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The use of occurrences of ideas for constructing and characterizing the design space

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Abstract

This study explores the construction, characterization, and measurement of the design space using a novel approach that centres on First Occurrences (FOs) and Re-Occurrences (ROs) as metrics. Expert architects' cognitive behaviours during the design process were investigated empirically to gain insights into design space evolution. Findings reveal a consistent generation and revisiting of ideas, signifying an ongoing development of the design space. Future research should incorporate diverse methodologies and broader participant sample for a more comprehensive understanding.

Keywords: design cognition, design space, first occurrence, protocol analysis

1. Introduction

Designing is a multifaceted cognitive activity during which decisions are made, ideas are generated, and designs evolve (Cross, 2011). Since design problems are inherently ill-structured (Simon, 1973), designers develop the design process by constructing their design space, unique to that design activity, using their knowledge and expertise. The design space represents the realm of potential ideas and design solutions available to designers. This cognitive space serves as a framework for carrying out design activities (Dorst & Cross, 2001). It facilitates the generation and exploration of ideas, providing a mental landscape for the complexities of the design process (Dorst, 2011). Within this space, ideas are conceived, iterated upon, and transformed into tangible design outcomes.

Recent years have witnessed a shift from the metaphorical interpretation of the design space, towards reifying it into a more tangible and measurable construct (Gero & Kumar 1993; Gero & Milovanovic, 2022a; Kan & Gero, 2017; Perisic et al., 2021). This transformation aligns with the broader trend in design research, which seeks to study the underlying cognitive processes driving design thinking (Goldschmidt, 1997). However, a comprehensive understanding of the design space, its construction and characterization, and its implications for design thinking and performance through time remains underexplored. This understanding is important for advancing design theory and practice and holds significant implications for creative problem-solving (Cross, 2006; 2011). As research in this area progresses, it promises to shed light on the mechanisms underlying design processes and the cognitive pathways leading to design solutions. In this paper, we aim to characterize and measure the design space using a new syntactic approach based on the first occurrences of design ideas and their re-occurrences throughout time during a design session. Our research questions are as follows:

RQ1. How can design spaces be characterized, constructed, and measured?

RQ2. What is the temporal construction of the design spaces generated by expert architects during the design process, and how can it be measured?

RQ3. What can we learn about the cognitive behaviour of expert designers while constructing their design spaces?

2. Design ideation: Exploring the design landscape

Design ideation is a critical behaviour in the design process, involving the generation, evaluation, and evolution of ideas. Extant research emphasizes divergent thinking where novel ideas are generated, and convergent thinking where the selection and refinement of ideas take place (Gabora, 2018; Hu et al., 2019). The concept of First Occurrences (FOs) of ideas has been introduced in the study of design ideation (Gero & Kan, 2016). FOs represent the initial introduction of design ideas during a design session, marking a change or a novel direction in the design process. A study of FOs offers insights into the earliest stages of design ideation, shedding light on a designer's cognitive and creative processes (Gero & Milovanovic, 2022a).

Understanding the use of FOs and their role in design ideation is essential for comprehending the mechanisms underlying idea generation in the design process. By examining the characteristics and patterns of FOs, a fuller understanding of the dynamics and cognitive processes contributing to the emergence of new design ideas can be gained. This understanding extends to the re-occurrences (ROs) of ideas throughout the design process, providing new insights into how ideas are revisited over time. FOs and ROs represent the introduction and evolution of processes, collectively advancing our understanding of how design ideation unfolds. The measures of FOs and ROs model how design thinking influences the structure and characteristics of the design space.

3. Characterizing the design space using FOs and ROs

A design space can be defined as a varying space of potentialities constructed during the design process (Kan & Gero, 2018). The design space serves as a representation of the ideas and concepts that designers develop over time to produce a design solution that materializes into a design artifact (Bucciarelli, 2001). Goel & Pirolli (1992) defined the design space in terms of design problem states and processes enabling state change. As ideas and solutions are generated, the design space is modified and expanded, creating opportunities for novel designs (Alsager Azayed et al., 2019; Gero & Kumar, 1993).

Traditionally viewed as a metaphorical construct, the design space is undergoing a new understanding, evolving from an abstract representation into a tangible and characterizable entity. Recent shifts in the field emphasize the need to comprehend its characteristics and its relationship with design ideation (Sopher et al., 2023) and the co-evolution of problems and solutions (Dorst, 2019). This shift advances research in design creativity (Gero & Kan, 2016; Gero & Kumar, 1993).

The design space, encapsulating ideation pathways and the potential design solutions generated (Gero, 1990; Persic et al., 2021), serves as a cognitive framework guiding the actions of the designer. Understanding the structure and evolution of the design space and its expansion is relevant for design thinking research (Goel & Pirolli, 1992; Maher & Poon, 1996). This shift from the metaphorical and abstract interpretation of the design space to a concrete construct provides the foundation for measuring its characteristics. This shift aligns with the broader trend in design research that focuses on the underlying cognitive processes driving design thinking and design creativity (Dorst, 2011; Dorst & Cross, 2001).

