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What Constitutes Good Design? A Review of Empirical Studies of Design Processes*

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The authors conducted a meta-analysis in which they sampled over 40 journal articles of empirical studies of the design process. The articles were selected from several journals that are indexed in PsychInfo. They were reviewed and indexed according to whether or not those articles mentioned and/or focused one or several of 15 common design process elements. These elements consist of a bootstrapped framework that the authors constructed from past experience in studying the design process and from validation from literature. The coding was conducted by an additional expert in design, and the results were shown to have reliability greater than 80%. The results show which elements of the design process have been studied most frequently, and of those studied, which were documented to contribute to an effective design outcome. Both the framework and the coding outcomes contribute to a stronger understanding of the overall design process that relies upon existing, more fine-grained empirical studies of design.

Keywords: design processes; meta-analysis; design outcomes.

BACKGROUND

WHAT CONSTITUTES good design? For this article we surveyed and reviewed over 40 journal-published, empirical studies and case studies of design in order to derive a common set of reported design process elements. Further, we explored this same literature from the perspective of which elements are reported to be associated with good (effective) design practice. The intentions of this effort are to offer a common set of effective design process steps and to focus attention onto areas of design that require additional exploration or investigation. The point of identifying the design process elements in this paper is to take a meta-perspective on empirical approaches that have looked at design and have documented observable, describable design activities.

What are some reasons for taking such a meta-perspective to understanding good design? First, there are a number of published empirical studies on various parts of the design process. Such empirical approaches typically focus in-depth on a particular aspect of design and attempt to situate that aspect in a larger design context. Studies of this type lend themselves to providing quality data about these particular aspects. The value of these studies can be extended if their findings can be assembled into a broad, integrated perspective. The end result of this exercise ought to be a common set of effective design stages that can be useful for practitioners of design and for organizations whose practices rely upon effective design processes. Such is the case especially for organizations that specialize in innovative design, for which new contexts, markets, and products emerge and shape worldwide practice.

Second, an integrated, meta-perspective on design based on previous empirical studies can focus attention onto understudied areas in the design process. Not all aspects of the design process have been studied or documented empirically at equal degrees of depth or breadth. As it may turn out, the landscape of empirical studies of design can point to areas in which further exploration can generate more understanding of effective design practice.

Third, a more integrated, meta-perspective on design can point to ways for which design can be used as an effective vehicle for learning. Design-based learning has been explored as a way to engage students to enhance their abilities to solve real-life problems and to reflect on their learning processes. This style of active learning is an extension of project-based learning, which is argued to enable students to relate problems to science concepts [1, 2]. Design-based learning differs from project-based learning in that, in addition to constructing and building, students engage in a design and planning process that follows engineering design. The ability for learning science researchers to anchor their evaluations of design-based projects can be informed by having a validated framework for design that considers multiple, integrated aspects of the overall design process. Such a study can also permit learning science evaluations of design to consider how different learning styles [3] can be engaged at various stages of the design process from an overall design process perspective.

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Finally, in terms of engineering education, design has become explicitly recognized as an important outcome of what undergraduate engineers need to experience and to achieve [4]. Specifically, Criterion 3 of accreditation standards states that their program must demonstrate that their graduates must have:

b) an ability to design and conduct experiments, as well as to analyze and interpret data;
c) an ability to design a system, component, or process to meet desired needs [4].

In addition, Criterion 4 specifies that an engineering student's professional development must include a major design experience that integrates much of their earlier skills, coursework, and standards:

b) One and one-half years of engineering topics, consisting of engineering sciences and engineering design appropriate to the student's field of study. . . . Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs [4].

An examination of previous empirical design aspects in order to identify which contribute to good design can serve as a way for engineering professions to re-examine design education in order to emphasize the aspects of design that lead to effective design.

A meta-analysis of a design process can also highlight in greater specificity what has been documented to show the uniqueness of the type of thinking that is associated with design. Herb Simon emphasized that design mainly involves thinking about the artificial in a process involving mostly synthesis, whereas other types of thinking, such as scientific inquiry, focus more on analytical thinking. Design is also a highly goal-directed enterprise in the pursuit of a normative outcome. What designers produce is the result of making clear an outcome that embodies some attributes that can be specified but also have not yet been achieved. Design places more emphasis on the functional nature of what is being produced. It also involves the functional decomposition of an overall design outcome, so that these functional aspects can be examined separately and later integrated into a functional whole. Finally, design involves a large degree of symbolic manipulation and representation in order to explore complex relationships among various aspects of a particular design [5].

FRAMEWORKS ON DESIGN

One place to start a process of constructing evaluating a set of design elements involves looking at some other frameworks that discuss the design process. Simon [5] proposed what knowledge needs to be taught so that a true science of design can emerge:

1. Frameworks for rational choice among given alternatives (e.g. Utility theory, decision analysis, statistical modeling)
2. Procedures for optimizing among alternatives (e.g. linear programming)
3. Effective methods for searching space of solutions for 'satisficing' goals and constraints
4. Effective, or satisfactory, allocation of resources for searching among alternatives, including partial paths of searches [5].

In addition, Simon advocated exploring alternative representations of design problems. The authors have considered these elements of design when they began compiling a list of common design elements.

Techniques and frameworks from systems analysis and design also provide some past insights into key stages in designing large-scale systems. For example, Gibson [6] wrote that the process of systems analysis and design consists of seven stages that rely upon interaction and iteration among these stages:

1. Determine the goals of the system
2. Construct meaningful indices of performance
3. Consider alternate candidates for solutions
4. Rank alternatives
5. Validate solutions
6. Iterate
7. Take action [6].

These two frameworks reflect some of the disciplinary origins of the authors, who have pooled their expertise in the areas of studying the cognitive science of design and systems analysis and engineering in order to begin a bootstrapping process for identifying and validating a common set of design elements.

The order in which the design process elements identified in this paper are presented should not be taken as a descriptive or normative representation of the way in which the design process proceeds in practice or as observed in an educational task setting. As Mawson [7] argues, sequential models of the design process tend to be misrepresentations of the way practitioners actually do design, and they do not offer a useful structure for the way that pupils learn design; instead, such models, which tend to be oversimplified, linear representations of design, serve as a useful 'administrative' function for teachers who may lack expertise in design activities. Portraying and teaching design as following a linear, or algorithmic structure therefore serves the wrong constituency in education.

