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A STEP BEYOND TO OVERCOME DESIGN FIXATION: A DESIGN BY ANALOGY APPROACH

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Design fixation is a phenomenon that can negatively impact design outcomes, especially when it occurs during the ideation stage of a design process. This study expands our understanding of design fixation by presenting a review of approaches that report its reduction or elimination, as well as metrics employed to understand and account for design fixation. The study then explores the relevant ideation area of Design-by-Analogy (DbA), with a fixation experiment with 73 knowledge-domain experts to overcome design fixation. The study provides a design fixation framework and constitutes a genuine contribution to effectively identify design fixation mitigating approaches in a wide range of design problems, and provides concrete evidence of cognitive mechanisms to overcome fixation.

1. Introduction

Humans are designers by definition, constantly creating and searching for means to improve, adapt and facilitate their lives by generating solutions that affect themselves or their surroundings.

Sometimes this creative design process is inhibited by continuously working under the same paradigm, i.e., by fixating on previous or current solutions. Fixation, understood as the inability to work around existing solutions or the focus on developing mere variants of existing solutions, can be triggered by different causes, such as a designer's unfamiliarity or limited knowledge of analogous fields of study, limitations due to cognitive blocks, and comfort with the familiar existent and feasible sets of solutions. This unwanted and frequently occurring phenomenon has been the subject of considerable study (from a research and practical viewpoint) due

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to its impact and importance in design, and problem solving in general. The relevance of studying fixation effects in ideation, creativity, concept generation, and processes across knowledge domains to develop innovative solutions, lies in the often negative impact it has in the early stage of ideation by limiting design space exploration, and, therefore, narrowing the range or divergent possibilities of solutions.

A number of methods have been developed to combat design fixation; one class of methods is known as Design by Analogy (DbA) that has shown effectiveness in generating novel and high quality ideas, as well as showing the capacity to avoid or minimize design fixation when solving design problems. To visualize a basic conceptual framework of the DbA possibilities, let’s consider the problem of providing light to an enclosed space. One of the earliest solutions was the candle, which belongs, in part, to the chemical domain (combustion of a material). Another later solution was the light bulb developed from the electrical domain (generation, regulation and application of photons through, for example, the vibration of atoms within a solid conductor).

The example allows us to introduce two key topics. First is design fixation, because if there are no effective and reliable means to explore and expand the design space, a designer might be caught within a particular paradigm or domain; and, using the lighting example, will explore ways to improve the candle while not developing disruptive solutions. Second is the relevance of ideation cognitive models. One model considers ideas emanating from one of three sources or processes: serendipity, discovery, or analogy. Analogical transfer from experiences and external sources with similarity relations is the predominate source of ideas in this model. Because candidate solutions from analogies originate from more than one domain (chemical and electrical in our lighting solution example), it is important to enable designers to identify and reach distant domains to explore innovative or disruptive solutions.

The present study seeks to address a number of important research questions: (1) there are a number of approaches to alleviate fixation that have been studied, but have they been presented in a collective and cumulative way, that is, holistically integrated to understand their challenges and implications in different fields?; (2) from previous studies, are there sufficient and comprehensive metrics to understand and account for fixation?; (3) to build a better understanding of the suite of identified techniques, does the presence of fixation manifest with the same trends/behaviors in transactional problems as to the reported for engineering-product based problems; and (4) to accomplish such initial understanding, a particular relevant ideation area which is design by analogy is chosen, where the question exists to evaluate if a semantic DbA method can provide domain experts with the ability to overcome fixation for transactional problems?

2. Background and Context

2.1. Design fixation

There are several definitions about what fixation is and what it encompasses. Definitions differ in accordance with the context of the design objectives, human activity, or field of knowledge. Examples include memory fixation, problem solving fixation [1], cognitive fixation [2], conceptual fixation, knowledge fixation, functional fixation, operational fixation [3], design fixation [4], and variant fixation [5]. All of the categories of fixation share characteristics, such as the persistent -and often unconscious- commitment to a limited set of alternatives.

Design fixation is described as the inability to solve design problems by: employing a typical or familiar method ignoring new or better ones, self-imposing constraints [6], or limiting the space of solutions merely by means of developing variants [5,1,7].

A number of causes can contribute to design fixation. Some are the subject of research studies [8,9]. Researchers suggest that design fixation may depend on expertise [8], or designer's unfamiliarity of principles of a discipline or domain knowledge [9,10], on personality types [11], on the unawareness of general technological advances, or on conformity due to proficiency in the methods and supporting technologies of an existing solution [1].