An unexplored area closely related to the evolving notion of the design space, deals with the study of First Occurrences (FOs) of ideas and their repeated occurrences (ROs) within this space. The latter metric is introduced for the first time in this paper. Such an approach can be used to describe how the design space can be constructed, characterized, and expanded throughout the design process (Gero & Milovanovic, 2022a). Some studies used occurrences to examine the rate at which the design space expands (Martinec et al., 2020), reflecting the cumulative cognitive effort set across the design session (Kan & Gero, 2017). Other researchers have regarded FOs as a proxy to measure divergent thinking and design creativity (Gero & Milovanovic, 2022b).

Design spaces can be conceived of as occupying multiple dimensions, where each dimension is a concept. Each FO adds a dimension to the design space, thus constructing it as designing proceeds. This multi-dimensional space can be represented in two dimensions by locating concepts relative to each

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other either syntactically or semantically. FOs can be related to each by temporal distance (how close in time they were introduced) or by word distance (e.g., two FOs that are n or fewer words apart are related). They can also be related by the semantic distances of the individual FOs. These provide foundational structures for the space.

Extending previous studies on FOs to explore syntactic measures can provide an increased understanding of the design space, and how it becomes populated with ideas and evolves over time (Gero & Kan, 2016; Sopher et al., 2023). This analytical approach can also offer insights into the cognitive processes underlying creative ideation and problem-solving.

4. Method

4.1. Case study

The research presented in this paper is based on a controlled experiment in the form of a case study where four male architects each individually worked on an identical design task in a single design session. All four architects have at least 15 years in professional practice, and also serve as design studio teachers. The experiments took place in a lab setting, with each session lasting 55 minutes. Sessions were divided into two parts lasting 40 and 15 minutes respectively. The first part was devoted to dealing with the design task while exploring potential design solutions. In the second part they were asked to produce a final design solution. Participants received a design problem to solve and a task sheet with general instructions. They were required to verbalize their thoughts to enable recording their design activity. A camera captured the participants' sketches (Figure 1). The design task required designing a small museum located in an urban area characterized by historical and modern buildings (adapted from Casakin & Kreitler, 2011).

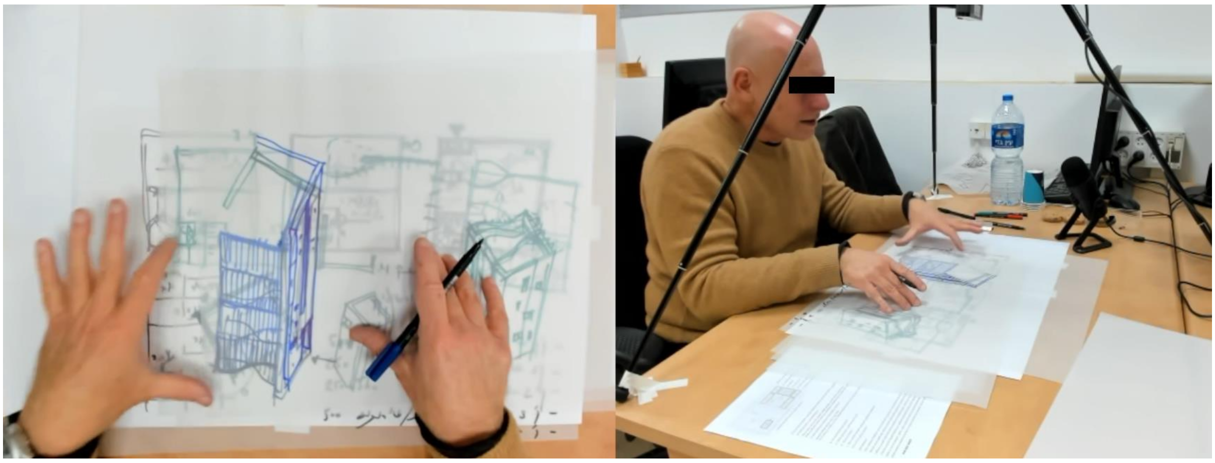

Figure 1. The experiment setting

4.2. Characterizing and measuring design spaces

We employed protocol analysis techniques (Van Someren et al., 1994) to provide evidence of design thinking and used the results to characterize and measure the design space. A total of 3.50 hours of verbalizations were recorded, transcribed, and segmented into one-minute epochs. Design spaces constructed by these designers were analysed by syntactically tracking the distribution of FOs and ROs of design issues generated during the design activity The number of FOs in a session is a measure of the size of the design space (Gero & Kan, 2016), while the number of ROs is a measure of the focus on the ideas re-instantiated.

To track the temporal construction of the design space, we analysed the cumulative occurrence of FOs and ROs throughout the design session. The slope of the cumulative FOs is the rate of divergent thinking, while the slope of the cumulative ROs can be seen as a temporal proxy for revisited ideas – a measure of convergence. Additionally, we analysed the ratio and the percentage of FOs and ROs as syntactic measures of the cognitive effort on ideation through the design process.

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4.3. Natural language processing to identify first occurrences and re-occurrences of design ideas

The study employed Natural Language Processing (NLP) techniques to track the occurrences of First Occurrences (FOs) and Re-Occurrences (ROs) in design sessions. This NLP method presents an automated, versatile approach for objectively identifying the first introduction of ideas and their recurrent appearance during the ideation process. Specifically, algorithms based on the YAP package (Tsarfaty et al., 2019) were utilized for the analysis of the Hebrew language spoken during the design sessions.

