Perceptions of Complexity in Design Representation: Implications for an Understanding of Design Practice

James Andrew Self, Ulsan National Institute of Science and technology (UNIST)
Seong-geun Lee, Ulsan National Institute of Science and technology (UNIST)
Hyeonseok Bang, Ulsan National Institute of Science and technology (UNIST)

Abstract

From the ubiquitous hand sketch to high fidelity prototypes, designers employ design representation as a means to externalise, reflect upon, develop and communicate design intentions. As a result of their importance, efforts have been made to identify and classify the different attributes of the various representations used during design practice. In this study an existing quantitative approach to the identification and classification of complexity within design representation is used as a coding frame in a content analysis of design representation present within 50 industrial design case-studies. Results indicate the complexity scale's limitations as a means of analysis due to the subjective interpretation required in its application. Conceptual and developmental design representation is particularly resistant to the objective measurement of complexity. Results indicate the limitations of research which attempts to objectively quantify and classify design representation. Instead we provide further evidence to indicate understanding of conceptual representation is best achieved through the framing of design as a subjective construction, sensitive to personal interpretation and deployed as part of a reflective conversation with the situation.

Keywords

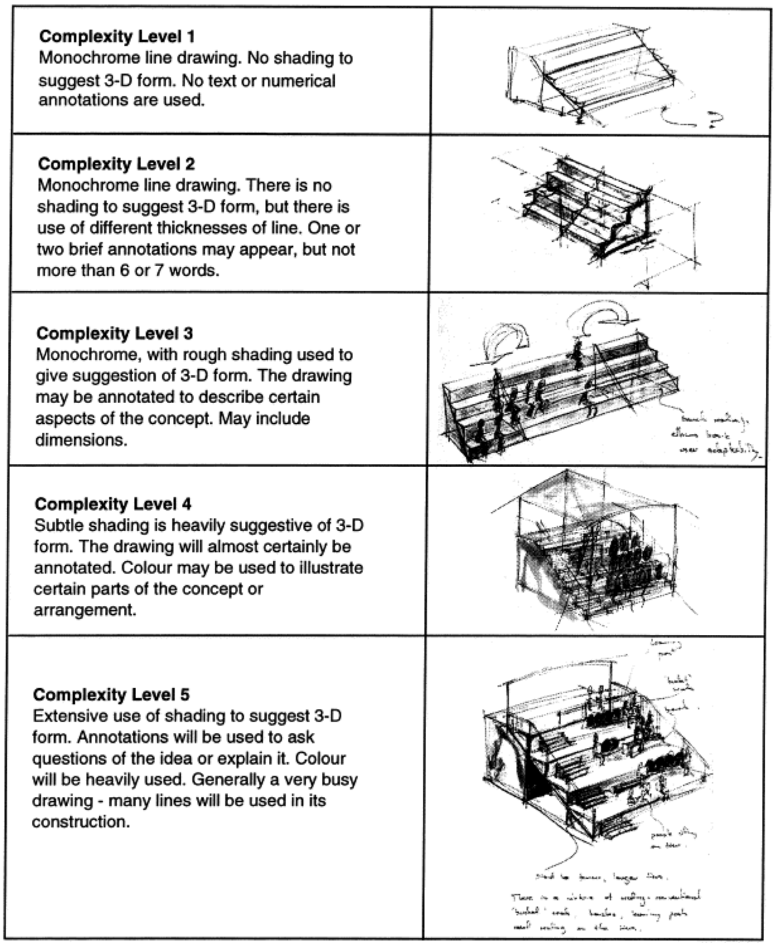
Design Representation, Design Practice, Reflection-in-Action

From the various and widely used sketch to high fidelity, pre-production prototypes design representation is employed as an essential tool to support the practice of industrial design (J. Self, Evans, & Dalke, 2014). Representation is used for a variety of purposes, from the quickly drawn thinking sketch to persuasive renderings and digital CAD models (Visser, 2009; Goldschmidt and Porter 2004; Pei et al., 2011; Cross, 2007). In this way, design representation is employed both as a means to support reflection-in-action (Schon, 1983), and to communication design intent to other stakeholders (Cross, 2008; J Self, Evans, & Dalke, 2013). Considering its various and critical role in support of practice, studying design representation provides opportunities to develop understanding of the particular nature of design activity and the kinds of knowing and thinking it involves (Cross, 2007).

