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INFORMATION PROCESSING THEORY IN THE EARLY DESIGN STAGES

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Keywords: empirical study, information-processing theory, design behaviour, uncertainty perception

1. Introduction

Developing appropriate theory is one of the main challenges facing engineering design [Cross 2007]. Theory helps to both explain design activity but also support greater research impact in the domain. It is useful for gaining a more comprehensive understanding of design activity and developing suggestions for improvements and support. One theory that may be particularly applicable to the early design stages is Information Processing Theory (IPT) as it is linked to the design process with regard to the key concepts considered. IPT states that designers search for information if they perceive uncertainty with regard to the knowledge necessary to solve a design challenge. They then process this information and compare if the new knowledge they have gained covers the previous knowledge gap.
In engineering design, uncertainty plays a key role, particularly in the early design stages which has been highlighted as the fuzzy front end. To solve this uncertainty, designers collect and exploit information to mitigate uncertainty in design decisions [Love and Roper 2009]. This is then turned into knowledge in order to make it applicable to the designer's and business' needs [Cousins et al. 2011]. Finally, the new knowledge is shared between the design team to reduce ambiguity with regards to its meaning and to build a shared understanding – reducing perceived uncertainty. Thus, we propose that Information-Processing Theory is suitable to describe designer activity in the early design stages and a potentially useful theory to adopt in engineering design.
The aim of this paper is to explore whether the predictions of IPT apply to empirical designer activity in the early design stages. Based on the literature on IPT, a mental framework is presented that depicts the theoretical predictions. This is applied to an experimental study with student engineers solving a product design task. The results show that IPT is indeed a useful theory and we discuss the implications for the field.

2. Theoretical framework

Information Processing Theory was first introduced by Daft and Lengel [1983] and explicitly links the three concepts of uncertainty perception, information seeking and knowledge sharing. When presented with a product innovation challenge, designers may perceive uncertainty with regard to solving this challenge. Then, they will start seeking information to reduce this perceived uncertainty and create knowledge. This knowledge is then shared with the design team. This section presents a short review of approaches in uncertainty perception, information seeking and knowledge sharing.

2.1 Uncertainty perception

Uncertainty is defined as a potential deficiency in any phase or activity of the process which can be characterised as not definite, not known or not reliable [Kreye et al. 2012]. The perception of this

uncertainty can have significant implications on people's decisions and actions. Perceived uncertainty can make a person feel unsure or unconfident in his/her decision making. It can also make a person feel overconfident if they ignore or underestimate uncertainty. As such, perceived uncertainty may differ from the actually existing level of uncertainty (extant uncertainty). Yet, it is this perceived uncertainty that influences designers actions and decisions.
To analyse and measure a person's uncertainty perception, the expressions used in their explanations and naturally occurring conversations can be utilised [Windschitl and Wells 1996]. These uncertainty expressions can be either quantitative or qualitative statements [Van der Sluijs et al. 2005]. Quantitative statements can support decision making by depicting for example a Probability Density Function (pdf) that shows the decision outcomes in connection to probabilistic values. Qualitative uncertainty statements tend to be more intuitive and consist of verbal statements such as "not sure" or "expected" and indicate that a person is uncertain about a specific decision, task or context but may not be able to assign a numerical value. It has been found that people prefer to express uncertainty using qualitative statements [van der Gaag et al. 1999]. Thus, we will use qualitative uncertainty expressions to measure the designer's uncertainty perception. This is described further in Section 3.

2.2 Information seeking

In the context of IPT, information seeking comprises both acquisition and processing [Cousins et al. 2011]. Acquisition refers to the collection, recording, reviewing, and filing of new information [Lynn et al. 1999], while processing refers to the use of this new information through interpretation, reasoning, drawing interferences or learning [Daft and Lengel 1983]. These aspects of information seeking have been found to be both relevant for and applicable to engineering designers. For example, Aurisicchio et al. [2013] analysed the use of information sources and information seeking activity carried out during the design process.
Focusing on the interaction between the user and information source, there are a wide range of possible characterisations for information seeking activity. One classification was found to be both pragmatic and well-grounded and differentiates between "finding source" and "finding within source" [Robson 2011]. Adopting this classification allows for a need-based perspective without attempting to define a fully realised taxonomy of all possible aspects of information acquisition. This is considered a useful breakdown given the scope of this paper, which is to link information seeking to uncertainty perception and knowledge exchange.