NLP is instrumental in automating the initial stages of data preparation, encompassing tasks such as transcript cleaning, tokenization, and stemming. This automation not only expedites the research process but also ensures the consistent handling of data across all sessions, reducing the risk of subjective bias, human errors, and inconsistencies. To structure the design space, the study focused solely on the identification and retention of FOs and ROs of concepts. For instance, using the NLP script, verbalizations such as "All the buildings in the town are built mainly of local stone" were parsed to extract concepts like “buildings,” “town,” and “stone” for further analysis.

5. Results

In this study we characterize design spaces as quantifiable entities, combined with integrating FOs and ROs as analytical measures. This approach represents a paradigm shift in design research, moving from abstract representations of design processes to the concretization of design acts. In this paper we focus only on the construction of the design space.

The quantitative analysis produced an average of 285 FOs and 672 ROs for a session, including 224 FOs and 469 ROs within the initial 40 minutes and 61 FOs and 203 ROs in the final 15 minutes This represents a ratio between FOs and ROs of 0.42 in the whole session, 0.48 in the first part and 0.30 in the second part of the process. Normalizing the FOs and ROs by time, on average the four designers generated 9.52 FOs and 12.21 ROs per minute for a complete session, including 5.60 FOs and 11.70 ROs in the first part of the session, and 4.06 FOs and 13.53 ROs in the second part. On average, the results show a decrease in the rate of FOs, and an increase in the rate of ROs generated in the final 15 minutes. The average cumulative occurrence of FOs and ROs for all designers is graphically depicted in Figure 2. Examining the frequency of FOs and ROs over time indicated a consistent pattern, characterized by linear occurrence for each designer. This uniform behaviour persisted in both the first and second parts of the design session for FOs and ROs. For FOs, the *R-squared* values (0.96 and 0.88) suggest that the linear regression models are a reasonable fit for the data in both parts of the design ideation process. The positive slopes indicate a uniform rate of introduction of FOs during the design session. The rates of 5.39 in the first part and 6.66 in the second part indicate an increased introduction of FO in the later epochs. This finding suggests that the designers continued producing FOs even in the second part, highlighting the presence of divergent thinking in the later design phases.

For ROs, the *R-squared* values (1.00 and 0.98) show that the linear regression models are a good fit for the data in both parts of the process. The positive slopes indicate a uniform rate of introduction of ROs during the design session. The rates of 12.66 in the first part and 14.55 in the second part suggest a higher rate of introduction of RO in the later epochs. This finding suggests that as expected, these designers continued producing ROs during the process, highlighting the presence of focus and refinement in the later design phases.

Additionally, in all cases, the cumulative graph of FOs intersected that of ROs early in the design session, signifying the early evolution from the generation of new ideas without repetition to a recurrent generation of concepts throughout the design process.

The distribution of FOs-ROs and percentages per epoch among the designers is illustrated in Figure 3. The figure represents a relationship between the percentage of FOs and ROs (y-axis) and the natural logarithm of epochs (ln(x), where x is the epoch) on the x-axis. The data is divided into the two parts of the session. The combined model for all the design process (R-squared =0.64) suggests a logarithmic relationship between the percentage of FOs and ROs and epochs as a proxy for time. The negative coefficient for the natural logarithm indicates a decreasing trend of FOs, but the overall fit is moderate,

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as indicated by the R-squared value. The model for the first part of the process (R-squared=0.69 also follows a logarithmic pattern, and the fit is slightly better than the overall model. The negative coefficient indicates a diminishing rate of change in the percentage of FOs generated by the designers, and an increase of ROs with each additional time unit in this part of the session. The model for the second part of the process shows a different behaviour with a positive coefficient for the natural logarithm. This suggests an increasing rate of change in the percentage of FOs with each additional time unit in this later segment, which contrasts with the first part of the session.