There exists a growing body of work aimed at understanding design practice through the investigation of tools of design representation. For example, Tovey et al. (2000) studies the characteristics of CAD (Computer Aided Design) representation and its influence upon practice by comparing the use of CAD and traditional drawings in automotive design. Pei et al. (Pei, Campbell, & Evans, 2008) have developed a taxonomic classification of design representation in an attempt to support collaboration between industrial and engineering designers during new product development. An extension to Pei et al. (ibid) taxonomy has been proposed by Kim et al. (2013), who indicate its shortcomings in the classification of conceptual design representation. In a further example, Cross (1999) presents research to develop understanding of the nature of design problems through an investigation which focuses on the analyses of sketching and its role in support of design practice. Through the development of a notation systems which focus on transformation (Goel, 1995), Do et al. (2000) attempts to interpret the designers' thinking as part of an investigation focused upon design drawings. In this way Do et al's (ibid) study aims to understand the relationship between representation through drawing and its association to design practice. In a seminal work, Goel (1995) explores representation through sketching to suggested important insights into the role sketching plays during conceptual design due to its ambiguous nature, semantic density and ability to provide opportunities for transformations between and among design ideas.

Design Representation

As these previous works attest, the study of design representation offers a fertile ground with the potential to provide insights into design practice and the kinds of designerly ways of knowing and thinking it requires (Cross, 2007; Visser, 2006). As such, complexity within design representation has seen attention in its potential to provide a means to identify and classify design representation. These existing studies take a systematic and objective approach to the identification, measurement and classification of complexity, often through quantitative analysis. For example, McGown et al. (1998) suggest a quantification of the levels of complexity present within design representation as sketches is required to, 'appreciate the pattern of information flow in the conceptual sketching activity' (McGown et al., p. 445). McGown et al. (ibid) present a 5 level complexity scale (see also Rodgers et al. (2000) to measure the complexity of information communicated within representation (Figure 1).



Complexity Level 1 Monochrome line drawing. No shading to suggest 3-D form. No text or numerical annotations are used.	
Complexity Level 2 Monochrome line drawing. There is no shading to suggest 3-D form, but there is use of different thicknesses of line. One or two brief annotations may appear, but not more than 6 or 7 words.	
Complexity Level 3 Monochrome, with rough shading used to give suggestion of 3-D form. The drawing may be annotated to describe certain aspects of the concept. May include dimensions.	
Complexity Level 4 Subtle shading is heavily suggestive of 3-D form. The drawing will almost certainly be annotated. Colour may be used to illustrate certain parts of the concept or arrangement.	
Complexity Level 5 Extensive use of shading to suggest 3-D form. Annotations will be used to ask questions of the idea or explain it. Colour will be heavily used. Generally a very busy drawing - many lines will be used in its construction.	

Figure 1 McGown et al. (1998) Levels of Complexity Scale

The scale has subsequently seen use as a means to measure the quantity of information present within design representations (Alcaide-Marzal, Diego-Más, Asensio-Cuesta, & Piqueras-Fiszman, 2013); to support an analysis of the content of automotive sketches (Tovey, Porter, & Newman, 2003); and to explicate the complexity of designers' sketches in a study that explored the relationship between complexity in design representation and the number of sketches produced (Chen, 2004).

