CREATIVE PERFORMANCE IN EXTREME HUMAN ENVIRONMENTS: ASTRONAUTS AND SPACE

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CREATIVE PERFORMANCE IN EXTREME HUMAN ENVIRONMENTS: ASTRONAUTS AND SPACE

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EDITORIAL
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Editorial: Creative Performance in Extreme Human Environments: Astronauts and Space

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Editorial on the Research Topic

Creative Performance in Extreme Human Environments: Astronauts and Space

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Exploration of the universe increases the need to gain insight on creative performance in extreme environments, as astronaut's and cosmonaut's survival may even depend on it. Although the pandemic underscores its relevance, the present Frontiers Topic was initiated before the onset of this extreme human environment on Earth, stemming from the Guest Editor's work experience with gifted, and space enthusiastic students before her Ph.D. and Space studies. The development of a domain of creativity "not when it is easy"—a double entendre referring to the famous words by President JFK on going to the moon and other things, in his words "not because they are easy"—represents a contrast to the generally focused on optimal environments. The composition of the presented contributions demonstrates the newness of this research domain. From the innovative articles, a research agenda emerges, which will be discussed in the next paragraphs.

The opinion article "*The Overview Effect and Creative Performance in Extreme Human Environments*" (White), by the author of the *"Overview Effect,"* offers a rich description of this phenomenon, and includes a call to investigate scientifically the report of positive, and possibly related, effects. The author paints a colorful account of astronaut's and other explorer's experiences, and this demonstrates the contrast in space between calmly gazing out of the cupola, and at the same time the constant preparedness for potential problems, which might in his words be "two sides of the same coin," because relaxation and meditation could enhance creative performance under stress. White further suggests focusing on research on earth-gazing in relation with the "Overview Effect."

The brief research report *"Creating Ambassadors of Planet Earth: The Overview Effect in K12 Education"* (van Limpt-Broers et al.) represents a first empirical study on the "Overview Effect" of children (ages 9 and 10), induced by a virtual reality (VR) experience, a simulation of viewing Earth from space ("SpaceBuzz"). The simulation proved effective and as measured with self-report survey's, created awe and the "Overview Effect," specifically through the feeling of presence. The study also demonstrated learning effects of awe for children with lower prior knowledge, and via the "Overview Effect." The authors found an intricate gender difference of the angle of eye gaze, and a relation with the overview experience, in line with White's suggestion. The authors propose that more future research therefore could focus on learning through VR experience.

The opinion article "*Space for STEAM: New Creativity Challenge in Education*" (de Vries), proposes to integrate knowledge on scientific creative cognition within STEAM education, specifically issues related with cultural differences which impact teaching and learning. The combination of different research approaches could shine a light on how practical and cultural differences in teaching might foster or hinder development of creative cognition. An example is given, based on the "Cultural Actuation Model" (CAM) of creativity (de Vries, 2018). The CAM, which is based on empirical research, relates values of cultural contexts to the fostering of higher, or lower, original, and more, or less, fluent creative performance. The example (in the **Supplementary Material**) shows four different cultural contexts related to values of "Tolerance of Ambiguity and Uncertainty" and "Power Distance" to these different kinds of creativity.

The Hypothesis and Theory article "*The Big Bang of Originality and Effectiveness: A dynamic Creativity Framework and Its Application to Scientific Missions*" (Corazza and Lubart) presents a Space-Time Model, which represents an application of the CAM's methodology to an adult work environment (e.g., during a mission), by distinguishing as well four contextual quadrants which are related to the cultural value of "Tight-Looseness" and higher or lower original, and more, or less, fluency, of creative potential, together with the concept of intelligence. The authors embed their Space-Time model further in the theory of the Dynamic Universal Creativity Process (DUCP) which originates creativity in the "Big Bang." The original DUCP theory therefore extends creativity principles beyond humans. The authors invite future researchers to carry out research on the "material" and "biological" layers.

The conceptual analysis "*What does Safety Mean in Safety-Critical Environments?*" (Bourgeois-Bougrine) offers an in-depth analysis of underlying mechanisms and psychological dimensions of creative processes related with insight, improvisation and creative problem-solving in life-critical situations. The author not only offers a comprehensive overview on distinct concepts, but explains their relations with creativity, and foresees implications for research in neuro-ergonomics, specifically the neural basis of creative insight problem-solving in life-critical situations. The author suggests that future research on differential psychology could concern the traditional attributes of creative individuals in safety contexts for operational performance, such as for training in simulators and other virtual reality environments.