During the design process, design fixation can emerge when example solutions are presented [12, 13,14,8,15,16], when there has been a considerable amount of resources invested on a potential solution [17], when there are weak or ill-defined problem connections either internally (within component elements of the problem) or externally (between the problem and other problems or external factors) [18], and when there are more vertical (refined version of same idea) than lateral transformations (moving from one idea to another) [19].

Design fixation research is critical due to its potential impact on design outcomes and the potential to improve designers' abilities to generate innovative solutions. Studies from design and engineering science, as well as cognitive science, have provided intriguing findings, but not all results have managed to permeate across the fields.

Design fixation mitigation has the potential to enable a broader exploration of feasible design spaces, a perceptible increase in creativity, as well as new applications made possible through analogy from cross-domain transfer [20].

2.2. Ideation approaches to overcome fixation

Design process success depends highly on ideation stage results [21,22]. Extensive studies have focused on the improvement of metrics for evaluating ideation processes and associated mechanisms: quality, quantity, novelty (originality), workability (usefulness), relevance, thoroughness (feasibility), variety, and breath [18,23,24,25,26,27,28,29,30,31]. Some of these have considered design fixation in a quantitative and direct way; or as a qualitative incidental discovery; or measured indirectly as linked to one or more of the ideation metrics.

Recent ideation studies have shown some degree of effectiveness in overcoming design fixation. Based on this information, Table 1 was developed to understand, collectively and cumulatively, approaches to overcome design fixation. The table is defined by means of two parameters:

- *Trigger or source* provided by the method, which is classified as Intrinsic and Extrinsic. Intrinsic corresponds to methods that derive from either intuition or designers' experience. Extrinsic comprises methods that make use of heuristics or prompts.
- *Implementation method* that can be either Individual or in a Group.

There are methods that can be found at the intersection of the parameters here presented, for example: functional analysis is an extrinsic method that can be applied individually or as a group; hence, its position lies at the intersection of the two levels established for the "implementation method" parameter.

Table 1. Collective and cumulative mapping of approaches to overcome fixation

Trigger or Source	Implementation method	Method/Technique/Approach	Reference(s)
Intrinsic	Individual Level	Problem re-representation/ reframing	[21]; [8]; [32]; [33]
		Enable incubation	[34]; [35]; [36]; [37]; [38]; [2]; [15]; [39]; [40]; [41]
	Group Level	Diversify personality type	[8]; [11]
	Individual ∩ Group	Expand level of expertise or domain knowledge	[42], [10], [9], [39], [43], [44], [45]
Extrinsic	Individual Level	Abstract formulation of the problem	[33]
		Use of C-K expansive examples	[12]
		Pictorial examples	[46]; [13]; [9]; [16]; [47]
		Audio recorded examples	[49]; [50]
		Provide analogies	[48]; [15]

Trigger or Source	Implementation method	Method/Technique/Approach	Reference(s)
		Provide analogies along with open design goals	[51]; [52]; [16]
		Use of design heuristics	[53]
		Idea generation enabled with computational tools	[54]; [8]; [18]
		Graphical representations	[13]; [55]; [47]
		Use word graphs	[56]
		Explore WordTrees	[57]; [58]; [50]
	Group Level	Electronic Brainstorming (EBS)	[49]; [50]
		6-3-5/C-Sketch	[43]; [40]; [59]
	Individual ∩ Group	Provide de-fixation instructions	[13]
		Develop physical artifacts (prototyping)	[13]; [17]; [60]; [61]; [62]
		Apply SCAMPER	[63]; [40]; [39]
		Provide a creative design environment	[64]; [39]
		Perform product dissection	[65]
		Develop functional models	[66]; [8]
Intrinsic ∩ extrinsic	Group Level	Translate the design process into a Linkography	[67]
Intrinsic ∩ Extrinsic	Individual ∩ Group	Apply TRIZ	[68]
		Conduct a morphological analysis	[71]

2.2.1. Intrinsic approaches

Intrinsic approaches correspond to the set of techniques and methods where ideas are triggered from intuition or previous experience.

Problem re-representation/reframing is an individual method that increases retrieval cues for analogical inspiration or expands design space exploration either increasing originality metric which lack is associated with fixation, or quantity metric, or having low quantities of repeated features [21,8,32,33].

Incubation, consist in separating or disconnecting from the problem by taking a break or performing a non-related task, so as to access other critical information where insightful and intuitive ideas may emerge enabling development of novel or original solutions [34,35,36,37,38,2,15,39,40,41].

At the group level, diversify personality type comprises the way people prefer/tend to interact with others. This factor has been found to have a significant impact in design activities. For example, extroverted persons get more involved in dissection activities that have the potential to increase creativity [8,11].

