Design Science

Uncertainty Driven Action (UDA) model: A foundation for unifying perspectives on design activity

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Abstract

This paper proposes the Uncertainty Driven Action (UDA) model, which unifies the fragmented literature on design activity. The UDA model conceptualises design activity as a process consisting of three core actions: information action, knowledge-sharing action, and representation action, which are linked via uncertainty perception. The foundations of the UDA model in the design literature are elaborated in terms of the three core actions and their links to designer cognition and behaviour, utilising definitions and concepts from Activity Theory. The practical relevance and theoretical contributions of the UDA model are discussed. This paper contributes to the design literature by offering a comprehensive formalisation of design activity of individual designers, which connects cognition and action, to provide a foundation for understanding previously disparate descriptions of design activity.

Key words: design activity, information processing, communication, conceptual design, design theory

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1. Introduction

Design activity refers to a complex phenomenon enacted by a designer (Visser 2009; Cash, Hicks & Culley 2015) and connecting information, knowledge (Sim & Duffy 2003), and object domains (Gero & Kannengiesser 2004). The term itself has a number of possible definitions and uses in the literature. At its most general, it has been used to describe the whole process and practice of design with respect to the organisation (Pahl & Beitz 1996), as well as specific stages or elements in the product development process e.g. embodiment design (Pugh 1989). Here, activity is framed with respect to a specific product development goal and describes organisational behaviours (Wynn & Clarkson 2005). In this context, normative development processes are driven by organisational rationalisations and decision making e.g. as in Decision Based Design (Hazelrigg 1998). In contrast, authors such as Andreasen, Thorp Hansen & Cash (2015) use design activity to describe the interface between design practice and reflective improvement. Here, the interaction between an individual's external behaviour and internal cognition produces an emergent activity process (Evans & Stanovich 2013). Despite these differing uses, design activity is predominantly applied with respect to the designer. For example, Sim & Duffy (2003) describe an individual's design activity as a knowledge-based input/output system moderated by the design goal. Hence a general definition of design activity is adopted: *design activity is a goal directed system where cognition, behaviour, and motivation are integrated, with respect to the 'bringing-into-being' of a design artefact* (Dorst & Cross 2001; Bedny & Karwowski 2004; Cash *et al.* 2015). This definition builds on Activity Theory (Leont'ev 1981), which describes human activity as the unity of behaviour and cognition (Bedny & Karwowski 2004), and explicitly differentiates this work from the terminology commonly used to describe e.g. normative new product development processes with respect to the organisation.

Current models of design activity vary widely in terms of the levels and perspectives they address; from individual mental simulation (e.g. Ball & Christensen 2009), to overall work processes (e.g. Cardella, Atman & Adams 2006), and from conceptualisation (e.g. Andreasen *et al.* 2015), to informational (e.g. Robinson 2010*a*). These varied perspectives have provided significant insights into design (Horvath 2004), and form a core focus of design research (Cross 2007). However, the lack of integration across perspectives and levels has led to a theoretical fragmentation of the literature (Love 2000, 2002), that must be addressed in order to further theory building in design (Papalambros 2015). For example, co-evolution describes fundamental developments in a designer's understanding of the problem/solution space (Dorst & Cross 2001), while the Design Ontology (Storga *et al.* 2010) describes a range of possible activities, such as planning and testing, which are themselves distinct from the activities described by Sim & Duffy (2003). Although all three works deal with aspects of design activity, their theoretical integration remains unresolved. This raises questions as to the fundamental nature, drivers for, and components of design activity. Thus, fragmentation poses a significant challenge for design activity research (Cash *et al.* 2015), as well as the design research community more generally (Love 2002; Papalambros 2015).

Fragmentation of the design activity literature has two main implications for the field. First, current models typically focus on specific aspects of activity, such as sketching (Scrivener, Ball & Tseng 2000), without providing a framework for linking these descriptions to, for example information seeking (Robinson 2010*a*). Thus, developing a cohesive description of design activity directly building on a single current model is not possible. This fundamentally limits the descriptive and predictive power of research claims in this domain. For example, no single model captures the interaction between designer understanding (Oxman 1997), the subsequent actions taken (Sim & Duffy 2003), and the underpinning iterative learning process (Demirbaş & Demirkan 2003), in a single unitary sense connecting behaviour and cognition (Bedny & Karwowski 2004). Second, fragmentation hinders theory development with regard to design activity. Specifically, the lack of a common theoretical model significantly hinders efforts to integrate, elaborate on, and explain diverse empirical findings (Briggs 2006). This has been criticised by Love (2000) who highlights the importance of integrative theory in the design domain. As such, there is a need to unify the fragmented perspectives on design activity in a new foundational model in order to support future theoretical and empirical development in the field.

This paper addresses this need by proposing a cohesive model of design activity. The proposed Uncertainty Driven Action (UDA) model conceptualises overall 'design activity' based on a review of existing formalisms described in the literature. The UDA model describes three *core actions: information* *action* (dealing with data parts and their manipulation), *knowledge-sharing action* (dealing with understanding and its development), and *representation action* (dealing with external representations such as sketching). The UDA model links these core actions through uncertainty perception, which is defined as: a designers' perceived lack of understanding with respect to the design task and its context (Ball *et al.* 1997; Kreye, Goh & Newnes 2011), and has been shown to connect some aspects of behaviour and cognition in the design domain (Wiltschnig, Christensen & Ball 2013; Christensen & Ball 2016*a*,*b*). As such, this paper contributes a comprehensive formalisation of design activity that brings together prior theoretical and empirical work in the UDA model.

2. Approach

In order to connect disparate research on design activity and unify existing perspectives an analytical conceptual approach is needed (Wacker 1998). This links shared elements and underlying theory via logical relationship building (Barrick, Mount & Li 2013). This relationship building follows a logic-based approach (Wacker 1998), which delivers new insights by logically developing relationships between defined concepts to form an internally consistent theory (Wacker 1998). This section presents this approach in two stages, first identifying current design activity formalisms to form the basis for initial conceptualisation i.e. defining the key concepts to be related, and second analysing these formalisms and their link to the wider activity literature in order to distil the UDA model i.e. relating the defined concepts to form an internally consistent theory.

2.1. Identifying current formalisms

To identify current formalisms of design activity, a review of relevant publications in design research was conducted. Specifically, the following journals were reviewed as a starting point: *Design Science*, *Design Studies*, *Journal of Engineering Design (JED)*, and *International Journal of Design (IJD)*. These journals represent interdisciplinary design research (Design Science, Design Studies), engineering design focused research (JED), and more industrial design focused research (IJD). Design Studies is the highest impact interdisciplinary design journal, while IJD and JED are the highest rated journals in their sub-domains. These journals thus provide the basis for identifying current formalisms of design activity and the research areas they represent bound the scope of the unification claims reported in this work.

The keywords used for this review were: *theory*, *model*, and *framework*, implemented separately via a *full text* search, from *archive start* to *2016*. This resulted in 1426 responses for theory, 2007 for model, and 1042 for framework. All responses were filtered by the authors based on whether they explicitly described a 'formalism' of design activity. This assessment was based on self-identification by the original authors of the reviewed papers i.e. the original authors specifically describe their formalism as a model, theory or framework. For example, the Design Ontology (Storga *et al.* 2010) was described by Storga *et al.* as a potential framework for understanding product development work. Similarly, the ontology presented by Sim & Duffy (2003) was self-identified as a system model. Where works described formalisms from outside the design domain the original reference was followed up and also included in the review. For example, Beylier *et al.*

(2009) utilise Markus' (2001) theory of knowledge reuse. Papers reporting single variable relationships or empirical results only were excluded at this stage. The initial inclusion criteria for the review were thus: (1) published in a major design research journal; (2) explicitly self-identify and describe a formalism (theory, model, framework) of design activity; (3) excluding single variable relationships or purely empirical characterisations. This resulted in the initial identification of 66 unique theories, frameworks, or models (henceforth referred to as *formalisms* for brevity). Although this list is not exhaustive, sufficient formalisms were reviewed such that common concepts could be robustly identified.

2.2. Analytical approach

A five-step approach was used to analyse the identified formalisms. First, it was necessary to establish at what level prior formalisms describe design activity. This builds on an understanding of human activity as multi-level consisting of activity, task, and action, linked to cognition (Leont'ev 1981; Bedny & Harris 2005). Activity describes a motivation directed aggregation of lower level 'tasks', which are themselves aggregations of lower level 'actions', which connect directly to human cognition (Bedny & Harris 2005). Here motivation shapes overall activity, and gives a direction to the system of goals and sub-goals directing tasks and actions respectively (Leont'ev 1981). Motivation is long-term, situated, and of varying magnitude. It is possible to hold several motivations at a single time, such as the simultaneous motivations to design a creative product and to build a well-working team (Bedny & Harris 2005). Lower level goals and sub-goals are thus directed by motivations. Here goals and sub-goals are conscious conceptualisations of a desired future state (Bedny & Harris 2005). Specifically, the following definitions were applied in the analysis of existing formalisms based on Activity Theory (and are subsequently used throughout for consistency):

Activity level: subjectively distinct periods of behaviour associated with fulfilling a motivation (Leont'ev 1981), which are not temporally distinguished. As more than one motivation can be simultaneously held by a designer more than one activity can be progressed at one time, as illustrated by the parallel arrows at this level in figure 1 (Bedny & Harris 2005). An example activity is creating a novel design concept.

Task level: temporally and subjectively distinct periods of behaviour, associated with fulfilling a goal under specific conditions (Leont'ev 1981). Each higher-level activity can link a number of tasks, but the tasks themselves can only occur sequentially (Bedny & Harris 2005). An example task is brainstorming ideas on paper.

Action level: temporally distinct periods of behaviour, associated with achieving immediate, defined sub-goals linked to completing the overarching task (Leont'ev 1981; Bedny & Karwowski 2004). Actions form generic building blocks from which higher-level behaviours (tasks and activities) are composed. An example action is representing part of an idea via a sketch.

Cognitive level: a continuous process and structured system of processing units that describes the storage of concepts, propositions, or images etc. as well as the system of internal mental processes underpinning behaviour (Bedny & Harris 2005). Dominant mental processes also underpin the taxonomic grouping and classification of actions (Bedny & Harris 2005). An example mental process is embodied cognition.

