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Creativity in the Design Process: Cognitive Actions and Conceptual Transformations

Creatividad en el proceso de diseño: acciones cognitivas y transformaciones conceptuales

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ABSTRACT

This research explores the complex relationship between creativity and cognitive processes during the design process, focusing on the mechanisms that stimulate conceptual expansion and shifts in understanding how creative insights emerge. The study involved 25 participants who employed the think-aloud protocol to tackle a specific design task. Linkographic entropies derived from verbal data collected during design sessions were employed to identify critical moves (CM) and their corresponding design decisions. The CM networks were analysed and coded using the Function-Behaviour-Structure (FBS) ontology to classify design actions. Furthermore, semantic analysis was conducted to categorise the types of design transformations as either conceptual expansions or conceptual shifts. The findings reveal that conceptual shifts are achieved solely through Synthesis, while conceptual expansions serve as the foundational elements for these shifts. Cognitive actions—specifically reformulations and evaluations—were found to facilitate conceptual expansions and contribute to conceptual shifts at various levels. The effectiveness and type of these conceptual transformations are influenced by the distance between the knowledge sets used during cognitive actions. Formulation and Analysis do not contribute to fostering conceptual transformations. The study contributes to a deeper understanding of the cognitive processes underlying design creativity, providing insights for both design education and professional practice.

Keywords

creativity; cognitive processes; conceptual expansion; conceptual shift; design thinking; Function-Behaviour-Structure (FBS) ontology; linkography

RESUMEN

Esta investigación explora la compleja relación entre la creatividad y los procesos cognitivos durante el proceso de diseño, centrándose en los mecanismos que estimulan la expansión conceptual y los cambios para comprender cómo surgen las ideas creativas. El estudio contó con 25 participantes que emplearon el protocolo de pensamiento en voz alta para abordar una tarea de diseño específica. Las entropías linkográficas derivadas de los datos verbales recogidos durante las sesiones de diseño se emplearon para identificar los movimientos críticos (MC) y sus correspondientes decisiones de diseño. Las redes de MC se analizaron y codificaron utilizando la ontología Función-Comportamiento-Estructura (FBS) para clasificar las acciones de diseño. Además, se realizó un análisis semántico para clasificar los tipos de transformaciones de diseño como expansiones conceptuales o cambios conceptuales. Los resultados revelan que los cambios conceptuales se logran únicamente a través de la síntesis, mientras que las expansiones conceptuales sirven como elementos fundacionales para estos cambios. Las acciones cognitivas, en concreto las reformulaciones y evaluaciones, facilitan las ampliaciones conceptuales y contribuyen a los cambios conceptuales en varios niveles. La eficacia y el tipo de estas transformaciones conceptuales están influidos por la distancia entre los conjuntos de conocimientos utilizados durante las acciones cognitivas. La formulación y el análisis no contribuyen a fomentar las transformaciones conceptuales. El estudio aporta a una comprensión más profunda de los procesos cognitivos que subyacen a la creatividad en el diseño, dando ideas tanto para la enseñanza del diseño como para la práctica profesional.

Palabras clave

cambio conceptual; creatividad; expansión conceptual; linkografía; ontología función-comportamiento-estructura (FBS); pensamiento de diseño; procesos cognitivos

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INTRODUCTION

Most studies on how creativity emerges in the design process have focused on what influences and nurtures creativity, how designers combine irrelevant thought matrices and produce new ideas, and how this process can be observed. Existing research is grounded in various paradigms, primarily categorised into two prominent perspectives. The first viewpoint posits that creativity remains mysterious and cannot be explored, strengthening the notion of its inherent mystery. In contrast, the second perspective argues that creativity arises from collaborating concepts across disparate contexts—a phenomenon termed bisociation. Proponents of this viewpoint claim that creative insights emerge through a cognitive process and can therefore be researched (Sawyer, 2006).

Researchers advocating for the traceable nature of creativity are further divided into structuralists and non-structuralists. Non-structuralists, including Donald Schön, argue that creative insights are generated by reapplying previously successful ideas to a problem through trial and error (Finke et al., 1992). Contrariwise, structuralist theorists, led by Arthur Koestler, contend that creativity emerges via the unconscious restructuring of problem and solution spaces (Finke et al., 1992). Structuralists claim that creative insight transpires when two distinct knowledge sets converge successfully. Similarly, Nigel Cross (1997a) posits that the essence of creativity lies in constructing effective connections between the problem and solution spaces throughout the design problem-solving process. This emphasises the crucial role of differing cognitive styles in facilitating creative insights, necessitating an investigation into how knowledge is transformed within this context.