McGown et al's (op cit) original complexity scale (Figure 1) has provided opportunities to quantitatively assess the information present within design representation. Much existing work related to investigations of and into design representation has also focused upon understanding their use and significance through an objective analysis of the characteristics of individual instances of representation. The taxonomy developed by Pei et al. (2011) describes design representations in terms their various characteristics and relates this to the kinds of activity they support. Pei et al's. (ibid) systematic classification provides an indication of the nature of design activity as various design representations are employed, from the ambiguity of a thinking sketch to the high fidelity of a pre-production prototype. The study is indicative of the information exchanged during each stage in the design process, form divergent, conceptual exploration to convergent specification during detail design. Similar to Pei et al (op cit), Alisantoso et al's (2006) description and classification of design modelling methods through clustering suggests a set of guidelines to support practitioners in their choice of appropriate models. In research by Schenk (2007) a taxonomy of design drawings based upon their use is presented. The study proposes the use of the taxonomy which characterises, classifies and analyses drawings will help less experienced designers understanding the nature of design drawing. In contrast, Gershenson and Stauffer (1999) develop a taxonomy to deal with the design requirements of product design in a more effective way. Their system of classification aims to contribute to the product design process through gathering and managing design requirements which are then deployed in defining product specifications.

Existing research employing taxonomy as a means to identify, describe and classify design representation indicates the advantages of classification. Through classification, hierarchy and relationships among taxons, dimensions or categories may be identified with the potential to develop a richer, more holistic understanding of design representation, its role and use.

However, this study provides evidence to suggest the limitations of the identification and classification of representation through methods that employ objective quantification and analysis. Namely, we provide evidence to indicate the limitations of the complexity scale (Figure 1) as a means to identify and classify complexity within design representation. The study suggests that, although objective observation and logical analysis provide opportunities to clearly define complexity within design representation, the subjectivity inherent in the qualitative application of the complexity scale make uncertain its reliability as a means to define representation and validity it as a tool for classification. As such we speculate that the measurement of complexity through the quantification of features and elements as a means to describe and taxonomise design representation is limited by the subjectivity required in the application of any such scale and taxonomy. Moreover, we suggest the limitations of the quantitative, objective approach provides evidence to indicate the wider limitations of a rational, classical sciences model of design practice; or a science of design (Simon, 1996). In contrast we speculate that the limitations of the scale’s application provide further evidence to support a constructionist view of human perception and thought during design activity. Rather than complexity existing a prior within a design representation to be objectively measured and explicated by quantitative means, the extent of complexity is critically determined by the designer’s own reflection upon representation. As such, understanding complexity, or any other principle or phenomena within design representation, and so extending our knowledge of design practice, requires an exploration of the skills and experiential knowledge present in the construction of and reflection upon design representation (Visser, 2006, 2009). This exploration may require methods that best capture the interaction between designer and design representation to provide knowledge and understanding of representation as it relates to situated thoughts and actions; as it is experienced by the design practitioner.

Aims

The work presented here forms part of a larger study aimed at contributing to an understanding of the role and significance design representation plays in designerly thought and action (Kim et al., 2013). The study aims to contribute to existing attempts to classify design representation as a means to consider their role and significance for design practice. With these aims in mind, the study addresses the following research questions:

> How effective are methods of taxonomic classification in the identification, description and categorisation of design representation?
>
> What can an analysis of the effectiveness of taxonomic classification tell us about the nature of design representation and the kinds of thinking and action it supports?

The reflection upon and communication of design intentions, through design representation, appears to be critical to the kinds of thinking and actions performed during design practice (Buxton, 2007; Cross, 2007; Goldschmidt & Porter, 2004; Visser, 2006). In addressing the research questions above, the authors seek to contribute to a growing body of work which aims to understand designerly ways of thinking, knowing and acting through the investigation of design representations, their significance, role and use. Contributing to this wider aim and scope, the paper presents results of an analysis of complexity within various design representations using an existing complexity scale.

Methods

A qualitative content analysis was conducted in an attempt to measure and analyse levels of complexity within the various design representations presented within 50 case-studies of design practice published in Bjornlund et al., (2001) and Haller and Cullen's (2004). The 50 case studies present and describe the use of design representation by practicing designers through images of sketching, visuals, drawings and prototypes of varying degrees of fidelity taken from live design projects. These 50 cases constituted the study's units of analysis. Figure 2 illustrates the segmented representations of one of the 50 units of analysis (case-study 12).