2.3 Knowledge exchange

Once information has been collected and processed, it is exchanged in order to build shared understanding within the organisation or team [Daft and Lengel 1983]. In the context of this work the primary area of focus with respect to knowledge exchange is the internal exchange within the design team. This internal exchange characteristic has been shown to be the most effective basis for team learning [Berchicci and Tucci 2010], particularly in highly uncertain situations, such as those encountered during the early design stages.
Here knowledge exchange has a range of characteristics. It can occur through, formal, informal, explicit and implicit channels [Daft and Lengel 1983]. In the context of team performance, effective exchange is associated with reduced conflict, improved shared understanding, fostering agreed guides for behaviour and, fundamentally, improved performance [O'Leary-Kelly et al. 1994]. This is intrinsically linked to the concept of shared mental models in the design domain and also the shared understanding and appreciation of problems and uncertainties affecting the team. Thus, knowledge exchange is a key part of product design process and is intrinsically linked to uncertainty.

2.4 Conceptual framework

In order to provide an explanative frame for understanding IPT in the design context, a conceptual framework is proposed. This guides the data collection and analysis in terms of the information processing cycle, connecting the key IPT concepts and is depicted in Figure 1. The starting point is the designer's perceived uncertainty. This leads to the information seeking cycle, where the designer aims to reduce their uncertainty by acquiring information and processing it through interpretation and sense-making. This results in a change of their perceived uncertainty. The new state of perceived uncertainty then feeds into the knowledge exchange cycle, where information is shared in the design team. The shared knowledge leads to further individual processing activity. This, again, results in a change of their perceived uncertainty. Each cycle can be completed multiple times when solving the design challenge. Eventually, by iteratively moving through the two cycles, the designer reduces his/her perceived uncertainty by finding a solution to the design task.

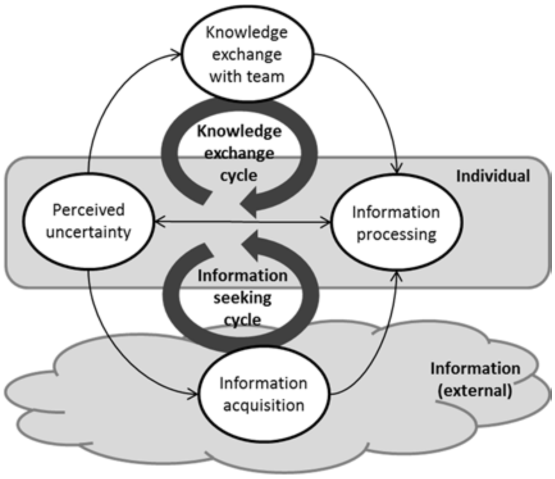

Figure 1. Research framework of the information-processing cycle in design teams

3. Research method

Applying IPT to design practice, we investigate the following two research questions (RQs).

1. What is the influence of designers' perceived uncertainty on their information-seeking activities in product innovation projects?
2. How do the designers' uncertainty perceptions influence the knowledge-exchange activity in design teams?

A qualitative observation study is presented, utilising a simple electro-mechanical design task and a protocol type analysis. This constitutes a structured observation study mirroring the design process phases and linking to the research framework proposed in Figure 1.

3.1 Study set-up and sample

The observation study focused on two key stages of the early design process: initial information seeking and initial ideation. These were selected in order to provide a clear analogy for the conceptual framework in the study process. The two sessions were linked by the design task: "You are to design a universal camera mount for use on an aerial vehicle. The aerial vehicle is to be used by an amateur photographer, primarily to take still photos." For each session a written brief detailing the task was provided and read aloud. Other verbal interactions were scripted and in addition a double blind design was used meaning neither the facilitator nor the participants were aware of the research framework or the RQs. Table 1 summarises the two sessions.