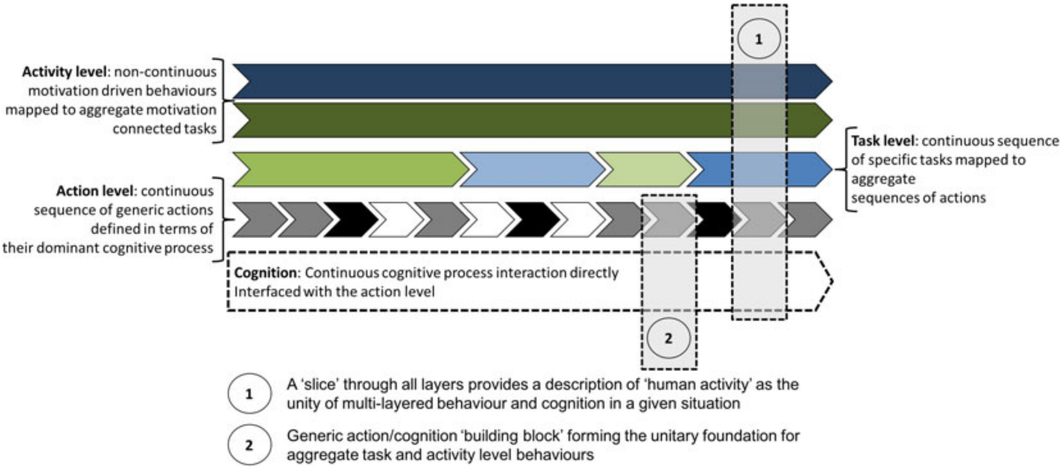

Figure 1. Human activity composed of multiple aggregate levels built on a generic, unitary action/cognition foundation.

A 'slice' through all four levels provides a description of human activity as the unity of multi-level behaviour and cognition in a given situation (Bedny & Harris 2005), consistent with both cognitive (Bedny & Karwowski 2004) and behavioural theory (Oliver 1980; Miltenberger 2011). This conceptualisation of activity is illustrated in figure 1. Here, higher-level activity can be characterised with respect to unitary building blocks (highlighted in figure 1) at the interface between the action level and cognition level. These unitary building blocks define core actions, which interface directly with cognition and are grouped and taxonomically defined with respect to their dominant cognitive processes (Bedny & Harris 2005). This has two main implications for evaluation of current formalisms of design activity. First, dominant cognitive processes can be inferred from described behaviours (Scaife & Rogers 1996; Wilson 2002) even where such a link is not characterised or described explicitly. Thus all formalisms describing some type of action, task or activity were explicitly included in the presented analysis despite the fact that many of these focus on behavioural rather than unitary (i.e. connecting behaviour and cognition) descriptions. Second, although it is possible to infer cognition connected to behaviour the reverse is not necessarily possible. Formalisms that describe abstract characterisations of the logic underpinning design or cognitive processes that are only generically associated with behaviour cannot be linked to specific actions. For example, Hatchuel & Weil's (2002) C–K theory characterises reasoning in design and is only generally connected to behaviour. Thus it cannot be linked to specific actions. Similarly, problem/solution co-evolution (Dorst & Cross 2001) provides an abstract formalism characterising understanding development in design but again does not connect to specific actions. Formalisms that provide only cognitive or abstract logical descriptions (15 formalisms) were thus excluded from this review because it is not possible to identify the specific unitary 'action/cognition' building blocks necessary for a unifying model of design activity. This follows the focus on activity as the unity of behaviour and cognition and introduces a fourth inclusion criterion: formalisms explicitly describe design behaviour or behaviour and cognition in a single model. Thus 51 formalisms were taken forward into the initial analysis (Section 3.1).

In the second step, the identified formalisms from Step 1 were examined in more depth on the action level. When existing formalisms did not explicitly define actions, the articles were further examined to identify the actions underpinning the model. This resulted in a diverse list of specific action sub-types. Formalisms were analysed at the action level for three main reasons. First, actions directly interface with cognition, and can be generically classified in terms of each action's dominant cognitive process (Bedny & Karwowski 2004). For example, gesture and sketching are distinct behaviours but can both be understood in terms of the representational aspects of external or embodied cognition (Scaife & Rogers 1996; Wilson 2002), and thus can be conceptualised as specific instantiations of a generic representation action (Bedny & Karwowski 2004). This allows for a unifying understanding across the diverse descriptions found in the design literature. Second, the action level provides the foundation upon which the higher aggregate levels of task and activity are built (Bedny & Harris 2005). These higher levels connect strings of actions in any number of sequential configurations dependent on the subject and situation. Finally, actions can be described as a self-regulating system where the individual progresses through a cycle from formulating the goal and assessing its conditions, deciding on and executing the action, and evaluating the outcome to generate a new sub-goal formulation (Engeström 2000). This links to characterisations of behaviour and cognition, critical to understanding causation in this context (Oliver 1980; Miltenberger 2011). Thus, it is possible to cohesively connect diverse descriptions of design activity, at the action level via generic actions, consistent with underlying theories of activity, behaviour, and cognition (Leont'ev 1981; Miltenberger 2011).

In the third step, core actions were identified by clustering the specific action sub-types from Step 2 with respect to the dominant cognitive processes explicitly or implicitly linked to the action in the reviewed formalisms. This assessment was based on the logic that actions provide independently observable and generic building blocks suitable for identifying similarities between formalisms (Engeström 2000; Bedny & Karwowski 2004), and can be grouped and taxonomically classified with respect to their dominant cognitive processes (Bedny & Harris 2005). Where action sub-types were described purely in terms of behaviour with no explicitly suggested cognitive process, possible dominant cognitive processes were established based on additional literature describing the action sub-type. Thus each action found to be generic and common across formalisms i.e. core, were explored in depth. This enabled us to establish three core actions, which can provide a unifying understanding of design activity.

In the fourth step, connections were identified between the three core actions identified in Step 3. These connections were required because a 'comprehensive' model of activity consists of the following elements with respect to the self-regulating action system (Oliver 1980; Engeström 2000; Miltenberger 2011): *antecedent* i.e. the cause or driver for an action, *behaviour* i.e. the external action itself, and *consequence* i.e. evaluation of the outcome. The identified core actions provide the behavioural elements and connections between these elements can be established via an antecedent/consequence mechanism. Antecedent/consequence thus forms the specific causal mechanism for the three core actions by defining how they interact with cognition to form a self-regulating system where goal outcomes can be evaluated (Engeström 2000). Such self-regulation typically links basic cognitive (Evans 2008) and metacognitive processes (Schraw & Dennison 1994). While basic cognitive processes are connected directly to action, metacognitive processes allow an individual to evaluate the limitations of their current knowledge or understanding as well as regulate basic cognitive processes (Schraw & Dennison 1994). Metacognitive processes thus form a key bridge from a purely behaviour/cognitive model to one that can account for memory, knowledge, and understanding because they provide knowledge about cognition. They account for individuals' understanding of their own knowledge state, which forms a key part of design co-evolution (Dorst & Cross 2001). Metacognition further regulates basic cognitive processes and can thus provide a platform for connecting diverse core actions in a single model (Schraw & Dennison 1994). Metacognitive processes have further been demonstrated as important to directing design activity in prior empirical research (Ball & Christensen 2009). Thus, while each core action must be connected to a dominant cognitive process, a metacognitive antecedent/consequence mechanism is needed to link these core actions.

In the fifth step, the core actions were combined with cognitive and metacognitive processes in a conceptual model to fulfil the research aim. This brings together and connects core actions via common causal mechanisms, consistent with fundamental theories of human activity (Bedny & Harris 2005; Miltenberger 2011) and prior understanding of design activity. Thus, although each element in the model draws from extant literature the final model offers a novel conceptualisation of those elements. This provides a unifying model of design activity and a foundation for future design activity research.

The five steps are reported as follows: Steps 1 and 2 in Section 3.1, Step 3 in Sections 3.2–3.4, Step 4 in Section 4, and Step 5 in Section 5.

3. Existing formalisms of design activity

In this section, the core actions are first distilled from the reviewed formalisms before they are individually explored in more detail with respect to the wider design and activity literatures.

3.1. Overview and scope of current formalisms

The 51 identified formalisms are summarised in Table 1, where they are grouped with respect to their constituent core actions. This grouping was not assumed *a priori* and is for table clarity only. Table 1 outlines the formalisms' general view on design activity as well as each of the specific action sub-types they describe. Each action sub-type is labelled with respect to its core action, again for clarity: information action (**I**), knowledge-sharing action (**KS**), representation action (**R**). In addition, for each formalism, the cognitive process associated with action is highlighted (labelled as **Cog** in Table 1). This is either *explicit* i.e. the original authors state their perspective on the link to cognition with respect to a defined cognitive process (highlighted in bold in Table 1) or *implicit* i.e. a cognitive process is inferred from the authors' writing, referencing, and behaviour descriptions because no explicit statement is given. For example, Kavakli & Gero (2001) describe external cognition as the foundation of their work, and cite other papers where this cognitive process has been explicitly highlighted although

Table 1. Overview of formalisms associated with design activity, categorised with respect to their related core actions

Name	Where used	General view on activity and cognition	Specific action sub-types described
		Information action	
Applied axiomatic design	(Suh 1998; Thielman & Ge 2006)	Activity underpinned by axioms: independence and information **Cog:** implicit information processing	**I:** Structure information w.r.t. functional v. physical domains; populate information in structure; evaluate the information structure; optimise the information structure
CoMoDe	(Gonnet, Henning & Leone 2007)	Design objects are developed through informational actions **Cog:** implicit information processing	**I:** Model design as information system; generate data about the design; evaluate data
Context, activities, and support data	(Beylier *et al.* 2009)	Activity as an objective driven information process within a project context **Cog:** implicit information processing	**I:** Analysis; formulation of assumptions; criteria specification; characterisation of materials; modelling; specification of boundary conditions; application of loads; analysis processing; post-processing results; checking and controlling; answering the customer by comparing objects and data
Knowledge management in engineering design	(McMahon, Lowe & Culley 2004)	Process connecting information (from products, systems, staff, and processes) and expertise **Cog:** implicit information processing	**I:** Information query; filtering/routing; retrieval; browsing
		Knowledge-sharing action	
Search for ideas in associative memory	(Liikkanen & Perttula 2010)	Mechanisms of idea production as a memory-based activity drawing on knowledge **Cog:** explicit memory-based cognition	**KS:** Idea generation