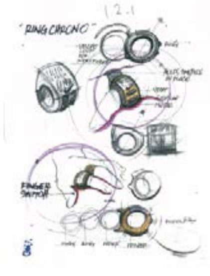
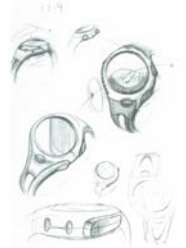
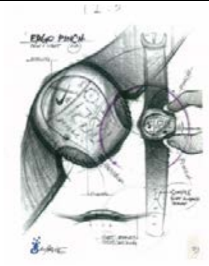
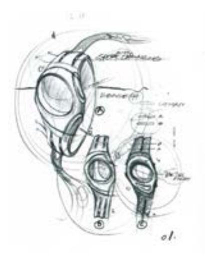
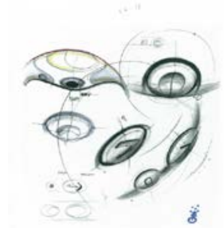
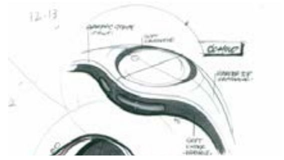
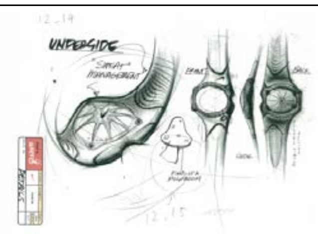
Seg. No.	Unit of Analysis (Representation)	Seg. No.	Unit of Analysis (Representation)
12.1		12.8	
12.2		12.9	
12.3		12.10	
12.4		12.11	
12.5		12.12	
12.6		12.13	
12.7		12.14	

Figure 2. Segmented representations of one of the 50 units of analysis

In a previous study the same 50 units of analysis were used to define and classify the attributes of design representations (Kim et al., 2013). As such, the instances of design representation were previously segmented using thematic criterion. That is, images of design representations and their associated captions were segmented into units of coding according to the different attributes of the representations presented in the case-studies. In order to reduce the likelihood of subjectivity in the segmentation of the design representations, a sample of representation (10 case-studies) were segmented into units of coding by 2 coders individually. Any differences in segmentation were then discussed. This process resulted in 419 segmented representations across the 50 case-studies. These 419 constituted a previous study's units of coding. For the current study, the same units were revisited and reviewed by 2 coders in order to assess their segmentation. As a result the 419 units were reduced to 362. Segmented examples of design representation were excluded where it was found to be unclear if the image was in fact a photograph of the final product, rather than a high fidelity prototype for example.

In order to assess the level of complexity present within each of the 362 segmented units of coding, a levels of complexity scale, first developed by Mcgown et al. (1998) and Rodgers et al. (2000), and slightly adapted by first Tovey et al. (2003) and later by Alcaide-Marzal et al. (2013) was used as the bases for the categories or 5 dimensions of a coding frame (Figure 1). That is, the criteria for assessing levels of complexity were the extent to which coders considered a segmented unit of coding to agree with 1 of the 5 complexity levels. As such, the coding of the segmented design representation required the element of subjective interpretation present in any qualitative content analysis. However, attempts were made to mitigate the inherent subjectivity in the application of the coding frame through the coding of representations at separate times by different coders.

Each of the 362 units of coding was assigned to the coding frame's 5 complexity dimensions by two coders at separate times. Both coders received the same description of the aims of the study: to assess the complexity inherent in various design representations through the application of the 5 level complexity scale. Both coders were research assistances within the same research group at the same institution. Both had equivalent education and experience of design and the use of design representations. In terms of their level of expertise, both fell into the category of 'Advanced Beginner' as defined by the Dreyfus and Dreyfus (1980) model of skills acquisition.

Coding proceeded from case 1 to case 50 until all 362 units of coding had been assigned to 1 of the coding frame's 5 dimensions. The absolute frequencies of coding along the 5 complexity dimensions were then compared to assess inter-coder reliability. That is, coder 1's coding performance was compared with coder 2's to assess the reliability of the complexity levels (their ability to describe complexity in design representation) and the validity of the coding frame (its ability to classify design complexity). Finally inter-coder agreement was compared between the different types of representations present within the 362 units of coding. This comparison resulted in the identification of a relationship between conceptual and developmental representations and an increase in disagreement between coders.