Koestler (1964) characterises the creative process as establishing novel relationships between unrelated knowledge chunks and thought matrices. He argues that the creative process is finding implicit similarities and distinguishing them to produce a creative idea. The effort to find the implicit relationships between unrelated chunks of knowledge and thought matrices causes a temporary imbalance in cognition schemas. This instability, arising from linking disparate matrices, generates more challenges requiring resolution to restore cognitive equilibrium (Koestler, 1964) akin to balancing the design problem and solution space. According to Schön (1983), to solve a design problem creatively, it is necessary to find out what the problem is. In other words, the problem should be reconstructed, and sub-problems should be defined effectively. Cross (2008) emphasises that "the mysterious, creative part of designing" (p. 40) is the capability to find the problem, identify possible solutions, and create connections between the problem and the solution space by using a particular way of thinking. Establishing unconventional links between knowledge components is essential for achieving creative insights; Cross (1997b) terms this connection as a "creative leap," while Koestler (1964, p. 45) refers to it as "fusion" or "a new intellectual synthesis." Individuals aiming to develop creative insights must synthesise new concepts from diverse knowledge domains, suggesting that creativity arises from highly structured and systematic cognitive processes.

Margaret Boden (1998) posits that this structuring can be achieved by exploring and transforming existing conceptual spaces through mapping. While conceptual spaces consist of interconnected information networks organised by their associations (Warr, 2007), Boden (1995) further delineates conceptual spaces by emphasising their unique structures characterised by dimensions, paths, and boundaries. Such approach allows for the identification of exploration and transformation as two distinct strategies for mapping conceptual spaces. Exploration involves seeking unknown niches within an established conceptual space (Boden, 1995) and is generally deemed less creative than transformation. Transformation entails altering specific dimensions of a conceptual space by adding or removing constraints.

Within the design context, both types of mapping are substantial: conceptual expansion and conceptual shift. Conceptual expansion involves the augmentation of existing concepts by integrating relevant information at their boundaries (Hampton, 1987; Wan & Chiu, 2002; Ward et al., 2002; Ward et al., 1997). According to Vinod Goel (1995), conceptual expansion represents a vertical transformation where an existing idea is elaborated and expanded within the conceptual space. While conceptual expansion enriches the existing framework, it does not facilitate the simultaneous integration of information from multiple perspectives, resulting in a less creative process than that observed in conceptual shifts (Ward et al., 1997; Goel, 1995). Conversely, conceptual shifts involve transforming one or more dimensions of the conceptual space, leading to the emergence of new conceptual structures that could not have arisen prior. The novelty of these ideas increases with the degree of transformation they set in motion (Boden, 1998). Goel (1995) categorises this process as lateral transformation. Achieving a conceptual shift entails synthesising disparate and unrelated concepts to generate a novel idea.

Designers possess a unique skill set that enables them to recognize relationships among various variables and potential multivariate causes, all while managing multiple relationships and outcomes. They adeptly map, transform, and synthesize matrices of disparate knowledge and thought processes to develop innovative design solutions. In line with this, the primary objectives of this study are to investigate the relationship between creativity and cognitive actions during the design process, with a focus on conceptual expansions and shifts. The study will also identify the mechanisms through which cognitive actions—such as reformulation, synthesis, and evaluation—facilitate creative insights. Additionally, it aims to analyse the role of knowledge integration and the distance between knowledge sets in promoting conceptual transformations, while providing empirical insights into how design education and professional practice can enhance creativity through structured cognitive processes. Ultimately, this research seeks to enrich the theoretical understanding of creativity in design by linking cognitive actions to the emergence of creative solutions

METHODOLOGY

This study unfolds over a two-step process designed to clarify the relationship between design creativity and designers' cognitive actions that breed conceptual expansion and transformation. Twenty-five undergraduate architecture students (15 males, 10 females) aged 20 to 27 (mean age: 21.52) voluntarily participated in the study. Among them, 32% were in their second year, 24% in their third year, and 44% in their fourth year. The participants were recruited through faculty announcements.

In the initial phase, participants were presented with a design problem, allowing researchers to capture the linkographic entropies of their design sessions. Participants employed the think-aloud protocol to articulate their thought processes while solving the problem, with each design session limited to 45 minutes. All parameters were standardised, and the experiment was carried out on the same design problem in a uniform setting using identical materials to maintain participant consistency. Prior to initiating their design sessions, participants received guidance on implementing the think-aloud protocol, and their sessions were recorded using a voice recorder. The collected verbal data were subsequently transcribed, and the design decisions were coded employing the protocol analysis framework. Connections among these segments of decisions were established, enabling the derivation of linkographic entropies using the Linkography method.