The point of identifying the design process elements in this paper is to take a meta-perspective on empirical approaches that have looked at design and have documented observable, describable design activities. Although they are the result of clustering similarities, the categories are nevertheless representative of design activities. Identifying these elements serves to highlight which activities get the attention of researchers reporting on case studies and empirical studies of design.

METHODOLOGY

The authors began the process of identifying and clustering design process elements/stages from their past experiences in cognitive studies of design and systems engineering design. The discussion of earlier frameworks by Simon [5] and Gibson [6] reflect some of the disciplinary origins of their initial thinking. These past experiences led them to consider sampling articles from several journals, mostly in *Design Studies* and *Cognitive Science*, to check the feasibility of identifying empirical studies of design and being able to characterize some of the design stages discussed in such articles. The authors next recorded a series of elements that they believed characterized the design process, an initial framework of design activity descriptors. This framework was used to code an initial set of five empirical journal articles in *Design Studies* and *Cognitive Science*. The framework was adjusted and re-clustered after extensive discussions on whether the identified elements were adequately descriptive, comprehensive, and distinct.

After this initial validation, additional articles were identified through a database search of PsychInfo using these keywords: design; engineering design; design process; design methodology; and cognitive analysis of design. The searches using these keywords located articles between the years 1993 and 2003.

From this initial set, the articles were screened briefly according to some basic criteria for inclusion. Articles that were included must be from a peer-reviewed journal and must involve an empirical investigation of design. The article needed to come from a journal in which a review of a design process represents a major interest in the community that would read such an article. The empirical analysis needed to emphasize the cognitive aspects of design, not personality issues.

COMMON DESIGN PROCESS ELEMENTS/STAGES

The bootstrapping procedure discussed in the previous section resulted in a set of 15 elements/stages commonly found in the design process. Each step represents a distinct aspect of a design activity. Each is mutually exclusive in terms of documenting a specific describable aspect of the design process. However, because a designer can be engaged in activities that have multiple goals and meanings, it is possible for more than one criterion to be applicable at a time; for example, if a designer is working on framing what problem needs to be solved (Explore Problem Representation) while using a sketch (Use Graphical Representation), two design aspects are applicable. The design aspects are thus mutually exclusive in terms of defining specific aspects of design, but they are not necessarily mutually exclusive with respect to a particular event during the design process.

Explore problem representation

This design criterion refers to how designers go about framing the design task or problem. Framing the design task can involve defining or exploring a problem, issue, or artifact that needs to be analyzed, synthesized, investigated, or constructed.

The way in which designers construe their task can have an impact on what aspects of a design a designer emphasizes, on what solutions paths designers choose, and on which goals and constraints designers meet. This aspect of design can occur early in the design process when a designer or design team deliberates what their task really is or is about. However, designers can also decide in the midst of exploring a particular design that what he or she actually wants to make or solve is different from the way they previously construed it.

For example, Guenther *et al.* [8], reported that one of the differences between experienced designers, who had no university educational training or training in design methodology, and designers who did have university training in design methodology was that the former group generally pursued shorter design processes with narrower objectives and singular solutions. The latter group tended to spend more time exploring, clarifying, and changing the problem.

Another characteristic associated with exploring the representation of the problem involves devising or discovering when to stop pursuing the design or the problem; in other words, when the solution or design fits how the problem or design has been framed. Simon [5] has characterized the design process as an open-ended search process with no universal stopping rule at optimality; instead, design involves a process of 'satisficing', or deciding when a configuration is good enough to be called complete. Therefore, evidence that a designer is working on the problem representation involves instances in which the designer decides what the end product will be.

Explore graphical representation/visualization

Designers often use a strategy of representing some aspect of a design or design problem using graphics or visual media. The main distinction of this category involves the use of visual means to construct a representation, contrasting with a verbal representation (such as a list of requirements), a quantitative representation (such as a list of measurements), or other alternative forms of representation (such as kinesthetic, as in the case of a prototype or mock-up). Designers often sketch their ideas or use graphics software, such as a CAD program.

This criterion differs from the problem representation criterion in that framing the problem represents a broader focus on conceptual issues that can take form in various modes of representation, whereas the graphical representation criterion focuses on specific dimensions of a design task that have largely been constructed within a conceptual framework. Representing something graphically does not necessarily involve a stopping condition associated with final design requirements.

A designer often attempts to visualize details of a design in order to explore the design's overall configuration, the design's relationship to its context, or to explore some feature of the design in greater detail. Visual representations also can facilitate communication on a design team, and they also can structure interaction with end users who may be involved in providing input into the design process.

Use functional decomposition

Instead of focusing on what the designed artifact needs to do overall, a designer may decide to break down a design into several more-detailed aspects to investigate how they perform, interact, and contribute to the overall functionality.

The use of functional decomposition serves to simplify complex, confounding aspects of a design by isolating them to discover which have the most impact on the overall design's functionality.

Gary Bradshaw [9] has written about how the Wright Brothers used functional composition in their pursuit of designing aircraft and has argued that their strategic use of functional decomposition accounts for how they solved the problem of flight before others did. Instead of designing and building entire glider configurations and testing them, the Wright Brothers broke down the problem of flight into components such as providing lift through wing configurations, providing thrust using a powerplant and propeller combination, and providing stability and control using wing warping and movable control surfaces. The Wright Brothers were able to design and test each component separately and then reassemble their results into an overall design.

Explore engineering facts

A designer who explores engineering facts delves into a specific knowledge domain regarding some property of an aspect of a design.

The designer may do this in order to double-check what can be taken as a given; to pursue a desired, documented outcome; to articulate some common principles on which the design can be based or communicated to others; and to come to grips with what others have investigated related to the design.

For example, when Jay Forrester was designing the first electronically programmable memory systems for project Whirlwind, he explored the magnetic properties of magnetic-ceramic materials whose induced magnetic poles represented 1's or 0's of writable and retrievable information bits [10].

Explore issues of measurement

This criterion involves examining the way quantitative information is gathered relating to some aspect of a design.

Designers may question or explore methodologies they use to quantify aspects of their design to discover or determine whether more effective strategies for collecting quantitative information could improve their ability to make what they want to make.

For example, when engineers were designing the first stage F-1 engines for the Saturn V rocket, a design that leapfrogged previous designs in terms of thrust significantly, the engineers needed to design new test stands and acoustical equipment for eliminating combustion instability due to the resonant properties of the engine's geometry [11].