Table 1. Summary of the experiment

Session	Duration	Setting	Description
Information seeking	50 min.	Individual	Given the design task, the participants were required to search for required information, specifically for feasibility level technical information on camera mounting devices
Ideation	50 min.	Team	Given the information they found in session 1, the participants brainstormed possible product designs, specifically focusing on product ideas for mounting a camera on a balloon.

Twelve participants were randomly selected from 40 final year masters-level students of a product design and development course at a UK-based university. In the context of this study student engineers provided the best basis for comparison due to the relative homogeneity of education, industrial experience and background – reducing the likelihood of confounding variables being introduced by the population. The students were randomly allocated to design teams. A team size of three was selected to give the widest scope for generalizability whilst reducing the possibility for side conversations [Cash et al. 2012]. Participants were videoed during both sessions and logbook and individual computer use were recorded. The videos were synchronised for the data analysis. Overall the study setup followed the method outlined by [Cash et al. 2013] to ensure rigour and repeatability.

3.2 Data analysis

The data was analysed using the VCode software following a protocol based approach. This provided a systematic means for encoding and analysing the qualitative data and has been widely used in the design field. Although, coding large bodies of data is challenging a layered approach was used, with each element coded independently. Relationships could then be established either through statistical comparison of overall totals or via temporal relation, where two codes occurred simultaneously e.g. an *explicit uncertainty* term was used during a period of *abstract knowledge exchange*.

3.2.1 Coding uncertainty perception

To analyse the designers' uncertainty perceptions, a list of terms and phrases denoting explicit and implicit uncertainty awareness as well as terms for negating uncertainty was compiled. This was based on an review of the literature in management, engineering, computer sciences and communication research, with each term being explicitly drawn from extant validated works e.g. Friedman et al. [1999] and Hurley et al. [2011]. For brevity, individual citations are not presented here. Table 2 depicts the list of qualitative uncertainty expressions that were used for the analysis. The level of uncertainty perception was established by counting the number of terms used by the participants.

Table 2. Terms of uncertainty perception and negation

	Terms included with exemplar references
Explicit uncertainty	Uncertain, uncertainty; risk, risky; variation, vary, variable; chance; confident, confidence, not confident; imprecise, imprecision; vague, vagueness, vaguely; ambiguous, ambiguity; x%, probable, probability, probably; likely, unlikely; uncertainty modelling techniques such as Sensitivity analysis or Monte Carlo; unknown, not known, don't know; ignorance, ignore, ignorant; Interval statement (e.g. maximum, minimum, worst case, best case, biggest, smallest, heaviest, lightest); on average, mean, around
Implicit uncertainty	Re- (redo, renegotiate, reschedule etc); mis- (miscommunicate, misunderstand etc); change, changed; maybe, perhaps; expected, expect, expectation, expectedly, unexpected; possible, impossible, not possible, possibly; potential, potentially; if … then, in case, depending on, depend on, alternative, alternatively, otherwise; different, differently; suggest, suggestion, suggested; almost, most; undecided, not decided; predict, forecast, estimate; guess, think, wonder, thought, reckon, imagine; may, could, can, might; suppose, supposed to, supposedly; assume, presume, presumably, presumed; lack of …, not enough, missing (knowledge, information, data etc.); available (data, information, evidence etc.); confusing, confused, confusing; experience, inexperience, inexperienced; vagueness in statement (some sort of …, seem to …); not sure, unsure; not clear, unclear, clarify, clarification, clarity; not defined, undefined; common, not common, commonly, usually, usual, typically, typical; disagree, disagreement, not agree; not understand, not understood
Negation	Certain , sure, assured, assurance, precise, precisely; exact, exactly; well known, well understood, well defined; definite, definitely, absolutely, absolute; agree, make sense; clear, clearly; never, always

3.2.2 Coding information seeking

Based on the review in Section 2.2 the information seeking coding schema focused on the difference between 'finding source' and 'finding within source' [Robinson 2010]. Finding source related to the use of specific search facilities i.e. search engine, search box, and other indexing sites or services. Finding within sources related to seeking within a specific website, searching for information related to the product and included all sites with information relevant to the task (e.g. Wiki's, forums, catalogues, manufacturers' websites and patents). These categories were mutually exclusive.