Table 1. (continued)

Conversation theory	(Dong 2005; Pask 1975)	Knowledge construction occurs through conversations where knowledge is made explicit **Cog:** explicit group cognition	**KS:** Knowledge shared via conversation
Team mental model theory	(Dong, Kleinsmann & Deken 2013)	Team members use knowledge to realise actions consistent and congruent with their team **Cog:** explicit group cognition	**KS:** Naming – judging and expressing perception of importance; moving – developing the concept and sharing ideas; reflecting – questioning the direction they have taken
Theory of dynamic memory	(Oxman 1990)	Knowledge structures support the process of explanatory thinking underpinning design **Cog:** explicit knowledge-based cognition	**KS:** Analogising; cross-indexing; matching to prior knowledge
Activity model of product development	(Fairlie-Clarke & Muller 2003)	List of activities associated with the business process, part of a more general ontology **Cog:** implicit social cognition	**KS:** Develop company strategy; set company objectives and develop operational plan; execute company operations; control outcome of company operations
Communication activities	(Medland 1992)	Hierarchical description of communication activity, problem handling, and truth development **Cog:** implicit social cognition	**KS:** Delegation; reporting; awareness spreading; problem reporting
Community of practice	(Kanstrup 2014)	Joint activities and joint understanding link people in developing skills **Cog:** implicit social cognition	**KS:** Sharing of interests; engagement in shared activity; negotiation; developing shared tools, experiences, languages, and processes

Table 1. (continued)

Knowledge management systems	(Markus 2001)	Knowledge contributors, knowledge intermediaries, knowledge seekers **Cog:** implicit social cognition	**KS:** Formalising knowledge; elicitation; dissemination; search for or reuse content from a knowledge management system
		Representation action	
Function-behaviour-structure framework	(Gero & Kannengiesser 2004)	Actions framed with respect to interaction between external and internal worlds **Cog:** explicit experiential cognition	**R:** Formulation; synthesis; analysis; evaluation; documentation; reformulation
Fixation	(Viswanathan *et al.* 2014)	Understanding and context linked to knowledge sharing and staging, as well as experience **Cog:** explicit embodied cognition	**R:** Idea manifestation
Thought–language model	(Fox 1981)	Conscious and unconscious processing of sensation with respect to the external expression of language **Cog:** explicit thought/language cognition	**R:** External expression via language as well as physical media
Design creativity and understanding of objects	(Daley 1982)	Linking visual schema, linguistic schema, and value structures with conscious propositional knowledge **Cog:** explicit embodied cognition	**R:** External expression
Re-representation	(Oxman 1997)	Re-representation: externalisation of knowledge structures via representations **Cog:** explicit embodied cognition	**R:** Externalisation of knowledge structures in representations; sketching; drawing
Long/short term and Visio-spatial working memory	(Bilda & Gero 2007)	Cognition underpinned by working memory linked to representation via visio-spatial working memory **Cog:** explicit external cognition	**R:** Sketching; drawing

Table 1. (continued)

An integrated generative design framework	(Singh & Gu 2012)	Evaluation, representation, generation, and performance are interconnected **Cog:** explicit experiential cognition	**R:** External representation
Creative segment theory	(Sun *et al.* 2014)	Idea generation, idea expression, and visual feedback loop **Cog:** implicit embodied cognition	**R:** Sketching; drawing objects; drawing objects from another perspective; drawing context; drawing annotations; overstriking
Imitative and constructive simulation	(Taura *et al.* 2012)	Design thinking based on external and internally observed data **Cog:** implicit embodied cognition	**R:** Dealing with words; dealing with images; constructive simulation
Fundamental creative planning loop	(Hertz 1992)	Registration > synthesis > creation, and feedback via synthesis > expression > sensing > registration **Cog:** implicit embodied cognition	**R:** Physical expression
Perceptual crossing	(Deckers *et al.* 2012)	Subject, object, and event are linked via activity and reciprocal perception **Cog:** implicit embodied cognition	**R:** Perceiving perceptive activity of people; perceiving perceptive activity of object; perceiving presence; perceiving action; perceiving expressivity
The design situation represented by a systematic grammar	(McDonnell 1997)	Situation defined as: initial motivation, context, design proposal, development strategy, and security constraints **Cog:** implicit experiential cognition	**R:** External proposition; interpretation
Two-search model of design problem solving	(Liu 1996)	Designer uses a shape restructuring search then a knowledge transforming search iteratively **Cog:** implicit embodied cognition	**R:** Pre-attending; attending; encoding; pattern-matching; rule application

Table 1. (continued)

Theory of mental imagery	(Kavakli & Gero 2001; Kosslyn *et al.* 1984)	Mental imagery and perception are connected to physical activity **Cog:** implicit external cognition	**R:** Drawing; looking; moves
Design representation schema	(Cardella *et al.* 2006)	Common representation activities associated with different design process stages **Cog:** implicit external cognition	**R:** Read text; deal with diagram; write text; sketch; modelling
Rational problem solving/reflection in action	(Dorst & Dijkhuis 1995)	Designer as an information processor/designer reflecting through action **Cog:** implicit information processing/experiential cognition	**R:** Write; sketch/drawing action; gesture
		Information and Knowledge-sharing actions	
Theory of collective cognition	(Kleinsmann *et al.* 2012)	People build shared mental models via: accumulate > interact > examine > accommodate **Cog:** explicit collective cognition	**I:** Retrieving; structuring; filtering; storing **KS:** Exchanging; negotiating; evaluating; interpreting; integration; deciding; acting
Coordination theory	(Suss & Thomson 2012)	Dependencies between activities and resources create problems that constrain subsequent activity **Cog:** explicit coordinated information processing	**I:** Work; read; store **KS:** Prepare; review
Information processing theory	(Aurisicchio, Bracewell & Wallace 2013)	Information work and knowledge sharing linked to problem solving and bounded rationality **Cog:** explicit information processing/external cognition	**I:** Information; analysis; evaluation **KS:** Confirmation; comparison; constructive generation; explanatory generation

Table 1. (continued)

Information driven design activities	(Wild *et al.* 2010)	Information actions from analysis and seeking to learning, manipulation, and archiving **Cog:** implicit information processing	**I:** Feasibility study; analysis; testing; information gathering; informing; documenting **KS:** Training
Design activity	(Wang *et al.* 2013)	Activity as a system (task) with input/output, resources, and goals **Cog:** implicit experiential cognition	**I:** Information dependency **KS:** Knowledge dependency
The blackboard framework for behaviour	(Whitefield & Warren 1989)	Knowledge sources communicate with a central 'blackboard' data structure **Cog:** implicit information processing	**I:** Information structure **KS:** Knowledge exchange
Accessing information for engineering design	(Macleod, McGregor & Hutton 1994)	Requirements drive a process where human knowledge and external information are integrated **Cog:** implicit information processing	**I:** Dealing with external information; dealing with requirement specification **KS:** Dealing with human knowledge
Collaborative design taxonomy	(Ostergaard & Summers 2009)	Dependencies between team, communication, information, approach, and problem **Cog:** implicit social cognition	**I:** Inform; request; record **KS:** Commit; guide; express; decide; propose; respond
Design Ontology *and* Merged Ontology of Engineering Design	(Ahmed & Storga 2009; Storga *et al.* 2010)	Ontologies of activity in terms of its information and knowledge characteristics **Cog:** implicit information processing	**I:** Dealing with abstract attributes; dealing with abstract relations; dealing with the physical object **KS:** Dealing with the physical process

Table 1. (continued)

Category framework for design behaviour	(Peeters *et al.* 2007)	Framework splitting activity into design creation, design planning, and design cooperation **Cog:** implicit information processing/social cognition	**I:** Gathering information **KS:** Establishing the design goal; generating ideas and solutions; elaborating the design; restricting/combining solutions; establishing the concept; phase transition; reflecting on the design; adjusting based on reflection; planning time; establishing responsibilities per discipline; keeping schedule; evaluating the schedule, use of time, or meeting of responsibilities; adjusting the schedule, use of time, or responsibilities based on evaluation; making arrangements about the cooperation within the team; cooperation; evaluating the cooperation; adjusting the cooperation based on evaluation; communication; making decisions; documenting decisions
Modelling production management	(Moscoso 2007)	Activity in a wider process linked to resources, structures, processes, KPI's and capabilities **Cog:** implicit information processing	**I:** Preparation; planning **KS:** Controlling; process re-engineering; documentation of best practices
Engineering workflow model	(Rouibah & Caskey 2003)	Activity has a role, executing resource, and triggering event **Cog:** implicit information processing	**I:** Link data **KS:** Link people
Design activity schema	(Cardella *et al.* 2006)	Common actions in a design process **Cog:** implicit information processing	**I:** Gather information; feasibility analysis; evaluation; calculate **KS:** Identify need; define problem; generate ideas; decision; communication

Table 1. (continued)

Ontology of generic engineering design activities	(Sim & Duffy 2003)	Ontology of design activity as a knowledge-based input/output system linked to a design goal **Cog:** implicit information processing	**I:** Abstracting; associating; composing; decomposing; defining; detailing; standardising; structuring/integrating; synthesising; analysing; evaluating; selecting; information gathering; searching; simulating; testing/experimenting; modelling **KS:** Generating; decision making; constraining; exploring; identifying; planning; prioritising; resolving; selecting; scheduling
Activity-based modelling approach	(Ge & Wang 2007)	Activity is fundamental linked to information flow in the wider group context **Cog:** implicit information processing/social cognition	**I:** Input information; output information **KS:** Share information; process in the group; identification and internalisation of information across a stakeholder group
		Information and Representation actions	
Autogenetic design theory	(Vajna *et al.* 2005)	Development through evaluation, selection, replication, recombination, and mutation **Cog:** implicit information processing	**I:** Research; information seeking **R:** Evaluation, selection; replication; recombination; mutation
Spectrum of design activity	(Pugh 1989)	Activity space spanning innovatory–conventional in terms of synthesis and expansion of options **Cog:** implicit information processing	**I:** Market analysis; specification **R:** Conceptualisation; Computer aided detailed design;
		Knowledge-sharing and Representation actions	
External memory	(Van Der Lugt 2005)	Internal memory is externalised in the design which then feeds a shared external memory **Cog:** explicit external cognition	**KS:** Individual external memory; shared external memory **R:** Verbalisation; gesture; sketching; physical representation