Build normative model

Designers may spend time articulating what the desired, ideal outcome of their design ought to look like. Such ideal outcomes constitute a normative representation or model of their design—what their design might look like if they were not constrained or limited. The term 'model' in this criterion includes multiple forms of representations—verbal, visual, tactual, physical, etc . . .

This criterion is different than 'Explore Problem Representation,' which can involve descriptions of any current conditions of the context of the design as well as desired outcomes, whereas 'Build Normative Model' involves only ideal or (imagination-based) optimal, not merely desired, outcomes for the design.

Normative model building can also apply to design process management, not just artifact representation. The fact that the criterion includes 'model' means that the designer(s) make some attempt at formalizing the desired outcomes. Formalizing requires some attempt at comparing, critiquing, and testing, in addition to articulating. Problem framing does not necessarily require this level of formality.

This criterion is important because oftentimes designers limit their solutions narrowly to what they believe are inviolable constraints and limitations. Building a normative model is different from redefining constraints or exploring the scope of constraints because the normative model involves the suspension of constraints in constructing an ideal outcome.

An example of a case that involved the building of a normative model includes Susan Lyons', Albin Kaelin's and William McDonough's design plans for a textile product and production system that eliminates the concept of waste by making the product benignly compostable and the production system with zero effluents. Such a conception proved valuable for this design team for constructing a successful product that achieved many goals at minimizing (and in many cases eliminating) environmental impacts [12].

Explore scope of constraints

After a designer or a design team articulates and accepts a particular frame of the design problem and a working set of goals for the design, the designer(s) typically face factors, or constraints, that limit how a design can fulfill these goals within that problem frame. These constraints may be conceptual or physical. Oftentimes, a designer may decide to investigate to what extent a constraint or set of constraints become salient. The activity of a designer spending effort to learn more about how constraints are affecting the design, falls under this 'explore scope of constraints' criterion.

This criterion is different from exploring the problem representation because exploring the scope of constraints does not involve a possible redefinition of the overall design goal or goals, whereas exploring the problem definition does. Instead, exploring the scope of constraints refers to a situation where goals and most constraints are fixed; only a few are explored.

For example, breaking the sound barrier for controlled, piloted aircraft was an effort that required a great deal of effort and design readjustments. The sound barrier represented the main constraint on controlled flight, and designers explored multiple configurations in order to determine which designs were able to meet the constraint of controlled supersonic flight.

Redefine constraints

This criterion describes the activity when a designer decides to investigate further what is involved with a constraint or set of constraints to reconfigure the way that that constraint or set becomes salient for the design. Instead of modifying the goals of the design and constraints (which would be the case when a designer is exploring the problem representation) or instead of focusing on one constraint to see to what extent it shapes a design, a designer may redefine a constraint in order to achieve an original goal, but by using a design that may not otherwise conform to the original constraint.

Ball [13] has summarized previous research efforts that investigated the way designers balance a structured design approach (by sticking with a plan of design goals and constraints) and an opportunistic approach (by switching the set of salient constraints to take advantage of an unexpected configuration or new information).

Conduct failure analysis

Not all designs fulfill their goals or desired outcomes. Designers oftentimes pay attention to when their designs fall short of their goals or do not meet performance expectations. They can be deliberate (systematic and purposeful) in their investigation of what the reasons were that caused a design to fail, or they can look at failures on a more ad-hoc basis to learn about them. Either mode counts as a failure analysis activity in design in this paper.

In addition, a design may not be failing with respect to a global set of performance criteria—there may be only a few dimensions of underperformance. Designers may also investigate failures with respect to this smaller set as part of failure analysis activity. In either case, the focus of this activity is to gather knowledge associated with what produces the failure. Treating failed designs as disconfirming cases of performance can be a learning strategy in this aspect of design.

There are many examples of analyses of failed designs. Doerner [14] reports that subjects who test more hypotheses and look at more failed designs tended to produce more satisfactory outcomes over time. Chiles [15] chronicles a long list of large-scale engineering failures, ranging from the Hindenburg to Apollo 13 to Three Mile Island and how designers can learn from such failures.

Validate assumptions and constraints

The flip side of learning from a disconfirming case of failure can be an investigation of success in order to gain more confidence in a design. Designers oftentimes test their designs in order to confirm that they are falling within constraints as expected and that the assumptions they made about the design appear to be holding true. Validation can also involve ensuring that the representation of the user's, or other stakeholder's expectations for the design appear to be met by engaging them in the design process at various stages.

Search the space (evaluate design alternatives)

This criterion describes a designer's actions to use some framework of performance criteria (goals and constraints) to search for and evaluate potential solutions for the design. Designers may use various strategies and procedures to guide this process.

Simon [5] characterizes design as a goal-directed, heuristic search process in which the goals are not necessarily fixed. Part of this search activity involves considering what alternative configurations can meet the current state of which goals and constraints are applicable. Ball [13] summarizes the debate on whether the search process consists of a structured process of breadth-first followed by depth searches for solutions.

Thomas Edison, in his quest to construct a lighting system that used high-resistance filaments in incandescent bulbs, searched an enormous number of alternative filament configurations and materials to find a filament that was stable, provided enough light, was economical, and was possible to manufacture. He eventually designed a lampblack carbon filament as the outcome of his search for a viable filament [16].

Examine existing designs/artifacts

This criterion describes a subset of activities of the previous criterion. Sometimes designers borrow solution ideas from designs that already exist and that relate to the design problem. They may also look at what has been done previously in order to improve upon those designs in various design dimensions. This criterion describes the activity of when designers spend effort looking at what alternatives exist relating to their design problem.

Follow interactive/recursive/iterative design methodology

This criterion describes cases in which designers can be documented to follow a design process that involves the purposeful jumping around through various aspects of design activities instead of sticking to a fixed sequential model of design. Oftentimes the jumping around comes from following a process that encourages interactions with other designers, other stakeholders, or other processes that initiates and/or structures the shifts in activities.

Explore user perspective(s)

In this design activity designers involve users in various aspects of the design process in order to capture their requirements and needs for the design's performance. Designers can engage users using past user knowledge and experience, structured interviews, mock-ups, simulations, prototypes, questionnaires, or final design configurations, among others.

