ENTROPY IN INNOVATION AND CREATIVITY MEASUREMENT: AN INTEGRATIVE REVIEW

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Abstract: Drawing inspiration from Physics and Information Theory, the concept of entropy has been employed across a myriad of contexts to quantify chaos, surprise, complexity, or inherent randomness in systems. Further, across the years, its utility in evaluating creative and innovative processes is noteworthy. This study reviews entropy's use in innovation and creativity evaluation. We analyze 26 studies by 69 authors, grouping results into four areas: Systems Innovation, Arts, Law, and Neuroscience. Entropy aids in evaluating innovation capacities, including patent assessments and brain activity analysis, including the assessment of complexity and divergent thinking. Overall, the findings accentuate the role of entropy as an important instrument in measuring complex constructs within recent interdisciplinary discussions.

Keywords: innovation; indicators; entropy; information theory, creativity.

Resumo: Inspirando-se na Física e na Teoria da Informação, o conceito de entropia tem sido empregado em inúmeros contextos para quantificar o caos, surpresa, complexidade ou aleatoriedade inerente em sistemas. Além disso, ao longo dos anos, sua utilidade na avaliação de processos criativos e inovadores é notável. Este estudo revisa o uso da entropia na avaliação de inovação e criatividade. Analisamos 26 estudos de 69 autores, agrupando resultados em quatro áreas: Inovação de Sistemas, Artes, Direito e Neurociência. A entropia auxilia na avaliação das capacidades de inovação, incluindo avaliações de patentes e análise da atividade cerebral, abrangendo a avaliação da complexidade e do pensamento divergente. No geral, os resultados destacam o papel da entropia como um importante instrumento na medição de construtos complexos em discussões interdisciplinares recentes.

Palavras-chave: inovação; indicadores; entropia; teoria da informação; criatividade.

Resumen: Tomando inspiración de la Física y la Teoría de la Información, el concepto de entropía ha sido empleado en una miríada de contextos para cuantificar el caos, sorpresa, complejidad o aleatoriedad inherente en sistemas. Además, a lo largo de los años, su utilidad en la evaluación de procesos creativos e innovadores es notable. Este estudio revisa el uso de la entropía en la evaluación de innovación y creatividad. Analizamos 26 estudios de 69 autores, agrupando los resultados en cuatro áreas: Innovación de Sistemas, Artes, Derecho y Neurociencia. La entropía ayuda en la evaluación de capacidades de innovación, incluyendo evaluaciones de patentes y análisis de actividad cerebral, abarcando la evaluación de la

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complejidad y el pensamiento divergente. En general, los hallazgos acentúan el papel de la entropía como un importante instrumento en la medición de constructos complejos en discusiones interdisciplinarias recientes.

Palabras clave: innovación; indicadores; entropía; teoría de la información; creatividad.

1 INTRODUCTION

Innovation and creativity are two pivotal constructs to socio-economic progress and the unfolding technological evolution, being ceaselessly involved with the development of diverse frameworks and methodologies. These instruments, specifically measures and indicators, aim to assess the breadth and depth of innovation and creativity influence, relating to the significance and subtleties of these processes (El-Murad & West, 2004). Despite the wealth of research and the amount of tools that have been developed, the quest for an indicator that can reliably and comprehensively encapsulate the multi-dimensional nature of creativity and innovation remains an ongoing challenge (Phan, 2013).

This endeavor is crucial as the accurate measurement and understanding of innovation and creativity holds the key to fostering these valuable traits in individuals, teams and societies, driving advancements across various domains, from technology to business, education and the arts (Dziallas & Blind, 2019). Each unique approach contributes a piece to the larger puzzle, offering different perspectives on what counts as innovative or creative and how these qualities might be enhanced or inhibited.

In response to this need for more sophisticated, nuanced measures, there is the exploration of entropy - a concept derived from Physics and Information Theory (IT) - as a potential metric. Entropy, a quantifiable measure of uncertainty or disorder within a system (Natal et al., 2021), presents a promising approach in this scenario. The application of entropy to innovation and creativity hinges on the insight that these domains are often characterized by high degrees of diversity, novelty, and complexity - all of which can be captured by the concept of entropy (Bratianu, 2019).

In its original context, entropy was used to quantify the amount of disorder in a thermodynamic system. Claude Shannon (1948), the developer of modern Information Theory, later adopted this concept to measure the amount of uncertainty or randomness in information. The adaptation of entropy as a measure of innovation and creativity serves as a natural extension of its use in IT, given that both creativity and innovation inherently involve the generation and manipulation of new information (Sherwin, 2018).

