by their own experience and decisions, with such traits as personality (Feist 1999), motivation (Collins and Amabile 1999; Prabhu et al. 2008), experience (Goncher et al. 2009), and numerous personal characteristics (see Torrance 2008) influencing what they do, and the manner in which they do it. This whole ecosystem also works within a certain context, in terms of environment (Amabile et al. 1996), and constraints imposed on activity such as in complex design environments (Eckert et al. 2009), or design change environments (Eckert et al. 2012).

Given the inter-relationship of these areas and the influence that each has, it is unsurprising that the study of the field of creativity has been broad in scope. However, it is surprising that to date very little research has studied the relationships between creativity and specific designer behaviour in a major part of the design process—the later stages (as defined in Table 2). To illustrate, while much work concerns design behaviour, only nine relevant papers could be found that relate specifically and distinctly to later stages of design (see Table 1).

Thus the focus of the work presented here is to study the creative behaviour that occurs in later stages of the design process. This has been achieved through detailed study of the designer behaviour that occurs throughout the design process, using two independent but complementary studies and the use of a developed content analysis coding scheme [see Snider et al. 2013, 2014)]. The purpose of this paper is, through the exploration of the occurrence and nature of creative behaviour, to show the differences and similarities between early- and late-stage design behaviour.

Initially, the paper sets the context and background to the work in terms of the nature of early- and late-stage design, the very idea of design behaviour, and creative behaviour throughout the design process. Following, the paper presents the coding scheme developed for use in both studies, the methodologies and results, and forms ten characterisations of creative design behaviour found specifically in early-stage design, late-stage design, or throughout the design process.

1.1 Early- and later-stage design

In the study of later-stage design, it is first important to clarify what is meant by these terms. Typically, the engineering design process is divided into four discrete stages—analysis, concept, embodiment, and detail design (Pahl and Beitz 1984; Pugh 1990; Cross 2000; Howard et al. 2008), which are described as either differing in terms of focus, chronological location within the design process, or location within the system hierarchy at which work is occurring.

Following Howard et al. (2009), this work considers the stages of the design process to be defined by the focus of activity being completed, and iterative throughout the development of the product. By the nature of design, for each system, sub-system or component there is a certain quantity of every stage of the design process that will be

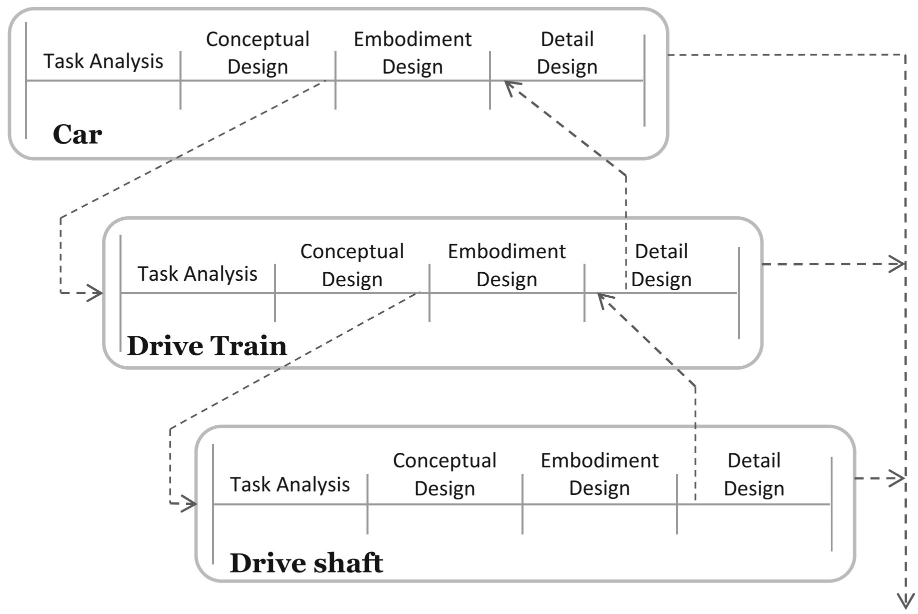


Fig. 2 The appearance of design stages throughout the process, following Howard et al. (2009)

completed—just as task analysis must be completed in initial ideation for any product, some measure of task analysis must be completed for each low-level component that goes into it. Equally, just as an interface between two components must be designed in detail, so must the sub-system or system to which they belong.

This understanding is illustrated in Fig. 2. Just as a vehicle will go through an entire design process, so will the sub-systems within it and the components within those. The implication of this repetition is that both "early" and "late" in relation to design process stages are misnomers. Both early-stage and late-stage type design activities can and will occur at any point in time and any level of system hierarchy. This important distinction underlines the need to understand the design process as an entirety and hence the entirety of creative behaviour within it.

Such thinking then requires definition of the stages of design by focus of activities that occur within each, a view that can be found in much research (see Ullman et al. 1988; Huang and Kusiak 1998; Gero 1990; Howard et al. 2008; Dieter and Schmidt 2009) and also agrees with such observed design behaviours as breadth and depth-first strategies (Ball et al. 1997), more cyclical or iterative descriptions of the design process (Knott 2001; Dorst and Cross 2001; Smulders et al. 2009), and recognises that designers may be opportunistic in their process, jumping between higher and lower levels of detail throughout their work (Guindon 1990; French 1992; Visser 2006). The stages of design in this work are then defined as in Table 2. While there is certainly similarity in the determination of design stages as defined here and those defined by hierarchy or chronology (i.e. the physical design cannot be developed in detail without prior exploration of function and task analysis), the definitions used in this research avoid the pitfalls of categorising tasks that are different in nature as similar simply because they occur on a similar level of the system hierarchy or at a similar point in time.

Table 2 Definitions of design process stages

Design stage	Definition
Analysis	Determine the desired and required functions of the system, in order for it to complete its purpose
Concept	Conceive the system functions in detail through preliminary description of system behaviour
Embodiment	Design detailed system behaviour through preliminary description of system structure
Detail	Design and finalise system structure, and all aspects that may influence it

Regardless of perspective as stages varying through focus, chronology, or hierarchy, the boundaries between stages are in reality unclear and have the potential to be entangled by many overlapping variables. Within this work, the boundary between early and late is drawn from the definition of stages by the focus of the designers' actions and activities, placing the distinction between concept and embodiment design as defined in Table 2. This approach is taken for four reasons. First, the focus of designers is known to shift through the design process, as has been demonstrated by other researchers. As such, defining by focus will create differentiation between sections of the design process as followed by designers. Second, the definitions of stages are based on the process and tasks of the designers, rather than external or situational conditions such as budget, and are therefore applicable in all contexts involving the work of a designer. Third, the design process is studied in its entirety, from initial task analysis to detail design. This non-chronological approach ensures no data points of later-stage design activities are discarded, while also allowing contrast to be made against earlier stages. Fourth, the distinction between early and late stage can be identified directly from the designers work, and as such can be directly detected from observational study. While other distinctions between early and late are possible and would have potential to generate interesting findings in their own right, this distinction follows the aims of the work and allows a focus on currently less-understood phenomena.

Early- and late-stage designs are therefore defined as follows:

> *Early-Stage Design*: Work concerned with the task analysis and conceptual design stages of the engineering design process.
> *Late-Stage Design*: Work concerned with the embodiment and detail stages of the engineering design process.

1.2 The concept of design behaviour

In the following of a creative process, it is the actions of a designer that lead to the generation of a creative product. Following the work within the field of Activity Theory (Leont'ev 1978; Kuutti 1988; Kaptelinin et al. 1995; Bedny and Harris 2005), these are described as *activities* or *tasks*, see Table 3.

The importance of this definition is that tasks are subordinate in a hierarchy to activity and are representative of the actual actions of designers within their personal process. An activity describes the element of the higher-level design process that the designer is trying to complete (described within Activity Theory as their *motivation* for working), while a task forms a lower-level procedure with a specific goal, which is in itself aligned with the overall

Table 3 Differentiating activities and tasks

	Definition	Example
Activity	A body of working associated with fulfilling a required part of the design process, described from the perspective of the higher-level design process	Concept Design Layout selection Form optimisation
Task	Individual elements of working associated with fulfilling an immediate, defined goal of the designer, which in combination lead to fulfilling a required part of the higher-level design process	Identify primary functions Brainstorm concepts for function fulfilment Evaluate options using a concept evaluation matrix

motivation for completing the activity. From a perspective of human behaviour, these definitions place focus on the actions of the designer. This work aims to study the designer and what they do, and so it is concerned with the human-action based *tasks* that a designer completes, rather than the *activities* that form part of the higher-level design process itself.

These definitions then allow an important consideration in the study of designer behaviour—that each person is able (and perhaps likely) to complete a different series of tasks in the pursuit of identical activities. The higher-level *activities* and *motivation* for their completion may be similar, but the manner in which they are achieved (through a designers *tasks*) may be different.

This potential individuality is a vital subject for study and can only be understood through study of designers directly. Study of patterns, similarities, common, and unusual tasks give a medium for understanding the manner in which individuals complete their work, the "better practice" of expert or creative designers, and similarity or difference in the actual appearance of creative behaviour.

1.3 Creative behaviour in the design process

As described in Sect. 1, the study of creative behaviour is here considered to be the study of those elements within a design process that may lead to the generation of a better solution, particularly the activities performed, the sequence of actions, and the patterns in behaviour through which activities are completed. In the literature, identification of a creative output is often seen as requiring judgement of such by an observer (see Amabile 1996; Csikszentmihalyi 1999). This work follows this thinking, but also recognises that the designer, the process followed, and the context in which work is occurring all have a significant role in the final form of the output. There are many elements that can affect the product, and so affect its judgement as creative. As such, creativity in process does not guarantee the production of a creative output, but does increase the *potential* for the *interpretation* of a product as creative [where a creative output will have the properties of originality, value, and unexpectedness (Howard et al. 2008)]. Creative behaviour within engineering design is therefore defined as follows:

> *Creative Behaviour*: The sequence of actions of a designer that generate the potential for a product to be interpreted as a creative output.