Encourage reflection on design process (self-reflect)

Designers may spend time reflecting upon their own process that they used to achieve their production goal(s). Self-reflection can occur in the midst of the design activity or after the activity has been completed.

Donald Norman [17] has written about the importance of self-reflection in the process of solving problems and in developing expertise. Engaging in self-reflection initiates a process of restructuring and transforming experiential knowledge.

REVIEW PROCEDURE

The primary author conducted the review and coding of the journal articles. He discussed his results with the second author, who posed questions to clarify the way the articles were coded. After completing the complete set of over 40 articles, an additional expert in engineering design reviewed a sample of 11 articles from the set of 40 to validate the coding. This additional expert reviewed one sample article (not included in the database) as practice after which he was given feedback through discussion with the authors. The additional reviewer then proceeded to code two articles, after which the reviewer and the authors discussed the procedure once again in order to clarify the task and check the degree of correspondence. The additional reviewer then completed a review of ten randomly selected articles from the database, and the degree of correspondence of coding was shown to exceed 80 percent across all coding dimensions.

The coding procedure consisted of two main parts: characterizing the study and characterizing the findings relating to design. Both parts were accomplished using a spreadsheet template. For each article the reviewer was permitted to write down whatever notes that the reader thought would help him for the coding. The reader was permitted to re-read the article as many times the reader wished. The reader was permitted to fill out the template during the reading or at the end of reading. The reader was permitted to revise the ratings as desired.

Part 1 of the procedure/template consisted of items related to classifying the type of study in the article. The dimensions, along with possible values, consisted of:

Level of expertise in design

The minimum criterion of qualifying as an expert designer was 5–7 years. Novices typically constituted subjects with design experience ranging from college graduates in design to practitioners having 5 years of experience. Beginners were undergraduates who have not completed their degrees or others who had no formal training or experience in design.

Level of expertise in domain

The criteria for experts, novices, and beginners were the same as the experience levels in the Expertise in Design dimension. The actual coding of expertise in design and domain used the following conventions:

- Beginner = 0–1 years of prior experience; includes students just starting their educational exposure.
- Novice = 2–5 years of prior experience; includes senior students who are in their fourth year/senior year of education.
- Expert = people with more than 5 years of expertise.
- Expert/novice = a contrast study in which experts and novices are compared.
- Various = a study in which there are participants with multiple levels of expertise.

Type of task examined

The types of activities included in the survey spanned many different categories. Some of the more common tasks included software and new consumer product development. The actual coding used the following conventions:

- Engineering: includes mechanical, electrical, aeronautical, nuclear, civil, and other non-computer related engineering design tasks.
- Computer programming and software: includes software design and software usability tests; programming and theory of programming; and computer hardware design.

Real/artificial task?

A real task refers to a case in which the subjects of the studies were engaged in designing something to meet an actual need or outcome. For example, one of the software design tasks involved designing groupware for chemical engineering processes that would be used at a company. An artificial task refers to cases in which subjects were studied while engaged in a simulated activity. The coding followed this convention:

- Real = an actual design task in a practitioner setting.
- Artificial = a simulated design task or a problem constructed in an educational setting.

Type of study/methodology

This dimension captured the data gathering and processing strategies that the surveyed articles reported. The studies used such techniques as video, verbal, and/or written protocols, detailed case studies, ethnographic analysis, user interviews, among others. The ways in which the various protocols were encoded and processed were noted if any special techniques were used during these stages of data processing. The actual coding protocol consisted of:

- Case study = a documented reporting of a design process that does not involve specific protocol analysis.
- Verbal protocol only = voice conversation was recorded, coded and analyzed.
- Verbal + Other = voice and some other (video, written) type of protocol was used.
- Ethnography = a description that occurs at a greater level of detail than a case study, but does not involve recording participant actions beyond the writing of the researcher's observations, which become the raw data for analysis instead of a recording of the participants' voices, video, etc . . .
- Interviews (structured/unstructured) = the researcher interviews subjects to get them to report their experiences post-hoc.
- Video protocol only = recording of participants' actions on video tape and constructing a classification protocol from that record for analysis.
- Written protocol only = examining the drawings and sketches of participants using a classification scheme.

Group or individual?

If the subject engaged in their design task alone, then that activity was counted as an individual activity. If the subjects acted in a concerted effort, then they performed their design task as a group. Some of the studies examined designers working alone and within a group setting on the same task. These instances counted as having both individual and group activities.

Which part of design cycle?

Constructing this category required multiple revisions and reclassifications, because there is no accepted, standardized, meaningful and defined design cycle. The categories for this dimension were generated by using the design process designations that the empirical studies themselves mentioned as their focus. This strategy produced a wide span of categories, ranging from conceptual design, requirements definition, goal analysis, preliminary design, problem definition, and redesign, among other categories:

- Various = several parts of the design task.
- Preliminary design = involves working on the framing of the problem and the conceptual aspects of a design, including basic modeling.
- Preliminary design through coding = all the stages between working on framing the problem through writing computer code.
- Preliminary design through detail design = all the stages between working on framing the problem through working on the more specific features and/or aspects of a design.
- Preliminary design through prototype construction = all the stages between working on framing the problem, detailed design, through constructing a prototype.
- Preliminary design through release = all the stages between working on framing the problem through what it takes to get the product into the marketplace.
- Redesign = taking an old design and redesigning it to meet new specifications.
- Software usability = evaluating software using usability protocols or involving users in improving the product's performance.
- Requirement construction and testing = process for eliciting, defining, validating, and testing user requirements.
- Preliminary design through product testing = all the stages between working on framing the problem through testing a product.

Part 2 of the procedure/template involved coding what the study focused on and what the study reported as significant. There are four possible options for each of the fifteen design process elements discussed in the previous section. The four options are:

- +1 = factor reported as significant for good design. This means that the study focused on that particular design criterion and reported that

Table 1. Journals represented in the review database

International Journal of Human-Computer Interaction	10
Design Studies	8
Cognitive Science	3
International Journal of Man-Machine Studies	3
Behaviour & Information Technology	2
International Journal of Human-Computer Studies	2
International Journal of Technology and Design Education	2
Journal of Engineering Design	2
Applied Ergonomics	1
Ergonomics	1
Human-Computer Interaction	1
International Journal of Intelligent Systems	1
Journal of Applied Psychology	1
Learning and Instruction	1
Proc Instn Mech Engers	1
Thinking and Reasoning	1
Total	40

it is significant in terms of a positive impact on the design process.