Level of expertise or domain knowledge is an approach at the intersection of the individual and group levels. The individual attribute emerges with designer’s immediate knowledge, but can be modified when working in teams, by using distant and/or different domain knowledge due to interactions with others [42,10,9,39]. However, there are results that indicate that novices generate more original concepts [43], while others show that experts consider deeper knowledge and technological detail in their solutions due to a more evident association between problem and previous knowledge [44]. Some possible causes for mitigating fixation for “level of expertise or domain knowledge” relate to problem solving strategies/methods or incubation. The first is because experts have the ability to frame and break down a problem into more manageable parts [42,10], to work with incomplete or ill-defined problems [45], as well as identify relevant information, patterns and principles in complex design problems [10]. The second is because experts have been exposed to a wide range of problems, situations and solutions [9].

2.2.2. Extrinsic approaches

Extrinsic approaches correspond to sets of techniques and methods where ideas are triggered by means of prompts or with stimulus/assistance external to the designer. Abstract formulation of the problem is classified as an individual approach that promotes divergent thinking processes and generation of original ideas [33].

Another set of approaches correspond to the use of examples: C-K expansive examples that allow exploration of knowledge beyond base line [12], pictorial examples that allow designers to consider additional general design information without constraining the design [46,13,9,16,47], audio recorded examples where listening to a number of ideas enables retrieval of long-term memory concepts or access to concepts distantly associated to generate original ideas. These stimuli show a positive impact on the number of ideas generated [49,50].

An interesting set of approaches provide analogies that assist in restructuring the problem and triggering new clues to developed solutions [48,15], and in addition providing open design goals may influence cognitive processes in filtering information that will be then incorporated in the concept solutions, leading to an increase in originality [51,52,16].

The use of design heuristics promotes divergent thinking by providing multiple (can be sequential and systematic) ways to approach a problem and generate creative solutions (novel and original) [53].

Idea generation enabled with computational tools allows alternating among types of problem representations and providing semantic or visual stimulus that will generate more productive ideas [54,8,18].

Graphical representations offer a cognitive structure by means of external representation. This approach allows externalization of design complexity, condenses information and enables lateral transformations, i.e., moving towards different ideas across a design space, meta-analogical categories, or functional/process types [13,55,47].

Word graphs [56] and WordTrees [57,58,50] provide a synergic combination of analogies, semantic and graphical information, computational tools and graphical representations that may lead to the generation of diverse results.

At the group level, two combinations of other approaches are: Electronic Brainstorming (EBS) and 6-3-5/C-Sketch. For EBS the interaction between members is enabled by a computer interface that prompts sets of ideas, overcoming production blocking [49,50]. The 6-3-5/C-Sketch methods are a combination of "use of examples," "use of design heuristics" and "use of graphical representations" that provides a sequential structure with visual and textual information shared amongst designers with structured processes [43,40,59].

Table 1 presents six approaches at the intersection of the individual and group levels:

- Provide de-fixation instructions that make designers aware of features/elements that should be avoided and enables overcoming fixation effects to avoid repeating ideas or features and produce novel ideas [13].
- Develop physical artifacts to deal with design complexity (mental load). These models represent mental concepts as well as identifying and managing fixation features [13,17,60,61]. However, critical feedback during concept generation with prototyping may be perceived by the designer as a validation and could lead to increased design fixation [62].
- SCAMPER allows problem reframing, provides a series of problem abstraction considerations convolved in a set of seven operator categories, increasing creativity through the use of high-level analogies and metaphors that expands the design space [63,40,39].
- Provide a creative design environment, because a nurturing and encouraging environment may be a motivation or remuneration source that assists designers in overcoming fixation [64,39].
- Perform physical, symbolic, or product dissection allows "examination, study, capture, and modification of existing products [or systems]." The method improves form and function understanding to develop new and different ideas [65].
- Develop functional models enables the representation functionality to explore alternative means to link customer needs with product function, thus generating novel solution approaches [66,8,88].

There are two sets of methods that are located at the intersection of the parameters defined to elaborate Table 1. The first corresponds to the intrinsic and extrinsic intersection at the group level; and the second, to the intersection of all parameter levels. For the first, translating the design process into a Linkography, where the resulting graphs represent designer's cognitive activities and, through analysis of backlinks and forelinks, convergence and fixation can be identified and actions can be implemented [67]. For the second (all parameter levels), TRIZ and conducting a morphological analysis are identified, where prompts, meta-analogies, and systematic exploration assist in mitigating fixation. TRIZ facilitates new solutions by representing the contradictions in design problems and mapping them to Altshuller's design parameters and fundamental principles [68]. A study comparing graphical representations (sketching) and no technique against TRIZ showed that TRIZ enhanced the resulting novelty of solutions [71,75]. Morphological analysis decomposes a problem into functional categories and possible means to achieve them, and enables a systematic search for new solutions by combining different elements recorded in a resulting matrix [71,88].