Within the literature, there is much research on the elements of designers' process that lead to the increased potential for a creative product to be generated. Schon (1983) and Cross (2004) advocate the reflective process of experts as encouraging re-framing the problem, allowing an original solution to be developed. Here, the act of forcing an unusual starting point encourages the development of an unusual solution. Boden (2004) and Wiggins (2006) highlight that creative behaviour can occur both through direct exploration of a conceptual space, or through transformation of the conceptual space and the rules that describe it. Parallels can be drawn from this view to several different findings in research, including that creative designers work from first principles rather than an experience-based frame of reference (Cross 2004; Jansch and Birkhofer 2007); that starting with unusual exemplars and perspectives also produces more creative outputs (Finke 1990; Ward 1994; Finke 1995); and to work on fixation, which finds that initial priming of certain frames limits the scope of the output to those frames (Jansson and Smith 1991; Purcell and Gero 1996) which must be broken through a process known as de-fixation (Linsey et al. 2010). Another complementary view is that of the forced structuring of problems as ill-structured (see Simon 1973; Thomas and Carroll 1979; Candy and Edmonds 1997; Cross 2004), in which creative or expert designers will treat their work as an ill-defined problem, even when a well-defined structure is available. This forces an initially unknown or unusual process to be formed and followed, leading to the development of a creative solution.

In all of these examples, and many other descriptions of creative processes within the literature, a common thread is that found in the classical descriptions of creativity of Guilford (1956). The prime characteristics of a creative process, and those required for a creative solution, are *divergence* and *convergence*. In the former, a designer will identify options through exploring a range of possible solutions and information. In the latter, the designer will discriminate between these and, through evaluation and combination, select a single, highly suitable result. Although both are vital within the creative process (Cropley 2006), as is discussed in Sect. 2.2, divergence in particular is characterised by exploration through attempts to deviate from the norm in terms of possible solutions, the problem set, and the way in which it may be completed. This may occur either through active exploration of the solution space, or through more passive deviation following single solution principles that break away from those that are typically well-defined or understood. Such thinking is abundant in the literature and can occur through traditional and direct techniques such as those previously listed, as well as: brainstorming (Osborn 1953) or analogising (Chan et al. 2011; Gonçalves et al. 2013), identification of emergent properties (Gero 1996), exploration of problem through co-evolution of problem and solution spaces (Maher and Poon 1996; Dorst and Cross 2001), the following of opportunistic design processes (Guindon 1990; Visser 1994; Bender and Blessing 2004), and thinking in classical creativity literature such as described by Wallas (1926) and explored by Boden (2004).

As a result, creative behaviour is understood to be that which includes an element of divergence or creative convergence, in which the designer will diverge within their task, and/or creatively converge through exploration of combinatory solution principles or their problem. In other words, the actions within a designer's behaviour that increase the potential for a solution that is creative to be produced will include divergence or creative convergence, as is identified as vital within much creativity literature. This definition is used to build the coding scheme used for analysis in this work.

1.4 Later-stage creative behaviour

Despite the attention given to the study of creativity, a significant bias has existed to date in the literature towards the earlier stages of the design process, or the design process in general. Even considering just the subject of designer behaviour without specific attention to creativity, the later stages of design have been neglected.

Given the importance of later-stage design in transforming a potentially primitive solution concept into a fully fledged product, and the significant amount of time, effort, and budget that this requires, this is a major omission. Previous research, based on chronological definitions, has shown that later-stage design maintains a substantial difference in focus of activities to early (see Sect. 1.2), as well as having the potential to be subject to higher complexity (Eckert et al. 2012) and higher constraint (McGinnis and Ullman 1990; Howard et al. 2011). As such, it cannot be assumed that creative behaviour will manifest in the same manner in later-stage design as early or that understanding and support techniques for creative design studies in early-stage design will be applicable in later stages. The consequent lack of understanding of later-stage creative behaviour and the potential contrast to early stages are the subject of this work.

1.5 Purpose of study

The work performed aimed to address three research questions in turn:

> Is creative behaviour seen in the behaviour of designers working within the later stages of the engineering design process?
> Are there substantive differences in the creative behaviour of designers working between the early and late stages of the engineering design process?
> What, if any, are the characteristics and patterns of creative design behaviour throughout the engineering design process?

The first of these concerns the appearance of and ability to detect creative behaviour within the behaviour of designers working in later-stage design situations. The contention of this work is that the creative process continues beyond the early stages and that its study is therefore necessary for complete understanding. The second concerns the nature of later-stage creative behaviour and states that it will by some manner be different from that in early stages, a logical proposition given the difference in task focus at later stages. Should this be confirmed, it demonstrates that creative behaviour in later-stage design should be studied individually and that current understanding cannot be assumed to be relevant. Following these, the third uses the results of the studies to identify elements of typical behaviour, either in terms of the specific stages of the design process or through the design process in general. In identifying consistent patterns in creative behaviour, there is scope to clarify the nature of creative behaviour itself, and lead towards more detailed control and support of designers within their processes.

The studies presented here aim to answer these questions through empirically demonstrating the appearance of creative behaviour in later stages of engineering design, detecting substantive differences in the nature of later-stage creative behaviour in comparison with early-stage creative behaviour, and more generally in identifying common characteristics of creative behaviour throughout the engineering design process. This is completed through two studies, with implications for the control of the design process and active improvement of output, and the manner of support of creative behaviour in each stage.

2 The framework and coding scheme

To complete the aims of this work, a framework and coding scheme have been developed. Relevant elements are presented here, with details of development elsewhere [see Snider et al. (2013), Snider (2014)]. The aim of the framework and coding scheme are to allow the direct study of the designers' behaviour within their individual design process in a quantitative manner. Following the definitions of Sect. 1, behaviour is defined here as:

Behaviour The sequence of tasks completed by a designer, towards the completion of a specific activity

This definition implies the need to identify and categorise individual tasks of designers throughout their completion of higher-level design process activities. Following the purpose of this work, there is also a need to identify the appearance of creativity in such behaviour and to classify it by type. The way in which these requirements are met are described in the following sections.

2.1 Types of task

In order to identify and classify types of task, it is necessary to have a clear understanding of the elements that it contains. Tasks in this work are an individual element of work with a specific output goal (see Table 3). In wider literature, tasks are understood to have three required components; an input, an output, and some transformation between the two (Klein 2000; Stokes 2001). A task can therefore be described more qualitatively as the process by which a designer transforms a specific input into a specific output. This work takes these three elements—input, output, transformation—and uses them to produce the categories for types of task identified.

2.1.1 Task input and output

Looking at the definitions of stages of the design process given in Table 2, there is a difference in focus of activities through the process. As a result, it is to be expected that the output of tasks of designers will also vary through the design process stages.

This work defines output of tasks in a similar manner to the stages of the design process—by the focus of the designer at that particular point in time. It can be understood that designers will focus on producing one of two types of output through their tasks—either a development to the *information content* of the design space, or a development to the way in which it is applied to the design output—the *application* manifest in the design itself. By this understanding, in one type of task the designer will be aiming to produce an output of developed *information* content, and in the other a more developed version of the design itself, in a physical or virtual form (here termed *application*). More specific examples of are given in Table 4. These input and output types closely relate to those proposed within the literature on knowledge-based engineering, such as by the activity entities utilised within the MOKA framework for coding engineering activity (Klein 2000; Stokes 2001).

This distinction can also be seen specifically in definitions of types of creative working within the literature. Based on the work of Gero (2000) and Dym and Brown (2012), the aim of any creative task can be either to extend the design space through introduction of new variables and knowledge (synonymous to a creative development of the *information content* of the design space), or be to extend the design space through causing existing design variables to take new forms or values (synonymous to a creative

Table 4 Examples of information and application type inputs and outputs

Task input Current design space *information* content	Task output Developed or newly identified *information* content
Current design requirements	More developed design requirements
Previous design iterations	More developed understanding of or newly identified options for functional fulfilment
Current functional requirements	More developed understanding of or newly identified options for technology to include
Current technological options for inclusion	More developed understanding of design properties in relation to (e.g.) stress/strain profiles
Current understanding of design properties (i.e. through results of analysis, e.g. stress/strain profiles)	
Current manifestation of the actual design output (*application*)	**Developed manifestation of the actual design output (*application*)**
Current preliminary concepts	More developed design concepts
Current detailed concepts	More detailed/finalised design concepts
Current individual component designs	More detailed component drawings
Current layout/design configurations	More developed/finalised design layouts and sub-system interfaces
Current design models/drawings	More developed/finalised design models/drawings

development in the *application* of some element of the design space to the design output).

Any task output comes initially from a specific input, altered by the work of a designer. With output options of either developed *information content* or developed *application* of that information, it is logical that the input to any task will be pre-development *information content* or a more primitive version of the *application* (a more primitive version of the design itself).

Information-type Any task input or output represented by information content within the design space.

Application-type Any task input of output represented by some manifestation of the design output itself.

2.1.2 Task transformation

A task transformation is the process by which a designer turns the input into the output. Taking the two input and output types presented in Sect. 2.1.1, there are four individual transformations that may occur, and therefore four types of task transformation as identified by the coding scheme. These are as presented in Table 5. By utilising both foci found within design (*information-type* and *application*-type) as input and output in all permutations, this work aims to classify all design work that occurs. Again, this use of input, output, and transformation to classify all design work closely follows that found within knowledge-based engineering theory.