Table 1. (continued)

Experiential learning theory	(Demirbaş & Demirkan 2003)	Iterative learning: experience > observation > abstract conceptualisation > experimentation **Cog:** explicit experiential cognition	**KS:** Sharing experience **R:** Analysing the situation; experimentation; reflecting;
Multimodal communication	(Eris, Martelaro & Badke-Schaub 2014)	Mental models are externalised through representations to form shared understanding **Cog:** explicit group cognition/embodied cognition	**KS:** Expression, negotiation, identification of differences; integration of viewpoints **R:** Draw; write; talk; gesture; storing ideas; conveying information; representing ideas; engaging attention
Design as problem solving	(Jonas 1993)	Perception and thus problem/solution knowledge result from activity **Cog:** implicit information processing	**KS:** Communication **R:** Perception from 'activity'
Fixation	(Crilly 2015)	Idea generation is affected by context as well as prototyping and learning **Cog:** implicit experiential cognition	**KS:** Idea generation; education; training **R:** Prototyping
Macroscopic analysis of design processes	(Suwa, Purcell & Gero 1998)	Activity in terms of physical, perceptual, functional, and conceptual **Cog:** implicit external cognition	**KS:** Explore issues of interaction between artefacts and people; consider psychological reactions of people; make preferential and aesthetic evaluations; set up goals; retrieve knowledge; organise or compare elements **R:** Make depictions; look previous depictions; other physical actions; attend to visual features; attend to spatial relations

they themselves do not define an explicit theory of cognition. The 51 identified formalisms were evaluated with regard to the level of their descriptions (based on Figure 1), the characterisations of the action level, and in terms of the processes they describe.

Evaluating the formalisms in terms of level, it was found that current formalisms collectively describe a wide range of specific activities, tasks, and actions. No current formalism describes the full interaction across all levels necessary for understanding design activity completely (Figure 1). For example, one of the most extensive formalisms provided by Sim & Duffy (2003) touches on representation but does not deal with sketching, gesture or many of the other representation sub-types. Current formalisms typically focus on the activity or task level, and deal with the designer, their surroundings, underlying cognition, and aggregate activity, but few connect generic actions and their dominant cognitive processes. Further, formalisms offer a large breadth in descriptions of specific action sub-types, ranging from general 'external or physical expression' (Hertz 1992; Singh & Gu 2012) to highly detailed breakdowns of representational gesture, sketching, drawing, and writing (Suwa *et al.* 1998; Sun *et al.* 2014). Descriptions vary in perspectives on the processes underpinning activity and do not deal with core actions able to support wider unification and connection across formalisms. For example, Conversation Theory (Pask 1975) focuses on knowledge sharing via language and does not provide for integrating information or representation actions such as those outlined by Vajna *et al.* (2005) or Sun *et al.* (2014). Thus, current formalisms do not provide a basis for unification across levels, based on core actions.

Evaluating existing formalisms on the action level, stark differences were found with regard to described sub-types and their links. No single formalism covered all action sub-types or provided a framework able to synthesise the wide range of descriptions in the literature. This can be partially attributed to the fact that most reviewed formalisms (Table 1) describe design activity disconnected from cognition. Of 51 formalisms only 17 offer some description of the link between action and an explicitly framed cognitive process (Table 1). For example, while the Design Ontology (Storga *et al.* 2010) provides an excellent overview of specific information and knowledge-sharing action sub-types, these are described in behavioural terms without being explicitly linked to a cognitive process. Similarly, Moscoso (2007) focuses on actions with respect to the manufacturing process, and thus provides behavioural descriptions without connecting these to cognition. While this general focus on behaviour does not diminish the contribution of the listed formalisms, it does mean that no current formalism is suitable for providing a unifying model of design activity.

Evaluating the formalisms in terms of the processes they describe it was found that most formalisms tend to either describe the antecedent for action or action itself but not both. For example, co-evolution offers detailed insight into the underpinning drivers for action (Dorst & Cross 2001), but does not connect this to a fully realised framework of activity. Similarly, Sim & Duffy (2003) and Storga *et al.* (2010) detail specific action sub-types but do not tie them to cognitive and metacognitive processes in terms of antecedent/consequence. Thus current characterisation of design activity, built on a self-regulating system connecting core actions and cognition, is incomplete (Oliver 1980; Engeström 2000; Miltenberger 2011). This initial analysis results in three distinct limitations preventing the development of a unifying model of design activity based on current formalisms:

(1) Lack of cohesive theoretical description of aggregate activity built on core actions linked to cognition.
(2) Lack of common and generic core actions able to connect the varied descriptions of design activity currently found in the literature.
(3) Incomplete theoretical description from antecedent-to-consequence connecting core actions and cognition.

Due to these limitations, it was necessary to identify core actions that enable unification of design activity. This was done in four phases. First, all explicit cognitive processes were clustered based on common theoretical elements. For example, a cluster of explicit cognitive processes could be identified by their common focus on describing processes where mental structures are externally represented, whether formalised as external cognition, embodied cognition or experiential cognition. This resulted in three clusters: *information-based cognition* including coordinated information processing (Suss & Thomson 2012), and information processing (Aurisicchio *et al.* 2013), *knowledge-based (group) cognition* including memory-based cognition (Liikkanen & Perttula 2010), group cognition (Pask 1975; Dong 2005; Dong *et al.* 2013; Eris *et al.* 2014), and collective cognition (Kleinsmann *et al.* 2012), and *representation-based embodied cognition* including external cognition (Van Der Lugt 2005; Bilda & Gero 2007; Aurisicchio *et al.* 2013), embodied cognition (Daley 1982; Oxman 1997; Viswanathan *et al.* 2014), experiential cognition (Demirbaş & Demirkan 2003; Gero & Kannengiesser 2004; Singh & Gu 2012), and thought/language cognition (Fox 1981; Eris *et al.* 2014).

Second, the specific action sub-types associated with these three clusters were grouped using explicitly connected formalisms in order to distil core actions characterised by these dominant cognitive processes. For example, the specific action sub-types associated with the initial 'representation-based embodied cognition' cluster included formulation, synthesis, analysis, evaluation, documentation, reformulation, language-based representation, physical representation, idea manifestation, external expression, sketching, drawing, gesture, physically storing ideas, physically conveying information, representing ideas, and physically engaging attention (Table 1). Based on this an initial definition was developed for a core action of representation able to accommodate each of these specific action sub-types with respect to a common dominant cognitive process.

Third, this initial core action definition was evaluated with respect to all formalisms that implicitly connected to *representation-based embodied cognition*, and their associated specific action sub-types. Again these action sub-types were listed and incorporated into the core action conceptualisation where they could be connected to the underlying cognitive process. Where action sub-types did not fit with the underlying cognitive process connected a specific core action, they were compared with other cognitive process clusters. This was the case with, for example, Vajna *et al.* (2005), where the action sub-types: *evaluation, selection, replication, recombination*, and *mutation*, were all framed within the original text as representation-based actions but were analogous to actions described with respect to formalisms explicitly connected to information-based cognition. This resulted in the identification of a set of action sub-types for each of the three cognitive process clusters.

Fourth, the sets of action sub-types were synthesised through a definition of the core action. These definitions were evaluated iteratively to eliminate possible overlap in action sub-types. This process resulted in three core action definitions based on the reviewed formalisms in Table 1: information action, knowledge-sharing action, and representation action. These core actions bring together the various formalisms from the literature in terms of common cognitive processes.

We propose the three core actions as a foundation for connecting current formalisms of design activity. However, despite the review and distillation of the core actions reported in this section, further refinement is still required due to the lack of definitive descriptions in the existing literature, the high variety of action sub-type descriptions, and relative lack of explicit links to dominant cognitive processes. The review was thus expanded to include the wider design literature where there are many empirical works not described with respect to a specific formalism. For example, Wasiak *et al.* (2010) provide an extensive list of specific action sub-types associated with information action, without explicitly connecting to a formalised model of design activity or to a specific cognitive process. The specific logic underpinning this expanded review is to establish the nature and scope of the core actions and their sub-types in the empirical design literature. This elaboration is necessary to ensure the robustness of the core actions by contrasting and integrating these additional works. Thus the nature of the core actions and their connection with the design and activity literatures via dominant cognitive process and a common metacognitive process is explored in the following sections, which expand the scope of the original review.

3.2. Information action

Information action can be defined as dealing with data parts and their manipulation (Court 1997). This type of action is associated with cognitive processes describing how data parts are identified, manipulated, and transformed into information and subsequent knowledge (Wilson 1999). This includes the collection, recording, reviewing, and filing of data parts (Blandin & Brown 1977) via various means including human and non-human (Robinson 2010*a*), formal and informal (Fidel & Green 2004). This type of action and its associated cognitive process deal with data parts detached from an individual's beliefs (Belkin, Oddy & Brooks 1982; Song, Van Der Bij & Weggeman 2005). It has been shown to be a distinct and important action within design work (Cave & Noble 1986; Puttre 1991), accounting for a significant portion of engineers' and designers' time (Court 1997; Robinson 2010*a*). Further, identification and selection of data parts plays a critical role in ideation and design creativity (Gonçalves, Cardoso & Badke-Schaub 2016). Some authors even characterise design primarily as an information transformation process where data parts are sought, reasoned about, and stored, via e.g. seeking and requesting (Aurisicchio, Bracewell & Wallace 2010; Wasiak *et al.* 2010).