The conceptual analysis on "*The creative Brain Under Stress': Considerations for Performance in Extreme Environments*" (Vartanian et al.) explains the altered dynamic interaction during creative performance under acute and chronic stress of the Default Network (DF), Executive Network (ECN), and the Salience Network (SN). The authors give an overview of existing knowledge on findings related to internally related thought, external sensory input, and the role of attention to maximize survival in extreme situations. In general creativity is thought to be negatively impacted by stress. The authors suggest to further scientific knowledge by continuing research on network neuroscience under stress conditions, also including during positive experiences in space as with the "Overview Effect," to determine possible relations with creative performance.

The conceptual analysis "*How the Immune System Deploys Creativity: Why We Can Learn From Astronauts and Cosmonauts*" (de Vries and Khoury-Hanold) proposes that the immune system is a contributing factor within a multivariate theory of creativity. This entails that future research could search for individual differences in three subdomains. These concern (1) analysis of individual differences on how the immune system regulates (creative) behavior and cognition, (2) individual differences on if some people's immune system reacts more creatively than another person's immune system to an environment or aggressor (variety and number of diseases), and (3) because properties of the immune system show a surprising amount of parallels with the creative processes (e.g., divergence and convergence), future research could search for individual differences in creative properties of the immune system itself. Athletes (performing in an imagined extreme environment), as well as astronauts, are an interesting group to investigate this subject further.

The conceptual analysis on "*Creativity and Cognition in Extreme Environments: The Space Arts as a Case Study*" (Hays et al.) represents a socio-cultural perspective on this Research Topic. The article emphasizes the differences of the Earth and space environmental factors and proposes to apply the 4E cognition framework. This framework relates creative cognition to embodiment, enactment, and embeddedness in an (space or Earth) environment. Their authentic taxonomy to situate the different forms of space art distinguishes the dimensions of (1) where art is created, and (2) where art is experienced. The authors foresee that new sub-disciplines, or branches, will emerge, according to art disciplines (e.g., fashion, architecture).

The opinion article "*Exploring Similarities Across the Space and Theatre Industries*" (Chterev and Panero), compares domain-specific and domain-general characteristics between actors and astronauts. The article discusses remarkable parallels through issues such as creative problem solving, personality traits, social skills, isolation, and pretend and simulated environments. The authors suggest that the development of the field of research on creativity in extreme human environments could benefit from insight on transferable factors, also to fill gaps in literature.

Each contribution suggested new or overlapping future agenda points, which can now broadly be categorized into 5 branches of the research agenda, or in space terms, research galaxies. The first branch could be called (1) "*Classic Creativity in Extreme Environments,*" which includes all psychological contributing factors which are maybe altered in space. Within this branch there are subdomains such as virtual creativity, group creativity, and developmental issues. This further includes a variety of approaches such as socio-cultural analysis of creativity, as space offers the unique chance to study "a culture in the making." All knowledge can be applied on Earth, for example in the educational domain. It could be argued that all existing "Earth-bound" creativity research should be replicated in an extreme environment as space because dynamics and correlations could differ with those found on Earth. However, as broad as this generalization might seem, it would limit and miss riveting possibilities of research on creativity in extreme human environments. This Research Topic overall demonstrates that the field can expand into unknown realms. Examples are a future branch of (2) "*Medicine and Creativity,*" which includes the immune-system, as well as the eye-gazing, and a third branch of (3) "*Theoretical Principles of Creativity,*" concerning creativity expanding away from human creativity, such as the DUCP. Future research in this branch might well lead to additional insights on the phenomenon of the concept itself, as well as human creativity. Another branch concerns (4) "*Experience and Creativity,*" a domain which largely exists theoretically. Studies during scientific missions are well-suited to gain knowledge on this under-researched subject. Finally, a fifth branch could be called (5) "*New Creativity,*" the appearance of new human and maybe even alien forms of creative expression in space. In sum, and continuing the use of space vocabulary, future research exploration might discover additional new galaxies of the universe of insight on creativity.