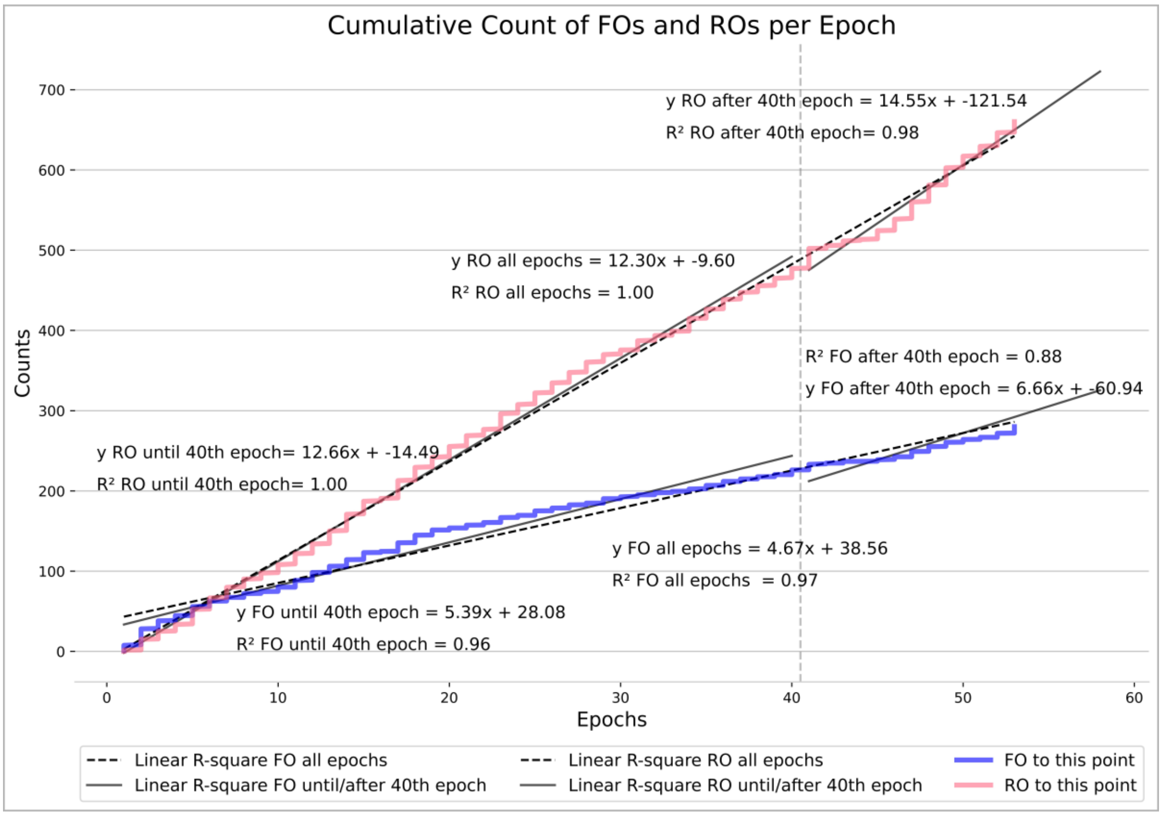

Figure 2. Average cumulative occurrence of FOs and ROs through time by the designers

Figure 4 presents the same data that Figure 3 in a different way. It illustrates the distribution of FOs-ROs and their ratio per epoch among the designers. The relationship between FOs and ROs in the different epochs provides more accurate insights into the linear rate of introduction of ideas and focus shift over time in the two parts of the design process.

From a qualitative analysis of the results depicted in figures 3 and 4, based on the higher number of FOs than ROs observed in the first part of the session, an intensive cognitive effort in generating new ideas can be observed at the beginning, with a subsequent decline as depicted by the regression curve. Throughout this part of the process, there were fluctuations characterized by peaks and valleys in the FOs and ROs, displaying a general trend towards a decrease in FOs. However, in the end of the second part of the process, where designers were requested to produce a final design solution, the increase in FOs suggests a continued effort in generating new ideas until the completion of the task.

The relationship between the number of FOs and ROs (y-axis), and epochs as a proxy for time (x-axis) is shown in Figure 5. The model for FOs suggests a negative approximate linear relationship over time. The R-squared value of 0.46 indicates a moderate fit. The negative coefficient indicates a decreasing trend in the number of FOs produced over the epochs, but the standard deviation (std=2.13) indicates some variability around the regression line among the designers. In contrast, the model for the ROs suggests a positive linear relationship between the count of ROs and the epochs. However, the R-squared value is low (0.05), indicating that only 5% of the variability in the count of ROs is explained by the linear regression model. The positive coefficient implies an increasing trend in the generation of ROs

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over epochs, but the high standard deviation (std=2.99) suggests substantial variability among the designers.