- 0 = factor mentioned in study, but not reported as significant for good design. This code was used for factors mentioned in passing in the article, even if the factors were not the primary focus of the study.
- –1 = factor found not to correspond with good design (i.e., be actively bad). This code was used when a design factor was a focus of the paper and when the paper reported that the particular design element diminished good design practice.
- n/a = factor not mentioned in study

RESULTS

Overall, there were 40 articles that were reviewed and included in the analysis. The 40 articles represented 16 different journals, as is broken-down in Table 1.

Experts in both design and various domain areas were more heavily represented in the database and analysis. Tables 2a and 2b show the distribution of articles as broken down by levels of expertise.

Nearly half of the types of design tasks examined in the database consisted of engineering design tasks in mechanical, electrical, structural, civil, automotive, and other types of engineering. Nearly 40% consisted of design tasks associated with computer programming and software design tasks. The remaining articles consisted of various design tasks in architecture, branding, marketing, and other non-engineering or computer-related areas.

Of the 40 articles, 24 of them involved studies for which the subjects of study were engaged in a real design task for their analysis; 15 of the 40 articles involved subjects working on artificial tasks; and 1 article consisted of a study that included both real and artificial tasks.

Table 3 displays the distribution of the type of methodologies the empirical studies used for their analysis. The database has nearly equal representation of case studies; verbal protocol studies only; and verbal, video, and written protocol studies. The remaining quarter of the database is spread among ethnographic studies, interviews, video only, and written only protocols.

About half (21 out of 40) of the studies involved subjects working on individual tasks. 14 articles involved group tasks, and 5 of the articles involved studies using both individual and group tasks.

The articles disproportionately studied parts of the design process that are more often associated with the earlier stages of design. Mentioned earlier, the process of design in terms of thinking processes does not follow a linear path Mawson [7]; however, when examined from a perspective that traces how products make it from the idea stage through release to the marketplace, a linear representation can serve as a rough approximation of how such processes operate.

The results of the coding of the fifteen different design elements were categorized according to three different dimensions. First the results were categorized according to the frequency with which they were reported in the set of articles. This dimension consisted of three categories: high reporting, moderate reporting, and low reporting. A design element was included in the 'high reporting' category if it was mentioned as a focus in more than 50% of the articles included in the database. The element was considered to be in the 'moderate reporting' category if it was mentioned as a focus in 25% to 50% of the articles. Finally, elements that

Table 2a. Levels of expertise in design

Level of Expertise in Domain	Number of Articles
Beginner	1
Novice	5
Expert	21
Expert/Novice	5
Various	8

Table 2b. Levels of expertise in domain areas

Level of Expertise in Design	Number of Articles
Beginner	1
Novice	4
Expert	24
Expert/Novice	5
Various	6

Table 3. Methodologies used in the database articles

Case Study	11
Verbal Protocol Only	9
Verbal + Other	9
Ethnography	4
Interviews (Structured/Unstructured)	3
Video Protocol Only	2
Written Protocol Only	2
Total	40

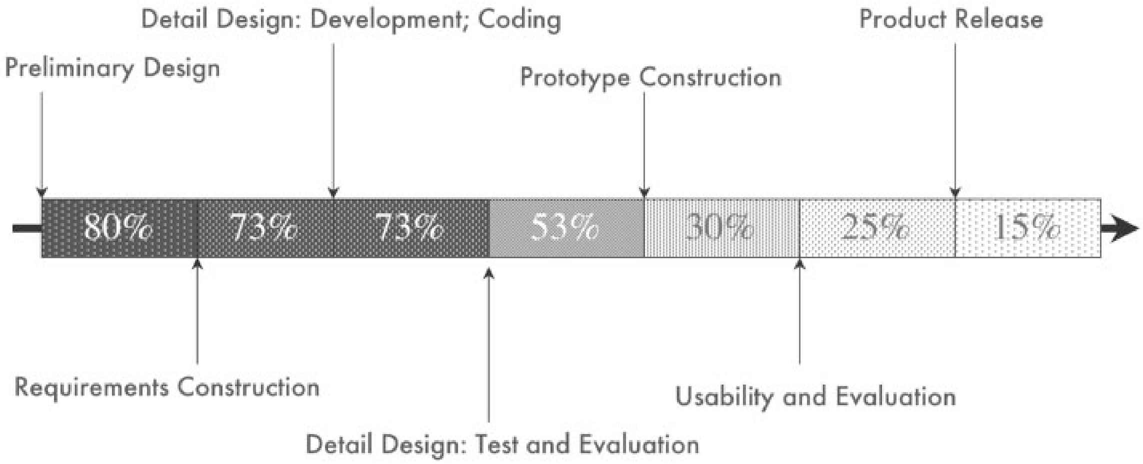

Fig. 1. Stages of the design cycle represented in the database.

were reported in fewer than 25% of the articles were considered to fall in the 'low reporting' category.

Second, of the elements for which reporting occurred as a specific focus (not just mentioned in passing) and the element was noted as being a factor for good/effective design, the articles were categorized according to whether the factor should be considered as significantly good for design, maybe good for design, or unlikely good for design. Articles that were mentioned as being good for design in over 75% of the times they were mentioned at all were considered to fall into the 'significantly good' for design category. Design elements that were mentioned as being good for design between 25% to 75% of the times they were mentioned at all were categorized as 'maybe good' for design. Finally, elements that were mentioned as good for design less than 25% of the time they were mentioned at all were categorized as unlikely good for design.

Third, of the elements for which reporting occurred as a focus, if the element was noted as being actively bad for design more often than good for design, then the elements was categorized as 'bad for design.' Not all combinations of this conditional structure eventually had elements in every possible category. Tables A1 and A2 summarize the results of the coding.

Tier 1: Design elements significant for good design (high reporting frequency)

The design elements that were reported with a high degree of frequency and were also categorized to be significant for good design are:

- Explore problem representation.
- Use interactive/iterative design methodology.
- Search the space (explore alternatives).

Based on this analysis, these three items were most often recorded in empirical studies that showed that positive design outcomes were associated with people who used at least one of these three strategies in their design process. An implication of this finding is that such design process steps should be emphasized in the process of becoming an expert (or in the actual expert practice) of design. Because the sample of journal articles included more experts in their empirical studies means that likely these three design elements are associated with expert design processes that are effective.