In the second phase of the research, participants' critical design decisions, termed critical moves (CM), were identified based on calculated entropies. Each CM network was coded using the Function-Behaviour-Structure (FBS) ontology (Kan & Gero, 2009). This coding process elucidated the design transformation types (e.g., Analysis and Synthesis) associated with the decisions forming the network. At the conclusion of the second phase, an in-depth semantic analysis was conducted to assess whether the design decisions that influenced cognitive activities originated from near or far knowledge sets.

Think-Aloud Protocol

The think-aloud protocol is a method of acquiring insights into a subject's cognitive processes whilst performing a predefined task. Researchers frequently employ this methodology to understand cognitive functioning during design, providing a straightforward approach to collecting raw data on reasoning and problem-solving frameworks (Ericsson, 1998; Gursoy, 2010; Someren et al., 1994).

Despite concerns regarding the potential for thought manipulation and distortion due to linguistic limitations and cognitive constraints, protocol analysis remains an important methodological tool for investigating cognitive processes in problem-solving, particularly in design research (Cross, 2006; Ericsson, 2006). However, such an objection is unfounded regarding the think-aloud method, considering that it eliminates participant interpretation by relying on a straightforward verbalization process and treats verbal protocols, which are accessible to anyone, as objective data (Someren et al, 1994). Given the difficulties in accessing cognitive processes during design activities, researchers often use a combination of protocol analysis and real-time verbal reporting. This approach allows for a deeper understanding of designers' thought processes and decision-making strategies in play at ongoing activities or tasks. By capturing both the verbal expressions of their thoughts and analysing the logs of their actions, this method provides valuable insights into the complexities of the design process.

Data collection through think-aloud protocols requires participants to articulate all thoughts that arise as they engage in their tasks within a set timeframe. Researchers need to record this verbal activity and log the recordings into text format, which is then segmented into sequential design decisions to yield a structured dataset suitable for analysis. The 12 tips for applying the think-aloud method include ensuring methodological appropriateness by choosing the right method (concurrent or retrospective), sampling purposefully with a representative and heterogeneous group, creating a quiet and controlled task setting, providing clear and limited instructions, conducting domain-specific warm-up training, avoiding interruptions during sessions, capturing verbalizations completely through recordings and notes, transcribing verbatim to include all details, allowing participants to think aloud in their preferred language, triangulating data with other methods for validity, flexibly analysing data using qualitative or quantitative approaches, and addressing reactivity and non-veridical concerns through precise instructions and cross-validation (Noushad et al., 2023).

Linkography

Linkography is a method used to reveal the structural patterns of design reasoning by analysing the cognitive activities of designers. With this method, the design decisions that contribute to solving the design problem and the connections between these design decisions are determined and visualised graphically. A design decision can be associated with both previous and subsequent decisions. If the decision is not linked to other decisions, it can be left alone, or if it has more than one link, it can be linked to several decisions. Backlinks are links that relate to previous decisions. Forelinks are links that relate to subsequent decisions. Orphan decisions are design decisions that have no connection whatsoever. A design decision with more links than most in the design session is called a critical move (CM). These decisions are critical because they generate more new ideas than other decisions. Therefore, CMs have a crucial role in the emergence of creativity (Goldschmidt, 2014; van der Lugt, 2001). However, only some CMs can be considered creative insight. For a CM to be deemed creative, there must be a synthesis of irrelative knowledge chunks and thought matrices in the decision network that produces the CM.

Function–Behaviour–Structure (FBS) Ontology

The FBS ontology offers a framework for classifying design decisions during the design process. Gero and Kannengiesser (2007) suggest that an object's design encompasses three ontological characteristics: function, behaviour, and structure. Design decisions arise from interlinking and transforming these three attributes. Gero (1990) elucidates transformations through the following model:

> The purpose of designing is to transform function F (where F is a set) into a design description D in such a way that the artefact being described is capable of producing these functions. For example, when designing windows, some of the functions include the provision of daylight, control of ventilation, and access to a view. The design description would take the form of drawings and notes. Thus, a naive model of design is F→D, where → is some transformation. There is, however, no direct transformation capable of achieving this result (Gero, 1990, p. 28).