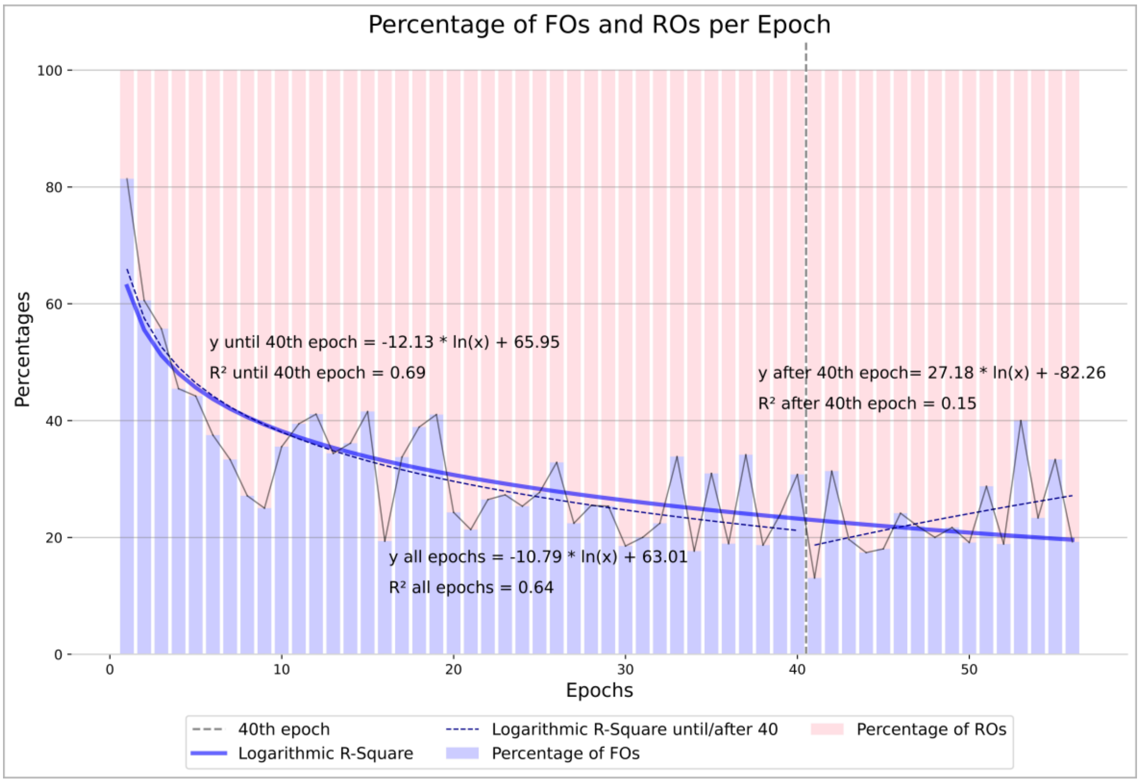

Figure 3. Percentage of FOs and ROs generated through time by the designers

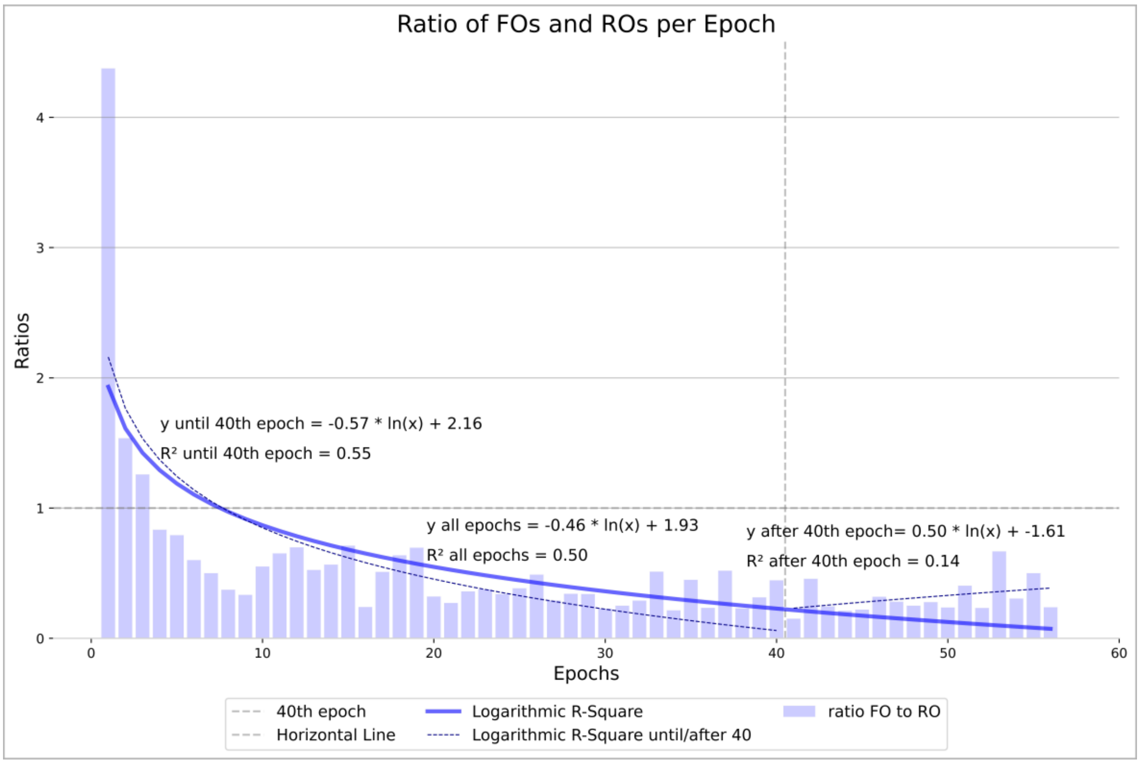

Figure 4. Proportion of FOs and ROs through the session among the designers

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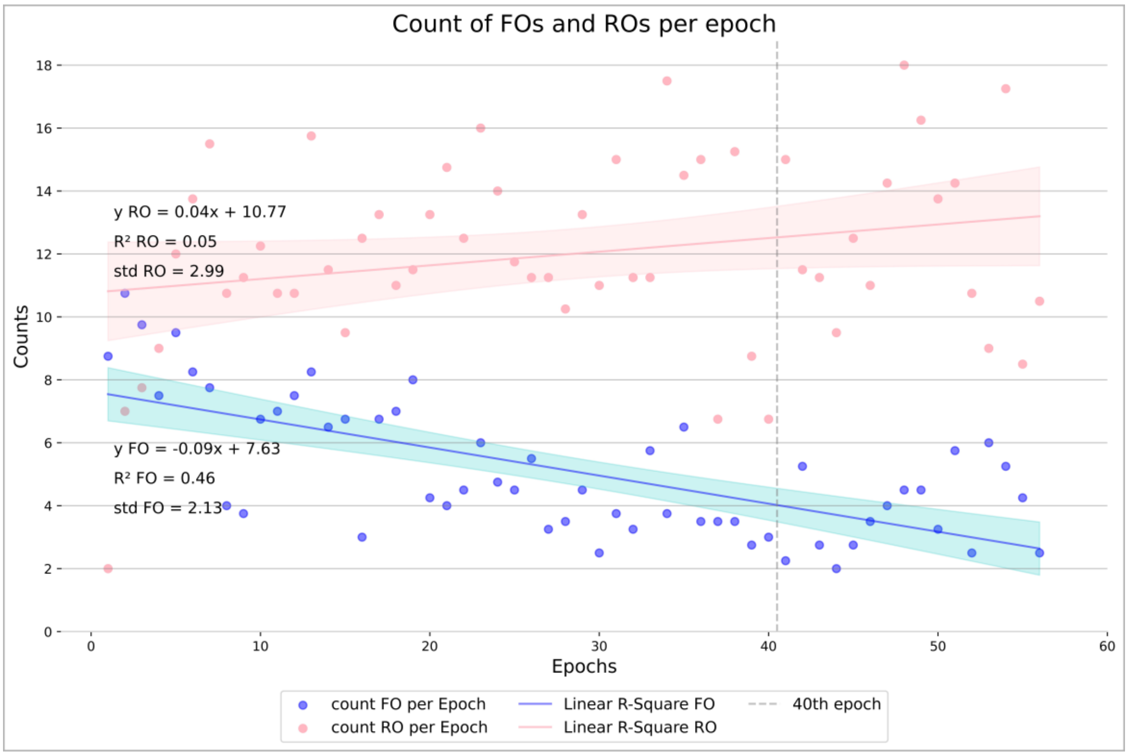