Therefore, within this scope, this work explores the potential of entropy in innovation and creativity indicators, exploring its theoretical underpinnings, practical applications, potential limitations, and avenues for future research. Through an integrative review, the complex phenomena of innovation and creativity is discussed, providing paths to researchers and practitioners, in order to guide their efforts to foster these important constructs.

2 INNOVATION, CREATIVITY, INDICATORS AND ENTROPY

Innovation is the development of new ideas, methods, or products enhancing efficiency (Forbes, 2016). It can be radical (unique to the world) or incremental (novel within a market) (Witell et al., 2016; Souto, 2015). It's a tool for businesses to add value and advance, requiring new business models comprising various concepts from marketing to finance. Innovation drives transformation, identifies profitable changes, and can appear in various forms like products or plans (Forbes, 2016; Baranskaitė & Labanauskaitė, 2021). Value creation through innovation is now seen in multi-dimensional terms, including social aspects (Hagedoorn et al., 2022). Assessing innovation is vital for understanding its impact and selecting appropriate performance indicators remains a topic of debate (bin Ali et al., 2020).

Creativity, essential for innovation, is elusive due to its intangibility (Vanzin et al., 2015). Divergent thinking is one method of evaluation, using tools like the Torrance Tests of Creative Thinking (TTCT) to measure idea generation aspects (Toivainen et al., 2017). Direct evaluations, like the Consensual Assessment Technique (CAT), provide an expert-led perspective (Baer & Kaufman, 2019). The "flow" concept describes deep involvement in creativity, revealing insights into challenge-response mechanisms (Csikszentmihalyi et al., 2014). Some fields, like engineering, have domain-specific evaluative tools. But creativity's multifaceted nature makes its full encapsulation challenging, with factors like cultural sensitivity influencing its assessment (Byrne et al., 2003).

They both, innovation and creativity, being complex and multifaceted, pose challenges for measurement (Dziallas & Blind, 2019). In organizational aspects, they are influenced by internal factors like organizational culture and external ones like market conditions (Souitaris, 2002), with their dynamic nature requiring ongoing assessment (Miller et al., 2020). These constructs can be context-dependent, necessitating evaluation in various settings. Therefore, accurate assessment demands a holistic, context-specific approach (Kanó et al., 2023).

Additionally, entropy quantifies information uncertainty in data, with its roots in Thermodynamics and Information Theory (Shannon, 1948). In physics, it defines thermodynamic system characteristics (Menéndez & Pérez-Suárez, 2020). Throughout the years, fields like Ecology have adopted entropy to measure domain-specific aspects that present uncertainty or surprise, like biodiversity (Pielou, 1966). Various entropy-based and other indices, like Simpson's Diversity Index and Rényi Entropy, are available for diversity quantification (Purvis & Hector, 2000; Leinster, 2020; Fedor & Zvaríková, 2019).

3 METHODOLOGY

This study employs an integrative review of the literature on innovation indicators, conducted in accordance with the PRISMA Protocol 2020. This protocol, recognized for its robustness in systematic reviews and meta-analyses, facilitates the identification, selection, and synthesis of pertinent studies, thereby providing a comprehensive understanding of the concept under investigation (Page et al., 2021). According to Botelho et al. (2011) an integrative review process typically unfolds in six key stages: initially, it involves the identification of the overarching topic and the selection of a precise research question to guide the review; the second stage consists of establishing specific inclusion and exclusion criteria, which helps to define the scope of studies to be included in the review; this is followed by the third stage, where pre-selected studies are identified and further refined into a group of selected studies, which aligns with the set criteria; during the fourth stage, these selected studies are categorized based on relevant characteristics or attributes; the fifth stage of the process involves a thorough analysis and interpretation of results derived from the selected studies and, finally, the sixth stage encompasses the presentation of the review, culminating in a synthesis of knowledge that provides comprehensive insights into the research question.