AUTHOR CONTRIBUTIONS

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The Big Bang of Originality and Effectiveness: A Dynamic Creativity Framework and Its Application to Scientific Missions

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This article introduces a theoretical framework to conceptualize the dynamics of the phenomenon of creativity, which is then applied to the specific case of scientific missions for the exploration of the universe. Static definitions of creativity are insufficient for this purpose, as they fail to describe states of creative inconclusiveness as well as the time and culture-dependent estimation of the value of the outcomes of a creative process; therefore, a dynamic definition of creativity is introduced, justified, and adopted to build a dynamic creativity framework. Within this framework, creativity episodes are shown to be mutually interconnected through several mechanisms (past and future concatenation, estimation, and exaptation), to form a dynamic universal creativity process (DUCP), the beginning of which can be traced back to the Big Bang of our universe. The DUCP entails several layers of complexity (material, biological, sociocultural, and artificial), showing that creativity is not only a psychological construct for humans but rather a unifying cosmological principle. Context embeddedness is discussed in-depth, introducing a taxonomy based on the concepts of tightness and looseness as applied to conceptual space and time. This theoretical framework is, then, applied to the discussion of the design, realization, and operations of scientific missions for the exploration of the universe, taking as a reference the terminology adopted by the European Space Agency.

Keywords: creativity, dynamic universal creative process, cosmology, scientific missions for space exploration, tightness and looseness, definition of creativity

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INTRODUCTION: THE DYNAMIC CREATIVITY FRAMEWORK

We live in a world of uncertainty, dynamically evolving at a very fast pace (Rosa, 2003; Corazza et al., 2010; Feather, 2013), and creativity is arguably the engine of this fundamental unpredictability. It should, therefore, appear to be paradoxical that most definitions of creativity appear to be static, involving a definitive assessment of originality and effectiveness or similar statements, such as novelty and utility (Stein, 1953; Mayer, 1999; Parkhurst, 1999; Runco and Jaeger, 2012; Simonton, 2012; Martin and Wilson, 2017). We believe that basing a theoretical framework that should embrace the entire phenomenon of creativity on a static definition is clearly insufficient; it would be like trying to understand the plot of a thriller movie only through the final scene where the culprit is judged and jailed. A sense of extreme dissatisfaction would surge, and questions would be immediately raised: "What happened before the trial? What led to this end result? Could we please know the entire story?" In other words, in order to understand a dynamic, intriguing, and complex phenomenon, we need to be concerned with the entire *process* underlying the phenomenon itself, and not with a snapshot judgment of part or all of its outcomes. One might argue that the same standard definition of creativity as requiring originality and effectiveness (Runco and Jaeger, 2012) applies also to the creative process; however, this is unfortunately not the case for two very important reasons. First, in the course of any creative process which constitutes a real challenge, there are many instances of failure, in which the solution one is seeking is not found: under the static standard definition, these phases (which can also take very long time) could not be defined as "creative," because neither originality nor effectiveness could be identified, and correctly so! This is a crucial problem, because in fact these temporary failures, which we identify as states of *creative inconclusiveness* (Corazza, 2016), are fundamental steps that all creative processes and persons must go through and show that they can be overcome. They are the very essence of the creative exploratory path, as shown very clearly by the example of one of the most prolific inventors of all times, Thomas Alva Edison (Edison, 1948; Wills, 2007). As a matter of fact, it has been shown that the history of artistic and scientific genius was paved by persistence and resilience in difficult times (Galton, 1869; Albert, 1983; Simonton, 1984; Eysenck, 1995). Evidently, this applies also to human creativity involved in scientific missions for the exploration of the universe. The second reason why a static definition of creativity is not able to capture the reality of a creative process is that no one, irrespective of his/her level of expertise on a knowledge domain, is entitled to give a final judgment on the originality and effectiveness of a product pertaining to that domain. Any assessment will always be subjective and partial: even the seemingly most objective measures such as uniqueness of a response (Wallach and Kogan, 1965) are in reality dependent on the sample of subjects participating to the experiment or analysis. Vice versa, in reality, any judgment depends on the entire context, an umbrella under which we classify the point of view of the judge and the surrounding culture, social space, and time epoch. Indeed, there are many cases of great creators who were not appreciated during their time: one example that stands out is certainly that of Vincent Van Gogh, who did not think much of himself as a painter and who sold only a single one of his works in the course of his lifetime (Van Gogh, 1978). Perennial glory for him would only come posthumously. To realize this fundamental fact allows us to grasp the true meaning of the *pragmatist maxim* by Peirce (1992–1999, p. 132): "*Consider what effects, which might conceivably have practical bearings, we conceive the object of our conception to have. Then, our conception of those effects is the whole of our conception of the object*." In other words, the estimation of a creative idea entails the conception of all of its effects that might have practical bearing on reality: a dynamic, future-oriented, and never-ending exercise.