Results, Levels of Complexity

Table 1 illustrates frequencies of agreement between 2 coders as 362 units of coding were assigned to the 5 dimensions of the complexity coding frame (*n=362*). Frequencies are shown as absolute (*Frequency f*), proportionate (*Proportionate f*) and as a percentage (% f).

Complexity Agreement	Frequency (f)	Proportion f	% f
Agreement	159	.439	43.9%
Disagreement, 1 Level of complexity	142	.393	39.3%
Disagreement, not coded & coded	37	.102	10.2%
Disagreement, 2 levels of Complexity	24	.066	6.6%
	n = 362	Sum = 1.00	Sum = 100

Table 1. Frequencies of agreement between 2 coders

As Table 1 illustrates the absolute frequency of agreement between coders was 159 (*f=159*); a percentage frequency of 43.9 *(%f=43.9*). Disagreement of 1 level of complexity between coders was 142 (*f=142*) or 39.3% (*%f=39.3*). For example, coder 1 coding at complexity level 1 compared to coder 2 coding the same unit at level 2. Units of coding coded by one coder (along any of the 5 complexity dimensions of the frame), but not coded by the other coder, were identified at a frequency of 37 (*f=37*) or 10.2% *(%f=10.2*). Finally, disagreement in the assignment of units of coding by 2 levels of complexity between coders were identified at a frequency of 24 (*f=24*) or percentage frequency of 6.6% (*%f=6.6*). As Figure 3 further illustrates, these results indicate limitations within the complexity coding frame in terms of its reliability as a means to identify complexity within design representation and validity in its ability to classify complexity along the frame's 5 dimensions.

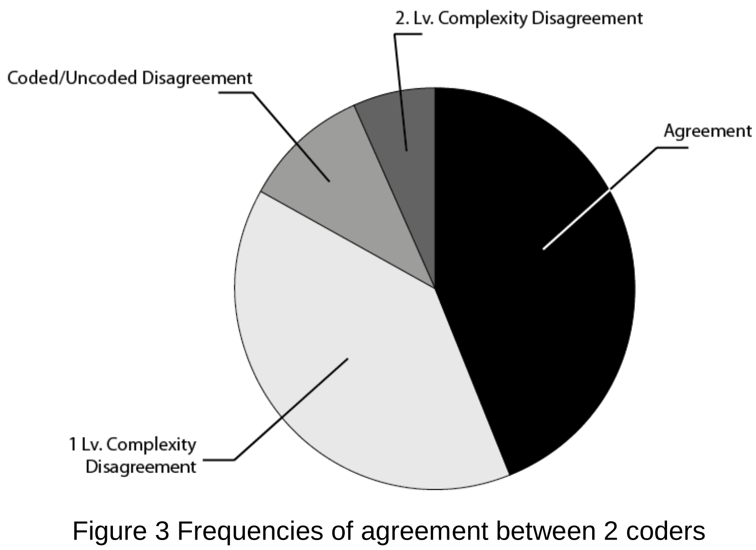


Figure 3 Frequencies of agreement between 2 coders

In terms of inter-coder agreement, results show a percentage frequency of 43.9% *(% f=43.9*) or a frequency of 159 (*f=159*) instances of units of coding assigned to the same dimension of the coding frame. However, the frequency with which disagreement in the assignment of units occurred also provides evidence to suggest the level of interpretation required in the assignment of units. This suggests that the explication and classification of complexity within design representation through objective quantification of the characteristics of complexity within instances of representation is unstable. That is, assessing complexity within design representation using existing complexity scales requires a level of subjective judgment that makes the scale unsuited to the purpose. Table 2 illustrates the frequency distribution of disagreement by 1 level of complexity across the 5 complexity dimensions of the coding frame.