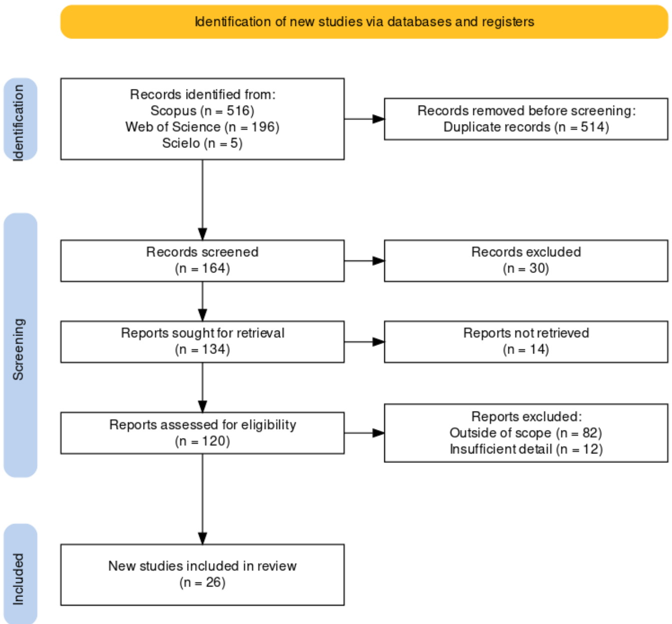
The literature search was executed across three major databases: Web of Science, Scopus, and Scielo, being selected for their extensive coverage of literature. The string used for search was used regarding Title, Abstract or Author Keywords, being as follows: ("entrop*") AND ("metric*" OR "measur*" OR "indicator*") AND ("creativity" OR "innovation"). The asterisks are used to cover plurals or derivative words such as “entropic” or “entropies”. The search strategy was meticulously designed to capture studies discussing the defining aspects of innovation, with a particular focus on product and process innovation. Upon completion of the integrative review, main aspects were delineated and the works synthesized and discussed.

4 RESULTS AND DISCUSSION

The schematic representation of the study identification process, as outlined by the PRISMA 2020 protocol, is depicted in Figure 1. The diagram delineates the sequential phases of identifying potential studies through various databases and registers, further encompassing the stages of Identification, Screening, and Inclusion in accordance with the prescribed PRISMA guidelines.

The compilation of the 26 works selected for the review is presented in Table 1. These works are authored by 69 different researchers across a span of four major categories - Systems Innovation, Arts and Design, Law, and Neuroscience and Psychology. The works range in publication date from 1985 to 2023, showcasing more than three decades of research.

Figure 1 – PRISMA flow diagram for the integrative review. Source: the authors



Source: the authors.

Table 1- Selected studies for the review

Reference	Title	Authors	Category
(Kanó et al., 2023)	Emerging synergies in innovation systems: Creative industries in Central Europe	Szakálné Kanó, I., Vas, Z., & Klasová, S.	Systems innovation
(Yuan & Zheng, 2022)	Improved intuitionistic fuzzy entropy and its application in the evaluation of regional collaborative innovation capability.	Yuan, X., & Zheng, C.	
(Cerreta et al., 2021)	Towards the Cultural Heritage Low Entropy Enhancement Approach: An Ex-post Evaluation Of Creative Regeneration Practices.	Cerreta, M., Daldanise, G., Girasole, E. G. d., Torre, C. M.	
(Sun & Xu, 2021)	Evaluation Model and Empirical Research On The Green Innovation Capability Of Manufacturing Enterprises From The Perspective Of Ecological Niche.	Sun, Y., & Xu, J.	