For these two reasons, given the necessity to account properly for creative inconclusiveness and the subjectivity of any judgment on the outcomes of a creative process, neither of which is captured by a static definition, a complete theoretical framework aimed at describing the entire phenomenon of creativity must be based on a dynamic approach (Beer, 2000; Beghetto and Corazza, 2019). This entails a dynamic definition of creativity, one that is able to subsume both instances of creative achievement and creative inconclusiveness and that should allow all the sociocultural variability that is intrinsic in the phenomenon (Glaveanu et al., 2019). To the aim of bridging these gaps, we adopt here a dynamic definition of creativity which is an evolution of the one presented in the work of Corazza (2016), according to which creativity requires *potential* originality and effectiveness. It should be clear by comparing this definition with the static one that the only difference lies in the insertion of the qualifier "potential" inside the definition, which applies to both originality and effectiveness. It is this single word that transforms a static picture taken by a photographer-judge into a dynamic process in which uncertainty dominates, but high levels of creativity can be attained by producing the conditions of high potential for possible future achievements of the goals of the process, or even serendipitous findings. The evolution of the definition presented in the work of Corazza (2016) that we propose here renders explicit the fundamental role of context in determining both the process itself and its interconnection with all of reality: *creativity is a context-embedded phenomenon requiring potential originality and effectiveness*. Context should be intended in its most general sense; in this article, it can be as vast as the universe but also as specific as a microscopic situation experienced by a specific being in a determined time instant. It can represent the different phases in the design and operation of a scientific mission for the exploration of the universe, as we will discuss later. Context embeddedness represents the fact that the resources, the affordances, the goals, the assessment criteria, and the sociocultural implications of a creative process all depend and cannot be isolated from the context in which they are displaced. Indeed, isolating a creative process from its context would be similar to studying the orbit of the Earth in the absence of the Sun: the solutions would be far from reality. In most cases, it will be the context in which the process is embedded that generates the presuppositions according to which the same outcome of the process can be considered either inconclusive or a creative achievement. We identify the *dynamic creativity framework* as the theoretical explanatory construction that descends from the adoption of the above dynamic definition of creativity.

BIG BANG AND THE DYNAMIC UNIVERSAL CREATIVITY PROCESS

Creativity Episodes

Along the lines of Corazza (2019a), we define a specific instance of a creative process as a creativity *episode*. Under the dynamic framework, creativity episodes can be studied singularly for reasons of practicality but in reality have no rigidly defined ending and have indefinite connection to the past, as their influence extends indefinitely in time. All creativity episodes are interconnected, and as seen from a macroscopic point of view, they form a single overarching process which we identify as the dynamic universal creativity process (DUCP; Corazza, 2019a). Let us see the details of this fundamental observation pertaining to creativity episodes, with the help of **Figure 1**, which is an evolution of Fig. 17.1 from Corazza (2019a).

First of all, creativity cannot exist *ex nihilo*: the only extant possibility is to gather material, information, and knowledge from the past and use it in a way never attempted before, knowing that what will come out will emerge out of this previous legacy and may not be reducible to it. This means that a current creativity episode is concatenated to those previous episodes that produced the outcomes that have now become our ingredients. And, the chain into the past will continue indefinitely until a sort of DUCP origin is found. We shall return shortly on this ontological point.

Second, once the creativity episode is activated, there is no predetermined time limit to its duration, even though there may be many practical reasons why it may be desirable to set a maximum duration. But this limit is not intrinsic: the search for alternative ideas can continue indefinitely, both if we are in a state of creative inconclusiveness (no results deemed worthy have yet been found) and if we or the society around us can claim a creative achievement! This may sound surprising, but it is actually the trademark of great creators: never be satisfied by the first idea that appears fit. Keep refining or challenging your results: avoid early closure and develop a high tolerance of ambiguity (Zenasni et al., 2008). In essence, a creativity episode on a worthy focus can potentially continue indefinitely in time and deliver several outcomes along the way.