Ignoring for the moment the notion of creative and non-creative tasks, this work uses these four task types exclusively to classify and understand the design process behaviour of each designer. Given this classification then, there are three important points to consider. First, design behaviour is by nature sequential and iterative. A designer will complete a number of tasks as part of any activity, with each task having an input and an output. Within any series of tasks, the output of one task has potential to be input to another; and previously completed tasks have potential to be repeated if new or developed information gives the opportunity for an improved result, or understanding of the problem changes. As a result, it is necessary in study of designers to consider the sequence of tasks that occur—termed in this work as their *design behaviour*.

Second, following the definition of activities by their focus, this work defines tasks by output rather than input. This gives an understanding of *what* the designer was working towards in each task, rather than by the resources they were using (which would be classified through the input). This classification allows understanding of the stepwise procedure of designers, through the goals that they were attempting to achieve at each point.

Third, while four types of task have been identified, two types of transformation can be surmised. Tasks can start and end with the same type of input and output (*information-type* to *information-type* or *application-type* to *application-type*), or can start and end with different types of input and output (*information-type* to *application-type* or *application-type* to *information-type*) (see Table 5). While the type of output of a task describes *what* a designer was focussing on in their tasks, the type of transformation describes *how* the designer reaches the output. When input and output are of the same type, this work describes the transformation as *within-type*, and when the input and output are of different types, this work describes the transformation as *cross-type*.

Table 5 Example task transformations

Input	Output	Transformation type	Example transformation
Information-type	Information-type	Within-type	Taking current analysis of stress/strain (input), identify potential materials for use in the design (output)
Information-type	Application-type	Cross-type	Taking the current description of requirements, produce an initial concept
Application-type	Information-type	Cross-type	Taking current component design, perform analysis to understand stress/strain profiles
Application-type	Application-type	Within-type	Taking an initial design of a component, finalise the dimensions and interface points

2.2 Identifying creative tasks

As discussed in Sect. 1.3, a creative process can be identified through the presence of divergence and creative convergence within tasks and activities. Note that, as defined in Sect. 1.3, a creative task is one in which the designers actions increase the potential for an output that is judged as creative to be produced.

Based on understanding from the literature, to produce an original, appropriate, and unexpected output (Chakrabarti 2006; Howard et al. 2008; Sarkar and Chakrabarti 2011), it is necessary for some form of divergence or creative convergence to occur (Guilford 1956; Brown 1996; Gero 2000; Dym and Brown 2012) within the designers actions. A creative task is therefore identifiable by evidence of divergence or creative convergence in the work of the designer. This can occur through exploration, or through myriad other creative behaviours (see Sect. 1.3). For the sake of differentiation between this work and the wider literature, in this paper evidence of these features is termed *expansion* and is identified through the appearance of behaviours as shown in Fig. 3. Note that in addition to expansion as might be typically interpreted from divergence within a design process, convergence is also a vital part of the creative process (Cropley 2006). Designers use convergent thinking as a narrowing and checking measure, used to select, identify, and rationalise the outputs of the divergent thinking stages, not normally to produce creative outputs in itself. Although in its process it can generate creative output when used as a combinatory measure that narrows the design space towards novelty, it is the divergent stages of design that initiate the production of creative output. Creative convergence is therefore also included in expansion. Also note that a process may contain both expansive and restrained episodes, and it is the summation of the entire process that leads to the output. As a result, expansive episodes can only be said to *promote potential* for a creative result and restrained episodes can only be said to *promote potential* for a non-creative result; therefore neither can preclude those outcomes.

As antonym to expansion, a *restrained* task is one that does not explore in its process. Instead, a designer is here understood to follow a more direct process, taking a single solution concept and developing into the final design output. This process can occur for a number of reasons, from the existence of a well-defined solution schema (Dym and Brown 2012) reducing the cognitive load required if the designer follows the prescribed pathway, through the use of past experience to remove the need for expansion [reducing cognitive load (de Jung 2010)], or through fixation creating attachment and preventing expansion (see Jansson and Smith 1991; Purcell and Gero 1996).

Creative behaviour is in this way identified at a low level in the behaviour of a designer—through the form of their individual actions. It is through summation and sequence of these low-level creative episodes that higher-

Fig. 3 Expansion and restraint in design tasks

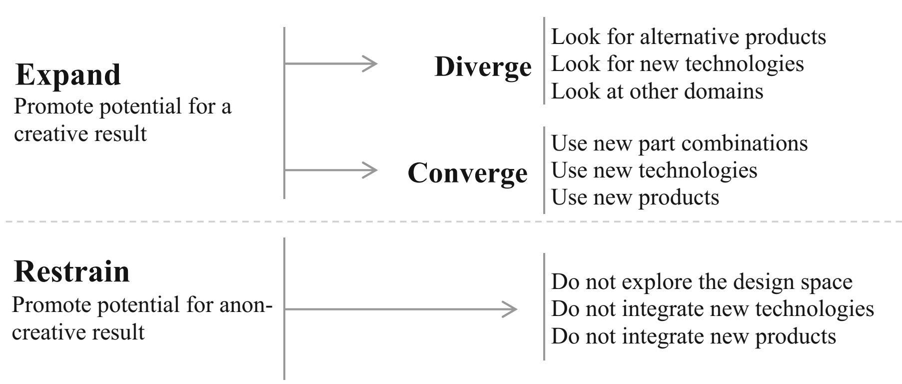


Table 6 The eight task types

	Input	Output	Transformation type	Creative/non-creative
1	Information-type	Information-type	Within-type	Creative (evidence of expansion)
2	Information-type	Application-type	Cross-type	Creative (evidence of expansion)
3	Application-type	Information-type	Cross-type	Creative (evidence of expansion)
4	Application-type	Application-type	Within-type	Creative (evidence of expansion)
5	Information-type	Information-type	Within-type	Non-creative (no evidence of expansion)
6	Information-type	Application-type	Cross-type	Non-creative (no evidence of expansion)
7	Application-type	Information-type	Cross-type	Non-creative (no evidence of expansion)
8	Application-type	Application-type	Within-type	Non-creative (no evidence of expansion)

level creative events occur within the designer's process. Accordingly, the appearance of single restrained or expansive task does not denote behaviour as creative or non-creative on its own. All tasks must be considered as part of a larger whole.

In relation to the types of task given in Table 5, the appearance of expansion or restraint raises the total number of possible task types to eight, the initial four in a creative manner (evidence of expansion), and the final four in a non-creative manner (no evidence of expansion). This gives eight possible task types as listed in Table 6.

It is expected that within the results of each study designers will demonstrate a variety of types of task in their work. For the purposes of analysis and as will be used in this paper, the type in each category that forms the majority of each designers tasks is described as their *approach*. For example, a designer may follow an *application-type output approach* if the majority of their tasks have an *application-type output*.

2.3 Summary

The elements of the coding scheme presented here form part of a more detailed framework and coding scheme that has been presented elsewhere [see Snider et al. (2013, 2014)]. Within, the behaviour of designers is studied through their tasks, which are in turn identified and classified through their type of output, type of transformation, and evidence for creative behaviour through expansion. Through these categories, the coding scheme allows the determination of the sequential process of a designer within their work direct, studying their behaviour directly. This work draws findings from the highest level of the coding scheme, drawing results from the appearance of creative behaviour and types of task completed, while in practice individual tasks were identified through lower-level 'knowledge entities' found within the designers work. The level presented here is appropriate for the analysis presented in this paper.

The coding scheme is also broadly applicable and independent of both design context and the product being designed, thereby allowing comparison and understanding to be drawn from behaviour across designers, working in different design situations, on different activities, with different motivations.

3 Methodology

Using this framework, the behaviour of 25 designers were analysed in two separate studies. These studies were designed to be directly complementary, with many of the weakness of the first addressed by the procedure of the second. Summary data for each study are given in Table 7. All undergraduate participants were based at the University of Bath. Table 7 also presents the contextual similarity between studies, which allows understanding of the cohesion between each.

The first study was a longitudinal analysis of the participants completing a 22-week individual project as part of their degree classification. Although completing different projects, each designer progressed through the typical stages of the design process, from initial task clarification to building a physical proof-of-principle prototype. The project structure is shown in Table 8.

Data were gathered and analysed through the use of the designers' logbooks, which they were required to keep as part of the assessment process. Logbooks were chosen due to the good representation that they can provide of the process followed (McAlpine et al. 2006), their ability to capture expansive processes (Currano and Leifer 2009), and the reliance of under-graduates on hand-drawn representations (Sobek 2002). Due to study practicalities, it was not possible to use other recording methods to gather further data such as full observation or protocol analysis (see Blessing and Chakrabarti 2009) and, as a result, some tasks could not be directly captured. This is a weakness of Study One that was rectified in the approach to Study Two. Additionally, the seven studied students were chosen for

Table 7 Study One and Two summary data

	Study One	Study Two
Participants		
Undergraduate participants	7	12
Average industrial experience	5 months	10 months
Graduate participants	–	2
Average experience	–	24 months
Expert participants	–	4
Average experience	–	159 months
Contextual similarity		
Study duration	22 weeks	4 h
Identical participant briefs?	No	Yes
Brief type	Physical product	Physical product
Design process stages	Initial brief to proof-of-principle prototype	Initial brief to review of detailed design
Participant environment	Standard, familiar environment	Standard, familiar environment
Data medium	Logbook	Logbook, video, screen capture, audio capture

Table 8 Project procedure (Study One)

Weeks 1–11	Weeks 12–22
Stage 1	Stage 4
Develop problem understanding	Develop final concept
Stage 2	Stage 5
Perform background research and develop initial concepts	Manufacture proof-of-principle working prototype
Stage 3	Stage 6
Report research and in-depth specification	Full report
Assessment	Assessment

the apparent completeness of their logbooks, in order to allow detailed coding. Each of these limitations was considered in developing the methodology for the second study.