Tier 2: Design elements may be significant for good design (high reporting frequency)

One design element was categorized as may be significant for good design was:

- Use functional decomposition

This strategy was mentioned frequently in the database of articles; however, when it was mentioned, it was not always mentioned as associated with good design. There are several interpretations of this finding. One could be that functional decomposition is a necessary aspect of design (hence mentioned frequently); however, the strategy is not perceived to make a large difference in achieving what is thought to be good design. Another interpretation is that the studies included in the articles tended to not focus primarily on this particular design stage in an evaluation of the design process—the focus may have been elsewhere. Because functional decomposition occurs often in design, however, it still gets mentioned in the studies.

Tier 3: Design elements significant for good design (moderate reporting frequency)

Of the 15 design process elements, 6 were reported to be significantly good; however, the certainty of this designation is less certain because they were mentioned less frequently overall in the database of empirical studies. These 6 elements are:

- Explore graphic representation.
- Redefine constraints.
- Explore scope of constraints.

- Validate assumptions and constraints.
- Examine existing designs.
- Explore user perspective.

The items in this category can be further sorted if the sampling size of studies were increased. These items appear to be promising for what is associated with effective design. Confidence in this categorization can likely be increased if the database included a larger number of articles.

Tier 4: Design elements may be significant for good design (moderate reporting frequency)

One of the fifteen design elements was mentioned less frequently as associated with good design when mentioned, and was mentioned fewer times overall:

- Build normative model.

Perhaps the nature of design itself makes one automatically think that it is necessary to project a normative outcome or model of what is being designed so that this type of thinking gets less emphasized when thinking about good design.

Tier 5: Items requiring further study (low reporting frequency)

The low reporting frequency category reveals which design elements in the database may be valid candidates for further empirical study because of their low level of being mentioned in the database of articles. These elements are:

- Explore engineering facts.
- Explore issues of measurement.
- Conduct failure analysis.
- Encourage reflection on process.

In the database, there tended to be less emphasis on engineering content knowledge/facts in the empirical studies. Also measurement techniques were not often mentioned. The low reporting of these two items may be due to the types of journals considered in this analysis. In general, more in-depth engineering content and measurement technique knowledge tends to be reported in engineering journals for specific disciplines rather than as a focus in a design process study. However, this finding suggests that there is an opportunity for more in-depth studies for how deep domain knowledge impacts the effectiveness of design outcomes. In addition, few studies tend to focus on the importance of design failures for improving design outcomes or on the way that design practitioners reflect on what they do as a meta-cognitive strategy for improving the quality of design process outcomes. These two areas represent possible fruitful areas for additional empirical studies for how effectiveness in the design process can be achieved.

CONCLUSIONS

What do the results of this meta-analysis contribute to answering the question of what constitutes good design? First, the analysis began by constructing a framework of design process elements using a process that characterizes the design process into 15 different stages. Having such a framework provides a method for linking together separate empirical analyses of design that focus on specific parts of the design process, not on the whole. Thus, other excellent sources of data on parts of the design process can provide linked insights into a broader view of the design process. The use of the 15-element framework permits the question of what constitutes good design to be refined into what specific parts of design do empirical analyses of design tend to associate with good design. This more specific question has been answered in the results section of the paper, which points to specific elements of the design process that these empirical studies have most often identified as being associated with good design.

Second, the decomposition into 15 specific design stages also permits an assessment of which areas tend to receive more frequent levels of attention than others. Answering the question of what constitutes good design requires being able to point to areas in which there has not been enough research attention in order to answer that question unconditionally. Thus, the results in this paper distinguish between which aspects of design the existing literature tends to focus on, and which aspects can benefit from further attention in empirical study.

Third, from an educational standpoint, teaching of design ought to focus on elements of design that have been documented to have higher levels of impact for achieving effective design. Results from this study point to the fact that it might be better to emphasize the importance of framing a design problem, using an iterative strategy, and spending time searching for alternative solutions to try than to spend time on teaching the importance of articulating normative outcomes for a design process. However, this advice should be taken with caution, given the fact that so many of the design process elements had a low level of reporting in the literature. An alternative perspective based on these findings could also point to areas of design that have not received enough attention and therefore may be invisible in terms of cognitive recognition of their importance, but present and important nonetheless. Education about design could therefore involve spending time on learning about these less-reported aspects of design as a possible way to make the invisible more visible and perhaps make refinement of these areas possible.

Finally, none of the 15 design process elements were found to be actively bad in terms of their impact/role in the design process. In fact, there have been very few studies that have documented what aspects of common design practice impact the design process negatively. Understanding both the positive and negative dimensions of influences on design process outcomes can lead to a more comprehensive perspective on achieving effective design.

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APPENDIX A

List of articles included in database

Fricke, G. (1999), Successful approaches in dealing with differently precise design problems, *Design Studies* **20**(5) pp. 417–429.

Guenther, J. a. K. E. (1999), Comparing designers from practice and designers with systematic design education, *Design Studies,* **20**(5) pp. 439–450.

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Table A1. Coding of the database articles