Third, while an actor or a team of actors is engaged in a creativity episode, other actors in the universe may be confronting similar endeavors: the interactions between these teams, either in the form of collaboration or of competition, form an indefinite extension in the action space of a specific creativity episode.

Fourth, suppose now that the subject creativity episode produces outcomes that are offered to the outside world, there are at least three mechanisms according to which the impact of these episodes can extend indefinitely into the future, as illustrated in **Figure 1**. The first mechanism is *estimation*: the dynamic extraction of the potential originality and potential effectiveness of a creative product entails that one imagines all possible values, in all possible futures, under all possible perspectives the product might have, as expressed by the pragmatist maxim mentioned above. Clearly, it is not a task that can be considered to be finished with a fixed amount of time and energy. This implies also that no one should ever be so arrogant to claim that his/her assessment of the creativity of the product is the final judgment, no matter the level of expertise of the judge. The second mechanism is *concatenation* into the future: just as the creativity episode under consideration took information from the past as an ingredient, the current outcomes may become ingredients of further episodes taking place in the future. And if, by chance or virtue, in the course of any of these future episodes, it is found that our episode under study produced outcomes that turn out *a posteriori* to have seminal value, our estimation of the current episode will have to be dynamically refined. In other words, the assessment of originality and effectiveness of past episodes is also dynamic. Finally, the third mechanism thanks to which the dynamic evolution in time of the impact of the outcomes of a creativity episode is indefinite is *exaptation* (Gould and Vrba, 1982): the possibility that an outcome of a creativity episode acquires in the future a totally new functionality that was not planned nor realized at the time of its generation. There are many instances of exaptation in the history of the arts, science, and technology, and so many more in biology, which is the domain in which the term was actually coined; not to be confused with adaptation. Whereas Darwinian adaptation foresees the evolution of an organism *via* DNA modifications and *a posteriori* discovery of higher aptness to the environment (Darwin, 1859), exaptation entails the search and discovery of new functionalities *with the same DNA*. The arguably unlimited power of exaptation becomes evident after reflection on technological evolution (Andriani and Cattani, 2016; Garud et al., 2016).

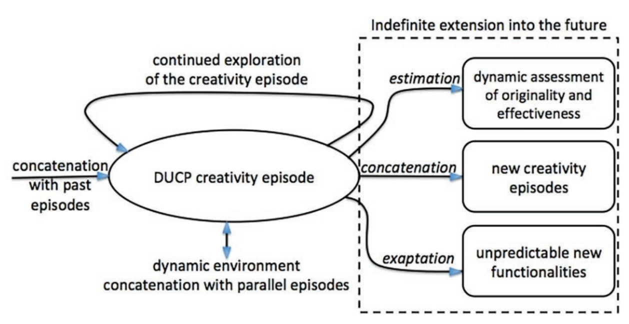

FIGURE 1 | A dynamic universal creativity process (DUCP) creativity episode and its mechanisms for extension into the future.

Clearly, the three mechanisms for extending the reach of a creativity episode into the future, namely estimation, concatenation, and exaptation, are non-orthogonal conceptual categories, so it is useful to clarify their main differences to justify their separation in the theoretical framework. Estimation refers to the appreciation of the properties of the outcomes of a creativity episode and does not necessarily lead to a new episode. Concatenation takes a past achievement as it is, with no concern for its estimation in all of its possible meanings, and exploits it as an ingredient for a new creativity episode. Finally, exaptation is the result of an effort to switch the functionality and meaning of an outcome, producing an explicit drift away from the objectives that drove the original creativity episode. As an example, let us consider the invention of the smartphone, a creativity episode that has had dramatic impact on the course of development of *Homo sapiens* in a relativity short amount of time (first models appeared around 2005). The estimation of the originality and effectiveness of the smartphone is continuously evolving with the number of possible applications that can be installed: present estimates indicate that there exist about 2 million software programs in each of the major application stores for smartphones. In terms of concatenation, the immediate step has been to take the principles and functionalities of the smartphone and transfer them to wearable devices, such as the wrist watch or the glasses. So far, the success of these devices is still limited, but they are likely to become customary accessories in the future. Finally, in terms of exaptation, it is to be noted that the main functionality of the smartphone in its initial conception was still that of a telephone augmented by side functionalities. But integrating one (or more) high resolution digital camera in the device unexpectedly turned the mainstream usage of the device from voice to images, so much so that the largest producers of cameras in the world soon became the smartphone manufacturing companies.