The cumulative information presented above provides a better understanding of current approaches as well as opportunities of integration of them to evaluate if synergic results can be achieved. This understanding has limitations due to the non-standard approach to identify and account for design fixation; nevertheless, it provides intriguing results and areas that should be further explored due to their positive results and connections, such as the "extrinsic" levels, where it appears that analogy, visual representations and examples may have the potential to have wide-spread effects. The associated classification of methods will allow the exploration and future categorization of new approaches where the possible outcomes may be predicted.

2.3. Existing design fixation metrics

This section explores existing metrics to investigate fixation and presents an alternative definition to explore and assess fixation that may be applicable in a broad spectrum of design problems ranging from service to products. From the literature, two distinctive types of metrics to account for design fixation may be identified: Direct and Indirect metrics.

2.3.1. **Direct Metrics**

These metrics start with the premise that fixation is measurable. These methods seek to inform the designer or investigator when fixation is present and attempt to show the connections without interpretation, i.e. will provide a crisp quantitative range of understanding for fixation concept.

Table 2 shows the classification developed by the authors for the direct metrics found during literature review. These definitions are coincident to the fixation definition provided in Section 2.1 and enable fixation identification and accountability.

Table 2. Direct metrics classification

Class	Metric(s)	Author(s)
Repeated Features	Lower fixation values indicate non fixated designs. % Fixation: $\frac{\text{\# of similar features}}{\text{number of questions rated by the coders for each design}}$	[11]
	Number and percentage of features included in solution compared to a provided example	[8], [9]
	Lower variety and novelty values will indicate design fixation presence $\text{Novelty} = 1 - \text{frequency} = 1 - \frac{\text{number of ideas in a bin}}{\text{total number of ideas}}$ $\text{Variety} = \frac{\text{number of bins a participant's idea occupy}}{\text{total number of bins}}$	[72]
	Measure functional fixation through dependent measures such as: (1) number of functional repeats, defined as the frequency of a given functional category at participant level, (2) number of functionally distinct designs, and (3) novelty (see below in this cell), as a measure of solution uniqueness $\text{Novelty} = 1 - \frac{\text{\# of functionally similar designs generated by other subjects}}{\text{total \# of designs for all subjects}}$	[16]
	Assigns at feature level a value for originality from a table and technical feasibility of the solutions (see flow diagram and scores in the right side of Table 1). Originality is evaluated after comparing the features in conceptual designs with the list of standard elements to be included. It is also found that the more feasible the designs the more fixated the participants became.	[43]
	Similarity degree between design brief of the project and the proposed solutions.	[62]
Non-redundant ideas	Number of non-redundant ideas generated with correlation with the total number of unique ideas generated.	[50]
	Presence of both, low quantity and originality in the generated solution. Originality is defined as the statistical infrequency of a particular solution, which is a percentage from 0 to 1.	[12]

2.3.2. Indirect Metrics

This set of metrics provides a relative range of fixation. Their estimations can be derived, but are not explicitly measured, i.e. fixation is determined through indirect indicators (usually related to other ideation metrics). These measurements imply that a designer may be fixated, but do not provide additional information to validate directly the degree of fixation.

Indirect metrics can be grouped in four types: metric related; the number of repeated functions; convergence and commitment to a single idea; and similarity of solutions to a design brief.

Table 3. Direct metrics classification

Class	Metric(s)	Author(s)
Design move-ments	Linkography (graph) and Shannon's entropy principle, where a given design process can be evaluated by analyzing all possible moves on the graph and if the moves are all interconnected, the ideas are convergent, which might be a sign of fixation.	[67]
	Employ Goel's type of transformations: vertical and lateral ([19]) to evaluate fixation. If there are more lateral transfor-mations than vertical, fixation can be prevented.	[55]
Self-assess-ment	Commitment to an idea via self-assessment. Surveys ask about perception of fixation reduction, generation of unexpected ide-as and workflow improvement.	[56]
Improve-ment of a response	Calculate fixation effects using the Remote Associates Test (RAT) that associates the number of problems solved correctly between fixating and non-fixating stimuli conditions. Fixation Effect=Non-fixation RAT proportion correct - Fixa-tion RAT proportion correct.	[73], [51]
Negative features	Assignation of a discrete value that ranges from 0 to 10, corre-sponding to the number of neutral and negative fixation fea-tures that are found at given check-in periods.	[74]
	Fixation identification as a focus in external features (form) and lower variety.	[65]

2.4. Design-by-Analogy (DbA) Method

After conducting the literature review, we explored a DbA approach due to its relevance, positive results and the apparent possibilities to have synergic results when integrated with other approaches. DbA methods are representative of across fixation mitigation approach; and may allow a better understand of design fixation.