As Gero (1990) mentioned, function (F) cannot be directly transformed to design description (D) but can be obtained by indirect transformations. The transformations encompass two major pathways: transforming function (F) into structure (S) (F→S) and subsequently transforming structure (S) into design description (D) (S→D). However, Gero (1990) emphasises that these direct transformations do not encapsulate design actions. For a transformation to be categorised as a design activity, it must entail behaviour (B), which can be categorised in the following types: the behaviour of the structure (Bs), derivable from S, and the expected behaviour (Be), derivable from F. Thus, the transformations occur as follows: S→Bs for the structural behaviour and F→Be for the expected behaviour. Table 1 outlines these FBS processes in detail.

Table 1. FBS transformations

Analysis	S→Bs
Evaluation	Be↔Bs
Formulation	F→Be
Reformulation I	S→S
Reformulation II	S→Be
Reformulation III	S→F
Synthesis	Be→S

Source: author´s own elaboration (2023).

The design process incorporates eight transformations, with primary transformations identified as Formulation, Synthesis, Analysis, Evaluation, and Documentation. Formulation transforms function into expected behaviour (F→Be). In Synthesis, the expected behaviour is transformed to structure (Be→S). The structure is transformed into the structure's behaviour (S→Bs) during Analysis. The expected behaviour in the Evaluation is transformed into the behaviour of the structure (Be→Bs). The structure is transformed into the design description (S→D) in the Documentation. The remaining three sub-transformations are Reformulations and involve the transformation of the structure into a new structure (S→S'), expected behaviour (S→Be'), and function (S→F').

RESULTS

Critical move (CM) thresholds were calculated for each participant to ensure the reliability of design decision networks. CMs with outnumbered connections among design decisions above the threshold were identified for analysis using linkographic entropies. Table 2 summarises the details of the identified CM networks.

Table 2. Details of the identified CM networks

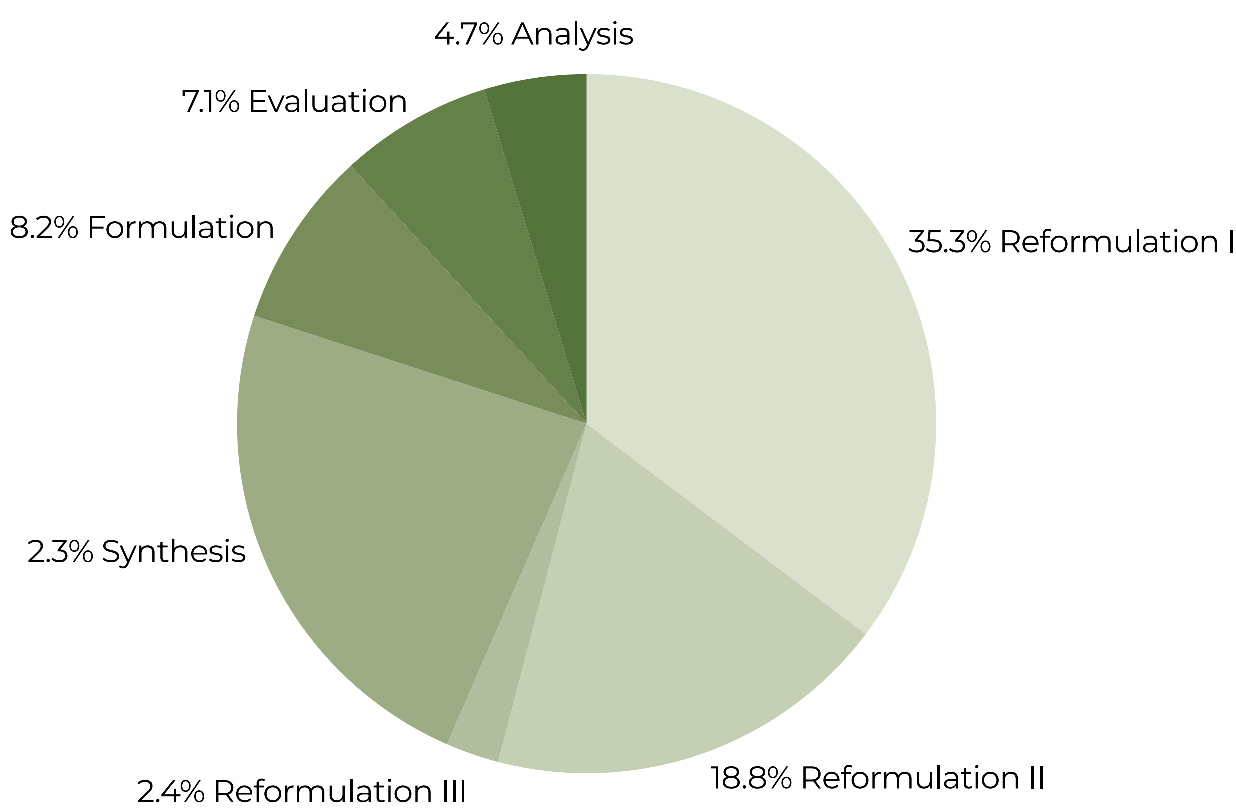
Participant	CM Threshold	Design Moves						
		CM	Backlinks of CM					
1	5	9	6	$Be^{i''''}$	8			
		S	Bsi	Be^{i}	$Be^{i'}$			
2	5	10	6	7	9			
		Be''	Be	S	Be'			
3	4	26	10	23	24	25		
		S'''	S	S'	S''	S'''		
4	4	19	10	12	14	17		
		S'''	S^{i}	S	S'	S''		
5	4	9	2	6	7	8		
		F	F	F^{i}	F^{i}	F^{i}		
6	4	47	8	9	45	46		
		S''	S	S'	Bei	Si		
7	4	97	89	93	94	95	96	
		Bs'	S	S'	S''	Bs	S'''	
8	4	44	24	27	35	43		
		S'''	S	S'	S''	Be		
9	5	90	12	15	62	75		
		S''	S	F	S'	Be		
10	5	21	8	16	18	19	20	
		S'''	S	S'	Bs	F	Be	
11	5	55	44	45	53	54		
		S	S	S'	Be	Be^{i}		
12	5	59	47	48	57	58		
		S'''	Bs	S	S'	S''		
13	5	26	3	4	11	20	25	
		Be'	B^{i}	F	B^{i}	Be	S	
14	5	61	35	36	39	52	58	59
		Be'''	Be	S	Be'	F	Be''	F
15	6	26	15	16	17			
		S	Be	S	Be^{i}			
16	4	51	44	45	46	48		
		S'	Be^{i}	S^{i}	Be	S		
17	5	10	3	4	5	6	9	
		Be	Bs^{i}	Be^{i}	Be	Be'	F^{i}	