Figure 5. Average occurrence of FOs and ROs throughout the design sessions

The fact that FOs exhibit a negative linear slope suggests that designers continued generating FOs during the entire design sessions at a constant but negative rate, indicating openness to exploring new ideas or possibly further alternatives, and consistency in expanding the size of the design space even during convergence stages.

6. Discussion

Design, as a set of cognitive processes, involves the generation and evolution of ideas and continual design development (Cross, 2011). These cognitive processes revolve around the construction of the design space, which serves as a mental framework guiding designers' endeavours (Dorst & Cross, 2001). The transformation of the abstract concept of the design space into a quantifiable and measurable construct marks a paradigm shift in design research (Kan & Gero, 2016; Perisic et al., 2021). This study seeks to lay the foundation for the understanding of the construction, characterization, measurement and temporal dynamics of the design space and its connection to the cognitive behaviour of experienced designers.

6.1. Constructing, characterizing and measuring design spaces

The design space, representing the set of ideas available to the designers who generated them (Dorst, 2011), has undergone a transition from metaphorical interpretations to a more tangible entity. Employing First Occurrences (FOs) and Re-Occurrences (ROs) as metrics for measuring the design space, this study presents the beginnings of an approach that can produce quantifiable insights into its evolution and syntactic content (Gero & Milovanovic, 2022a). The size, in terms of dimensions, of the design space is measured by the number of FOs. Each FO adds a dimension to generate a high-dimensioned space. ROs and their relation to FOs structure the design space. The analysis demonstrates a linearity in the production of FOs and ROs in the first part of the session, where designers approached the design and the second part, where they produced a final design solution. These indicate a consistent cognitive effort over time. These findings demonstrate the viability of using FO and RO metrics to quantify design space dimensions and structure over time, extending on past studies on metaphorical interpretations. Tracking idea generation and re-occurrence enables empirically examining and comparing design space development in the two parts of the design process across sessions. Integrating

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this syntactic approach with protocol analysis enabled to gain insight into the construction, characterization, and measurement of design spaces and their evolving nature (Dorst & Cross, 2001; Gero & Kan, 2016).

6.2. Temporal characterization and measurement of design spaces

The temporal analysis provides insights into the cognitive behaviour of experienced designers as they construct and navigate design spaces over time. Tracking the generation of FOs and ROs reveals an iterative behaviour of divergent and convergent thinking throughout the sessions (Chiu et al., 2023; Dorst & Cross, 2001; Gero & Milovanovic, 2022b).

The consistent, recurring emergence of FOs aligns with divergent thinking, denoted by designers' generation of the design space through the introduction of concepts. This occurs even in the second part of the session where the focus is on convergence to a specific design (Gabora, 2018). Newly introduced ideas, understood as situated creativity (Sosa & Gero, 2003), aligns with theories on enduring creativity across design stages (Dorst, 2011). Concurrently, the continuous expansion of ROs in the two parts of the design session reflects recurring idea revisitation and refinement (Kan & Gero, 2017).

Notably, increased FOs in the second stage highlights the nonlinear, iterative nature of design cognition versus fixed divergence-convergence sequencing (Adams & Atman, 2000; Dorst, 2019;). Meanwhile, fluctuating yet accumulating ROs through the process underscores the development or refinement of ideas towards a final solution in the second part of the session (Goel & Pirolli, 1992; Kan & Gero, 2017; Maher & Tang, 2003).

Overall, the interplay between regularly generating FOs and ROs shows an incremental, developmental approach to design spaces. Results reflect designers actively constructing their design spaces while demonstrating situated novelty by introducing FOs and re-examining idea suitability through recurring ROs (Gero, 2019; Sopher et al., 2023).

This persistent FO-RO intertwining signifies an ongoing ideation, concept refinement, and design space expansion even when convergence is required, as requested in the second part of the process. The recurring behavioural tendencies provide clues to the cognitive mechanisms underlying design space construction and expansion.

7. Conclusions

The study focused on the construction, characterization, and measurement of the design space using a novel syntactic approach based on First Occurrences (FOs) and Re-Occurrences (ROs). This explorative work provided a new understanding of the individual cognitive behaviours of professional designers during the design process. It has revealed a consistent intertwined pattern of generating and revisiting ideas along the design process, indicating the presence of divergent and convergent thinking and reflecting the constructive nature of the design space.