In the introductory example about lighting, there is evidence that design solutions can be found or adapted from pre-existing systems or solutions from other domains [75,71] for example: astronauts' vortex cooling systems that where later implemented as a means to mold and cool glass bottles [76]. Inspiration from analogous domains can be achieved by associations between shared characteristics, attributes, properties or functions, or purposes [77,78]. Once an association among a design problem and a solution in another domain is established, a solution to the design problem can be developed [42,79,80,57,81].

WordTree [57,58] and Idea Space System (ISS) [82,56] are two structured DbA methods successfully applied in the engineering and architecture respectively. Both methods are based on semantic transformation of textual representations of design problems (such as through Princeton's WordNet or VisualTheasaurus™), enable re-representation of the problem, and expansion of solution space due to new semantic associations, finding and exploring potential analogies and analogous domains [57,58,82,56,83,15].

The WordTree method constructs a diagram of "key problem descriptors (KPDs)" which can be key functions and customer needs of a given design problem [58]. KPDs are then placed in a tree diagram and semantically re-represented by hypernyms and troponyms. The WordTree Diagram facilitates associations; therefore, analogies and/or analogous domains can be identified. All analogies, analogous domains and new problem statements can then be used to enrich group idea generation that increases inspiration and refinement of the results in order to translate them into potential solutions to a design problem

3. Experimental Method

An experiment was conducted in Mexico using the WordTree DbA method presented in Section 2.4 to explore design fixation mitigation.

3.1. Design Overview

3.1.1. Participants

73 transactional process experts took part in the study. Participants were recruited from Lean Six Sigma Master Black Belt training programs held in Mexico from a range of background disciplines and involvement of 22 product and 14 service companies.

Domain knowledge expertise was based on following criteria: (1) professional background (undergraduate/graduate level transactional related), and (2) work role (more than 5 years managerial experience and intimate familiarity and interaction with transactional problems).

3.1.2. Design problem

A transactional design problem is chosen because there is little evidence of studying fixation with this problem type, specifically with domain knowledge experts. The experimental results have the potential to provide insights on how to avoid fixation when solving design problems for a broad spectrum of disciplines and practitioners.

The transactional problem was selected from a Lean Six Sigma consulting program project database from the past eight years. The selected problem was: "Reduce overdue accounts/unpaid credits."

3.2. Execution

The experiment has two treatments (control and experimental) and experimental phases (I and II) (Table 4). The control treatment is carried out without providing any method (No Technique – NT) in both experimental phases. Phase I of the Experimental treatment has the same condition of the control treatment (NT), and Phase II is carried out with the DbA method (With Technique – WT).

Table 4. Experiment phases and conditions

Treatment	Phase I	Phase II	Sample Size	Gender (Female/Male)
Control	NT	NT	36	11 / 25
Experimental	NT	WT	37	12 / 25

In both experimental phases, participants were asked to create (individually) as many solutions for the transactional problem as possible, recording solutions as a phrase, written description, and/or sketch/diagram.

Experiment phases are shown in Figure 1. Participants are first presented with the transactional design problem statement, and phase I began by asking participants to generate solutions without providing any ideation method. Participants had 15 minutes to complete this ideation task.

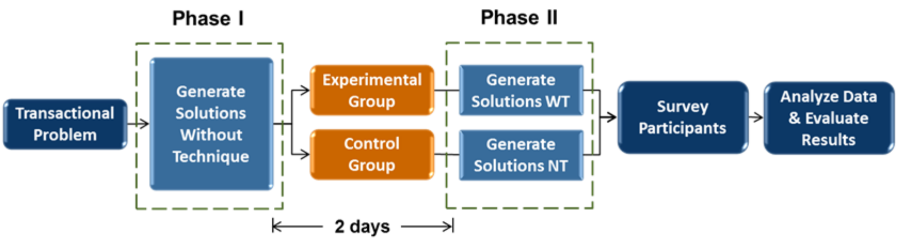

Figure 1. Experimental execution diagram

Phase I and phase II were held with a two-day period in between, and participants worked with the same design problem in both phases. Participants were divided into two groups: one control group and one experimental group, with even distribution of backgrounds, gender, and remaining demographics.

For phase II, participants from each treatment were taken to separate rooms. NT participants were asked to read the problem and continue generating solutions without providing them with any method. NT participants were given 15 min to complete this task. Meanwhile, WT participants were given a 15 minute tutorial of the WordTree DbA method and selected WordTree software (Thinkmap's Visualthesaurus©).