Interconnecting Creativity Episodes Into a Universal Process

Given the above discussion, it should appear clearly that creativity episodes can be studied in isolation for practical purposes, but they are really part of an indefinite flow which interconnects them all, and this is the essence of the DUCP concept. The various models for creative processes that have been proposed (e.g., Wallas, 1926; Mumford et al., 1991; Lubart, 2001; Kaufman and Baer, 2004; Sternberg, 2006; Corazza and Agnoli, 2015) fulfilled the goal of describing with variable levels of detail the development of *a single creativity episode*. However, due to the intrinsic dynamicity of the phenomenon, these episodes are never effectively concluded nor disjoint, as discussed above. Indeed, the extant and undeniable interconnectivity between creativity episodes may in fact be one of the *strongest reasons for advocating a dynamic approach in creativity studies*. This brings us to the definition of the DUCP, as follows: "*The active ensemble of all creativity episodes in the course of cosmic evolution*." The ensemble of all creativity episodes should be visualized as a tree-shaped structure of interconnected creativity episodes, each with its multifold creative potential that grows exponentially throughout history (Lehman, 1947; Enquist et al., 2008). The ensemble is active not only because it is continuously growing but also because concatenation with past creativity episodes changes the creative potential of those ancestors, perhaps changing what was considered to be a mediocre achievement into a seminal milestone!

The Origins of Creativity in Our Cosmos

Now the ontological question is: when did the DUCP process begin to exist? If we remain within the realm of human action, it appears immediately that we cannot limit our search within *Homo sapiens*, because evident creativity episodes were enacted by hominid ancestors: remains of a stone-tool industry have been found in Kenya at the Lomekwi 3 site in West Turkana, Kenya, as far back as 3.3 million years ago (Harmand et al., 2015). Given the prehistoric evolutionary stage of these hominids, it is natural to ask whether humans are the only beings that can be accredited with creative behavior: the answer is absolutely not. Reflecting on the phenomenon of the emergence of life on Earth (Judson, 2017), it appears practically impossible to surpass this astonishing novelty in terms of its potential for originality and effectiveness. Once this fact is realized, one becomes open to find creativity episodes in animals (Kaufman and Kaufman, 2004), in plants (Gianoli and Carrasco-Urra, 2014), in monocellular organisms (Nakagaki et al., 2000), arguably in artificially intelligent agents (Colton et al., 2009; Brynjolfsson and McAfee, 2014), and even in inanimate matter. The latter point is surprising and must be discussed: how is it possible that inanimate matter be considered "creative"? How could matter produce outcomes that are characterized by potential originality and effectiveness? The answer to this question enjoys a theoretical framework of its own, which is that of complexity and complex systems. The work by Ilya Prigogine, the 1974 Nobel prize for chemistry, focused on the dynamics of dissipative systems which are far from equilibrium, was the key to the start of this extremely important line of thought (Prigogine, 1967, 1996). Indeed, what Prigogine has shown is that in these conditions, the evolution of a non-biological system can have trajectories that are fundamentally unpredictable. By "fundamentally," it is intended that this unpredictability is not due to our inability to produce a mathematical model, but because of the intrinsic impossibility to predict the course of their dynamic evolution. It is this unpredictability that makes these trajectories a form of "creative achievement," in the sense that they are original and effective, and this allows matter in the universe to be transformed in a positive way and not toward complete disorder (entropy), as the second theorem of thermodynamics would seem to imply. Indeed, our universe is a dissipative open system, the equilibrium of which was dramatically disturbed by the first impulse, the Big Bang, a gigantic surge of energy, the consequences of which are still evolving after some 13.7 billion years, in the course of which nearly 2 trillion galaxies were formed (Conselice et al., 2016), each with billions of stars, and each star potentially surrounded by planets. Note that creativity in nonlinear, dynamic, complex systems is an active research domain of its own (Ambrose, 2014; Loreto et al., 2016; Gabora, 2017). The initial conclusion to this discussion is the following, perhaps surprising, statement: *the origin of the DUCP is the Big Bang*, after which an indefinite concatenation of creativity episodes emerged at the material layer, at the biological layer, and at the sociocultural layer of complexity. This cosmological view of creativity is very much in line with the process philosophy developed by Alfred North Whitehead (Corazza, 2020) in "Process and Reality" (Whitehead, 1978/1929, p. 21), whereby creativity is elected to be the ultimate metaphysical principle, thanks to which the multitude of elements in the universe come together, moment by moment, to form instantaneous reality: "Creativity is the universal of universals, characterizing ultimate matter of fact. It is the ultimate principle by which the many, which are the universe disjunctively, become the one actual occasion, which is the universe conjunctively."