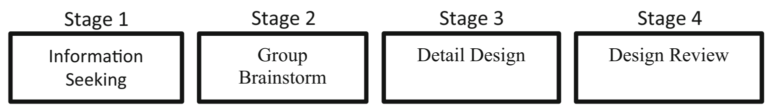
3.1 Purpose and procedure (Study Two)

Serving as an extension to the data collected within Study One and point of comparison for results, Study Two was designed to encourage a similar, although highly accelerated, design process. However, due to the weaknesses inherent in the methodology of Study One (see Sect. 3.5), it was vital that Study Two allowed increased confidence in findings. For this purpose, Study Two took several methodological steps to ensure validity and robustness of results. Further details of the methodology for this study have been published elsewhere (Cash et al. 2013; Snider et al. 2014).

The study occurred according to Fig. 4 over a period of four hours, designed to mimic a complete design process as described in the literature (Pahl and Beitz 1984; Hales 1987). Between each stage participants were permitted short, supervised breaks to prevent fatigue, during which they did not discuss the study. Groups consisted of three randomly assigned participants. Group stages were included in the experiment to more closely mirror the collaborative working environment as found in industry, which frequently contains both group ideation and individual working activities. However, as the focus of this work is to study individual behaviour, only stages 1 and 3 are included in analysis. Group creative behaviour is a valuable and interesting subject in its own right, but is not the focus of study within this work.

Throughout the study, the brief was to develop a remotely operated mount to be placed underneath a balloon for amateur aerial photography. The project brief was constant between designers. The purpose of each stage can be summarised as follows:

1. Clarify the problem through information seeking according to the designers' interpretation of the brief.
2. As a group, brainstorm and evaluate initial solution principles to meet the brief.
3. Taking a single concept from the previous stage as an input, develop a single design in as much detail as possible.
4. As a group, evaluate developed designs and, if necessary, develop improvements to aid in meeting the proposed brief.



Duration	50 minutes	50 minutes	90 minutes	50 minutes
Teamwork	Individual	Group	Individual	Group

Fig. 4 The structure of the second study

While within stage three in particular each designer may have been inspired by their conversation within stage two, it is only through evidence of expansion within stage three that their individual creative behaviour is noted. Group creative behaviour is a valuable and interesting subject in its own right, but is not the focus of study within this work.

In addition to data gathered through logbooks, as occurred in Study One, data were collected using webcams to view participants, Panopto recording software to capture computer screens (http://www.panopto.com) and LiveScribe (http://www.livescribe.com) notebooks and pens to capture real time, detailed logbook data. This comprehensive method ensured that confidence can be had in the completeness of the dataset, unlike within Study One.

In Study Two, due to study practicalities, early-stage data could not be collected for four of the industry-based participants. As a result, all comparisons of early-stage data in this work compare the seven Study One participants and remaining fourteen Study Two participants.

3.2 Further testing

In each study, the designers completed a creative style test similar to that of the Kirton Adaption-Innovation (KAI) test (Kirton 1976, 1978). This test has been shown to bear some correlation to creative level (Isaksen and Puccio 1988) and allows validation of the work and coding scheme against an external, independent measure.

3.3 Coding and analysis process

Coding of data for each study occurred through the same three steps:

Step 1—Identification of expansion, indicating occurrence of creative behaviour.
Step 2—Identification of input type, output type, and transformation type for each task.
Step 3—Identification of design stage of each task.

Each of these was completed in an individual pass to ensure focus was maintained, and each participant's data were coded in a single sitting to ensure the coder had complete understanding. Data were coded through identification of discrete knowledge entities (see Snider et al. (2013) for detailed explanation) taking the form of textual, numerical, sketch, drawing, or printed media affixed within the logbook, and subsequent judgement of the coder on the relationships evidenced between each. These knowledge entities were then identified as either an input or output to a task, followed by the transformations between. In this way, tasks were directly identified from evidenced markings within the data, and all markings within the data could be coded using the scheme. A detailed presentation of the coding scheme can be found in Snider et al. (2013) and Snider (2014).

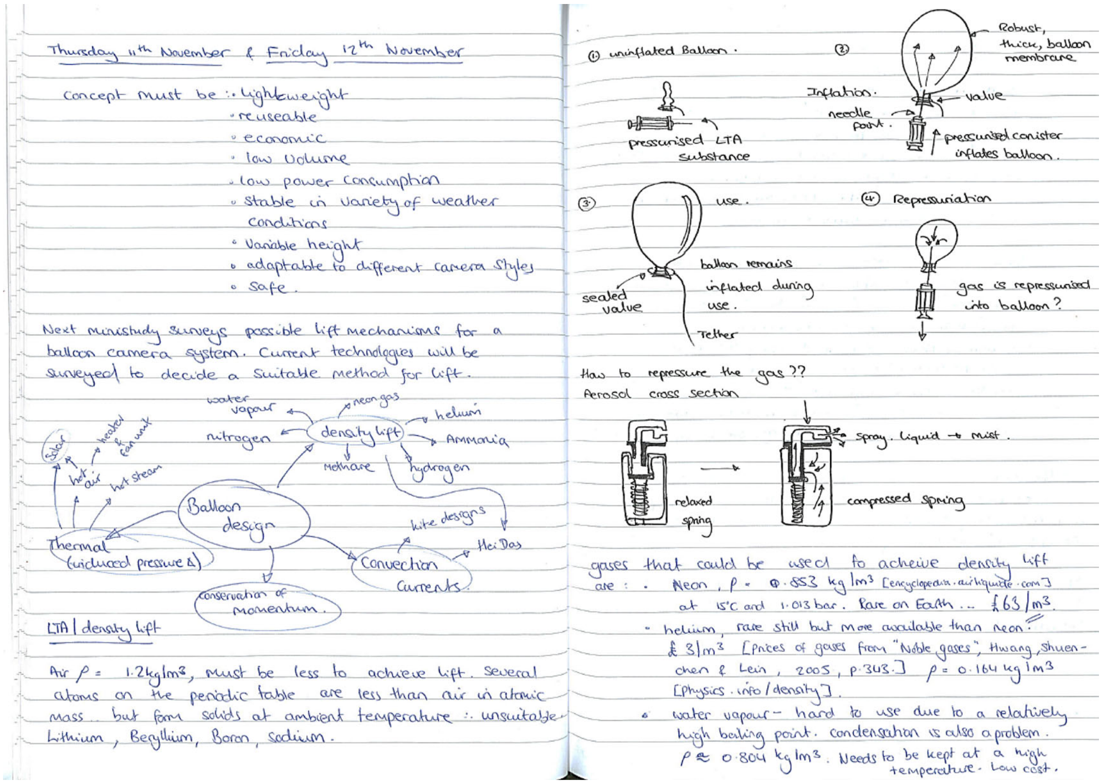
The only substantive difference in coding process came from the varied data set of Study Two, which required higher pre-processing and data synchronisation before coding could occur. Examples of raw and coded data are given in Fig. 5.

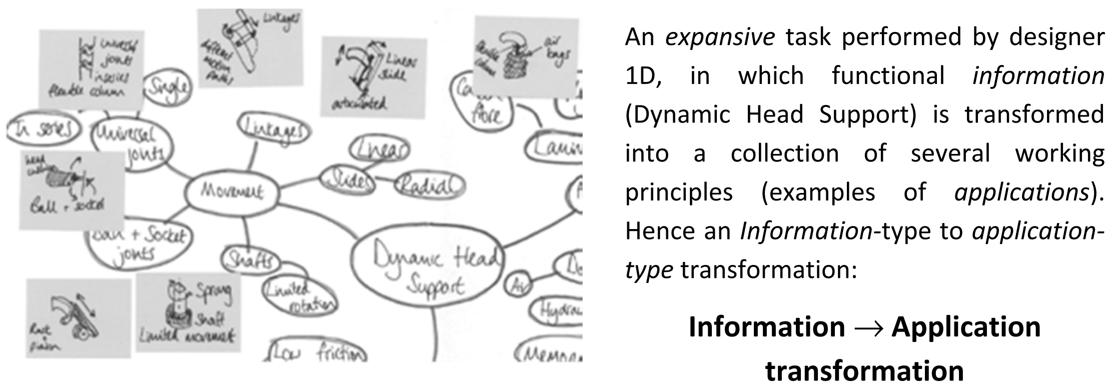
3.3.1 Coding validity and reliability

It is vital when developing a coding scheme that the results it produces are both valid and reliable, particularly when the coding process is latent in nature (Cash and Snider 2014; Potter and Levine Donnerstein 1999), as occurs in this case.

Construct validity of the scheme has been ensured through development from the existing literature and repeated application to sample data (which was not included in analysis). Internal validity has been ensured through the rules by which coding occurs, which have been designed to simplify the coding process without interfering in the judgements made by coders (Cash and Snider 2014; Snider et al. 2014). This approach is necessary to ensure validity when coding latent pattern data. Furthermore, the results have been compared to the results of an external measure of creative style [the KAI test (Kirton 1976)] to test for external validity.