Each participant was provided with a computer with Thinkmap's Visualthesaurus©. Figure 2 shows an example of relevant information and graphical associations between words displayed by the software. After the tutorial, participants were asked to generate solutions to the same transactional design problem using the provided method and software tools. For the searching task and ideating, WT participant were given 15 minutes.

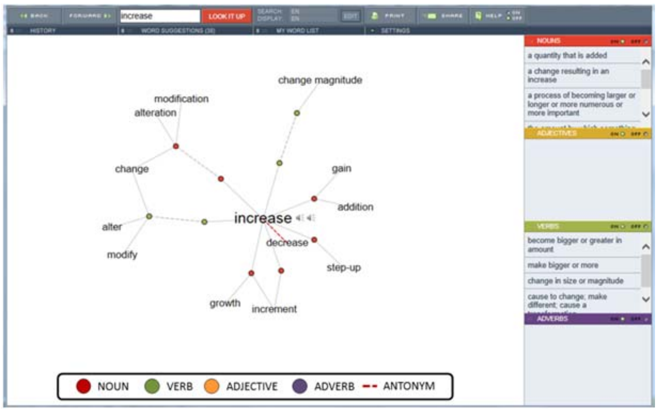

Figure 2. Exemplar output window from Thinkmap's Visualthesaurus©

During phase II, WT participants were required to select words that allow them to re-represent the design problem. The goal was to understand semantic retrieval from the participants' memories which allow them to switch domains while developing analogous problem statements, and, within these new domains, find analogous forms of solutions for the transactional problem. Participants were asked to list all alternative solutions they developed after extracting useful information form the provided software tools.

At the end of both phases, listed ideas were collected and rated by two domain knowledge expert raters to code and analyze the data. Participants were also asked to fill out a survey after completing each phase.

4. Analysis

The solutions (ideas) were counted individually and also were sorted into bins, i.e. into categories of ideas that share similarities in order to identify unique sets of solutions. The coding and analyses should establish connections to the comprehensive map of approaches to overcome fixation (Section 2.2) as well as the existent metrics (Section 2.3).

4.1. Accounting for Fixation

Given the predominantly semantic nature of the collected data for the transactional problem, and in order to align and compare the results of the present study with previous ones, we present our approach for measuring design fixation that captures the characteristics of transactional problems.

We assess design fixation building on the procedure outlined by Linsey (2010) and further developed by Viswanathan (2012) to account for repeated ideas. The proposed metric elaborates what a repeated idea is for the study and, instead of reporting an absolute value, contrasts this value against the total number of ideas developed. This approach provides a sense of the intensity of design fixation.

A design fixation definition is implemented as shown in Eq. 1:

$$Fixation = \frac{Total\ \#\ of\ repeated\ ideas}{Total\ \#\ of\ generated\ ideas} = \frac{Q_R}{Q_{Total}} = \frac{R_W + R_B}{Q_{Total}} \quad (1)$$

Eq. 1 provides the ability to perform statistical comparisons between experimental and control groups to evaluate method usefulness and effectiveness to overcome fixation in transactional design problem solving.

4.2. Quantity of ideas

A total of 1,133 ideas were extracted. Our design fixation metric is a dependent variable related to quantity of ideas generated and quantity of repeated ideas.

Three mathematical representations are defined: (1) Quantity of total ideas generated (Q_{Total}), (2) Quantity of repeated ideas (Q_R), where a repeated idea occurs when a participant develops slight variation of a previous idea, and (3) Quantity of Non-repeated ideas (Q_{NR}), which corresponds to the remaining number of Q_{Total} once repeated ideas have been removed.

$$Q_{Total} = \sum all\ ideas\ generated = Q_R + Q_{NR} \quad (2)$$

Eq. 2 shows that Q_{Total} can be expressed as the summation of all ideas generated at different levels such as by phase (I, II), experimental group (WT, NT), and participant. Also, Q_{Total} can alternatively be defined as the addition of its two sub-components: Q_{NR} and Q_R.