Information action has been generally characterised in terms of: finding data parts > reasoning about/validating > using (Belkin *et al.* 1982); driven by perceived need – connected to its role (Belkin *et al.* 1982). For example, Wasiak *et al.* (2010) and Cash, Hicks & Culley (2013) characterise information action in the design process in terms of its role e.g. solving. However, research has typically focused on sources and media, such as the internet (Oh, Oh & Shah 2009), or on aggregate information action with little link to design work, such as total information acquisition (Hult, Ketchen & Slater 2004). Thus although basic taxonomies of information action, such as that by Belkin *et al.* (1982), do exist, and have been included in manifest descriptions such as those offered by Robinson (2010*b*) or Cash *et al.* (2015), they have not been theoretically integrated with other core actions e.g. representation (Scaife & Rogers 1996).

Two main observations emerge from the literature on information action. First, new information is processed through reasoning or learning. It is then structured, and evaluated through experience (Tracey & Hutchinson 2016) before entering the '*human belief system*' (Song *et al.* 2005) to create knowledge. Thus information action must be distinguished from action related to knowledge sharing. Second, information action is connected to designers' understanding of a situation via their perceived need (Borlund 2003). This has been linked to designer uncertainty perception by Daalhuizen & Badke-Schaub (2011). Here, designers seek to resolve their uncertainty perception via information action including seeking, gathering, and reasoning about data parts (Kim & Lee 2016). This increases their understanding and thus gradually reduces uncertainty perception over time (Yu *et al.* 2016). The link between uncertainty perception and information action stems back to describing design as a decision making process under uncertainty (Beheshti 1993) where design progresses as design-related decisions are made and implemented (Wilson 1999; Suss & Thomson 2012). Thus, uncertainty perception forms a key motivator of information action described in the design literature. Thus, one key mechanism driving information action is the designer's aim to reduce their uncertainty perception.

3.3. Knowledge-sharing action

Knowledge-sharing action can be defined as dealing with the creation and development of shared understanding (Dong 2005). This type of action is associated with cognitive processes describing how knowledge is expressed with respect to an individual's understanding and beliefs (Court 1997; Chiu, Hsu & Wang 2006), as well as the structural (i.e. social), relational, and procedural (i.e. shared language or vision) context of an action (Song *et al.* 2005; Chiu *et al.* 2006). Thus these actions and their associated cognitive process are fundamentally linked to an individual's own understanding and beliefs, distinguishing them from information action (Song *et al.* 2005; Chiu *et al.* 2006). Knowledge-sharing action forms a critical part of idea sharing (Liikkanen & Perttula 2010), group creativity (Christensen & Ball 2016*a*,*b*), group learning (Shull *et al.* 2004), is underpinned by effective communication (Preston, Karahanna & Rowe 2006), and is often directed towards iteratively grounding shared understanding (Clark & Brennan 1991) where individuals seek to establish that shared knowledge is actually understood as intended. Thus knowledge-sharing action is characterised by its often discursive nature (Deken *et al.* 2012) where exchanges bring together, fact, rationale, context, varied perspectives, and exploration (Eris 2002; Aurisicchio *et al.* 2010). For example, Eris (2002) describes 22 specific types of question, while Aurisicchio *et al.* (2010) categorise knowledge-sharing requests with respect to their objective e.g. comparison, their subject e.g. product or process, and their response type e.g. retrieval of information. Further, knowledge-sharing action underpins collaborative creative efforts where exchange fosters knowledge acquisition and creation within a group (Shull *et al.* 2004), as highlighted in the recent work of Sauder & Jin (2016).

Knowledge-sharing action connects to design formalisms at all levels of description (Maznevski & Chudoba 2000; Dong 2005). However, research has typically focused on understanding knowledge sharing in terms of its role in the development of shared understanding (Preston *et al.* 2006; Kleinsmann & Valkenburg 2008), or its manifestation through various communicative media (Cash & Maier 2016). For example, Maznevski & Chudoba (2000) explore team effectiveness in relation to communication intensity; while Aurisicchio *et al.* (2010) highlight the need to support designers in sharing and capturing knowledge. No single taxonomy of knowledge-sharing action is completely accepted (Eris 2002; Aurisicchio, Bracewell & Wallace 2006), and despite the fundamentality of knowledge sharing (Fairlie-Clarke & Muller 2003) it has not been formalised in generic terms or with respect to its relationship with the other core actions.

Two main observations emerge from the literature on knowledge-sharing action. First, it is critically linked to the development of shared understanding (Kleinsmann & Valkenburg 2008). For example, Conversation Theory (Pask 1975) describes the gradual development of alignment in understanding expressed in terms of semantic coherence in word use, as illustrated in design by Dong (2005). Although this is also linked to a number of wider social processes (Busby 2001; Chiu *et al.* 2006), shared context (Humayun & Gang 2013), and quality of communication (Maznevski & Chudoba 2000), the development of shared understanding is a core characteristic of successful design teams (Dong 2005). It is important to note that although knowledge-sharing action is typically part of an interpersonal exchange it can also be captured in asynchronous modes, where the addressee is unknown or simply imagined, such as in personal letters or journals (Clark & Brennan 1991; McAlpine, Cash & Hicks 2017). Thus, although this is a core part of team interaction, the actions themselves are undertaken by the individual. Second, knowledge-sharing action can refer to vision and identity (Chiu *et al.* 2006), concept understanding (Dong 2005), solution understanding (Preston *et al.* 2006), and understanding of organisational elements e.g. team roles (Kleinsmann & Valkenburg 2008). Here, uncertainty perception is particularly connected to others' understanding of these elements as a driver for knowledge sharing in practice (Clark & Brennan 1991; Deken *et al.* 2012). Similarly the population of knowledge spaces e.g. problem/solution in co-evolution (Dorst & Cross 2001), can be related to uncertainty perception via the work of Kreye *et al.* (2011) and Christensen & Ball (2016*a*,*b*) who connect knowledge sharing, uncertainty perception, and underlying cognitive processes. Here, uncertainty perception is again characterised as a general metacognitive process which drives knowledge-sharing action.

3.4. Representation action

Representation action can be defined as dealing with the perception and manipulation of external representations of information (Scaife & Rogers 1996; Wilson 2002). This type of action is associated with cognitive processes describing the interplay between internal and external representations (Scaife & Rogers 1996; Wiltschnig *et al.* 2013). Representation action is often associated with knowledge structures and the exploration of the design space (Dorst & Cross

2001; Hatchuel & Weil 2003), and provides a cognitively economic means of externalising ideas (Brun, Le Masson & Weil 2016). This has been described via formalisms such as external (Scaife & Rogers 1996) and embodied (Wilson 2002) cognition, where an individual uses the interplay between internal/external representations to directly support cognition and develop understanding (Scaife & Rogers 1996; Wiltschnig *et al.* 2013). Representations have also been referred to as simulation in the design literature (Taura *et al.* 2012; Wiltschnig *et al.* 2013), as such, representation is adopted here for clarity. Specifically, representation actions deal with external representations e.g. prototyping or computational modelling, distinct from internal mental simulation as described by Wiltschnig *et al.* (2013). The importance of representation action is highlighted in numerous contexts e.g. via gesture (Cash & Maier 2016), prototyping (Sanders & Stappers 2014), or sketching (Schön & Wiggins 1992).

Representation action has been widely acknowledged as central to design work (Sim & Duffy 2003; Horvath 2004; Andreasen *et al.* 2015). In particular, research in this area has focused on understanding and describing representation (Dorst & Vermaas 2005), its relationship to reasoning about design (Dorst & Cross 2001; Hatchuel & Weil 2003), and how it is realised in practice (Kan, Gero & Tang 2011). For example, Kulkarni *et al.* (2000) examine how collaborative sketching can support idea generation/manifestation and joint representation in teams. Further, specific aspects of representation action have again been connected to uncertainty perception. For example, Gursoy & Ozkar (2015) show how penmanship and sketching help to reveal and resolve uncertainty perception while Scrivener *et al.* (2000) connect sketching and uncertainty perception explicitly in two ways: first, uncertainty perception forms a trigger for strategic shifts within sketching; second, sketching can engender uncertainty perception by elucidating differences between the drawing and the designer's own understanding and memory. Similarly, Gerber & Carroll (2012) highlight how prototyping also helps to elicit and resolve uncertainty perception, by allowing individuals to iteratively build knowledge and promote a sense of control. However, the centrality of representation action and its interconnection with information action and knowledge-sharing action are not fully captured in current design activity formalisms (Table 1).

Two main observations emerge from the literature on representation action. First, like descriptions of information or knowledge-sharing action, representation is typically described as a multi-faceted phenomenon, linking the design artefact (Gero 1990), the specific knowledge being represented (Storga *et al.* 2010), physical modality (Schön & Wiggins 1992), and model granularity (Maier, Eckert & Clarkson 2017). Thus representation action is closely linked to knowledge sharing. For example, representational gesturing can both facilitate individual understanding via external cognition, and the development of team shared understanding through e.g. mirroring and modification (Stempfle & Badke-Schaub 2002; Cash & Maier 2016). Second, representation is linked to improved understanding and ability to communicate within a team (Schön & Wiggins 1992; Scaife & Rogers 1996) e.g. by supporting the *Concept–Knowledge* interaction (Hatchuel & Weil 2003). Here, uncertainty perception is modified via representation surrounding the design artefact as illustrated by the work of Gerber & Carroll (2012) who describe uncertainty perception as a driver for representation action. Thus representation action is again linked to the driver: designer uncertainty perception.

4. Linking the three core actions through uncertainty perception

The three core actions identified and described in Section 3 conceptualise the unitary building blocks upon which a foundational understanding of design activity can be built. To link these unitary building blocks, a metacognitive element is needed (Section 2), suitable for connecting multiple cognitive processes, and thus connecting the three core actions. Key literature associated with each core action e.g. Daalhuizen & Badke-Schaub (2011) and Gerber & Carroll (2012), suggests that uncertainty perception forms a suitable metacognitive process for this purpose. Other possible concepts could be ambiguity (Ellsberg 2001) or risk attitudes (Davies 2006); however, uncertainty perception is the concept most commonly described in the metacognitive literature (Schraw & Dennison 1994; Christensen & Ball 2016*a*,*b*) and had been described in relation to each of the three core actions within the design literature. As such, this section explores the potential for uncertainty perception to connect the core actions via a consistent antecedent/consequence mechanism.