Creativity Beyond Humans?

The above theoretical framework foresees, therefore, that the creativity of humans represents but a small fraction of the DUCP, albeit the most significant one, as it is characterized by intentionality and intelligence: for this reason, we classify its creativity in the *strict-sense*. For an in-depth discussion about the rationale for allowing also a *wide-sense* view on creativity, one that does not necessarily require intentionality, extending the discussion to the biological layer, the material layer, and the artificial layer, the reader is referred to Corazza (2019a). For the purposes of this article, it suffices to say that this is in line with those approaches which have as a goal the *unification* of knowledge across different disciplines for the macroscopic understanding of cosmic evolution (Wilson, 1998; Henriques, 2003, 2011; Chaisson, 2009; Kauffman, 2016), as opposed to its segmentation into non-communicating silos. In other words, adopting this theoretical framework affords the possibility to create links between the development of originality and effectiveness across multiple levels of reality.

However, we should not leave this point without clarifying that attributing creativity to the material and biological layers does not violate the fact that creativity should be interpreted as a sociocultural category. It is still a human observer that understands and interprets the emergence of fundamentally unpredictable novelty in open physical or biological systems as creative phenomena. By the same token, emergence is a sociocultural category: the theory of complex systems is a symbolic framework of explanation developed by humans, the meaning of which can only be extracted through the use and within the boundaries of our extant culture.

We will focus the rest of this work on the sociocultural layer and on *Homo sapiens*, knowing, however, that we are immersed in a universe that is also evolving creatively toward growing levels of order.

CREATIVITY IN CONTEXT: TIGHTNESS VS. LOOSENESS

Considering the sociocultural layer of complexity in the DUCP, we intend here to discuss the characteristics of the context embedding the creative process and how they produce variable levels of potential originality and effectiveness. In other words, we are trying to answer the question: how can we classify the conditions that most significantly affect human creativity? As it turns out, the answer is multifold, and it depends on sociocultural variables that move along an axis going from maximum *tightness* to maximum *looseness* (Gelfand et al., 2011; Gelfand, 2012). Briefly, a tight society is one where there are very stringent norms, in which there is no tolerance for breaking the rules, in which behavior is encoded and monitored, not only by institutions but also by fellows. A paradigmatic example of a tight society might be the Republic of Singapore. At the other extreme, a loose society is one where norms are flexible and weakly applied, where there is tolerance for errors and violations, and in which behavior is quite free and socially liberated. A good example of such a society is, perhaps, given by New Zealand. It has been shown (Gelfand, 2012) that tightness and looseness are indeed new variables with respect to the more classic cultural dimensions such as collectivism and individualism and that they can be used to explain many societal characteristics, also in terms of innovation potential (Harrington and Gelfand, 2014). Here, we will use these concepts in a different way by applying them to two orthogonal dimensions of time and space.