Participant	CM Threshold	Design Moves											
		CM	Backlinks of CM										
18	5	46	9	19	21	27	28						
		S''	F	F^{i}	Be^{i}	S	S'						
19	6	76	17	72	73	74	75						
		S''	S	Be^{i}	Be	Be'	S'						
20	6	149	4	105	128	135	143	144					
		F	Bs^{i}	$Bs^{i'}$	$Bs^{i''}$	S	S'	Be					
21	6	24	11	14	19	20	22	23					
		Be	F	F'	S	S'	S''	S'					
22	6	57	24	25	32	33	34						
		Be	F	F'	F''	F'''	S						
23	6	63	19	22	27	53	54	62					
		Be'''	Be^{i}	S^{i}	F	Be	S	Be''					
24	6	143	7	8	9	43	51	53	74	78	138	140	141
		S	S^{i}	Bs^{i}	$Bs^{i'}$	Be^{i}	S	$Be^{i'}$	$Be^{i'}$	$Be^{i''}$	$Bs^{i'''}$	$Bs^{i''''}$	Bei''''
25	7	20	8	11	14	15	17	18	19				
		S'''	Be	Bs^{i}	F	S	Be	S'	S'				

Source: author´s own elaboration (2023).

An analysis of all participants' conceptual model of CM networks showed that reformulations were the most common action, comprising 56.5% of all actions (see Figure 1). Notably, 88% of participants engaged in at least one type of reformulation, highlighting the dynamic restructuring of problem and solution spaces necessary for tackling ill-structured design challenges (Ho, 2001).