3.2.3 Coding knowledge exchange

In order to trace the knowledge exchange relevant to design, the Design Ontology [Štorga et al. 2010] was used. This offers a systematic means of assessing the topics explored by the participants. This approach was favoured over more abstract models, such as, the Function-Behaviour-Structure framework, which give insufficient granularity for such an assessment. Overall topics were split into two groups, *physical* – describing an extant design or object – and *abstract* topics – describing features or designs not yet in existence. These are listed in Table 3.

Table 3. Design-specific knowledge exchange activities

	Code	Definition
Physical object	Material	The actual substance to be used by the technical product
	Technical product	The product itself, specific components, subassemblies and forms
	Technical product family	Variants of a specific technical product
	Technical document	Documentation with specific information about the technical product
	Human agent	The agent who will operate/interact with the technical product at different stages in the lifecycle
	Product lifecycle phase	Planning, design manufacture, distribution, exploitation (use) and disposal
Abstract attribute	Technical function	What a technical product is manufactured and used for
	Technical product characteristic	An internal attribute of the technical product, including form, dimension, tolerance, manufacturing method, surface texture, structural characteristics and spatial characteristics
	Design issue	An attribute by virtue of the technical products interaction with another entity – functional, environmental or lifecycle requirements

4. Research findings

In this section, the results for the three main aspects of IPT are individually explored with respect to design before they are brought together in Section 5.

4.1 Uncertainty perception in design teams

In terms of uncertainty perception (explicit, implicit, negation) there were substantial differences across the teams. Team 1, expressed twice as many explicit terms (70) compared to the other teams where there was no clear differentiation. Conversely, there were no major differences in the expression of implicit uncertainty – neither individually, nor in total (ranging from 338 to 412 total expressions). Finally, there were differences observed with respect to uncertainty negation, with Teams 2 and 3 using more terms. These comparisons suggest that Teams 2 and 3 were most certain, or confident, about the design task, while Team 1 was most uncertain. Further, the findings suggest that although the teams perceived similar levels of uncertainty (as shown by the similarity in number of implicit expressions), they differed in their ability to explicitly articulate this – suggesting a difference in the conscious awareness of uncertainty. These results are summarised in Table 4.

In the individual results one possible source of bias is the total time spent speaking – with less speaking resulting in less total expressions used. As such, all results are normalised against the time spent talking by each participant (expressions per minute). Here the only substantial difference of note is that Person 4.3 spoke for only 209 seconds compared to the mean total of 785 seconds. No obvious reasons presented themselves for this discrepancy and further exploration is beyond the scope of this work.

Table 4. Uncertainty perception on team and individual level (times mentioned)

Uncertainty perception	Team															
	1				2				3				4			
	Participant				Participant				Participant				Participant			
	1.1	1.2	1.3	Total	2.1	.22	2.3	Total	3.1	3.2	3.3	Total	4.1	4.2	4.3	Total
Explicit	26	16	28	70	12	4	6	22	10	11	12	33	15	13	0	28
Implicit	98	106	134	338	149	118	145	412	77	113	190	382	136	181	40	357
Negation	4	0	1	5	2	8	2	12	2	5	6	13	3	40	2	7

In Team 1 all three members showed a relatively high and evenly distributed, perception of explicit uncertainty. A possible explanation for this could be that they (subconsciously) influenced each other in a self-reinforcing process. In contrast, Person 1.1 was primarily responsible for most of the negation terms used. It would rather suggest that the three participants had a similar perception of the situation and the extant uncertainty but had different perceptions relating to negation. This explanation is further supported by the results for Team 2, where substantial differences were evident in the distribution of both uncertainty perception and negation. Specifically, Person 2.2 had a high level of negation despite using relatively few uncertainty terms overall. Further, Person 2.1 was the main contributor to the team's use of explicit uncertainty terms. In contrast, Teams 3 and 4 showed a more balanced distribution of all types of uncertainty terms and negation. This would suggest that neither of the proposed explanations fully explain the observed phenomena and, as such, the reduction of the information processing cycle to just the factors observed may be insufficient to explain the full decision making process. These results are depicted in Figure 2 for each person.