Reliability analysis of the coding scheme occurred on a sample of 10 % of the total tasks from the first study [a suitable quantity for analysis (Potter and Levine Donnerstein 1999)]. Testing was completed by the original researcher and a single coder who was uninvolved in the development process. The coder was trained and the rules of the scheme re-assessed to ensure reliability according to the procedure of Krippendorff (1981). This re-assessment was carefully performed as to not decrease scheme validity. The tested sample contained both data which was previously unstudied by the testers, and data which was selected





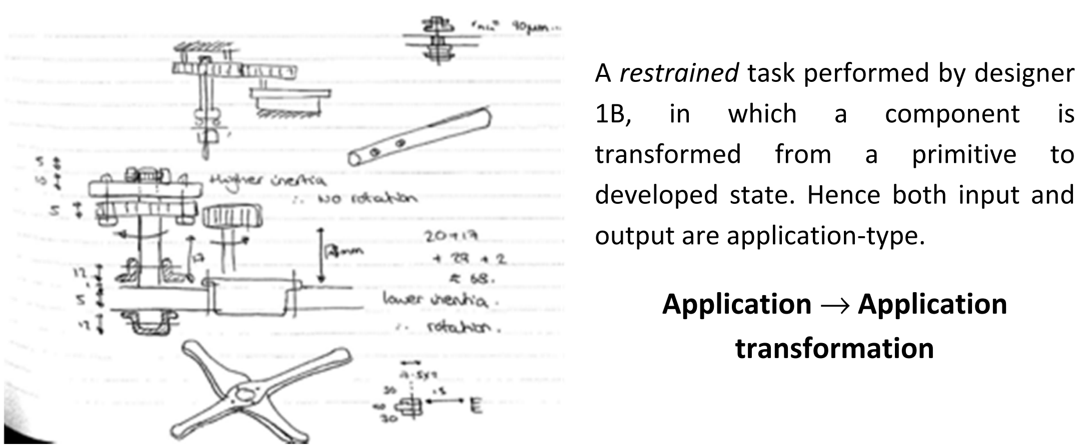


Fig. 5 (*Above*) Raw data of participant 1B; (*below*) coded data from participants 1D and 1B

for its recorded style, which was particularly difficult to code. To reduce memory effects, the researcher waited 2 months before re-coding this second set of data. Coding achieved a value for Krippendorff's alpha (Hayes and Krippendorff 2007) of 0.768, a suitable value for research such as that presented here (Klenke 2008; Blessing and Chakrabarti 2009).

3.4 Creative behaviour in the logbooks

While this work denotes creative behaviour only through the appearance of expansion within the tasks of a designer, it is useful to provide examples of creative behaviour that occurred in early- and late-stage design (see Table 9). Further exploration of different types of creative behaviour and their variation through each stage has potential to form interesting work in its own right.

3.5 Cohesion of studies

Due to their individual features, and as described in Tables 10 and 11, performing two studies allowed both extension of understanding and mitigation of the limitations that would be present should the studies be performed individually.

3.6 Quality analysis

In addition to analysis through the coding scheme, the outputs produced by the participants in Study Two were assessed for quality. In complement to the results of the coding scheme, this assessment allows identification of the practice that leads to better solutions. As one defining characteristic of creative behaviour is that it has potential to lead to better solutions (see Sect. 1), this analysis in comparison with that of the coding scheme allows a more detailed understanding of the creative behaviour of the designers to be developed. This analysis occurred according to a Consensual Assessment Technique [CAT, see (Amabile 1982)] and is discussed in Sect. 4.2.

Each design output as developed by the participants within Study Two was re-drawn in CAD by a single researcher, strictly according to the design of the participant, with dimensions and characteristics of each output derived from the working notes produced during the Study. Each design was also given a brief description of working principle to aid understanding. This consistent presentation allowed fair assessment of each.

Five experts took the roles of judges in the CAT, who had an average of 18 years engineering experience (range 7.5–29 years), and were asked to rate outputs on a five point Likert scale based on their interpretation of quality of the designs. All experts were presented with identical instructions and materials for familiarisation with the designs and were given equal time for assessment. Following assessment, all designs were ranked based on the expert judgements.

Table 9 Examples of early and late-stage creative tasks from logbooks (participant 1D)

Stage	Creative behaviour example
Early	Identify analogous products and their functional solution principles
Early	Brainstorm functional solution principles for brief
Early	Identify potentially relevant technologies
Early	Explore necessary requirements and impact of variations in values on functional capability
Late	Alter sub-system locations and assess impact on mass distribution
Late	Investigate drag and power requirements at several angles of incidence
Late	Identify, configure, and evaluate multiple layouts for specific mechanism
Late	Develop new mechanism to counter problems associated with its tested performance
Late	Assess multiple structures to minimise material use while maintaining force
Late	Design and evaluate wide-ranging operational regimes to maximise performance across conditions

Table 10 Cohesion between studies

Criteria	Comment
Complementary features	
Design stage	Design stages in each study were interpreted using the same scheme in a consistent manner
Creative behaviour	Creative behaviour in each study was interpreted using the same scheme in a consistent manner
Creative style/ approach	The creative approaches of each designer, as interpreted from the data in Sect. 3.3, are interpreted using the same scheme in a consistent manner
Creative style test	All designers completed the creative style test, and so some study of behaviour and creative style between designers and in comparison with the test can be performed
Task type	All task coding was identical in each study, and so can be collated for analysis where appropriate
Contrasting features	
Time scale	Study Two occurred under time pressure, and according to the procedure of the study. Study One is closer to typical design practice
Design completion	Designers in Study Two completed their design to varying degrees, dependent on their own working speed
Participants	Study Two used some expert designers, while Study One used undergraduates

Table 11 Strengths and weaknesses of studies one and two

Study One	Study Two
Weakness: only undergraduate participants	Strength: expert participants and experienced student participants
Weakness: differing project briefs	Strength: identical project briefs
Weakness: lower confidence in completeness of data	Strength: complete observation of participants
Weakness: lower number of participants	Strength: Higher number of participants
Strength: realistic task completed freely by the designers	Weakness: lower realism in constrained setting and situation of design study
Strength: longer-term study	Weakness: short-term study
Strength: un-intrusive data collection method	Weakness: disruptive data collection method

3.7 Correlation with creative style

While demonstration of the validity of the coding scheme has been presented elsewhere (Snider et al. 2013), further confidence can be formed through comparison with the results of the Kirton Adaption-Innovation (KAI) test, which each participant completed as part of the data gathering process.

As shown in Table 12, medium and significant correlations exist between the KAI test and the appearance of creative behaviour in later-stage design. As those with a higher score within the KAI scale are thought to be the more creative by traditional understanding (Kirton 1976; Isaksen and Puccio 1988), the correlation with late-stage expansion acts as one form of confirmation of validity of the coding scheme. The KAI scale is a fully external measure, and as such that it and expansion as measured by the coding scheme are significantly related demonstrates the ability of the coding scheme to identify creative behaviour.

Correlation has been calculated by a Spearman rank correlation, and significance demonstrated by a two-tailed Student's t test. All correlations would typically be interpreted as medium strength and positive.

Table 13 Summary data for studies one and two

	Study One	Study Two	Overall
Total tasks	1045	293	1338
Proportion early-stage (%)	18.3	34.1	21.8
Proportion later stage (%)	49.7	65.9	53.2
Proportion N/A (%)	32.0	0.00	25.0
Information-type	364	123	487
Application-type	347	170	517
Creative type	252	110	362
Non-creative type	459	183	642

4 Results

Summary data for both studies is presented in Table 13. In Study One, due to the nature of the data source as working document and record, there were a number of identified tasks that were not related to the completion of the project, such as to-do lists, report writing and presentation requirements, or personal notes of the participants. Following coding, such non-applicable tasks were identified and omitted from analysis.

4.1 Focus through the design process

Through the design processes which occurred in both studies, there was a distinct change in behaviour from that with an information-type focus in early stages, to that with an application-type focus in later stages (see Fig. 6).

This is a logical result and thought to be due to the nature of design and rules of the coding scheme. As discussed in Sect. 1.1, when defining design stages by focus rather than chronology or hierarchy, the purpose of early-stage design is to gather information and form functional solutions for the problem. In later-stage design, this changes to a focus on development of the physical solution itself. Accordingly, as identified empirically here, in early stages the designer must gather information and understand resources, with some concept formation and initial detail work. In later stages, the designer must

Table 12 Correlation of creative style and creative approach

First variable	Second variable	Correlation ($\rho = \ldots$)	Significance ($p = \ldots$)
Study One			
Creative style test	Late-stage expansion	0.714	0.0357
Study Two			
Creative style test	Late-stage expansion	0.534	0.0224
Combined			
Creative style test	Late-stage expansion	0.485	0.0141

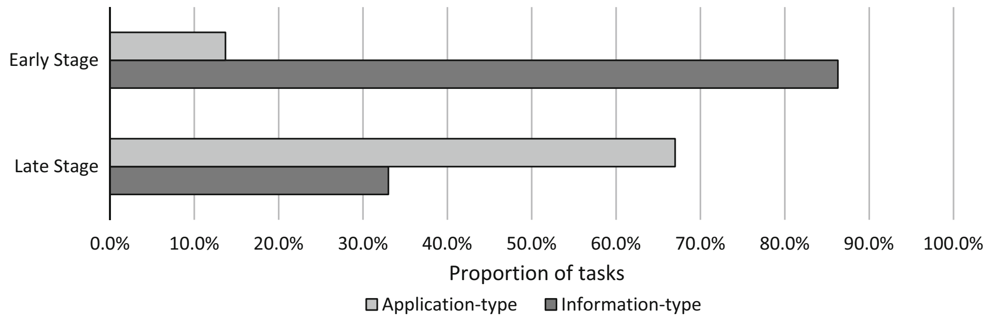


Fig. 6 Proportion of information-type and application-type tasks through the design process (both studies)

create a functional output (therefore focused on *application*), based on the information generated in early stages, or more primitive design versions. Similar understanding can be seen in the theoretical literature (Pahl and Beitz 1984; Pugh 1990), with some parallels potentially seen in empirical research (see Hales 1987), where the designers activities are observed to change throughout the design process according to the general process of typical design models.

4.2 The appearance of creative behaviour

Figure 7 presents the proportions of creative behaviour (as opposed to non-creative behaviour) identified within the early and late stages of the process for each study, when combined. In all cases the occurrence of creative behaviour decreased from early to late stages, but did remain on average above 25 % of total late-stage behaviour.