The two phases of the experiment offer two different sources for repeated ideas (QR):

- Repeated ideas within a phase (R_W): comprises all repeated ideas across all participants for which frequency (F) is greater than 1, i.e. was stated more than once (Eq. 3).

  $$R_{W_i} = \sum_{\mathrm{j=1}}^{\mathrm{b}} \sum_{\mathrm{k=1}}^{n} F_{ijk} - 1 \quad \forall\, F_{ijk} > 1 \qquad (3)$$

  where F_{ijk}=frequency of repeated ideas for the ith phase, jth bin, and kth participant; i=phase number (1, 2); b= number of bins (117); n= number of participants. A unit is subtracted from F_{ijk}, to maintain accountability of the total of ideas generated.
- Repeated ideas between phases (R_B): includes all ideas that were generated in Phase I that reappear in phase II at bin and participant levels (Eq. 4).

  $$R_B = \sum_{\mathrm{j=1}}^{\mathrm{b}} \sum_{\mathrm{k=1}}^{n} F_{2jk} \quad \forall\; F_{1jk} > 1 \quad \text{AND} \quad F_{2jk} > 0 \qquad (4)$$

  where F_{ijk}=frequency of repeated ideas for the ith phase, jth bin, and kth participant; i=phase number (1, 2); b= number of bins (117); n= number of participants.

The above definitions allow a systematic identification and measure of design fixation. A proper identification of the moment where the repeated ideas occurs sheds light about the temporal aspects or causal structure where a method can be more effective in overcoming design fixation, and provides an actual measure of the result of the method.

5. Results

5.1. Statistical data validation

A retrospective power study was performed to validate power of the statistical tests and statistical assumptions for conducting comparative sample tests. Four factors influence power: (1) significance level, (2) variability, (3) minimum difference (corresponds to difference between population means the study will be able to detect), and (4) sample size [84]. For the t-tests conducted in the study, factors were: significance level α=0.05; variability and the minimum difference depending on the metric being evaluated; and for the actual sample sizes of the study (NT=36, WT=37). It is found that all power values are higher than 91% for evaluated metrics; therefore, statistical analysis results are reliable.

Normality of data was evaluated and met by means of Anderson Darling Normality Test.

5.2. Quantity of ideation

In order to calculate fixation as presented in Eq. 1 of Section 4.1, it is necessary to determine its components Q_{Total}, Q_R and Q_{NR}. Table 5 presents the study's quantity of ideas across phases and group levels. Q_{Total} is equal to 1,133 ideas, which is composed by a total of 316 Q_R ideas, and a total of 817 Q_{NR} ideas.

Table 5. Quantity of generated ideas, repeated ideas, and non-repeated ideas

Q_{Total}					Q_R					Q_{NR}			
Control Group		Experimental Group		=	Control Group		Experimental Group		+	Control Group		Experimental Group	
Ph I	*Ph II*	*Ph I*	*Ph II*		*Ph I*	*Ph II*	*Ph I*	*Ph II*		*Ph I*	*Ph II*	*Ph I*	*Ph II*
326	328	286	193		45	172	47	52		281	156	239	141
t-value= 0.08 *p*-value=0.940		*t*-value=-3.37 *p*-value=0.002			*t*-Value=6.63 *p*-value=0.000		*t*-value=0.45 *p*-value=0.658			*t*-value = -4.97 *p*-value = 0.000		*t*-value = -4.19 *p*-value= 0.000	
Anova Ph I		*F*=1.82 *p*-value=0.182			Anova Ph I		*F=0.00* *p-value=0.953*			Anova Ph I		*F=2.75* *p-value=0.102*	

ANOVA (last row Table 5) shows no statistically significant difference in the quantity of ideas generated in phase I for both experimental and control groups which is to be expected considering that phase I corresponds to an equivalent non-assisted scenario for both groups.

A paired t-test comparing phase I and II for the control group's Q_{Total} shows no statistically significant difference, which is expected considering that phase II for this group is also non-assisted. A paired *t*-test comparing phase I and II for the experimental group's Q_{Total} shows statistically significant difference, which is consistent with previous cognitive studies where intervention scenarios add significant load due to cognitive processing [85,86,16].

For Q_R, a paired *t*-test comparing phase I and II for the control and experimental groups only shows a statistically significant difference in the quantity of ideas of control group, which is consistent with literature that design fixation in the form of repeated ideas can be higher if no method is employed [50,11,20].

Finally, for Q_{NR}, a paired t-test comparing phase I and II for the control and experimental groups shows a statistical significant difference in the quantity of ideas for both scenarios.

We now analyze the quantity of repeated ideas by its source as presented in Eq. 3 and 4. Table 6 summarizes the quantity of repeated ideas generated within and between phases for the experimental and control groups.

All columns but Phase II WT correspond to ideation without technique which corresponds to ideation with the DbA method.

Table 6. Repeated ideas by group, source and phase

	WT(37)		NT(36)	
	Ph I	Ph II	Ph I	Ph II
Total repeats within	47	24	45	40
Total repeats between	0	28	0	132
TOTAL	47	52	45	172
Average	1.3	1.4	1.3	4.8

From Table 6, for the control group, the quantity of repeated within is almost the same for both phases, and there is a large quantity of repeated ideas between phases, that is, participants repeated ideas they created in phase I. The experimental group reduced by half the quantity of repeated ideas within phase II, and the quantity of ideas participants repeated from phase I was approximately half.