Disagreement, 1 Level of Complexity	Frequency (f)	Proportionate (Prop f)	% f
Complexity level 1 to 2	24	0.169	16.9%
Complexity level 2 to 3	46	0.324	32.4%
Complexity level 3 to 4	31	0.218	21.8%
Complexity level 4 to 5	41	0.289	28.9%
	N = 142	Sum=1.0	Sum=100

Table 2. Frequency distribution of disagreement by 1 level complexity

Of the 142 instances of disagreement (*n=142*) the greatest frequency of disagreement was found where one coder assigned units of coding as complexity level 2, while the other assigned the same units to complexity level 3 *(% f = 32.4%),* followed by Levels 4 and 5 *(% f = 28.9*), levels 3 and 4 *(% f=21.8*) and 1 and 2 *(%f=16.9*). These findings provide evidence to suggest the different rates of reliability between the coding frame's 5 levels of complexity as measures to describe and classify complexity within representation. That is, complexity classified from levels 2 to 3 and 4 to 5 was resulted in greater frequencies of disagreement compared to levels 1 to 2 and 3 to 4.

Results, Levels of Complexity & Representation Types

Subsequent to the analysis of agreement between coders, the data was analysed to explore possible relationships between agreement rates and the types of representation present in the study's 50 units of analysis (50 design case-studies). That is, the authors explored any association between the kind of design representation coded and the frame's reliability and validity in the identification and classification of complexity.

This was achieved through the use of findings from a previous study, which built upon work attempting to identify and classify design representation through taxonomy (Kim et al., 2013; Pei et al., 2011). Within Pei et al's (2011) study design representations are classified within a staged model of design development, derived from a review of models of design process (Pei et al., 2008). In this previous investigation the same 362 units of coding were classified in terms of where within a process of design development they were most often used. Following existing staged models of the design development process, the 362 units were classified as concept, development, embodiment or detail design representation. This previous staged classification of the 362 units of coding classified each of the 362 units as instances of Concept Representation (*n=115*), Development Representation (*n=179*), Embodiment Representations (*n=42*) and Detail representation (*n=26*, Table 2). These classifications are used in the present study to explore associations between agreement rates and the kinds of representation present within the study's 50 units of analysis.

Categories of Agreement / Types of Representation	Concept Rep.	Development Rep.	Embodiment Rep.	Detail Rep.	
Agreement Frequency (f)	58	67	24	10	N= 159
Agreement % f	50%	37%	57%	38%	
One level **Disagreement** (f)	50	83	7	2	N= 142
One level **Disagreement** % f	43%	46%	17%	8%	
Two levels **Disagreemen**t (f)	5	11	6	2	N=24
Two levels **Disagreement** % f	4%	6%	14%	8%	
Coded/ Not coded (f)	2	18	5	12	N=37
Coded/Uncoded % f	2%	10%	12%	46%	
	N=115 Sum=100	N=179 Sum =100	N=42 Sum =100	N=26 Sum =100	Total: 362/362

Table 3 Categories of Agreement vs. Representation Types

Percentage frequencies of agreement were then calculated for each of the 4 representation types. That is, percentage frequencies for the 4 types of representation were calculated for each of the 4 categories of agreement presented in Table 1 and repeated in Table 3 above (Agreement % f, One Level Disagreement % f, Two Level Disagreement % f, coded/Uncoded % f). Calculations of percentage agreement frequencies (*% f*) were achieved using the following formula: *% f = f/n x 100*. This resulted in 4 % frequencies for each of the 4 types of representation (Figure 5).