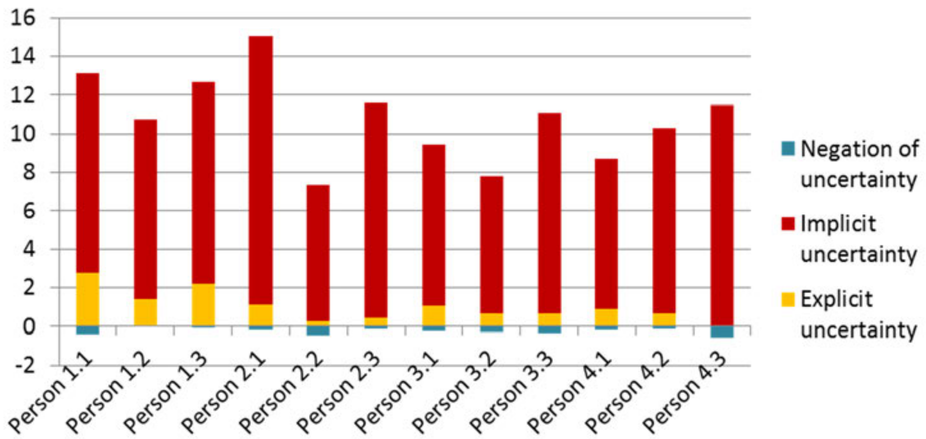

Figure 2. Individual uncertainty perception (in terms per minute) during ideation

4.2 Information seeking

The results for information seeking show a strong link between uncertainty perception and information seeking. In particular, two main findings are evident. First, there is a strong link between explicit expressions and time spent 'finding within source'. For example, Persons 1.1, 1.2 and 1.3 used most explicit uncertainty expressions and most time finding within source. Second, there is a strong negative link between negation expression and 'finding within source'. For example, Persons 2.2 and 3.3 used most terms negating uncertainty and spent least time finding within source. Although these results present, to varying degrees, across all the participants, Person 4.3 is a deviant case. She showed low uncertainty perception whilst spending an equivalent amount of information acquisition to other participants. However, this is likely attributable to the limited time spent speaking overall and, as such, will not be discussed further here. The results for information seeking are illustrated in Figure 3.