We used established NLP techniques in the quantitative exploration of design ideation, enabling a structured and data-driven foundation for our study. By employing a quantitative approach, we moved beyond qualitative assessments, allowing a systematic quantification of concept occurrences within design sessions, contributing to our comprehension of how design spaces are developed, characterized, and measured.

With the design space's dimension and structure in the form of a network connecting FOs and ROs it becomes possible to measure design thinking. To this end, using NLP techniques to measure the semantic distance between FOs as a proxy for creative ideas (Kenett, 2019; Lee et al., 2018) can contribute further to characterizing and understanding design spaces and related design and creative design processes.

However, there is a need for further exploration to increase our understanding of the complexities involved in constructing the design space and its temporal dynamics. Integrating diverse methodologies and participant pools in future research may enable further insights into the multifaceted nature of design space construction and its cognitive underpinnings. While this research is a step forward, its findings being predominantly based on a restricted group of designers will impact the broad applicability of the conclusions to a wider population of design practitioners. Moreover, the exclusive focus on FOs and ROs as metrics for exploring design space dynamics could overlook other critical aspects of the design process, prompting the exploration of additional metrics for a more comprehensive understanding. Follow-up studies should incorporate more designers across diverse domains. Comparisons of novices and experts of both genders could unveil skill differences in design space construction and expansion (Atman et al., 2007). Larger samples could better establish result validity and patterns. Additionally, exploring external stimuli such as the use of visual displays and analogies could further enhance our comprehension of the construction, characterization, and measurement of the design space.

Nonetheless, quantitatively measuring FOs and ROs enabled systematic mapping of design spaces over time. Combining protocol analysis with computational modelling could help simulate design space construction and navigation based on empirical data. Studying the relationship between design space construction with design outcome quality could contribute to a more comprehensive understanding of the cognitive processes in the evolution of design spaces.

In future research, we aim to investigate how fixation, a behavior characterized by the inappropriate use of concepts in the design process, impacts the construction and characterization of the design space. We will explore the relationship between design concepts used in shaping the design space and fixation, and how these affect design performance.

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References

Alsager Alzayed, M., McComb, C., Hunter, S.T. and Miller, S.R. (2019), “Expanding the solution space in engineering design education: A simulation-based investigation of product dissection”, *Journal of Mechanical Design*, Vol.141 No.3, p.032001. http://dx.doi.org/10.1115/1.4042426

Amabile, T. M. (1996), *Creativity in Context: Update to The Social Psychology of Creativity*. Westview Press, Boulder, CO. http://dx.doi.org/10.4324/9780429501234

Atman, C.J., Adams, R.S., Cardella, M.E., Turns, J., Mosborg, S. and Saleem, J. (2007). Engineering design processes: A comparison of students and expert practitioners. *Journal of engineering education*, Vol 96 No 4, pp. 359-379. http://dx.doi.org/10.1002/j.2168-9830.2007.tb00945.x

Bucciarelli, L. L. (2001). Design knowing & learning: A socially mediated activity. In C. Eastman, M. McCracken, & W. Newstetter (Eds.), Design knowing and learning: Cognition in design education. Elvesier.

Casakin, H. and Kreitler, S. (2011), “Correspondences and divergences between teachers and students in the evaluation of design creativity in the design studio”, *Environment and Planning B: Planning and Design*, Vol. 38 No. 4, pp. 592-611. http://dx.doi.org/10.1068/b3405

Chiu, M., Silva, A., & Lim, S. (2022), "Design Progress Dashboard: Visualising a quantitative divergent/convergent pattern of design team progress through Natural Language Processing", In *International Conference on-Design Computing and Cognition (pp. 67-84)*. Cham: Springer International Publishing. http://dx.doi.org/10.1007/978-3-031-20418-0_5

Cross, N. (2006), *Designerly Ways of Knowing*, Springer, Berlin.

Cross, N. (2011), *Design Thinking: Understanding how Designers Think and Work*, Bloomsbury Academic, London. http://dx.doi.org/10.5040/9781474293884

Dorst, K. (2011), "The core of ‘design thinking’ and its application", *Design Studies*, Vol. 32 No 6, pp. 521-532. http://dx.doi.org/10.1016/j.destud.2011.07.006

Dorst, K. (2019), "Co-evolution and emergence in design", *Design Studies*, Vol. 65 No. C, pp. 65-77. http://dx.doi.org/10.1016/j.destud.2019.10.005

Dorst, K. and Cross, N. (2001), “Creativity in the design process: co-evolution of problem–solution”, *Design Studies*, Vol. 22 No. 5, pp. 425–437. http://dx.doi.org/10.1016/S0142-694X(01)00009-6

Gabora, L. (2018), "Reframing convergent and divergent thought for the 21st century". *arXiv* preprint arXiv:1811.04512.

Gero, J. S. (1990), "Design prototypes: A knowledge representation schema for design", *AI Magazine*, Vol. 11 No. 4, 26. https://doi.org/10.1609/aimag.v11i4.854

Gero, J. S., and Kan, J.T.W. (2016), "Empirical results from measuring design creativity: use of an augmented coding scheme in protocol analysis", *Proceedings of the 4th International Conference on Design Creativity, 4th ICDC, Atlanta, GA, November 2-4*, 2016, pp. 1-8.