As may be expected given the existing bias in creativity research—that to the early stages—there is a higher occurrence of creative behaviour early in the process ($p \leq 0.0001$; Wilcoxon signed rank test). However, creative behaviour does not disappear in later stages—designers continue to follow a creative process and have potential to produce creative results. There is therefore a case for its specific study—it should not be assumed that creative behaviour will manifest across the process in the same manner (therefore providing opportunity for new understanding), or be assumed that support of designer behaviour in later stages can follow the same structure as early stages (therefore providing opportunity for new tools and support methods).

4.3 Later-stage creative behaviour

A primary distinction drawn within the coding scheme is between information-type tasks (which focus on generation of information) and application-type tasks (which focus on the actual application of the design). Looking directly at the proportion of each type of task that is completed in a creative manner by each participant highlights differences in creative behaviour, as shown in Fig. 8.

Figure 8 references participants first numerically by the study in which they took part, and then alphabetically by random assignment (i.e. participant 1E is participant E from Study One). In all results presented here participant references are consistent.

Although participants complete a higher proportion of application-type tasks in later stages (Fig. 6), the type of tasks that are more often completed creatively varies, with some more often creative in information-type tasks, and some more often creative in application-type tasks. Participant 1A, for example, was creative in 24.2 % of *information-type tasks*, and 17.5 % of application-type tasks; and participant 2D was creative in 40.0 % of *application-type tasks* and 25.0 % of information-type tasks.

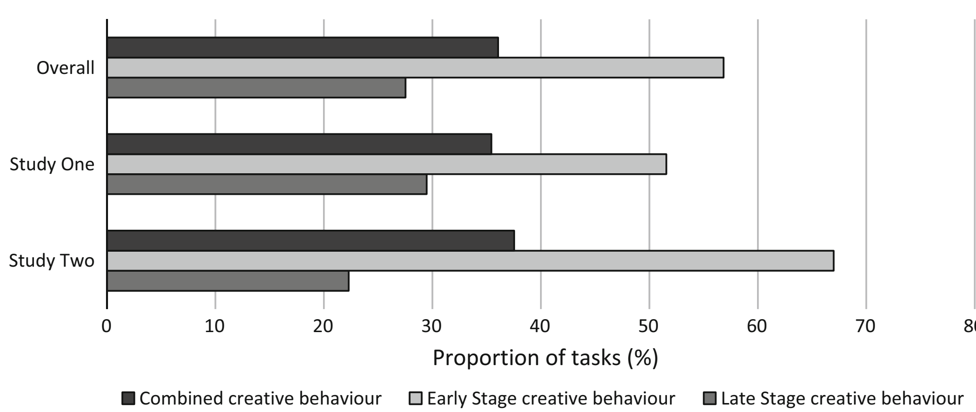
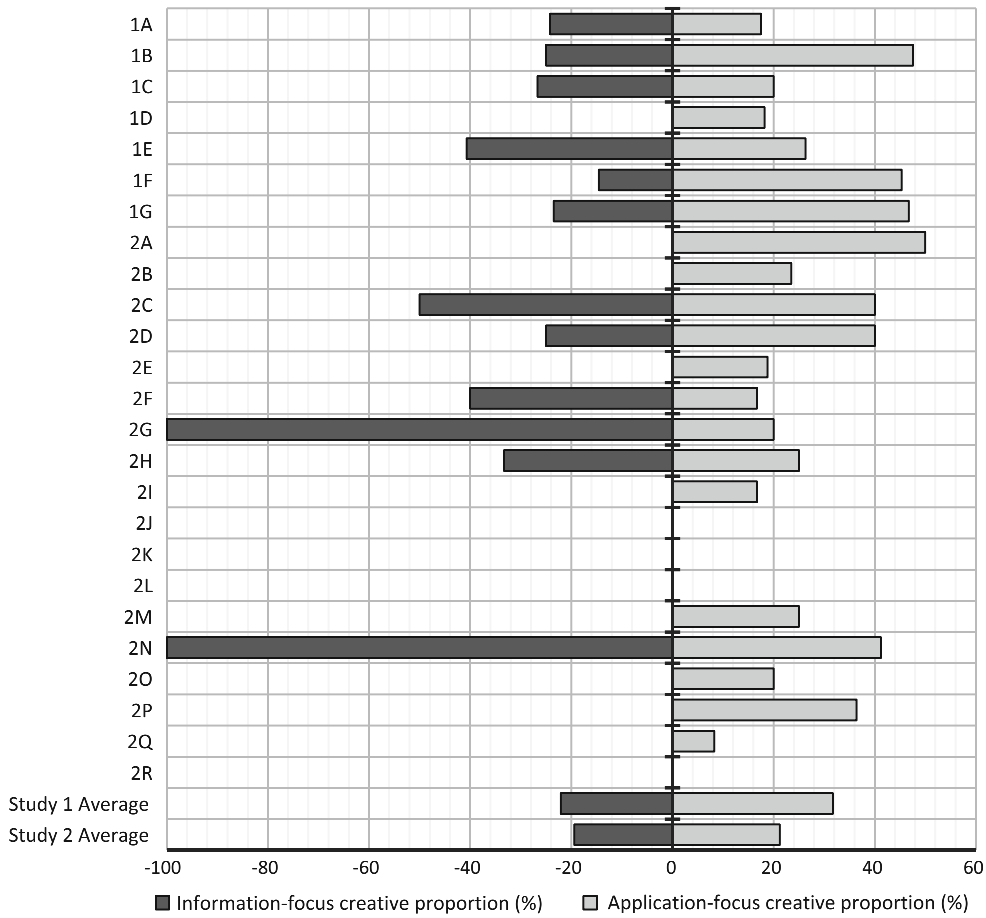


Fig. 7 Creative behaviour throughout the design process

Fig. 8 Proportions of creative behaviour in later stage design



In total, 8 of the 25 participants were more often creative in information-type tasks, 13 were more often creative in application-type tasks, and 4 were marked as non-creative (all from Study Two). The category of each designer's majority is referred to as their creative approach (Fig. 8).

There are different ways in which a designer will display creative behaviour in later-stage design, as judged by type of task. Some will more often be creative when identifying information, and less creative in how the design is formed; and others will less often be creative in identifying information, and more often creative in how they form the design. For example, a designer belonging to the former group may explore when identifying viable technologies for use in a design, but apply those technologies in a standard manner. A designer belonging to the latter group may be more likely to use whichever technology is commonly used for a given type of application, but be creative in how it is applied. These distinctly different approaches to creative behaviour have interesting implications—due to the different focus of each type of task, there are potentially very different methods to completion of each. A question then arises as to what can be learned from each approach in terms of encouraging or discouraging creative behaviour, and the support methods to provide given each approach has potentially to be distinctly different in the way it manifests.

As both approaches were detected in each study, certain potential causes of behaviour can be eliminated. In Study One, each designer completed a different brief (although over the same portion of the design process); in Study Two, each designer completed the same brief (again, over the same portion of the design process). In each study, designers had identical resources available to them. This demonstrates that the creative approach followed is not brief or output dependent—each approach appears regardless of identical or non-identical instruction. Further, each study utilised distinctly different methodologies suggesting that methodology and design situation is not the determinant of creative approach, and the comprehensive data capture method of Study Two demonstrates that the determination of creative approaches is not a result of the logbook recording style of the participants. Even within groups (as were present during the second study at certain points) designers did not all display identical approaches.

Table 14 Creative approach in early and later stages (both studies)

	Late stage	Early stage		
	Creative approach type	Information type creative proportion (%)	Application type creative proportion (%)	Creative approach type
1A	Information-type	37.0	33.3	Balanced
1B	Application-type	64.5	66.7	Balanced
1C	Information-type	33.3	0.00	Information-type
1D	Application-type	25.0	100	Application-type
1E	Information-type	42.3	71.4	Application-type
1F	Application-type	60.0	50.0	Information-type
1G	Application-type	68.4	66.7	Balanced
2A	Application-type	66.7	100	Application-type
2B	Application-type	40.0	0.00	Information-type
2C	Information-type	50.0	0.00	Information-type
2D	Application-type	–[a]	–[a]	–*
2E	Application-type	75.0	100	Application-type
2F	Information-type	66.7	33.3	Information-type
2G	Information-type	70.0	0.00	Information-type
2H	Information-type	71.4	50.0	Information-type
2I	Application-type	66.7	0.00	Information-type
2 J	Non-creative	66.7	0.00	Information-type
2 K	Non-creative	100	100	Balanced
2L	Non-creative	75.0	0.00	Information-type

[a] Due to data corruption, early-stage data is not present for participant 2D

4.4 Creative approach through the design process

Table 14 extends this analysis to the creative approaches of designers in early stages. Again, different approaches can be identified despite the variation and similarities in study methodologies and briefs set. However, further understanding can be gained through the variation in approach displayed by each individual designer in each stage.

In Table 14, there are 3 designers who increased their relative proportion of information-type creative approach and 12 who increased their relative proportion of application-type creative approach. Of these, 10 changed sufficiently to change their majority from one to the other. This demonstrates that although creative approach is not brief dependent, it may be stage dependent—the creative behaviour of a designer can and will change as they progress through the design process. A higher number of participants focused on information-type creative tasks in early stages, application-type creative tasks in later stages, and increased their application-type creative proportion as the process continues. These results suggest that there may be a tendency for stage dependence to vary from information-type creative to application-type creative through the design process, similar to (but less strongly than) the focus of design tasks as shown in Fig. 6.

Table 15 Average creative task proportion through design stages

Design stage	Overall creative proportion (%)	Proportion of creative tasks of different types through stages (%)	
		Information-type	Application-type
Early stage	66.7	60.6	66.7
Late stage	20.9	21.7	20.7
Overall	36.1	40.5	31.9

Supplementing this information with that in Table 15, it can be seen that the average proportions of types of creative task are very similar in early stage (60.6 % information-type, 66.7 % application-type) and in late stage. This suggests that each approach is equally viable and employed in each stage, again suggesting individual difference in each designer as the determinant for the variation.