Reference	Title	Authors	Category
(Gong et al., 2018)	An Improved Mutation Series Entropy-based Algorithm for Evaluation of Innovation Ability of Enterprises.	Gong, C., Bi, K., & Yang, Z.	
(Kaynak et al., 2017)	Comparing the innovation performance of EU candidate countries: an entropy-based TOPSIS approach.	Kaynak, S., Altuntas, S., & Dereli, T.	
(Guira & Vasile, 2017)	Organizational entropy and creative potential.	Guira, A., & Vasile, M.	
(Haiping, 2013)	An Empirical Study on Performance Evaluations of Regional Innovation System Based on Management Entropy Theory.	Haiping, S.	
(Ya-fei & Lu-cheng, 2007)	The concept of entropy and the performance entropy of regional technological innovation ecosystem.	Ya-fei, L., & Lu-cheng, H.	
(Grupp, 1990)	The concept of entropy in scientometrics and innovation research: An indicator for institutional involvement in scientific and technological developments.	Grupp, H.	
(Papia et al., 2023)	Entropy and complexity analysis of AI-generated and human-made paintings.	Papia, E. M., Kondi, A., & Constantoudis, V.	Arts and Design
(Daikoku, 2018)	Entropy, uncertainty, and the depth of implicit knowledge on musical creativity: computational study of improvisation in melody and rhythm.	Daikoku, T.	
(Chang et al., 2017)	Measuring information-based energy and temperature of literary texts.	Chang, M. C., Yang, A. C. C., Stanley, H. E., & Peng, C. K.	
(Chou et al., 2014)	A method for evaluating the creativity of comic strips.	Chou, H. W., Chen, Y. L., & Chou, S. B.	
(Chou et al., 2013)	Entropy of Linkography: Evaluating the creativity of short animation.	Chou, S. B., Chou, H. W., & Chen, Y. L.	
(Petrov, 2002)	Entropy and stability in painting: An information approach to the mechanisms of artistic creativity.	Petrov, V. M.	
(Badalamenti et al., 1994)	Lawful systems dynamics in how poets choose their words.	Badalamenti, A. F., Langs, R. J., & Robinson, J.	
(Koomen, 1985)	The entropy of design: A study on the meaning of creativity.	Koomen, C. J.	
(Sichelman, 2021)	Quantifying Legal Entropy	Sichelman, T. M.	Law
(Zhang et al., 2017)	An entropy-based indicator system for measuring the potential of patents in technological innovation: rejecting moderation.	Zhang, Y., Qian, Y., Huang, Y., Guo, Y., Zhang, G., & Lu, J.	
(Ueno et al., 2015)	Neurophysiological basis of creativity in healthy elderly people: a multiscale entropy approach.	Ueno, K., Takahashi, T., Takahashi, K., Mizukami, K., Tanaka, Y., & Wada, Y.	Neuroscience and Psychology
(Tan & Zhou, 2014)	Evaluation of the innovation ability of engineering students based on entropy theory.	Tan, W., & Zhou, S.	
(Shi et al., 2020)	Brain entropy is associated with divergent thinking.	Shi, L., Beaty, R. E., Chen, Q., Sun, J., Wei, D., Yang, W., & Qiu, J.	
(White, 2017)	Locating emergent creativity with similarity metrics.	White, C. W.	
(Kak, 2011)	Information and learning in neural systems.	Kak, S.	
(Jaušovec, 1998)	Are gifted individuals less chaotic thinkers?	Jaušovec, N.	
Total	**26 works**	**69 authors**	**4 categories**

Source: the authors.

Regarding the "Systems Innovation" category, there are 10 articles dating from 1990 to 2023. This indicates an ongoing and growing interest in this field over the years. Topics covered are mostly centered around the application of entropy theory and entropy-based methodologies in assessing and enhancing innovation capabilities, whether it's at the regional (Kanó et al., 2023; Yuan & Zheng, 2022; Cerreta et al., 2021; Haiping, 2017), organizational (Gong et al., 2018; Guira & Vasile, 2017), or even ecological (or ecosystems) level (Ya-fei & Lu-cheng, 2007). Interestingly, although few works focus on specific geographic contexts, like Central Europe and EU candidate countries (Kanó et al., 2023; Kaynak et al., 2017), the perspectives are aimed at a macro level, reflecting the global and localized dimensions of innovation. Also, a long-term perspective is established by Grupp's work (1990) which introduced the concept of entropy in scientometrics and innovation research, exploring the concept of entropy in various knowledge fields such as Research and Development, technology policy and industrial technology management, paving the way for subsequent studies.

With respect to "Arts and Design" category, there are 7 articles published between 1985 and 2023. This range suggests that the intersection of arts, design, creativity, and entropy-related concepts has been a sustained area of interest. The works focus on developing and applying methods to measure and evaluate creativity in different forms of artistic expressions, like music (Daikoku, 2018), painting (Papia et al., 2023; Petrov, 2002), literature (Chang et al., 2017; Chou et al., 2014; Badalamenti et al., 1994) and animation (Chou et al., 2013). These measures, often entropy-based, explore aspects like uncertainty, stability, and systems dynamics in the creative process, providing an intriguing view into the mechanics of artistic creativity.

Sichelman (2021) and Zhang et al. (2017) have explored the concept of entropy within the Law category. Zhang et al. (2017) uses Shannon's entropy to develop a system that quantitatively weighs eleven patent indicators from technological, economic, and legal viewpoints to isolate a set of patents deemed promising for technological innovation. Contrasting with conventional methods that rely on expert opinion, the entropy-based approach offers data adaptability, quantitative weighting, and objectivity. Sichelman (2021) leveraging IT, suggests a quantitative formalization of legal entropy to accurately measure the inherent uncertainty in laws, doctrines, or legal systems, presenting a unique entropy-based system for assessing a patent's potential for technological innovation. This novel approach goes beyond assessing ambiguity in legal texts to provide a comprehensive understanding of "modularity" in law, a concept that refers to the use of legal "boundaries" to economize on information costs. This model serves, for instance, as a valuable tool for legal Artificial Intelligence (AI) systems, allowing them to measure and store information about legal system uncertainties. Despite not providing a complete mechanism for calculating legal entropy, the study sets a significant foundation, hoping that continued advancements in legal AI will soon realize this model's wide-scale application.