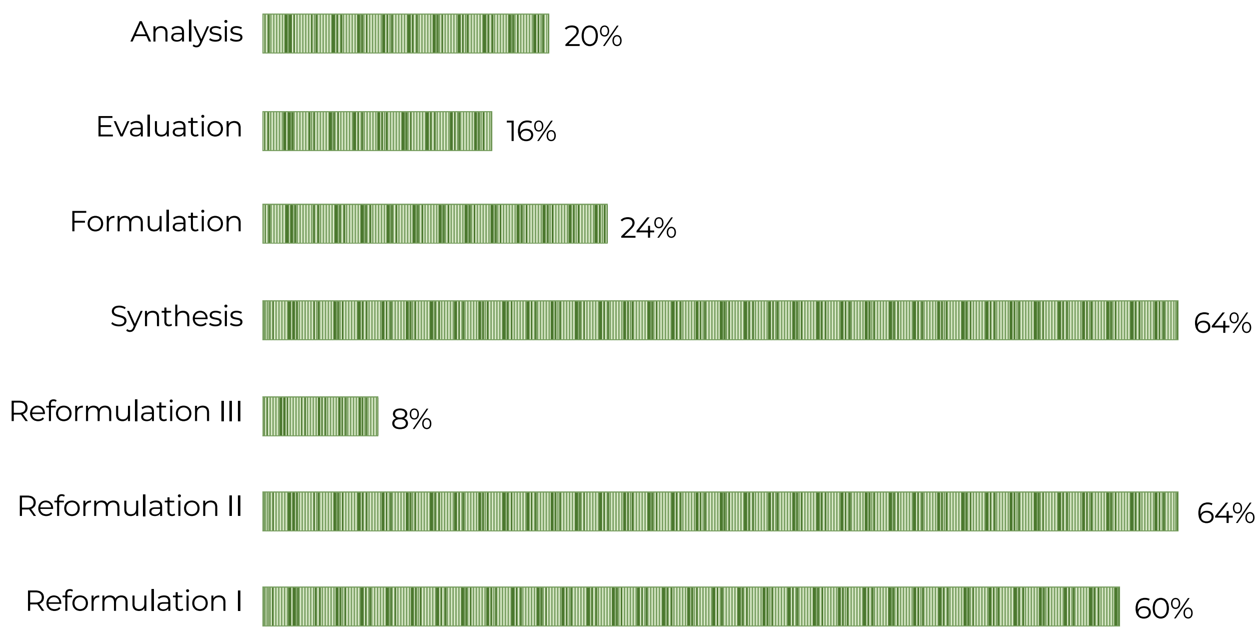
Figure 1. Frequency of FBS coded cognitive operations



Source: author´s own elaboration (2023).

The most frequent FBS transformation was Reformulation I (S→S'), observed at a rate of 35.3%. This finding aligns with similar studies in the literature (Ashrafganjouei & Gero, 2021; Gero & Milovanovic, 2020; Kan & Gero, 2009; Monache & Rocchesso, 2016; Shih & Sher, 2020; Tang et al., 2012). Reformulation I appeared in the CM network of 60% of participants (see Figure 2).

Figure 2. Percentages of participants who employed specific FBS transformations in CM networks



Source: author´s own elaboration (2023).

The second most frequent transformation was Synthesis (Be→S), with a frequency of 23.5% in the overall measuring and it was seen to come up in the CM networks of 64% of the participants. While this result aligns with the findings of Stefano Delle Monache & Davide Rocchesso (2016) and Tang et al (2012), it does not match other research findings, perhaps because it focused on the partial design processes that resulted in CMs, as opposed to the comprehensive design processes undertaken by the participants. It should also be noted that 44% of the participants' CMs are the product of direct Synthesis, indicating diverse creative engagement. The CMs of 78% of the participants who did not have Synthesis in the CM networks produced fewer forelinks than the backlinks.

Reformulation II (S→Be) was the next most common transformation, at 18.8%, consistent with Tang et al. (2012) findings. It was observed that 64% of participants engaged with Reformulation II.

Formulation (F→Be) emerged as the fourth most operated, recorded at 8.2% among 24% of participants.

Evaluation ranked fifth, with a usage of 7.1% (Be→Bs: 4.7%; Bs→Be: 2.4%). It was found that only 16% of the participants used Evaluation.

Analysis (S→Bs) emerged as the sixth most employed, with a recorded percentage of 4.7% among 20% of participants.

The least used FBS transformation is Reformulation III (S→F), with 2,4%. Only 8% of the participants used Reformulation III, paralleling findings from Gero & Milovanovic (2020), Kan & Gero (2009), Monache & Rocchesso (2016) and Tang et al. (2012).

DISCUSSION

Reformulation I (S→S')

The prominence of reformulation may indicate an iterative focus on form throughout the design process. Semantic analysis showed that in Reformulation I, participants evaluated the physical attributes of forms (such as curvilinear, angular, attractive, and wide) concerning both function and user interaction. However, these reformulations are often built upon closely related knowledge sets rather than integrating unrelated concepts, thus failing to achieve creative insights. For example:

Participant 7

M93: now... the first two [seating units] face to each other

M94: they [the two seating modules] will be close to each other on the front

Participant 20

M135: If we consider its [seating unit's] orientation, we have to have a structure that is open from the front, so that a wide frame can be seen from Konak pier where we can see the city light.