4.5 Creative behaviour through the design process

Results to this point have looked at types of creative task as determined by their output. As described in Sect. 2.1.2, an alternative method of classification is by the type of transformation that occurred during the task; termed

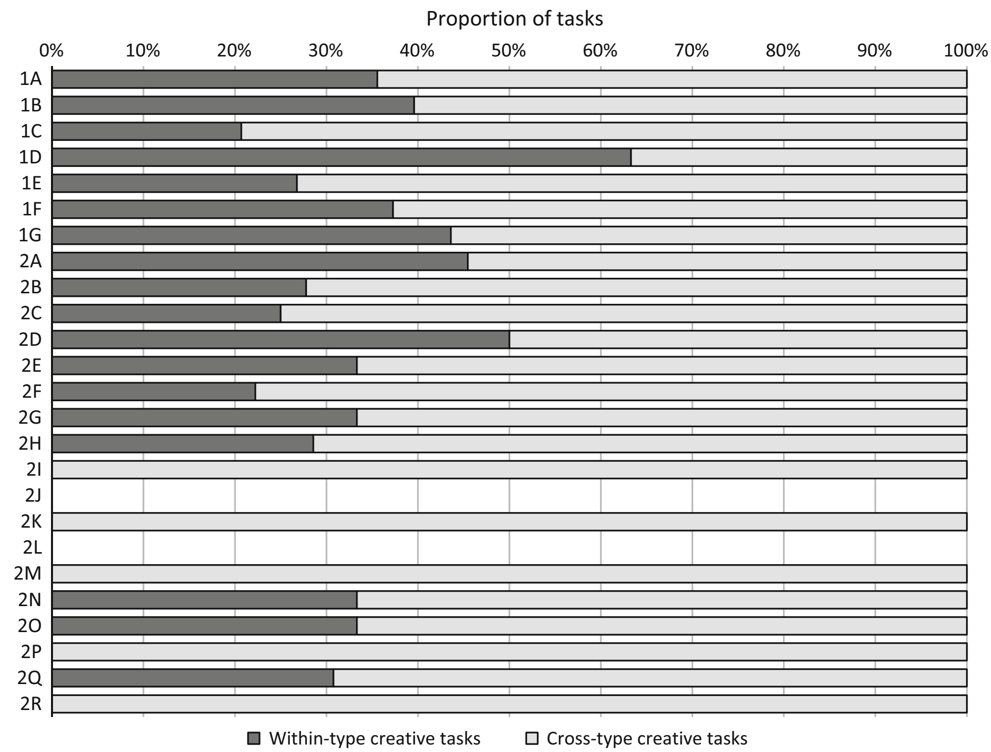


Fig. 9 Within and cross-type creative task proportions for each designer (later stage; both studies)

within-type when the input and output are the same type, and cross-type when the input and output are different. Figure 9 shows the relative proportions of within-type and cross-type creative tasks for each designer in both Studies, solely within later stages of the design process.

Clear within Fig. 9 is that in the later-stage designers (with the exceptions of 1D and 2D) are more often creative in *cross-type tasks* ($p \leq 0.0001$; Wilcoxon signed rank test; 37.8 % of total) than in *within-type tasks* (17.8 % of total). Note that Designers 2J and 2L completed no creative tasks in later stages, and thus no data can be provided.

This trend demonstrates a strong pattern in creative behaviour—the transformation from an *information-type* input to an *application-type* output (or vice versa), more consistently involves expansion than the transformation from an *information-type* or *application*-type input to a more developed version of itself.

This is discussed further in Sect. 4 and demonstrates a clear opportunity for deeper understanding of the nature of the creative process as directly identified in the behaviour of designers. Supplemented by Table 16, this data also suggest that this pattern is strong in later-stage design, but not present in early stages, where the proportion of creative tasks completed of each type is more similar. These data therefore reinforce that later-stage creativity is different to early stage.

Table 16 Creative task type proportions by type of transformation seen (both studies)

Design stage	Overall creative proportion (%)	Proportion of creative tasks of different transformations through stages (%)	
		Within-type	Cross-type
Early stage	66.7	58.1	53.3
Late stage	20.9	17.8	37.8
Overall	36.1	32.8	40.5

4.6 Quality and creative behaviour

As quality analysis was conducted on the outputs of Study Two, some understanding can be gained of the behaviours that lead to better quality results (see Table 17).

Three correlations between quality and designer behaviour were identified, all tested with Spearman's rank correlation and significance tested with a two-tailed t test. These provided evidence that a focus on information-type tasks in early stages, a higher proportion of creative behaviour in early stages, and a higher proportion of application-type creative tasks in later stages are associated with higher quality results. These correlations give suggestions of better practice in design, and the manner in which better solutions can be produced.

Table 17 Correlations with design quality from Study Two

First variable	Second variable	Correlation ($\rho = \ldots$)	Significance ($p = \ldots$)
Design quality	Early-stage information-type creative task proportion	0.701	0.00809
	Early-stage creative task proportion	0.542	0.0425
	Later-stage application-type creative task proportion	0.495	0.0434

5 Discussion

This work has presented numerous results from two complementary studies, each designed to increase understanding of the nature of behaviour throughout the design process, particularly that which is creative. This section now discusses these results, addressing first the initial two research questions posed in Sect. 1.5, and then forming discrete characterisations of early- and late-stage design behaviour in answer to the third.

5.1 Later-stage creative behaviour as an individual area for research

In Sect. 1.5, three research questions were posed to test the underlying assumptions of the work.

> Is creative behaviour seen in the behaviour of designers working within the later stages of the engineering design process?
> Are there substantive differences in the creative behaviour of designers working between the early and late stages of the engineering design process?

Addressing the first, by looking at the results presented in Sect. 3.2, Fig. 6 demonstrates that in excess of 20 % of the behaviour of designers in later-stage design is completed in a creative manner. While creative behaviour is in minority to non-creative and significantly lower than in early stages, the fact that it constitutes approximately one quarter of a designers' behaviour demonstrates the potential importance of creative behaviour throughout the design process. As a result, the focus of research into creative behaviour should not solely lie on early-stage design, as is common in the literature, but should consider behaviour throughout design.

The second research question has been explored by results in several sections of this paper, as summarised in Table 18. This again supports the need for specific study into later-stage creative design behaviour—it is different in nature to early, and so knowledge of early-stage creative behaviour should not be assumed to be entirely applicable.

Table 18 Results supporting the second research question

Section	Result
Section 3.1	Tasks in later-stage design are different in focus to those in early-stage
Section 3.4	The creative approach of designers can vary between design stages
Section 3.5	The transformation types of creative tasks in early-stage design are both within-type and cross-type to similar proportions
	The transformation types of creative tasks in later-stage design are more likely to be cross-type

5.2 Characteristics of design behaviour

The third research question in Sect. 1.5 calls for the identification of specific and discrete characterisations to be formed:

> What, if any, are the characteristics and patterns of creative design behaviour throughout the engineering design process?

This section identifies ten such characterisations, which can act either as a subject for exploration in further research or as grounding on which further work can be based.

5.2.1 Task focus and creative behaviour through design stages

Shown in Sect. 3.1, as the design process continues there is a switch in majority from tasks with an information-type output to tasks with an application-type output. In more tangible terms, this would be a variance from research and evaluation tasks, such as market analysis and technological research, to tasks concerned with the actual development of the design, such as layout design, configuration, and dimensioning.

There is a clear layer of necessity to this pattern. By their very nature the early stages of design are at a more primitive state than the late stages—there is little by way of a design product to consider. As such, much time is spent researching the possible requirements to include and designs that could be implemented, in order to make informed and effective design decisions. As the design process continues and the product begins to take shape, there is both option and need to focus on how it is put together, how it performs, and how it is made; all of which concern physical product rather than the knowledge and variables used for its production. This information-type to application-type drift is therefore a fundamental part of the design process and represents the necessity and purpose of the design stages.

These data therefore are interpreted as giving the following characterisations:

Early-Stage 1 (ES1)	Designers will focus on information-type tasks
Late-Stage 1 (LS1)	Designers will focus on application-type tasks

Further, creative behaviour exists in minority to non-creative in later stages, and approximately equal to non-creative in early stages. This can give the following characterisations:

ES2	Designers perform creative and non-creative behaviour in similar proportions
LS2	Designers perform creative behaviour, but in minority to non-creative

5.2.2 Designer creative approaches

As shown in Sects. 3.3 and 3.4 by Fig. 8 and Table 14, two different creative approaches can be identified throughout the design process; the first of which contains designers who are more often creative in information-type tasks, and the second of which contains designers who are more often creative in application-type tasks; a finding that demonstrates empirically some thinking in creativity literature—that creative behaviour is dependent on the designer in, for example, their personality (Feist 1999) or problem-solving style (Eisentraut 1997), and also suggests a certain context independence—according to theory designers will not resort to a certain approach in a certain situation.

There is, however, a tendency for the creative approach to match the predominant task type in each design stage, suggesting that the general purpose of the activities the designer is performing may have some influence on the approach followed. While there is no evidence here that design brief or process methodology impact the appearance of creative behaviour, the general type of work of the designer within each stage may.

These results suggest that designers are the determinant of the approach followed and that there is potential for each approach in each stage, but then contradict this finding by demonstrating that information-type creative behaviour is more common in early stages and application-type creative behaviour is more common in later stages. This disjunction can be clarified by looking at the quality of solutions produced. As shown in Table 17, those who produced better quality solutions are more creative in early-stage information-type tasks and are more creative in later-stage application type tasks. This then suggests that the tendency for approaches is actually a result of better practice—a learned behavioural approach based on what will lead to better results. While each designer can follow any approach, certain patterns that often lead to better results may have created a tendency for designers to follow them.