Utilising uncertainty perception as a common causal mechanism has three main advantages. First, it robustly links cognition (Tversky & Kahneman 1974; Daft & Lengel 1986) and behaviour (Ball *et al.* 1997). Uncertainty perception as a metacognitive process fulfils two key roles in connecting multiple cognitive processes and core actions: reflecting knowledge about cognition and regulating cognition itself. These roles of uncertainty perception have been described in the design literature by, for example, Gerber & Carroll (2012) who illustrate how uncertainty perception associated with declarative knowledge about self (sense of progress, self-belief etc.) and learning progression is affected by prototyping. Further, authors such as Deken *et al.* (2012) and Wiltschnig *et al.* (2013) describe uncertainty perception as a driver for a range of specific action sub-types, while Blandin & Brown (1977) and Hult *et al.* (2004) described it as a driver for overall activity. Thus uncertainty perception provides a general metacognitive process that connects to memory and individual experience by incorporating knowledge about cognition as well as regulating own cognition and directing action.

Second, uncertainty perception can be characterised consistently across levels (Figure 1) and across the three core actions. In particular, it connects understanding/knowledge, memory, and perception, to activity progression, thus bridging cognition and action. Further, as highlighted in Sections 3.2–3.4 uncertainty perception, defined as a general metacognitive process, has been shown to be an important driver with respect to each of the core actions despite the different empirical and behavioural foci of design research. The characterisation of uncertainty perception is explicitly general i.e. the conceptualisation of uncertainty perception used by Daalhuizen & Badke-Schaub (2011) with respect to information action is analogous to the conceptualisation used by Wiltschnig *et al.* (2013) with respect to representation action. Thus uncertainty perception provides a general mechanism that can be consistently characterised irrespective of specific behaviour or cognitive process, making it suitable for connecting multiple core actions associated with different dominant cognitive processes.

Third, uncertainty perception is fundamentally linked to an individual's understanding of a situation (Tversky & Kahneman 1974), making it theoretically consistent with the cognitive processes identified with respect to the core actions. In summary, uncertainty perception thus forms a key antecedent/consequence mechanism consistent with descriptions in the literature (Bedny & Karwowski 2004; Bedny & Harris 2005) and connects the three core actions, shaping their selection and sequential combination, and subsequently driving overall design activity.

An important distinction here is between the general concept of uncertainty, extant in a situation (extant uncertainty), and the metacognitive concept connected to an individual, in the sense of making him/her feel unsure or unconfident (uncertainty perception). *Extant uncertainty* can stem from organisational and social issues, technology development, or other aspects of a situation (Calantone & Rubera 2012), and is a characteristic feature of design work, linked to the unknown nature of the task outcome (Tracey & Hutchinson 2016). In addition there are a number of other concepts related to extant uncertainty, such as, ambiguity, equivocality, or 'lack of knowledge' (Suss & Thomson 2012). Ambiguity defines a situation where the available information or problem description does not give a consistent or coherent picture (Ellsberg 2001), while equivocality describes the possibility of there being multiple or conflicting interpretations of a situation (Daft, Lengel & Trevino 1987). However, before an individual can act on any such manifest concepts, they must perceive and process them with respect to their own understanding of the situation (Tversky & Kahneman 1974; Evans & Stanovich 2013), thus they are transformed into *uncertainty perception*. Manifest concepts such as extant uncertainty or lack of knowledge only affect activity if they are perceived by the designer via this metacognitive awareness (Schraw & Dennison 1994; Ball & Christensen 2009). Uncertainty perception describes the mental state of an individual, such as a designer, who faces uncertainty and may thus feel unconfident in their activity (Kreye 2016). Uncertainty perception thus provides a bridge from the literature that generally highlights extant uncertainty (or other manifest concepts) as an important feature of design work (Tracey & Hutchinson 2016) to an explicit causal mechanism linking behaviour and cognition in relation to design activity. This understanding of uncertainty perception is adopted throughout this work.

Uncertainty perception reflects how the designer understands a situation with respect to their personality, experience, and other personal characteristics (Kreye 2016; Tracey & Hutchinson 2016) and does not necessarily accurately reflect the level of extant uncertainty. Uncertainty perception thus captures an individual's understanding translated into an antecedent through perception, based on their own experience (Christensen & Ball 2016*a*,*b*; Tracey & Hutchinson 2016). This has been captured in the design domain where design activity is described as a chain of decisions made under uncertainty where knowledge develops (Beheshti 1993; Dorst & Cross 2001; Wiltschnig *et al.* 2013). Similarly, uncertainty perception has been highlighted in the wider product development literature as an important driver of activity (Daft & Lengel 1986; O'Connor & Rice 2013; Kreye 2016). Uncertainty perception thus forms a unifying mechanism with respect to cognition and the core actions (Daalhuizen & Badke-Schaub 2011; Deken *et al.* 2012; Gerber & Carroll 2012).

In the design literature a number of studies have connected the progression of specific action sub-types to uncertainty perception (Wiltschnig *et al.* 2013). Bringing the literature together, uncertainty perception has been separately described as a driver of specific information (Borlund 2003; Daalhuizen & Badke-Schaub 2011), knowledge-sharing (Deken *et al.* 2012), and representation actions (Wiltschnig *et al.* 2013). In addition, a small number of works have pointed to the role of uncertainty perception in directing the progression of specific action sub-types, such as stimulating recall within sketching (Scrivener *et al.* 2000). Descriptions of uncertainty perception in the design literature have two main limitations. First, the effect of uncertainty perception as a driver of activity has only been studied with respect to the progression of specific action sub-types (e.g. sketching). This is in contrast to formalisms where wider activity progression and connection across the core actions has been highlighted (Daft & Lengel 1986; Hult *et al.* 2004). Second, in design, uncertainty perception has been characterised predominantly as a unitary whole with no subdivision and using a binary existence scale. For example, Ball & Christensen (2009) treat uncertainty perception via binary schema i.e. either present/not present (Ball & Christensen 2009; Ball, Onarheim & Christensen 2010) or low/high (Wiltschnig *et al.* 2013; Christensen & Ball 2016*a*,*b*). This is in contrast to the multi-faceted, scalar conceptualisation found in the management literature (Hurley, Kosenko & Brashers 2011; O'Connor & Rice 2013) and necessary for understanding the multiple factors influencing the core actions. Thus, important insights can, and need to, be drawn from other fields such as psychology and management.

Given these considerations the impact of uncertainty perception on action varies in two main dimensions: *level* and *nature*. The *level* of uncertainty perception describes the overall amount of the perceived lack of understanding (Kreye *et al.* 2012). Here, an individual can perceive uncertainty anywhere from ignorance (where design factors are unknown or unknowable) to certainty (where the designer perceives no uncertainty regarding the design task). The level of uncertainty perception should reduce over the duration of the design activity (Wynn, Grebici & Clarkson 2011; Yu *et al.* 2016) because the designer's understanding of the development task gradually increases as interdependencies are clarified (Yu *et al.* 2016). As suggested by the recent work of Christensen & Ball (2016*a*,*b*) the dynamic interplay between changing uncertainty perception and action drive the overall progression of design activity.

The *nature* of uncertainty perception arises from its heterogeneous character in design (Kleinsmann & Valkenburg 2008; O'Connor & Rice 2013). This describes the perception of different uncertainty types as drivers of activity, by shaping action selection and sequential progression. For example, uncertainty can arise from the external environment (Kleinsmann & Valkenburg 2008) or the level of technical innovation in the design task (O'Connor & Rice 2013). Numerous works have illustrated how different uncertainty types, or combinations of types, influence activity in distinct ways (Bstieler 2005; Heavey & Simsek 2013). In design, all types can be expected to shape activity (Garcia 2005), particularly as designers often face multi-faceted problems where they must deal with team, organisation, and process issues in addition to pure product considerations (Kleinsmann & Valkenburg 2008). Specifically, Bstieler (2005) and Biazzo (2009) highlight how activity is typically driven by one or two types in any given situation. Thus the composite perception of these uncertainty types i.e. the nature of uncertainty perception, is an important determinant of design activity progression.

Finally, although uncertainty perception provides a robust and theoretically consistent link between the core actions underpinning design activity, it is not necessarily the only possible unifying element. However, due to the extent of the empirical and theoretical support for uncertainty perception, it provides an ideal unifying antecedent/consequence mechanism for the proposed UDA model.

5. The Uncertainty Driven Action (UDA) Model

This section describes the proposed UDA model. We first synthesise the three core actions together with uncertainty perception before describing the progression through the UDA model.

5.1. UDA Elements

The UDA model takes its starting point in the designer's *uncertainty perception*. Uncertainty perception forms the *antecedent* (i.e. causal mechanism) for activity in the UDA model because it motivates the three core actions described below. It connects activity to cognition via the core actions, with respect to memory and experience (Oxman 1990). It forms a metacognitive process that deals with an individuals' knowledge about their own cognition as well as regulation of cognition itself (Schraw & Dennison 1994). It is important to note that although current literature typically highlights the drive to *reduce* uncertainty perception over time (Ball & Christensen 2009; Yu *et al.* 2016), UDA uses the more neutral *modify*. This distinction is made to highlight the fact that actions can both increase or decrease uncertainty perception (Nagai & Gero 2012). However, overall reduction is to be expected over the whole duration of the design process (Hult *et al.* 2004). Uncertainty perception can be varied and complex because it includes level and nature, and captures uncertainty perception about the design itself as well as wider organisational issues (Kleinsmann & Valkenburg 2008). In combination, the level and nature of uncertainty perception can determine action selection and progression in terms of information, knowledge sharing, and representation. Further, changes in any of these dimensions (level, nature or both) form the trigger for shifting between elements within the UDA model. Thus the UDA model allows for the dynamic interaction between changing uncertainty perception and action progression, providing a unifying foundation for describing aggregate activity.

In *information action* a designer seeks to modify their uncertainty perception by working with data parts and their manipulation. This can be through e.g. collection, recording, reviewing, filing, archiving, seeking, and requesting (Blandin & Brown 1977; Robinson 2010*b*). Individual designers process this via reasoning or learning resulting in a new uncertainty perception state (Daft & Lengel 1986; Aurisicchio *et al.* 2010). The dominant cognitive process is information processing (Song *et al.* 2005). Examples of information action include, searching for data online (Aurisicchio *et al.* 2010), or providing/asking for specific data (Robinson 2010*a*).