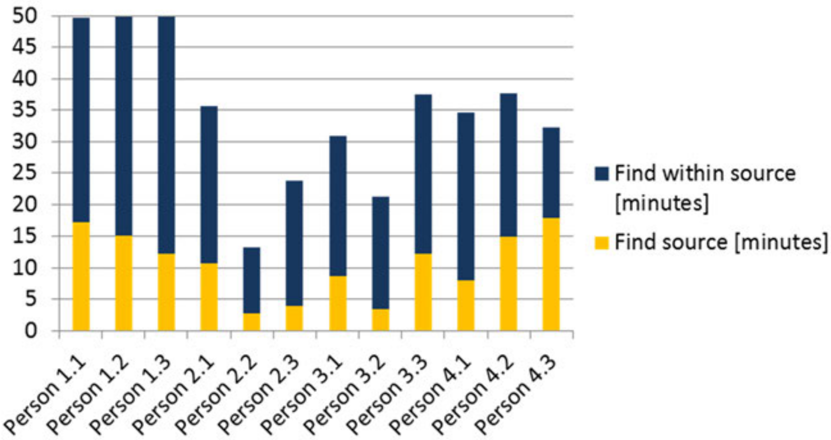

Figure 3. Information-seeking activity

4.3 Knowledge exchange

Linking uncertainty perception to knowledge exchange offers several possible explanations for the observed differences. This is exemplified by Team 1 who spent substantially more time discussing the lifecycle phases (almost double that of Team 3 and ten times that of Teams 2 and 4) whilst also having the highest explicit expressions. More specifically, they discuss the use phase, the users and use scenarios, and the weight and dimensions of the camera itself, where they used many explicit terms. This suggests that the lifecycle phases are a source of high uncertainty. This is supported by the fact that few terms for negating uncertainty were used. Further, Team 1 spent the most time discussing the human agent and more time on the technical documentation. As such, a link can be drawn between discussing lifecycle phases and uncertainty expression (either positive or negative). Further, a clear link is highlighted between the range of specific topics discussed and an increased perception of uncertainty. These results are summarised in Table 5, which shows a key link between the range of topics discussed and the amount of explicit uncertainty perception.

Table 5. Uncertainty connected to the design-specific knowledge exchange (in times mentioned)

Uncertainty perception	Material	Technical product	Technical product family	Technical document	Human agent	Lifecycle phase	Abstract technical function	Abstract technical product characteristic	Abstract design issue
Explicit	2	0	0	4	4	8	21	56	45
Implicit	7	0	0	6	33	77	276	853	158
Negation	0	0	0	0	2	2	4	22	2

The findings show that perceived uncertainty reduces as the design process progresses from abstract to more physically grounded discussions. This was shown particularly for Team 1 as discussed above. At the individual level there are, however, few clear patterns linking activity to uncertainty perception.

For example, both Person 1.1 and 1.2 spent significant time discussing the 'human agent' yet they share little commonality in terms of their expressions of uncertainty – particularly negation. There were no clear patterns linking individual results to team results. As such, it appears perception differs from person to person with different topics associated with uncertainty for each individual. Figure 4 depicts the time the individual participants spent on exchanging design-specific knowledge.

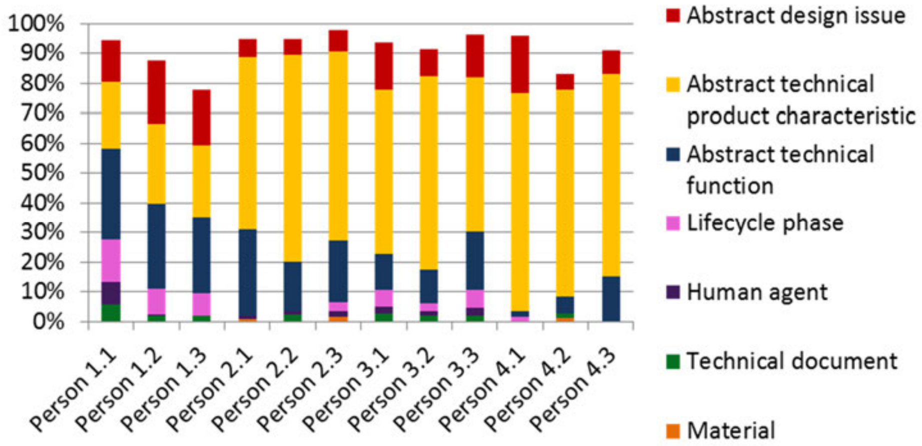

Figure 4. Individual design-specific knowledge exchange during ideation

5. Discussion

Relating uncertainty perception, information seeking and knowledge exchange, this section links the findings presented in Section 4 to the conceptual framework and subsequently Information-processing theory (IPT). In this respect, three major findings are highlighted. Key to the overall aim of the paper, a clear link between information seeking activity and uncertainty perception (RQ1) was found [Daft and Lengel 1983]. This serves to confirm IPT within the constraints of the early design stages and highlight its utility as a theory relevant for further understanding and modelling design activity. Specifically answering RQ1, participants with high levels of uncertainty perception also showed higher levels of information-seeking activity while participants with high levels of perceived certainty (i.e. negation expression), were less active in information seeking.