M143: maybe without expanding the seating unit much...

Gaining creative insight requires challenging initial design ideas, reframing problems, and addressing assumptions (Fakhra, 2012). However, Reformulation I aims to improve the form without challenging foundational design ideas or reframing problems. Therefore, Reformulation I, which only provides conceptual expansion, cannot be considered creative insight.

Synthesis (Be→S)

The remark that nearly half of the participants produced CMs through Synthesis and those who do not have Synthesis in their CM network produced fewer forelinks can be accepted as clear evidence that Synthesis, new idea generation and CMs are directly proportionate. A design decision which has outnumbered existing forward connections indicates a conceptual shift in design, and, thus, is a creative insight (Goldschmidt, 2014; van der Lugt, 2003). A comparative analysis showed that decisions arising from Synthesis consistently recorded more forelinks than those derived from other design actions.

Semantic analysis revealed that three-quarters of participants' Synthesis involved antonyms or contrasting concepts functioning as a thesis-antithesis dynamics (e.g., open-closed, coastal-sea, oval-linear, individual-public). This finding aligns with the conclusions of Chiu & Shu (2012) that opposite stimuli increase creativity and Kaya & Cikis (2017) that ideas constructed with contradictory concepts and dialectical thinking are more effective in creating creative results.

It has been determined that all CMs produced based on antonyms or oppositely positioned concepts as thesis and antithesis generate more forelinks than backlinks. Consequently, creating conceptual shifts and achieving creative insight becomes more accessible through the Synthesis of contradictory concepts, highlighting the significance of knowledge sets' distance in the creative process.

It is worth noting that analysis of the relationship between transformations indicated that Synthesis typically precedes Reformulation. This sequencing implies that a conceptual shift instigates a series of necessary structural, behavioural, and functional adjustments. As a result, a Reformulation arises as participants respond to the new concepts introduced.

Reformulation II (S→Be)

In performing Reformulation II, most participants (66.7%) assessed the expected behaviour of structures concerning user interactions. Therefore, it can be inferred that Reformulation II primarily rearranges the relationship between users and the form. For example:

Participant 2

M7: With more sharp lines...

M9: By this way, people can experience the sea by touching at this part [of seating unit]... where it [seating unit] penetrates the sea.

The transformations resulting from Reformulation II, which in the next step produced a synthesis, were found in the CM networks of the participants who evaluated an expected behaviour of a structure guided by user-centred principles. The resulting Synthesis may occur because analogies related to the user are more distant concepts than analogies related to the physical properties of structures. As it is known, using distant concepts in the problem-solving phase in the idea-generation phase positively affects ideation, synthesis and creativity (Fu et al., 2013; Hocking & Vernon, 2017; Jia et al., 2020).

33.3% of the participants who executed Reformulation II concentrated on how the structure's expected behaviour impacted its function. An analysis of this group's design decisions revealed that the knowledge chunks and thought matrices they utilised were distant concepts. Example:

Participant 21

M23: but the mobility will be achieved by designing small modules which can be integrated [to fixed module]

M24: and in the simplest case, the scenario can be like this... the fixed module defines a space

Nonetheless, like Reformulation I, Reformulation II results in conceptual expansion rather than inducing a conceptual shift, albeit with more effective contributions to creative insights. Although the knowledge sets and thought matrices are related in Reformulation II, they are relatively distant concepts compared to the ones used in Reformulation I.

Formulation (F→Be)

The semantic analysis of Formulation indicated a lack of substantial patterns among constituent concepts, which likely reflects participants' incomplete problem definitions at this stage. This observation aligns with the understanding that Formulation is a process used to create a new structure rather than engaging in reasoning (Ashrafganjouei & Gero, 2021), thus yielding no discernible conceptual expansion or shift.

Evaluation (Be↔Bs)

Interestingly, while Ashrafganjouei & Gero (2021) posited that Evaluation occurs post-analysis, this research also demonstrated its occurrence following Reformulation II, suggesting that design decisions can transition directly to Evaluation without necessitating earlier Analysis stages.

Semantic Analysis confirmed that user-related knowledge sets also informed the Evaluation processes, reflecting similarities with Reformulation II. Although Evaluation acts as a catalyst for conceptual expansion, it can also solidify the foundation for synthesis and consequently lead to conceptual shifts.