Gero, J. S., and Kumar, B. (1993), "Expanding design spaces through new design variables", *Design Studies*, Vol.14 No.1, pp. 210 221. http://dx.doi.org/10.1016/0142-694X(93)80048-H

Gero, J., and Milovanovic, J. (2022a), "Creation and characterization of design spaces", *Proceedings of DRS2022, Bilbao, Spain, 25 June - 3 July*. https://doi.org/10.21606/drs.2022.265

Gero, J., and Milovanovic, J. (2022b), "What is happening when designers from different disciplines work together", *Proceedings of the 13th Design Thinking Research Symposium - Expanding the Frontiers of Design: Critical Perspectives, DTRS13, Haifa, Israel, March 22-24*. http://dx.doi.org/10.1201/b22630-26

Goel, V., and Pirolli, P. (1992), "The structure of design problem spaces", *Cognitive Science*, Vol. 16, pp. 395–429. http://dx.doi.org/10.1207/s15516709cog1603_3

Goldschmidt, G. (1997), "Capturing indeterminism: representation in the design problem space", *Design Studies*, Vol. 22, pp. 425-437. http://dx.doi.org/10.1016/S0142-694X(97)00011-2

Hu, Y., Du, X., Bryan-Kinns, N., and Guo, Y. (2019), "Identifying divergent design thinking through the observable behavior of service design novices. *International Journal of Technology and Design Education*, Vol. 29, pp. 1179-1191. http://dx.doi.org/10.1007/s10798-018-9479-7

Kan, J.W.T., and Gero, J.S. (2017), *Quantitative Methods for Studying Design Protocols*, Springer International Publishing, Cham. http://dx.doi.org/10.1007/978-94-024-0984-0

Kan, J.W.T., and Gero, J.S. (2018), Characterizing innovative processes in design spaces through measuring the information entropy of empirical data from protocol studies, *Artificial Intelligence for Engineering Design, Analysis, and Manufacturing*, Vol. 32 No. 1, pp. 32–43. http://dx.doi.org/10.1017/S0890060416000548

Kenett, Y. N. (2019), "What can quantitative measures of semantic distance tell us about creativity?", *Current Opinion in Behavioral Sciences*, Vol. 27, pp. 11–16. https://doi.org/10.1016/j.cobeha.2018.08.010

Lee, L., Yu, R., Kan, J.W.T., and Gero, J.S. (2018), Exploring the differences between designing and describing designing, *Design Thinking Research Symposium - DTRS12, Seoul, South Korea, 15-16 November*.

Maher, M. L., & Poon, J. (1996). "Modeling design exploration as co-evolution". *Computer-Aided Civil and Infrastructure Engineering*, Vol. 11 No 3, 195–209. https://doi.org/10.1111/j.1467-8667.1996.tb00323.x

Martinec, T., Škec, S., Perišić, M.M. and Štorga, M. (2020), “Revisiting Problem-Solution Co-Evolution in the Context of Team Conceptual Design Activity”, *Applied Sciences*, Vol. 10 No. 18, p. 6303. http://dx.doi.org/10.3390/app10186303

Perisic, M. M., Štorga, M., and Gero, J. S. (2021), "Computational study on design space expansion during teamwork", *Proceedings of the International Conference on Engineering Design (ICED21), Gothenburg, Sweeden, August 16- 20*, pp. 691-700. https://doi.org/10.1017/pds.2021.69

Simon, H. A. (1973), The structure of ill structured problems, *Artificial Intelligence*, Vol. 4 No. 3–4, pp. 181–201. http://dx.doi.org/10.1016/0004-3702(73)90011-8

Sopher, H., Casakin, H., and Gero, J.S. (2022), "Effect of immersive VR on student-tutor interaction in design crits". *Proceedings of ECAADe Conference 2022, Ghent, Belgium, September 13-16*, pp.123–132. http://dx.doi.org/10.1007/978-94-010-9521-1_17

Sopher, H., Casakin, H., and Gero, J. S. (2023), "The Temporal effect of immersive VR on student-tutor interaction in architectural design crits", *Proceedings of eCAADe Conference 2023, Gratz, Austria, September 20-23*, pp. 191-200. https://doi.org/10.52842/conf.ecaade.2023.1.191

Sopher, H., Milovanovic, J., and Gero, J. S. (2022), "Exploring the effect of immersive VR on student-tutor communication in the architecture design crits", *Proceedings of in CAADRIA, 27th International Conference on Computer-Aided Architectural Design Research in Asia, Sydney, Australia*. Vol. 2, pp. 315-324. http://dx.doi.org/10.52842/conf.caadria.2022.2.315

Sosa, R. and Gero, J.S., (2003), Design and change: A model of situated creativity. *Approaches to creativity in artificial intelligence and cognitive science*, pp.25-34.

Tsarfaty, R., Seker, A., Sadde, S., and Klein, S. (2019), What's wrong with Hebrew nlp? And how to make it right. *arXiv preprint* arXiv:1908.05453. http://dx.doi.org/10.18653/v1/D19-3044

Van-Someren, M. W., Barnard, Y. F., and Sandberg, J. A. (1994), *The Think Aloud Method: A Practical Guide to Modelling Cognitive Processes*, Academic Press, San Diego, CA.