Finally, within "Neuroscience and Cognition", 8 works, dated between 1998 and 2021, constitute this category. The focus here is on cognitive processes and neural systems in relation to creativity (Ueno et al., 2015; White, 2017, learning (Tan & Zhou, 2014; Kak, 2011), divergent thinking (Shi et al., 2020). Several papers investigate the role and measurement of entropy in these contexts, such as brain entropy's association with divergent thinking and the neurophysiological basis of creativity. Moreover, there is a focus on specific population groups such as gifted individuals and healthy elderly people (Ueno et al., 2015), indicating the role of individual differences in the research (Jaušovec, 1998).

4.1 INNOVATION MEASURES BASED ON ENTROPY

Regarding innovation, one application of entropy is to analyze the nexus between innovation and performance within product/process, individual, organizational or other higher levels. Kanó et al. (2023) exemplify this, having deployed entropic statistics to explore the interconnections between different dimensions (geographical, technological, organizational) within creative industries in Central Europe. The insights gleaned from their entropy analysis underscore the predominant synergy in these industries at the local level of innovation systems, suggesting that the benefits of innovation accrue both locally and globally.

In parallel, Ya-fei and Lu-cheng (2007) researched the principle of performance entropy to assess the efficiency of regional technological innovation systems. Their study introduces a comprehensive metric framework developed through the Soft Systems Methodology (SSM), which offers a holistic, system-oriented approach to problem-solving. By adopting entropy analysis and factor analysis techniques, they facilitate the computation of performance entropy for the technological innovation ecosystem within a specific administrative region.

From that, the Management Entropy Theory, in this context, emerges as a powerful theoretical prism through which to scrutinize the performance of Regional Innovation Systems (RIS). This theory enables the capture of the aggregate innovation level and the developmental trend of RIS dynamically. Such an application of the Management Entropy

Theory finds resonance in the work of Haiping (2013). His research corroborates the view that the innovation performance of RIS arises from the intricate interplay between its constituent elements and between the system and its environment. Accordingly, the management entropy evaluation model furnishes a scientifically robust and dynamic interpretive tool that can assist policymakers in identifying bottlenecks to innovation performance enhancement, thereby laying the groundwork for strategic resource allocation and informed decision-making.

Still within the scope of economy and innovation systems, a novel economic perspective is introduced by Cerreta et al. (2021), who investigate the "low-entropy economy". This model prioritizes the minimization of physical urban transformation while valorizing existing heritage. It illustrates a visionary balance between heritage preservation and the promotion of innovation, economic growth, education, and social development.

Patent-based innovation is also analyzed. Through Zhang et al. (2017), compelling evidence supports the application of an entropy-based indicator system for the evaluation of patents' value within technological innovation. Their research highlights the potential of this approach to reveal “windfall patents”, previously overlooked by traditional methodologies, thereby enriching the pool of innovation assets.

Furthermore, Yuan & Zheng (2022) extend the application of entropy into the realm of fuzzy sets, specifically Intuitionistic fuzzy sets (IFSs). They demonstrate how intuitionistic fuzzy entropy can holistically encapsulate the uncertain and unknown dimensions of fuzzy information, thereby enhancing the assessment of regional collaborative innovation capabilities.

Lastly, it is worth highlighting that in the panorama of these research trajectories, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), originally developed by Hwang and Yoon (1981), is noted as a recurring methodological tool. TOPSIS is employed as an auxiliary tool in entropy-related studies, where it aids in the evaluation of innovation capability performance of countries and enterprises, as demonstrated by Sun and Xu (2021) and Kaynak et al. (2017). As such, entropy, in conjunction with other analytical tools, continues to offer new perspectives and valuable insights in the multidisciplinary study of innovation.

4.2 CREATIVITY MEASURES BASED ON ENTROPY

The diverse applications of entropy in assessing creative outputs and cognitive processes are consistently emerging across various domains. Chang et al. (2017) utilize entropy to quantify textual complexity and characterize an author's lexical processing. This approach is exemplified by the contrast between the information-based energy trends of Shakespeare's plays and Jin Yong's novels, with the former showing an initial rise and subsequent decline, and the latter decreasing over time. Thus, entropy not only measures text complexity but also contributes to the computation of information-based energy, offering a fresh perspective on evaluating writing performance.