Analysis (S→Bs)

Data revealed that participants resorted to Reformulation I prior to performing Analysis. Subsequent transformations varied, including a new Analysis, abandoning ideas, and reevaluating new problems by Formulation. The evaluation phase begins if an idea is approved following the Analysis. The Analysis can be accepted as a design action in which the problem and solution space equilibrium is resolved. Thus, the subsequent design actions are expected to be diversified. Semantic analysis revealed that participants predominantly focused on the behaviour derived from the structure by decoding the decisions about the structure during the Analysis. Therefore, Analysis does not cause any shift in the current state of the design, and it does not create a conceptual expansion either. However, only a few participants had Analysis in their CM network so that no strong inference could be drawn. Thus, the discussion about the Analysis remained at a presumption level.

Reformulation III (S→F)

Kan & Gero (2009) observed that Reformulation III is rare because it changes or redefines the design problem. Deriving a function from a structure is challenging since, in design, shaping the structure according to its intended function is crucial. However, new functions can be integrated into the structure if successfully achieved. Reformulation III was also the least frequently used transformation among participants in this research.

All participants operated Reformulation III later developed Synthesis in subsequent transformations. The reason may be the addition of new functions to the design due to Reformulation III. Adding a new function to the design requires expanding the existing conceptual space. Semantic analysis of Reformulation III shows the introduction of previously distant concepts that begin to congregate through the structure during Reformulation III, as evidenced by the example of the following:

Participant 9

M12: at some point, the [seating] unit extends as much it can be for lying down

M15: even... at some points of the seating unit, there will be locks for bicycles

Findings indicate that linking previously introduced distant concepts may facilitate conceptual shifts; however, additional data are required to substantiate this argument conclusively.

CONCLUSIONS

This research has examined the complex relationships between cognitive actions and conceptual transformations that play a fundamental role in generating creative insights during the design process. It draws on the findings from an empirical investigation involving 25 architecture students who employed the think-aloud protocol in 45-minute design sessions. The analysis of Linkographic entropies from these think-aloud protocols has unveiled critical insights into how various cognitive actions facilitate conceptual expansion and shifts.

The findings showed that conceptual shifts, essential for generating creative insights, are solely obtained through Synthesis. Synthesis enables designers to create novel solutions by combining previously unrelated concepts and identifying and bridging contradictions or opposing ideas. This emphasises the critical role of integrating distant and unrelated knowledge in the creative process. On the other hand, conceptual expansions achieved through reformulations and evaluations provide foundational support for the emergence of Synthesis. Semantic analysis showed that conceptual expansions contribute to the emergence of conceptual shifts at various levels depending on the distance of constituent knowledge sets.

Another interesting insight from this study is the minimal role of Formulation and Analysis in contributing to conceptual transformations. While Formulation is critical for defining a design problem and Analysis for evaluating design concepts, neither has been shown to influence the emergence of creativity directly. Neither formulation nor Analysis demonstrated any capacity to bridge concepts or restructure thinking patterns in the CM networks. Their methodological emphasis on definition and evaluation confines them to foundational rather than transformative roles in the design process. While formulation and analysis are essential, they alone are inadequate for fostering creativity. It is seen they offer structure and stability but lack the dynamic, integrative qualities necessary for generating creative ideas.

The results showed an evident framework that connects cognitive actions to conceptual transformations; creativity in design emerges from structured processes. Notably, the process of Synthesis leads to conceptual shifts by integrating distant knowledge sets. Additionally, conceptual expansions enhance existing ideas by incorporating related knowledge at their boundaries, gradually creating a more extensive cognitive framework. This framework links theoretical insights—such as Koestler's concept of bisociation and Boden's conceptual spaces—with empirical evidence, offering practical guidance for improving creative outcomes in design education and practice. The findings illustrate how specific cognitive actions contribute to creative outcomes, presenting a framework for enhancing pedagogical approaches. The critical finding is that conceptual shifts occur primarily through the Synthesis of distant knowledge sets, highlighting the importance of teaching designers to integrate unrelated and often contradictory concepts. This indicates a need to move beyond traditional skill-building exercises by incorporating explicit training in bisociative and dialectical thinking within educational settings. Studio projects could be designed to combine seemingly unrelated domains, and critiques could focus on valuing contradictory ideas as catalysts for creativity. Design curricula could be enriched by intentionally integrating non-disciplinary content, fostering cross-disciplinary collaborations and multi-disciplinary projects.

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