In *knowledge-sharing action* a designer seeks to modify their uncertainty perception by exchanging knowledge expressed with respect to their understanding and beliefs to e.g. develop a shared understanding with the design team (Daft & Lengel 1986; Dong 2005; Kleinsmann & Valkenburg 2008). Individual designers process this exchange resulting in a new uncertainty perception state. The dominant cognitive process is social cognition (Chiu *et al.* 2006). Examples of knowledge-sharing action include, expressing belief modified knowledge in conversation (Dong 2005), or creative exploration (Christensen & Ball 2016*a*,*b*).

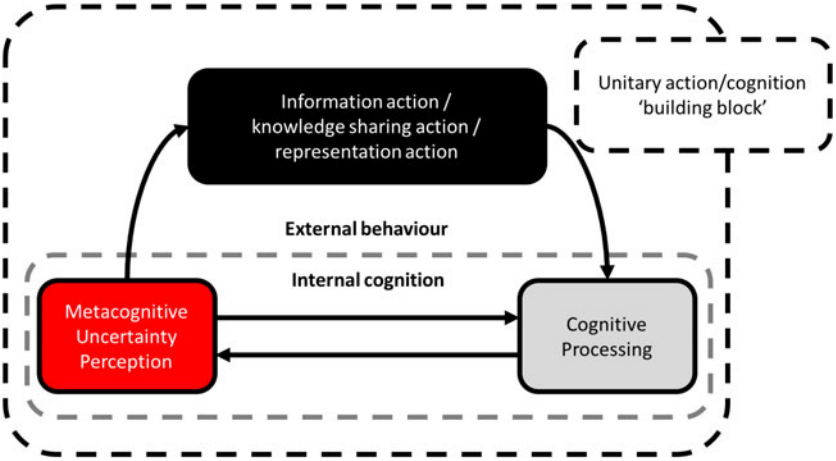

Figure 2. The UDA model linking internal metacognitive uncertainty perception (red) and cognitive processing (grey), and externally enacted information, knowledge-sharing, and representation actions (black). As a whole, the UDA model composes one 'building block' denoted by Note 2 in Figure 1.

In *representation action* a designer seeks to modify their uncertainty perception by the manipulation of external information representations through, for example, computational simulation (Lamarra & Dunphy 1998). Individual designers process this by reflecting on the external representation in relation to their internal simulations (Wilson 2002; Evans 2008). The dominant cognitive process is embodied cognition (Wilson 2002). Examples of representation action include, sketching (Schön & Wiggins 1992), prototyping (Gerber & Carroll 2012), or gesturing (Cash & Maier 2016).

In order to describe activity fully, behaviour and cognition must be considered in unity. Thus each of the core actions are connected to *cognitive processing* (Evans 2008), which allows for reflective practice (Schön & Wiggins 1992), reasoning, sense-making (Aurisicchio *et al.* 2010), creative imagination (Hatchuel & Weil 2002), and mental simulation (Wiltschnig *et al.* 2013). Cognitive processing includes both fast and un-deliberate, as well as slow and deliberate processes (Evans & Stanovich 2013), however, such decomposition is not necessary for the purposes of the proposed model. In particular, there is a relative lack of unanimity across formalisms of human processing in the psychology literature (Francis *et al.* 2009), as well as their application in the design domain. Thus by combining these elements the UDA model captures the whole cycle from uncertainty perception through behaviour to cognition, as a single unity of activity.

The UDA model is illustrated in Figure 2. Here the internal world of the designer (including *uncertainty perception*, *cognitive processing*, and the reflective link between them) and the external world where action can be observed (including *information*, *knowledge-sharing*, and *representation actions*) are explicitly connected via causal links to produce an overall unity between behaviour and cognition. As such, the model cannot be decomposed to only action or cognition if an overall understanding of activity is to be achieved. Thus, the model must be considered as a whole system. Actions are denoted in black – these include the three core actions as the common generic behaviours from which higher-level tasks and activities are composed; cognitive processing is denoted in grey – this comprises the cognitive processes that underpin the core actions, as well as the other systems making up an individual's cognitive framework; finally, uncertainty perception is denoted in red – this represents the metacognitive antecedence/consequence mechanism linked to understanding, that connects action and cognition. These elements together make up the unitary action/cognition building blocks at the foundation of activity (Section 2).

All of these elements together make up the foundation of activity, and are couched within the wider context of the situation and the designer (Briggs 2006). A full deconstruction of the different contextual factors that influence activity is beyond the scope of this work and forms a significant body of study in its own right (Bedny & Harris 2005). The context can include the wider social context (Dong 2005), discipline (Yilmaz *et al.* 2015), and personal experience (Christensen & Ball 2016*a*,*b*). Furthermore, the individual designer links to the wider group (design team and organisation) (Christensen & Ball 2016*a*,*b*; Kreye 2016). However, all actions in the UDA model are undertaken by an individual (and can all be carried out in any setting, in a group or alone), building on the core understanding of design activity as the unity of individual behaviour and cognition. Group dynamics can be understood by, for example, modelling the actions of each individual and then examining their connection and interaction (Garcia 2005). In this regard it is possible to imagine each individual as semi-autonomous within a network of connected individuals that act independently but influence each other through their actions (McCarthy *et al.* 2006). Alternatively, assessment of actions or uncertainty perception can be aggregated across a population in order to identify overall trends or quantitative relationships (Hult *et al.* 2004). Thus the individual can be connected to the wider group or system by building on the UDA model. However, this interaction is not currently well developed and is substantially beyond the scope of this paper. Finally, deconstructing each element into its sub-constituents e.g. internal processes underpinning cognition, or physical processes and specific instantiations making up the core actions, is also beyond the scope of this work. This is because current formalisms of design activity do not offer consistently detailed and accepted deconstructions of all elements.

5.2. UDA progression

The UDA elements are connected in a unitary model describing the synthesis of behaviour and cognition fundamental to understanding design activity (Bedny & Karwowski 2004), and cyclical action progression (Engeström 2000). Each cycle starts with an antecedent change in the designer's uncertainty perception. *Change* in uncertainty perception is used here as a driver for action (Christensen & Ball 2016*a*,*b*) and can be evaluated in absolute or relative terms (Chan, Paletz & Schunn 2012; Paletz, Chan & Schunn 2017). In reaction to this change in uncertainty perception the designer enters one of the three action cycles. These form the *behaviour* element of the model. The outcomes from this behaviour then feed into the designer's cognitive processing system (Bilda & Gero 2007; Evans 2008) where it drives a subsequent change of state in the designer's uncertainty perception. Cognitive processing (Evans 2008) and the change in uncertainty perception form the *consequence* element in the model and close the cycle. UDA thus captures the full cycle of action from antecedent to consequence, connecting

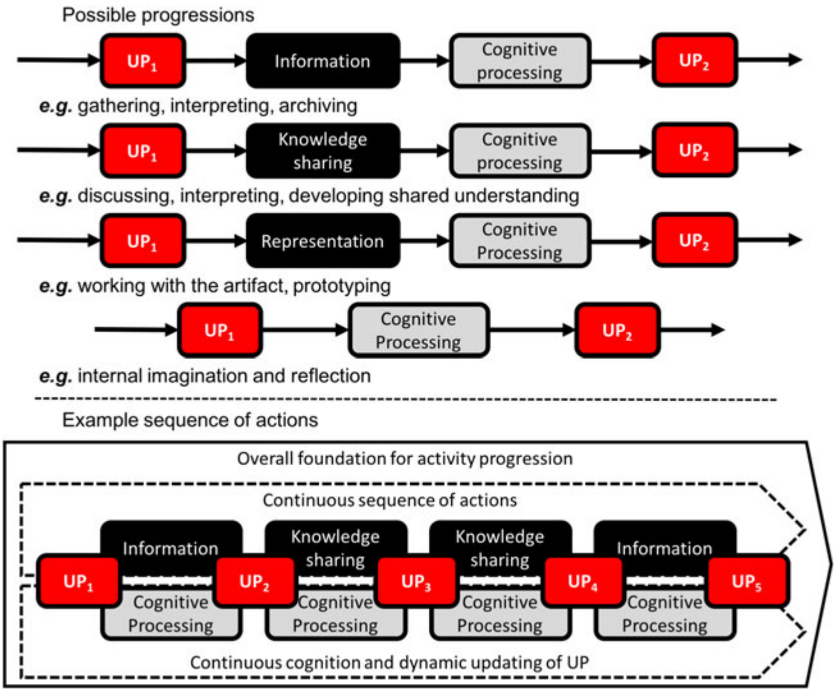

Figure 3. Possible progressions allowed by the UDA model, and an example sequence of actions linked by evolving uncertainty perception (UP_n). Here each action cycle in the sequence is a single iteration of the UDA model and together they form the foundation for activity as explained in Figure 1.

behaviour and cognition (Bedny & Karwowski 2004), to form the foundation for understanding design activity. In addition to the action cycles it is also possible for a designer to simply reflect on their own understanding through a cognitive processing/uncertainty perception loop.

Each cycle forms a generic building block that can be completed multiple times, for example, addressing different information sources (Song *et al.* 2005) such as searching for specific information on a webpage and then sharing the interpretation of that information with the team, communication modes (Cash & Maier 2016), or representation media (Sanders & Stappers 2014). Further, actions can be directed towards different design goals e.g. ideation or concept refinement (Yang 2009), or aspects of the design artefact (Gero 1990). The core actions and uncertainty perception dynamically interact and co-vary to provide the foundation for describing aggregate activity progression, i.e. the building up of an overall activity by the sequential connection of multiple unitary action cycles each encapsulating behaviour and cognition. Thus UDA is able to describe iterative, dynamic activity via the sequential completion of multiple action cycles.

The sequential progression through the UDA model is illustrated in Figure 3. This highlights the different possible progressions allowed by the model, as well as examples of the features of design work that these describe. Each cycle is initiated by the current uncertainty perception state (UP_1) and ends with a new uncertainty perception state (UP_2). Finally, a simplified abstract illustration is used to show the dynamic interaction between changing uncertainty perception and action progression.