Article	Level of Expertise in Design	Level of Expertise in Domain	Type of Task Examined	Real/Artificial Task?	Type of Study/ Methodology
a. Fricke, Gerd	Novice	Various	Engineering	Artificial	Video Protocol Only
b. Guenther, Joachim et al	Various	Various	Engineering	Artificial	Verbal Protocol Only
c. Adams, Robin S. et al	Beginner	Beginner	Various	Artificial	Verbal Protocol Only
d. Baird, F.	Expert	Expert	Engineering	Real	Ethnographic
e. Lloyd, Peter	Various	Various	Various	Real	Verbal Protocol + Other
f. Jagodzinski, P. et al	Various	Various	Computer Programming and Software	Real	Ethnographic
g. Ball, Linden	Various	Various	Computer Programming and Software	Real	Ethnographic
h. Ball, Linden et al	Expert	Expert	Computer Programming and Software	Real	Verbal Protocol Only
i. Lee, Adrianne and Nancy Pennington	Expert	Expert/Novice	Computer Programming and Software	Artificial	Video Protocol Only
j. Sobiesiak et al	Expert	Expert	Computer Programming and Software	Real	Case Study
k. Sawin et al	Expert	Expert	Computer Programming and Software	Real	Case Study
l. Ominskt et al	Expert	Expert	Computer Programming and Software	Real	Case Study
m. Healey and Herder	Expert	Expert	Computer Programming and Software	Real	Case Study
n. Kamper, Robert J.	Expert	Expert	Computer Programming and Software	Real	Case Study
o. Gruen, Dan et al	Expert	Expert	Computer Programming and Software	Real	Case Study
p. Wolf, Martin et al	Various	Various	Computer Programming and Software	Artificial	Video Protocol Only
q. Moreno-Munoz, Antionio	Expert	Various	Computer Programming and Software	Real	Interviews
r. Hall, roger	Expert	Novice	Computer Programming and Software	Real	Case Study
s. McFadden, Edward et al	Expert	Expert	Computer Programming and Software	Real	Case Study
t. Rist, Robert	Novice	Novice	Computer Programming and Software	Artificial	Verbal Protocol + Other
u. Schraagen, Jan Maarten	Expert/Novice	Expert/Novice	Other	Artificial	Verbal Protocol Only
v. Suwa, Masaki et al	Expert	Expert	Other	Real	Written Protocol Only
w. Goel and Pirolli	Expert	Expert	Various	Real	Verbal Protocol Only
x. Visser	Expert	Expert	Engineering	Real	Verbal Protocol Only
y. Guindon	Expert	Expert	Engineering	Artificial	Verbal Protocol + Other
z. Adelson and Soloway	Expert	Expert	Computer Programming and Software	Artificial	Verbal Protocol Only
aa. Guindon	Expert	Expert	Engineering	Artificial	Verbal Protocol + Other
ab. Rist, Robert	Expert/Novice	Expert/Novice	Computer Programming and Software	Artificial	Verbal Protocol Only
ac. Ball et al	Novice	Novice	Computer Programming and Software	Real	Verbal Protocol + Other
ad. Hill, Anne Marie	Novice	Novice	Engineering	Real	Case Study
ae. Davies, Simon P.	Expert/Novice	Expert/Novice	Computer Programming and Software	Artificial	Written Protocol Only
af. Burns, Catherine M. and Kim J. Vincente	Expert	Novice	Engineering	Real	Ethnographic
ag. Etelaepelto, Anneli	Expert/Novice	Expert/Novice	Computer Programming and Software	Real	Verbal Protocol + Other
ah. Hill, Anne Marie	Various	Various	Various	Real and Artificial	Case Study
ai. Busby, J. S. and K. Payne	Expert	Expert	Engineering	Real	Interviews
aj. Sonnentag, Sabine	Expert	Expert	Engineering	Artificial	Verbal Protocol + Other
ak. Sonnentag, Sabine	Expert/Novice	Expert	Engineering	Artificial	Verbal Protocol + Other
al. Dwarakanath, S. and K. M. Wallace	Expert	Expert	Engineering	Artificial	Verbal Protocol + Other
am. Busby, J. S.	Expert	Expert	Engineering	Real	Interviews
an. Lai, Jennifer et al	Expert	Expert	Computer Programming and Software	Real	Case Study

Article	Type of Study/ Methodology	Group or Individual?	Which Part of Design Cycle?
a. Fricke, Gerd	Video Protocol Only	Group	Various
b. Guenther, Joachim et al	Verbal Protocol Only	Individual	Various
c. Adams, Robin S. et al	Verbal Protocol Only	Individual and Group	Various
d. Baird, F.	Ethnographic	Group	Various
e. Lloyd, Peter	Verbal Protocol + Other	Individual and Group	Various
f. Jagodzinski, P. et al	Ethnographic	Individual and Group	Various
g. Ball, Linden	Ethnographic	Individual and Group	Various
h. Ball, Linden et al	Verbal Protocol Only	Individual	Preliminary Design
i. Lee, Adrianne and Nancy Pennington	Video Protocol Only	Individual	Preliminary Design
j. Sobiesiak et al	Case Study	Group	Preliminary Design through Release
k. Sawin et al	Case Study	Group	Redesign
l. Ominskt et al	Case Study	Group	Preliminary Design through Release
m. Healey and Herder	Case Study	Group	Redesign
n. Kamper, Robert J.	Case Study	Group	Requirement Construction and Testing
o. Gruen, Dan et al	Case Study	Group	Preliminary Design through Release
p. Wolf, Martin et al	Video Protocol Only	Individual	Software Usability
q. Moreno-Munoz, Antionio	Interviews	Individual	Software Usability
r. Hall, roger	Case Study	Individual	Software Usability
s. McFadden, Edward et al	Case Study	Group	Preliminary Design
t. Rist, Robert	Verbal Protocol + Other	Individual	Preliminary Design Through Coding
u. Schraagen, Jan Maarten	Verbal Protocol Only	Individual	Various
v. Suwa, Masaki et al	Written Protocol Only	Individual	Various
w. Goel and Pirolli	Verbal Protocol Only	Individual	Preliminary Design through Detail Design
x. Visser	Verbal Protocol Only	Individual	Requirement Construction and Testing
y. Guindon	Verbal Protocol + Other	Individual	Preliminary Design
z. Adelson and Soloway	Verbal Protocol Only	Individual	Preliminary Design
aa. Guindon	Verbal Protocol + Other	Individual	Preliminary Design
ab. Rist, Robert	Verbal Protocol Only	Individual	Preliminary Design Through Coding
ac. Ball et al	Verbal Protocol + Other	Individual	Preliminary Design through Detail Design
ad. Hill, Anne Marie	Case Study	Individual	Preliminary Design through Prototype Construction
ae. Davies, Simon P.	Written Protocol Only	Individual	Preliminary Design Through Coding
af. Burns, Catherine M. and Kim J. Vincente	Ethnographic	Group	Redesign
ag. Etelaepelto, Anneli	Verbal Protocol + Other	Group	Preliminary Design through Prototype Construction
ah. Hill, Anne Marie	Case Study	Individual and Group	Preliminary Design through Prototype Construction
ai. Busby, J. S. and K. Payne	Interviews	Group	Various
aj. Sonnentag, Sabine	Verbal Protocol + Other	Individual	Preliminary Design
ak. Sonnentag, Sabine	Verbal Protocol + Other	Individual	Preliminary Design
al. Dwarakanath, S. and K. M. Wallace	Verbal Protocol + Other	Individual	Various
am. Busby, J. S.	Interviews	Group	Preliminary Design through Detail Design
an. Lai, Jennifer et al	Case Study	Group	Preliminary Design through Product Testing