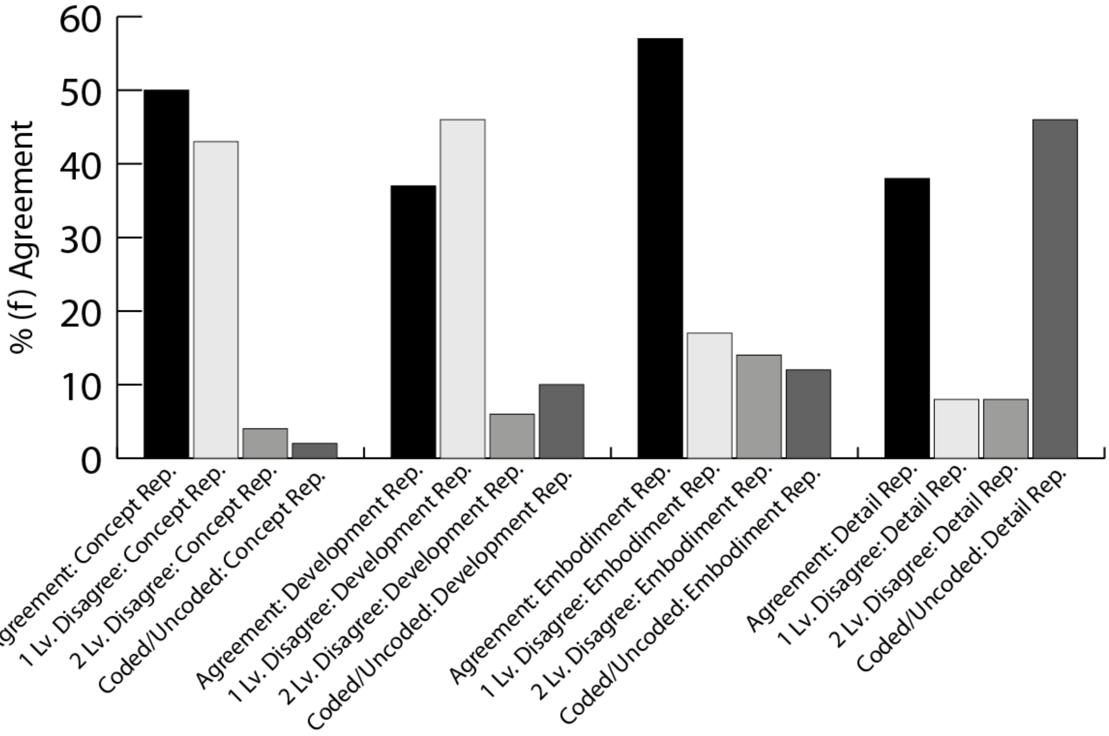


Figure 4 Percentage frequencies (% f) for 4 types of design representation, concept (left) to detail representation (right)

As Figure 4 indicates, there appears to be little association between inter-coder agreement and the type of representation coded (Black bar, Figure 4). That is, agreement between coders was identified across the 4 representation types at similar percentage frequencies (*Agreement: Concept Rep. %f=50, Agreement: Development Rep. %f=37, Agreement: Embodiment Rep. %f=57, Agreement: Detail Rep. %f=38%*). This suggests that the type of design representation coded for complexity has little effect upon the frequency with which coders agree. That is, the frequency with which agreement between coders was reached was not dependent upon the type of representation being assessed for complexity.

In contrast, the percentage frequency coders disagreed by one level of complexity differed between those units of coding classified as Concept and Development representations and those defined as Embodiment and Detail (white bar, Figure 4). The percentage frequencies of 1 level disagreement for design representation classified as conceptual or developmental were comparatively high (*1 Lv. Disagreement: Concept rep. %f=43, 1 Lv. Disagreement: Development Rep. %f=46*). In contrast percentage frequencies of 1 level of complexity disagreement were lower for representation classified as Embodiment or Detail (*Agreement: Embodiment Rep. %f=17%, 1 Lv. Disagreement: Detail rep. %f=8*).

This may indicate a relationship between disagreement by one level of complexity and the type of representation coded. That is, those representations classified as Concept or Development attracted higher levels of disagreement compared to Embodiment and Detail representations. This is indicative of a relationship between the assessment of complexity within conceptual and developmental representations and the reliability and validity of the complexity coding frame as a means of identification and classification. It may be that an objective quantification of complexity is less reliable in the identification and classification of complexity within conceptual and developmental representation. This then provides evidence to suggest the subjectivity required to assess complexity is also dependent upon the type of representation being evaluated. These results may point to the greater interpretation required in the assessment of complexity within concept and developmental representations. If this is the case, it is important to consider the implications this has for the assessment of representation through objective, quantitative means. It appears the individual's perception of complexity is subject to a personal interpretation of representation, and that the level of interpretation may be influenced by the type of representation used.