When studying the average of repeated ideas by participant, the distinctively different value is the one from the control group, Phase II. The other three averages were almost identical.

5.3. Fixation

Table 7 shows the results of calculating Eq. 1 to assess fixation in transactional design problem solving.

Table 7. Fixation (%) by Phases of both Groups

Group	***Experimental***		***Control***	
Phase	*Ph I*	*Ph II*	*Ph I*	*Ph II*
Fixation (%)	16.4%	26.9%	13.8%	52.4%

No statistically significant difference in the design fixation metric using a two sample *t*-test is found when comparing phase I of the experimental and control groups (*t*-value= 0.89, *p*-value=0.376). This result may indicate a base level of fixation for non-assisted scenarios. Table 7 shows that the fixation percentage is lower after applying the method (phase II). A two sample *t*-test between phase II of the experimental and control groups shows a statistically significant difference in fixation (t-value=-4.33, p-value=0.000) between both groups.

6. Discussion and conclusions

Recalling our research questions, and after completing literature review, it is evident that there has been a considerable number of initiatives to overcome design fixation, but they have not been presented in a form that is collective, cumulative, and a basis for predicting performance.

Analyzing the metrics used to understand and account for design fixation, it is concluded that there are several metric definitions and indicators, some share characteristics and intentions. Direct and indirect metrics are revised and grouped in an attempt to unify metric criteria. The proposed fixation metric captures previous work and builds on it to include a wider range of design problems such as transactional problems and can be applied to engineering, architectural and transactional design problems.

After exploring existent research about design fixation, it is found that, to the best of our knowledge, there are not applications of mitigating ideation methods or de-fixation methods in transactional design problems. Therefore, a relevant transactional problem was selected to expand design fixation research and analysis in a wider spectrum of problems. The results obtained are comparable with the ones obtained for engineering, allowing possible generalization of conclusions.

For the quantity generated ideas (Q_{Total}), it is found that phase I performance of both the control and experimental groups was the same, while phase II performance indicate a reduction in quantity for experimental group, which reflects the load that the method added cognitively. For the quantity of repeated ideas (QR), it was surprising to find that the quantity of repeated ideas for phase II in the experimental group was the same as the quantity of phase I for both groups, which shows that the WordTree DbA Method as a positive impact to overcome fixation to pre-developed solutions; while Q_R for the control group was three times the phase I results. After reviewing the quantity data, the quantity initially accounted for cognitive load within the experimental group and matched the quantity of repeated ideas for the non-assisted, control scenario. These differences in quantity were translated in fixation percentages revealing that there is a base level of fixation for non-assisted scenarios that remains statistically the same after applying the semantic word-based DbA method, while for phase II of a non-assisted scenario, it rises considerable (double the quantity of experimental group). These results highlight the efficiency of the semantic word-based approach as utilized by design experts to effectively manage design fixation.

Would fixation level during the ideation stage be significantly different using a DbA method compared with a non-assisted scenario? From the study results, there is evidence that in non-assisted scenarios, a considerable amount of time was employed developing solution variants (solutions that are not distinctive from each other), while analogical transfer provided by the semantic word-based DbA method enables problem re-representation, exploration of divergent words and enables effective solution space exploration to solve the problem. The DbA method used here combines and evolves previous approaches to overcome design fixation which explains its strength and robustness. From Table 1, the DbA method incorporates elements from different categories. It includes: reframing, by characterizing the problem and problem re-representation. It has a break of two days between phases that serve as an incubation period. It considers expertise that allowed working with incomplete information, frame the problem, identify relevant information and develop more solutions. It provides and enables analogical exploration. It uses software tools that in our case provides visual stimulation, a graphical representation of the semantic cognitive process allowing problem and solution representation. The positive results obtained from the experiment are not only aligned with existent research in design fixation, but also with reported results in the psychological and neuroscience fields [87]. Leynes et al. (2008) found that fixation can be overcome in two different ways: the first one was with an incubation period of 72 hours, and the second (and closely related to our approach) was presenting alternative semantic information to participants. They found that the block and unblock effect occur in different parts of the brain. The results of present study align with this finding, because after the semantic stimulation and analogy exploration, the participants were able to significantly overcome design fixation.

Examining results of the present study and contrasting them to the ones reported by design fixation researchers, it is also concluded that for the control group scenario, the time between the two phases (incubation) was proven relatively ineffective. This result indicates that for a non-assisted scenario, a different period of time than the one employed in this study may be required.

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