Table A2. Coding of the database articles, Part 2

Article	Explore Graphic Representation/ Visualization	Explore Problem Representation (Problem Framing)	Use Functional Decomposition	Explore Engineering Facts	Explore Issues of Measurement	Build normative model	Redefine Constraints	Explore Scope of Constraints	Conduct Failure Analysis	Validate Assumptions and Constraints	Examine Existing Designs/Artifacts	Follow Interactive/ Recursive/ Iterative Design Methodology	Search the space (evaluate design alternatives)	Explore User Perspective(s)	Encourage Reflection on Design Process
a. Fricke, Gerd	0	G	0	G	NF	NF	G	G	NF	G	NF	NF	G	NF	NF
b. Guenther, Joachim et al	NF	G	0	NF	NF	0	NF	NF	NF	NF	NF	B	G	NF	NF
c. Adams, Robin S. et al	NF	G	NF	NF	NF	NF	NF	NF	NF	NF	NF	G	NF	NF	G
d. Baird, F.	NF	NF	NF	0	NF	NF	NF	NF	NF	NF	NF	NF	G	NF	NF
e. Lloyd, Peter	NF	G	NF	0	NF	G	NF	NF	NF	NF	NF	NF	NF	NF	G
f. Jagodzinski, P. et al	NF	G	NF	NF	NF	G	NF	NF	NF	NF	NF	NF	NF	NF	G
g. Ball, Linden	NF	0	NF	NF	NF	0	NF	NF	NF	NF	NF	NF	NF	NF	G
h. Ball, Linden et al	NF	NF	0	NF	NF	NF	NF	NF	NF	NF	NF	NF	G	NF	NF
i. Lee, Adrianne and Nancy Pennington	NF	G	G	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
j. Sobiesiak et al	G	G	0	NF	NF	G	G	G	G	G	G	G	G	G	NF
k. Sawin et al	0	0	G	NF	NF	0	0	0	G	G	G	G	G	G	NF
l. Ominskt et al	NF	0	NF	NF	NF	G	NF	0	NF	G	G	G	G	G	NF
m. Healey and Herder	NF	NF	0	NF	NF	NF	NF	NF	G	G	G	G	G	G	NF
n. Kamper, Robert J.	G	NF	0	NF	NF	0	NF	NF	0	0	0	G	0	G	0
o. Gruen, Dan et al	0	G	0	G	NF	G	NF	NF	NF	G	G	0	G	G	NF
p. Wolf, Martin et al	G	G	G	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	G	NF
q. Moreno-Munoz, Antonio	G	G	0	NF	NF	0	NF	NF	NF	NF	NF	0	NF	G	NF
r. Hall, roger	G	G	NF	NF	NF	G	NF	NF	G	G	NF	G	NF	G	NF
s. McFadden, Edward et al	0	NF	0	NF	NF	NF	NF	NF	NF	0	0	G	0	G	NF
t. Rist, Robert	NF	G	G	NF	NF	NF	NF	NF	NF	NF	NF	NF	G	NF	NF
u. Schraagen, Jan Maarten	NF	G	NF	NF	NF	NF	G	G	G	G	NF	NF	G	NF	NF
v. Suwa, Masaki et al	G	G	G	NF	NF	NF	NF	NF	NF	NF	NF	NF	0	NF	NF
w. Goel and Pirolli	NF	G	G	NF	NF	G	G	G	NF	NF	G	G	G	NF	NF

Article	Explore Graphic Representation/Visualization	Explore Problem Representation (Problem Framing)	Use Functional Decomposition	Explore Engineering Facts	Explore Issues of Measurement	Build normative model	Redefine Constraints	Explore Scope of Constraints	Conduct Failure Analysis	Validate Assumptions and Constraints	Examine Existing Designs/Artifacts	Follow Interactive/ Recursive/ Iterative Design Methodology	Search the space (evaluate design alternatives)	Explore User Perspective(s)	Encourage Reflection on Design Process
x. Visser	NF	0	0	NF	NF	NF	G	G	NF	G	G	G	G	NF	NF
y. Guindon	NF	G	G	NF	NF	0	G	G	NF	NF	G	G	G	NF	NF
z. Adelson and Soloway	NF	0	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	G	NF	NF
aa. Guindon	NF	G	G	NF	NF	0	NF	NF	NF	NF	NF	0	G	NF	NF
ab. Rist, Robert	NF	0	NF	NF	NF	NF	NF	G	NF	NF	0	G	B	NF	NF
ac. Ball et al	G	G	G	NF	NF	G	G	G	NF	NF	NF	G	B	NF	NF
ad. Hill, Anne Marie	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	G	NF	NF	NF
ae. Davies, Simon P.	NF	0	G	NF	NF	NF	NF	NF	NF	NF	NF	G	G	NF	NF
af. Burns, Catherine M. and Kim J. Vincente	NF	G	NF	NF	NF	NF	G	G	NF	0	NF	G	NF	G	NF
ag. Etelaepelto, Anneli	NF	G	NF	NF	NF	NF	G	G	NF	NF	NF	NF	NF	G	NF
ah. Hill, Anne Marie	G	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	G	NF	NF	NF
ai. Busby, J. S. and K. Payne	NF	G	G	NF	G	NF	NF	NF	NF	NF	G	NF	G	NF	NF
aj. Sonnentag, Sabine	NF	G	G	NF	G	NF	NF	G	NF	NF	NF	NF	G	NF	NF
ak. Sonnentag, Sabine	G	G	G	NF	NF	NF	NF	NF	NF	NF	NF	G	G	NF	NF
al. Dwarakanath, S. and K. M. Wallace	G	G	NF	NF	NF	NF	G	G	NF	NF	NF	NF	G	NF	NF
am. Busby, J. S.	NF	G	G	NF	NF	G	NF	G	NF	G	NF	NF	G	G	G
an. Lai, Jennifer et al	NF	0	G	0	NF	NF	NF	0	G	G	G	G	G	G	NF
Number Good (G)	10	25	15	2	2	9	10	13	6	11	10	19	23	14	5
Number Neutral (0)	4	8	10	3	0	7	1	3	1	3	3	3	3	0	1
Number Bad (B)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**2**	**0**	**0**
Number not Focus (NF)	26	7	15	35	38	24	29	24	33	26	27	17	12	26	34
Total Articles	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40