Together the proposed elements and cyclical progression allow for a model that offers an integrative understanding of design activity built on a foundation of the three core actions connected to cognition. This is consistent with current design activity formalisms. Further, by integrating these elements the UDA model is able to describe the major features of design activity found in the empirical literature.

6. Discussion

Based on the UDA model, suggestions for future research directions in the form of 'propositions' can be derived. This section discusses the proposed UDA model with regard to its link to the design literature and subsequently suggests three propositions for future work.

6.1. Link to the design literature

The proposed UDA model extends the design literature by unifying previously disparate research. In particular, it unifies the varied descriptions of the core actions underpinning design activity. More generally it explains the gradual resolution of uncertainty perception related to the creation of a design artefact (Hult *et al.* 2004). Further, it extends prior descriptions of uncertainty perception as a driver of specific action sub-types and connects these in a generic model of design activity progression built on the sequential selection and combination of the three core actions. The UDA model hence formalises descriptions of design activity, consistent with Activity Theory as well as extant empirical studies of designing (Eris *et al.* 2014; Crilly 2015). The model's applicability is further supported by its consistency with prior empirical and theoretical work in the design literature. This illustrates the UDA model's robustness in linking behaviour and cognition, and its ability to integrate the three core actions underpinning design activity. Finally, the dynamic interaction between changing uncertainty perception and activity progression, driven by the action cycles, highlights the potential for explaining design activity from antecedent to consequence.

Each element included in the UDA model constitutes a distinct area of research in design. Although further decomposition is possible, current descriptions are not consistent across all elements. This bounds the scope of the proposed model without prescribing sub-categorisations. However, the proposed model does define the overall nature of each core action, based on its dominant cognitive process (Bedny & Karwowski 2004), and thus guides where such sub-categorisations could be included. For example, Eris's (2002) breakdown of questioning types offers a specific decomposition of one aspect of knowledge-sharing action. Other examples of knowledge-sharing sub-categorisations are Wasiak *et al.*'s (2010) breakdown of sharing action or Storga *et al.*'s (2010) ontology. It is important to note that the UDA model does not point to any specific sub-categorisations and thus does not preclude or favour one over the other.

Uncertainty perception captures both design specific (e.g. problem/solution) and wider factors (Daalhuizen & Badke-Schaub 2011; Kreye *et al.* 2011) characterised in terms of *level* and *nature*. Although uncertainty perception as a unitary whole has been studied in the design domain (Wiltschnig *et al.* 2013) no taxonomy or decomposition of design-related uncertainty perception exists. For example, Kleinsmann & Valkenburg (2008) highlight organisational sources of uncertainty, while others focus on social issues (Chiu *et al.* 2006), or specific aspects of design understanding (Storga *et al.* 2010). Further, no cohesive description of uncertainty perception exists in the design literature below the description currently used in the UDA model, which can be influenced by experience (Demirbaş & Demirkan 2003), situational factors (Kreye *et al.* 2012) and personality (Kreye 2016). In contrast, the management literature offers taxonomies of uncertainty as described, for example, by O'Connor & Rice (2013). Further work is needed to integrate these taxonomies in the design literature and determine the causal relationship with action selection in design. Thus, as with the core actions, the lack of a cohesive model of uncertainty perception means that it is not possible to decompose this element or its impact on design activity beyond what is described in the proposed model.

Together the elements of the UDA model support its ability to answer empirical and theoretical questions raised in the design literature e.g. how the interface between conversation and gesture jointly resolve uncertainty perception (Luck 2013), how designers progress through a design task by combining distinct units of action in a directed sequence (Christensen & Ball 2016*a*,*b*; Cash & Gonçalves 2017), or how co-evolution can be connected to directed action (Lasso*et al.* 2016; Cash & Gonçalves 2017). In particular, Cash & Kreye (2017) begin to empirically examine the utility of the UDA model in their recent protocol studies. However, significant questions remain as elaborated in the following section.

6.2. Propositions and further work

Based on the UDA model, three propositions can be formulated that provide concrete claims for testing in, for example, subsequent empirical studies (Wacker 1998), and provide directions for future research. First, a central feature of the model is uncertainty perception as the driver of the three core actions: information, knowledge sharing, and representation. The proposed UDA model extends descriptions in the design literature by explicitly stating the *causal* relationship between uncertainty perception and the core actions. Uncertainty perception can drive action selection and combinatory progression. Specifically, uncertainty perception generally motivates and mediates progression across actions (Calantone & Rubera 2012) and is linked to progression within specific instantiations of actions, such as sketching (Scrivener *et al.* 2000), and prototyping (Gerber & Carroll 2012). Thus we propose uncertainty perception as a major driver for the dynamic interaction between the core actions and higher-level activity progression, encapsulated in Proposition 1.

Proposition 1. *Uncertainty perception is a driver and antecedent of design activity, connecting progression across information, knowledge-sharing, and representation actions.*

This proposition refines and extends existing descriptions in the design literature in two main ways. First, it captures the varied role of uncertainty perception as a causal driver of design activity in terms of action progression. This connects higher-level research on aggregate activity (Hult *et al.* 2004) to studies at the action level (Christensen & Ball 2016*a*,*b*). It thus formally integrates fragmented descriptions of the effect of uncertainty perception as a cause of design activity progression. Second, it points to the need for further research exploring the role of uncertainty perception in connecting the multiple levels associated with design activity (Section 2). For example, this proposition points to the connection between activity level progression and fundamental characterisations of uncertainty perception and action level response. The UDA model thus provides a key bridge between the varied formalisms of design activity and wider activity related literature in the management and innovation research domains, highlighted as a key challenge for design research by the recent works of Luo (2015) and Papalambros (2015).

Second, the effect of uncertainty perception on design activity can be conceptualised based on its level and nature. As described in Section 4, *level* of uncertainty perception describes the overall amount of the perceived lack of understanding, while *nature* details the perception of different uncertainty types. Together, the level and nature of uncertainty perception affect action selection and progression with respect to the core actions: information, knowledge sharing, and representation. Changes in level and nature also influence how the core actions are realised in practice (Omta & de Leeuw 1997). Further research is needed to characterise how level and nature of uncertainty perception (and changes thereof) determine action selection and across-action progression. Recent work of Cash & Gonçalves (2017) shows that such examination is possible at the unitary action/cognition level conceptualised in the UDA model. It can be expected that a change in the level, nature or both of uncertainty perception may cause a designer to move from, for example, information action to knowledge-sharing action. For example, one combination of different uncertainty types may favour information action over the other two core actions captured in the UDA model. However, the exact impact of these differing changes is not clear. This is encapsulated in Proposition 2.

Proposition 2. *Change in uncertainty perception, characterised by level and nature, determines activity progression, in terms of action selection and combination across information, knowledge-sharing, and representation actions.*

This proposition contributes to the design literature by decomposing the effect of uncertainty perception beyond current characterisations. This allows for more fine grained understanding of designers' reactions depending on their perception of the situation (Daalhuizen & Badke-Schaub 2011), and organisational setting (Kreye 2016). It thus allows design researchers to determine the specific effect of uncertainty perception on design activity in terms of action selection and combinatory progression.

Finally, the UDA model suggests that it is the combined effect of action selection and combinatory progression that determines overall design activity progression, and thus design outcome. This follows prior conceptualisations of design that place activity at the heart of performance, but extends them by integrating the three core actions in a single model. Specifically, prior research has highlighted the individual importance of information (Wasiak *et al.* 2010), knowledge sharing (Kleinsmann *et al.* 2012), and representation (Bilda & Gero 2007) on design outcome, with little or no integration between them. The UDA model offers a means of bringing together descriptions of design activity and its impact on outcome. The connection between uncertainty perception and design outcome is encapsulated in Proposition 3.

Proposition 3. *The progression of uncertainty perception (level and nature) and activity determines the design outcome.*

This proposition contributes to the design literature by connecting the effect of uncertainty perception and subsequent action selection/progression to design outcome. This integrates antecedent, behaviour, and consequence elements in a single model in the design context (Oliver 1980; Miltenberger 2011). This complements and extends prior works that have focused on the antecedent/behaviour relationship between uncertainty perception and specific instantiations of the different core actions (Scrivener *et al.* 2000). Further, the focused nature of prior studies of uncertainty perception and action in the design context mean that direct links between overall activity progression and overall outcome have been difficult to characterise. Thus the UDA model enables researchers to understand complex motivation driven activities in terms of generic units, the combination of which underpin overall activity progression. In this way researchers are better able to target support for these core actions or decompose overall activity progression patterns in order to better understand where and when design support is needed.

7. Conclusion

This paper aimed to propose a cohesive model of design activity as a basis for unifying the design activity literature and as a foundation for future theory building in this area. This connects the diverse empirical and theoretical works in the design domain already exploring many aspects of design activity; and seeks to formalise a description of design activity as a goal directed system where cognition, behaviour, and motivation are integrated, with respect to the 'bringing-into-being' of a design artefact. Based on an analytical conceptual approach the *Uncertainty Driven Action* (UDA) model was proposed. This combines three core actions (information action, knowledge-sharing action, and representation action), and their associated cognitive processes via the designers' uncertainty perception, to explain the progression of overall design activity. The theoretical basis of the model was described and its practical relevance discussed with respect to the wider design literature. The model brings together a wide range of prior descriptions of design activity via the core actions, and connects these into a dynamic system via cognition and uncertainty perception. This provides a cohesive understanding of design activity as built on the sequential combination of fundamental actions.

The UDA model delivers three main contributions to design research. First, it offers a unifying description of design activity synthesising the core actions and uncertainty perception in a single model, with a consistent link to cognition in line with underlying Activity Theory. The three core actions further provide a platform for developing greater commonality in research on design activity, comparing insights from existing formalisms, and directing future typologies on the sub-types defining each of the core actions. Second, the proposed UDA model offers a causal explanation of design activity progression in terms of action selection and sequential combination, with respect to the common mechanism of uncertainty perception. This completes the antecedent–behaviour–consequence requirements lacking in prior formalisms and describes a 'complete' framework of design activity. Third, this research proposes important guidelines and directions for future research that will further theory development in the design literature.

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