Next, relating uncertainty perception and knowledge exchange (RQ2), the findings suggest a strong connection between perceived uncertainty and design-specific knowledge-exchange activities. Thus, in answering 'how' perception influences knowledge-exchange (RQ2) the results show that it is primarily governed by the range of topics, and somewhat by whether they are abstract or physical orientated. For example, a physical topic linked to high uncertainty perception was the discussion of the product's lifecycle, such as the manufacture, the end-user and the interaction between user and the product.

Finally, although there were a number of team and individual level patterns and links between the elements in the conceptual framework, there were few clear patterns linking individual and team levels. Overall this indicates that uncertainty perception is an individual attribute that is altered by team-level influences accounting for the observed heterogeneities in and between teams. However, further work is required in this context in order to fully account for the differences between levels in relation to the conceptual framework. These results are summarised in Table 6 with respect to the conceptual framework. Ultimately, the cyclical process proposed in the research framework was supported by the data. For example, the information seeking cycle was initiated by the designer's interpretation of the brief, which then lead to distinct patterns of information seeking, aiming to address their specific uncertainties e.g. how a camera might be mounted. Similarly, the team coming together after the information-seeking phase to first share their findings, before generating new concepts, exemplifies the knowledge exchange cycle.

The limitations of the presented findings are related to the nature and purpose of the presented study. We presented a small sample of twelve participants. A second important limitation is that in the context of the design process it is possible that these results reflect the relatively discreet seeking activities during the early stages and, as such, may not hold true as the design process progresses. However, significant further work is needed in order to fully explore the various possible explanations for these results as well as how they might change over the course of the design where processing and seeking become blurred. It is envisaged that the key variables outlined in this paper will be confirmed with a longer study. This could offer significant insight into the later stages in the design process, although further investigation is needed to confirm this. Further, although the aim of this paper has partially, been to offer an overview and highlight areas for more focused further research, there is significant scope for more in depth analysis of each area highlighted here.

Table 6. Summary of research findings and comparison to information-processing theory

Finding	1st iteration of information-processing cycle
Key predictions of IPT	1. IPT explicitly connects uncertainty perception, information seeking and knowledge echange [Daft and Lengel 1986], [Thomas and Trevino 1993], [Cousins et al. 2011] 2. Information seeking contributes to reduction of perceived uncertainty [Daft and Lengel 1983], [Thomas and Trevino 1993]
Findings for uncertainty perception	Individual differences in uncertainty perception lead to differences between and within the teams Similarities of levels of uncertainty perception between individuals with main differences in ability to express them explicitly
Findings for information seeking	Level of uncertainty perception linked positively with information-seeking activity, especially when searching for specific, product-related information Level of perceived certainty (negation of uncertainty) negatively linked to information-seeking activity
Findings for knowledge exchange	Positive connection between uncertainty perception and design-specific knowledge-exchange activities; High levels of perceived uncertainty (explicit and implicit) attached to abstract design topics

6. Conclusions

The aim of this work was to explore whether the predictions of IPT apply to empirical designer activity in the early design stages. Linking the three concepts of uncertainty perception, information seeking and knowledge exchange, IPT showed a high potential to explain the activity of engineering designers. Using an experimental study with a product design task, it was shown that IPT is indeed a useful theory, applicable to engineering design. The results highlight the need to shift the focus of the discussion towards integrating theory into engineering design. This will both improve our understanding and the applicability of theory to practice. In this context, the proposed research framework, building on IPT to describe the product design process as multiple iterations of the information-processing cycle, was both applicable and relevant as a basis for further research.

This leads the way for future research to further strengthen the use of theory in design research and improve our understanding. First, the findings need to be extrapolated to later design stages to investigate whether the predictions of IPT hold true in this setting as well. This will root IPT as a useful theory to explain design activity and designer behaviour. Further, there is a clear potential for the wider investigation of IPT as a foundation for design activity and communication in a number of design contexts, not just decision making under uncertainty. In particular developing the research framework would allow for a cohesive linking of several aspects affecting design performance. Here, the potential is particularly significant in the design domain where cohesive theoretical frameworks with strong explanative and predictive power have remained frustratingly elusive.

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