These data therefore are interpreted as giving the following characterisations:

Overall Process 1 (OP1)	Design behaviour and creative approach can vary between design stages
OP2	Creative approach is not determined solely by brief or methodology
ES3	An early-stage information-type creative approach can lead to better quality output
LS3	A later-stage application-type creative approach can lead to better quality output

5.2.3 Types of transformation and creative behaviour

Considering creative behaviour through transformation type presents a simpler interpretation. This category concerns the distinction between tasks that have an input and output of the same type, and an input and output of different types. The former would then typically be represented by such tasks as clarification of information or gathering of further detail on a subject; or of refinement of dimensions and configuration design. The latter would typically be represented by the implementation of a function into a system, or the evaluation of a part against its specification.

Almost without exception, designers were more often creative when completing cross-type tasks than within-type in later stages (see Fig. 9; Table 16). This is a significant finding about the nature of creative behaviour in later-stage design, particularly as the pattern is not present in early stages.

That cross-type tasks are more creative suggests a link between such a transformation and the need to explore. While further work into the reason for this pattern is required, it can be related to creative and non-creative behaviour as described in the literature. When developing an input into a more developed form of itself, there is a clear conceptual link, and reasonable potential for a designer to identify a procedure by which it can occur. There would then be less need for exploration—the designer knows their input, can understand their output, and can follow a known path to reach it. Such a procedure then follows the non-creative design process of Dym and Brown (2012). When developing an input into a different type of output (as occurs in cross-type tasks), there is less potential for a clear link between the two. When design can continue by a number of methods and there is little indication to the form of the output, there is a higher chance of the need for expansion; both in the output and in the method of reaching it.

Further, this pattern does not appear in early-stage design (see Table 16), suggesting that this pattern is a feature of later-stage design specifically. Although a hypothesis, this could be due to the inherent lack of clear path to a solution that exists in early stages. Due to the lack of information present (as is evidenced by the high need for information gathering seen both in the literature [see Pahl and Beitz 1984; Cash et al. 2013) and in this work (see Fig. 6)], there may be a higher likelihood of need for expansion in all types of task.

The stimulation of cross-entity tasks then serves as a potential method for the support and enhancement of designer process. Should a creative process and creative result be desired, stimulating the designer to complete a higher proportion of cross-entity tasks could be the initiator. Similarly, should a creative process not be desired, stimulating a higher proportion of within-entity tasks could have the appropriate effect. The method of this stimulation is a subject for further work, but could involve the use of specific types of brainstorming, or temporarily imposed constraints on the subject of a designers work.

These data can be interpreted as giving the following characterisation:

ES4 Both types of task transformation are frequently and similarly creative

LS4 The cross-type task transformation is consistently the most frequently creative

5.3 Creative behaviour in engineering design processes

Each of the results presented throughout Sect. 3 allows determination of some characteristic of designer behaviour and creative behaviour throughout the process, as are formed in Sect. 4.2. These characterisations are summarised in Table 19.

Although all novel in that within this work they are directly detected from the activity of engineering designers, these characterisations have varying originality in context of existing understanding, with some presenting support and extension to existing theory, and some presenting original findings. *OP1*, *ES1,* and *LS1* are all logical given the structure of the design process itself, from task analysis and information gathering through to physical product development (Pahl and Beitz 1984; Pugh 1990; Cross 2000). *OP2* is perhaps to be expected given the reliance of creativity on personal traits (Kirton 1976; Torrance 2008). *ES2* and *LS2* are perhaps to be expected given the increasing levels of constraint as the design process continues (McGinnis and Ullman 1990; Howard et al. 2011), which has potential to limit creativity (Onarheim and Wiltschnig 2010; Eckert et al. 2012), leading to a lower requirement for expansion in later stages.

The remaining four characterisations (*ES3, ES4, LS3, LS4*) are all of higher novelty and have broader implications for the study of creative behaviour in design research. Particularly through the direct detection of typical behaviours that have not previously been observed or explicitly theorised (*ES4* and *LS4*) and the identification of behaviour that lead to better results (*ES3* and *LS3*), there is grounding and direction for future research looking specifically at supporting design behaviour and increasing quality of design output throughout the process.

Table 19 Characterisations of design behaviour throughout the design process

Number	Characterisation
OP1	Design behaviour and creative approach can vary between design stages
OP2	Creative approach is not determined solely by brief or methodology
ES1	Designers will focus on information-type tasks
ES2	Creative behaviour occurs in similar proportions to non-creative
ES3	An early-stage information-type creative approach will lead to better quality output
ES4	Both types of task transformation are frequently and similarly creative
LS1	Designers will focus on application-type tasks
LS2	Creative behaviour occurs, but is in minority to non-creative
LS3	A late-stage application-type creative approach will lead to better quality output
LS4	The cross-type task transformation is consistently the most frequently creative

5.3.1 Implications for design methods and designer support

The purpose of the work presented here is to demonstrate the need for specific study of later stages of design and to generate specific characterisations on which further work can occur. While further work is needed to explore the extent of opportunities, these characterisations provide some idea of the manner in which later-stage design and creative behaviour can be supported and manipulated.

First, through the encouraging or discouraging of cross-type tasks, the proportion of creative behaviour may increase or decrease. Through tools or methods that encourage a cross-type task to occur, there is potential to increase the proportion of tasks that are completed creatively, thereby increasing the opportunity for a creative solution to be discovered. Such tools require development and validation through discrete study, such as testing of a variety of creativity methods and observation of the activities of designers who display dominant switching behaviour.

Second, the existence of differing creative approaches has implication for support. There is evidence that certain approaches are better applied in early-stage and later stages, and so evidence that certain approaches should theoretically be encouraged or discouraged in each stage. However, as the approach followed is designer-centric and determined by their personal approach, there is a question of how each may be supported. Depending on individual typical approach and that which typically produces better results, there may be numerous methods of supporting behaviour and altering the way that people work. For example, a different approach may be needed to encourage a designer who is usually more creative in information-type tasks to be more creative in application-type than to support a designer who is already more often creative in application-type.

Third, the characterisations of designer behaviour provide an evidenced-based description of actual design behaviour through the design process. There is then scope to explore existing design methods and support methods in context of these characterisations, to clarify how they work, to assess their suitability, or to suggest extension. For example, highly applied creative support methods such as SCAMPER (Eberle 1996) and TRIZ (Altshuller and Rodman 1999) would appear by the results of this work to be better suited to later-stage design, due to their focus on the design application, while methods such as brainstorming or would appear to be broadly applicable due to their ability to focus on any subject.

5.4 Limitations of study and further work

While the completion of two individual yet complementary studies strengthens confidence in each (see Sect. 3.5), there are some limitations to study that can be rectified with further work.

Due to the exploratory nature of the work, all characterisations would benefit from final validation through a single and comprehensive data set. Designed to balance the weaknesses of the other, the completion of two studies allows triangulation of results and confidence in patterns that appear with consistency. The studies were designed, however, to take an open stance and provide general information about the behaviour of designers, rather than to test and validate discrete hypotheses. In further work, hypotheses could now be articulated and tested in detail, investigating across design situations and contexts. This further work would be highly valuable.

While the work presented here includes results of experts working within industry, they do not constitute a detailed exploration of the differences between expert and non-expert design behaviour. This is a highly important subject in its own right, and as such there is value in the performing of work specifically studying the creative behaviour of industry experts working within their own context. Such a study would benefit from further participants and would require a comprehensive and longitudinal data collection process.

This work has identified patterns in creative behaviour, but has not explored the potential differences in creative behaviour in early and late stages. For example, there may exist patterns in scale of divergence, types of problem framing, and levels of fixation (amongst many others) that vary through the design process, each of which has potential to provide an interesting and valuable contribution to understanding of creativity in later-stage design.

Finally, the characterisations here presented give a description, but not an implication. This paper has hypothesised opportunities for designer support and improved design methods that may result from such understanding, but as the hypotheses are based on observation rather than intervention, each requires individual exploration and development to be exploited.

6 Conclusion

This work has presented the results of two studies focused on exploring designer behaviour throughout the design process, with a particular focus on later stage and creative design. This area has to date been neglected in the literature. The work has utilised a developed framework and coding scheme for analysis, which is designed to study the behaviour of designers directly from their actions as recorded in their working documents and computer activity. The framework and coding scheme were applied to the results of two studies; different in nature but designed to be highly complementary. The use of these two studies allowed triangulation of findings and mitigation of individual study weaknesses.

From these studies, this work has first demonstrated that creative behaviour does occur to a significant extent in later-stage design, and that its nature is substantively different to early stages. This is an important finding, creative behaviour in later-stage design is shown to be a worthwhile and valuable research topic that requires further study.

Through further exploration of the results from both studies this work has presented ten evidence-based characterisations of designer behaviour throughout the design process, ranging from those that are expected given extant literature, to those that demonstrate new contribution to knowledge. Particularly interesting is the appearance of differing creative approaches through the stages of design with a change in the types of task that are typically completed creatively as the design process continues; and the consistently appearing patterns creative behaviour, with near-all designers displaying a majority of creative behaviour in a single type of task (see *LS4*; Table 19).

Through exploration of these characterisations in further work, there is potential for the development of both deeper understanding into the nature of creative behaviour and of discrete and appropriate methods of support. By considering how creative behaviour manifests through the design process, there is potential to develop methods and support that could specifically encourage or discourage its appearance in a manner that is appropriate both to the design stage, and the individual personal approach of the designer.

Acknowledgments This work was performed within the Innovative Design and Manufacture Research Centre (IdMRC) at the University of Bath, supported by European Physical Sciences Research Council (EPSRC).

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