In the field of graphic art and design cognition, Chou et al. leverage linkography - a method also explored by Ken and Gero (2017) and Goldschmidt (2014). Analyzing short animations and comic strips, they discover a positive correlation between the entropy of linkography and creativity evaluation survey results (Chou et al., 2013; Chou et al., 2014).

In a parallel yet more technologically advanced application, Papia et al. (2023) assess the entropy of AI-generated and human-made paintings. Their findings reveal that AI-created artworks exhibit larger standard deviations in entropy and complexity compared to their human-created counterparts, indicating a potential limitation in AI's ability to capture the breadth of individual artistic styles within a genre. This research opens up possibilities for developing methodologies to distinguish between AI-generated and human-created artworks.

Exploring the intersection of neuroscience, psychology and cognition, Ueno et al. (2015) and Shi et al. (2020) apply entropy in the analysis of brain activity, particularly with regards to creativity. Ueno et al. leverage Multiscale Entropy (MSE) analysis to assess the complexity of electroencephalogram (EEG) dynamics across various temporal scales. They observe a correlation between higher creativity and increased EEG complexity, mainly at lower frequencies. On the other hand, Shi et al. focus on the relationship between Brain Entropy (BEN) and divergent thinking. They propose that higher BEN values, which indicate greater brain flexibility, correlate with individual variations in divergent thinking, underscoring the potential role of brain entropy in fostering creative cognition.

In contrast, Jaušovec (1998) identifies a reverse trend in gifted individuals, observing lower Kolmogorov entropy values, denoting less chaotic neural activity during problem-solving tasks. However, the researchers also highlight the challenges of applying non-linear methods like Kolmogorov entropy to short, noisy datasets like EEG, urging caution in interpreting such findings.

Overall, these studies demonstrate the versatile applications of entropy in creative and cognitive assessments, with implications ranging from text analysis to brain function exploration.

5 CONCLUSION

This study has addressed the complexities of measuring creativity and innovation and, through an integrative literature review on innovation and creativity indicators based on IT entropy, investigated the application of entropy within this realm. Through the review of 26 selected works authored by 69 researchers, it was identified four major categories - Systems Innovation, Arts and Design, Law, and Neuroscience and Psychology - which showcases over three decades of research. The compilation demonstrates the far-reaching applications of entropy theory and entropy-based methodologies in various fields, including the evaluation of RIS, the understanding of creative processes in the arts, the potential for legal analysis, and the implications for neuroscience and cognition. However, it's also noticeable that the majority of papers were published post-2000, which may indicate a recent surge in interest in the applications of entropy, also involving emerging technologies such as AI generated content (Papia et al., 2023).

Remarkably, entropy serves as a multifaceted tool, bridging disciplines and providing novel approaches to quantify and assess aspects like creativity, innovation potential, and cognitive processes. Yet, the breadth of its applications also reveals the complexity of this concept, as entropy-based models are adapted to unique disciplinary contexts, offering both challenges and opportunities for further research. The interdisciplinary nature of these studies signals a fertile ground for future investigations and applications of entropy theory in emerging domains, underscoring the importance of cross-pollination of ideas across disciplinary boundaries for robust scientific progress.

While the concept of information entropy provides an intriguing approach to quantifying creativity, its application is not without challenges. One hurdle is the task of defining and measuring “information” within the creative process. Moreover, high entropy (in EEG and brain activity) does not automatically imply creativity (Shi et al., 2020); without appropriate interpretation or utilization, a multitude of diverse ideas might result in chaos rather than innovative outcomes. Despite these potential pitfalls, the approach provides exciting new ground for research and understanding in the field of creativity studies. If developed effectively, this metric could allow for more standardized comparisons of creativity and inform strategies to foster creative thinking in various settings.

Lastly, with respect to future research, although a range of input indicators have been proposed in the academic literature to date, there remains a paucity of researches that explicitly link these input indicators with corresponding output, outcomes and impact measures (Taques et al., 2021). Therefore, future endeavors may be focused on the development of indicators that aptly encapsulate the impacts and outcomes of innovation initiatives, signifying a conscious move towards quantifying and evaluating the progress and effectiveness of innovation actions. Also, future research can explore the integration of different indicators within a comprehensive measurement framework. Such a framework could offer a more holistic perspective of creativity and innovation performance, thereby serving as a valuable tool for strategic decision-making processes.

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