In contrast to 1 level disagreement, results indicate no association between disagreement by 2 levels and the kinds of representation coded. That is percentage frequencies of 2 level disagreement across the 4 types of representations were more similar than 1 level of disagreement (*2 Lv. Disagreement: Concept Rep., %f=4, 2 Lv. Disagreement: Development Rep., %f=6, 2 Lv. Disagreement: Embodiment Rep., %f=14, 2 Lv. Disagreement: Detail Rep., %f=8*).

Finally, findings indicated a similar trend for disagreement related to coded and uncoded units. That is, across the 4 representation types a similar percentage frequency was observed for those representations coded by one coder but not the other (Figure 4). This was true with the exception of detail representation, which indicated a far greater percentage frequency for Coded/Uncoded representations (*Coded/Uncoded: Detail Rep., %f=46*). This may be explained by the response of the coder to the identification of this anomaly. It appears that the coder made a unilateral decision rule not to code units of coding perceived to be technical or detail parts drawings.

Discussion & Conclusions

These results provide evidence to suggest issues with the levels of complexity in their ability to objectively quantify the complexity of design representation. Moreover, findings indicate design representation associated with conceptual and developmental design, as opposed to detail design, are most resistant to assessment through objective quantification. Why conceptual representation defies rational, objective analysis and objective interpretation is still unclear.

However, results provide evidence to indicate the limitations of quantitative, objective methods in defining and classifying design representation, particularly those often used during conceptual design. The assessment and measurement of the characteristics of design representation is associated to and influenced by the designer's own subjective reflection upon and interpretation of the representations they construct (Visser, 2006). We speculate that, due to the subjective interpretation inherent in the construction and use of representations as tools for design, any attempt to identify and classify the characteristics of design representation (complexity included) must account for the designer's own personal construction of reality through the reflective conversation (Schon, 1983) with tools of design representation.

There is little doubt design representation plays a critical role in the practice of design. Further studies are now required to understanding and define representation. These studies must however investigate representation as it is experienced as a means to provide further insights into the human activity of design. That is, how does the subjective interpretation of design representation influence the ways in which their complexity is experienced and understood? What influences objective interpretation of more conceptual design representation and what implications may this have for the ways in which they support designerly ways of thinking and knowing?

We position these findings as further evidence of the limitation of a notion of design as a rational problem solving process (Simon, 1996). We suggest a classical sciences approach to the analysis of the character of design, through quantitative objective observation, does not account well for the designer's own personal and subjective interpretation of design representation. Any attempt to measure, define and classify the characteristics of design representation, particularly conceptual representation, must account for the 'artistry of design'; the personal, more subjective and interpretive dimension of designerly activity.

Looking at design through the lens of reflective activity (Schon, 1983) or conversation with the situation (Lawson, 2004), design practice may best be described as a constructed experience; highly sensitive to the skills, knowledge, experiences and personal interpretation individual designers bring to the externalisation, development and communication of design intent. This study has indicated the role of subjective perception as an influence upon how conceptual design representation is experienced by individuals with similar design skills and backgrounds. As such, the study provides evidence to indicate how interpretation of complexity is not only dependent upon the inherent, physical properties of the design representation; its levels of complexity as existing in the world ready to be experienced and classified. Instead the study indicates how, in order to better understand representation as it relates to designerly ways of thinking and knowing, representation must be investigated as an activity rather than an outcome. Studies must take a constructionist approach to the exploration of design representation that attempts to understand their significance for design by going beyond the interpretation and classification of their inherent features.

This study achieves an illustration of how perceptions of design representation are dependent upon subjective interpretation. As a result we propose a fundamental requirement of research into design practice is the use of theory and methodologies which account for and build upon design as an experiential act of doing and knowing.

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