Suppose that the creativity episode under consideration can be classified to belong to a certain conceptual or semantic space (Newell and Simon, 1972; Perkins, 1992; Boden, 2009), containing the knowledge that is relevant to the domain, including problems, constraints, and solutions, and expandable in view of present and future innovations (Kauffman, 2016). This conceptual space S can itself be tight or loose. A tight conceptual space is one where there is only the possibility for a single correct solution, at most with few variations on the theme, with many constraints, and where is very little or no tolerance for ambiguity and mistakes. In the terminology introduced by Perkins (1992), this would correspond to a Homing space, for which the structure of the problem indicates in itself the solution, allowing for an optimization of a response. On the contrary, a loose space is one where many alternatives are possible, with little or no preconditioning on the outcomes of the process, with ample possibility to accept paradigm shifts, and high tolerance for ambiguity. Referencing again to Perkins (1992), this would correspond to a so-called Klondike space, in which the most productive search is performed as an exploration of an unstructured space (see also Boden, 2009). It may be useful to fix our minds on two examples. Solving a mathematical problem in a new way is a creativity episode embedded into a tight space: there is only a single correct solution to the problem, and all the alternative procedures that one could devise must be conceived under the tight constraint of step-by-step correctness. On the other hand, consider writing a novel in a new genre: this is a goal that generates a creativity episode embedded in a loose context; the conceptual space is ill-defined (what do we mean by "new genre"?), and there are an indefinite number of possible outcomes, the value of which can only be seen *a posteriori*, because it is essentially unpredictable and highly dependent on who will be called on to judge it. In terms of the cognitive components of creativity, it should be evident that convergent thinking (Cropley, 2006) appears to be more fit in a tight space, whereas divergent thinking (Runco and Acar, 2012) would seem to belong to a loose space. However, appealing as these connections might seem, we should avoid building a one-to-one correspondence between the context characteristics and the ensuing cognitive components, for two reasons. First, irrespective of the context, any creative process will always use a combination of convergent and divergent thinking components, depending on whether one is defining the focus of attention, gathering relevant information, generating ideas, assessing outcomes, etc. Second, context produces a situation, an environment in which the actor operates according to his/her thinking style, but there is no cause-effect relationship between context and thinking components. This can lead to variable levels of accord or mismatch: for example, using divergent thinking in what society considers a tight space might lead to inefficiency, but perhaps also to the breaking of a consolidated paradigm. On the other hand, preferring convergent thinking in a loose context is clearly possible even though it might limit one's freedom of thought and action, and perhaps be classified as boring behavior and/or personality.

Now let us consider the time variable *T*. As we have discussed before, under the dynamic creativity framework leading to the DUCP, there are no intrinsic constraints to the time duration of a creativity episode, so even this variable becomes part of the description of the context in which the process is embedded. Tight time *T* means that the context imposes stringent specifications on the time interval within which results are expected to come out of the process, and there is little or no tolerance for delay. Indeed, in extreme conditions, a delay could endanger one's life, so much so that adhering to the time constraints becomes a matter of survival. Delay could also be severely punished by institutions. At the opposite end, loose time *T* means that there are ample periods of time during which outcomes can be produced, estimated, exapted, and concatenated. Planning is not at a prime, and there is ample tolerance for delays. The introduction of the concepts of tightness and looseness in the time dimension can be linked to the line of research related to the effects of time pressure on creativity (Amabile et al., 2002; Baer and Oldham, 2006). A sort of implicit theory exists about the fact that high time pressure, hence tightness in the *T* dimension, would lead to more creative solutions. A paradigmatic example would be that of the Apollo 13 mission in 1970, during which an explosion occurred, damaging the air filtration system and building carbon dioxide in the cabin. This was a clear life-endangering problem to be solved in extremely tight *T*. All NASA engineers, scientists, and technicians started to work on the problem, producing a solution based on the same material available onboard. The solution was inelegant and far from perfect, but it worked and saved three lives. However, as pointed out by Amabile et al. (2002), it would be incorrect to directly extend the validity of such examples to the more general context of the workplace. Indeed, it has been shown that having uninterrupted quiet time during specified periods every day can lead to higher creativity and wellness in the workplace. When time pressure cannot be avoided, it is, in any case, useful to make coworkers feel as if they are in a "mission," so that they share a common fate (Amabile et al., 2002). It is interesting to note that the relationship between tightness of time *T* and the creative potential will not be linear but, in general, curvilinear: Baer and Oldham (2006) have found an inverted U shape, moderated by openness to experience and support for creativity.

Space-Time Quadrants in the ST Plane

By crossing these two dimensions of space *S* and time *T*, each one varying from extreme tightness to extreme looseness, respectively, in the horizontal and vertical dimensions, four quadrants are formed in a conceptual ST-plane:

- Quadrant I: Tight S – Tight T (pure tightness)
- Quadrant II: Loose S – Tight T (hybrid looseness-tightness)
- Quadrant III: Loose S – Loose T (pure looseness)
- Quadrant IV: Tight S – Loose T (hybrid tightness-looseness)

As we will show in the following, these four quadrants correspond to very different contextual conditions, leading to quite different forms of potential for originality and effectiveness of creativity episodes. Let us discuss them following a trajectory that starts at Quadrant I, then on to II, IV, and finally III.

Quadrant I: Tight S – Tight T

In these conditions, context is tight both in space *S* and time *T*. The constraints are typically so strong that the actor is forced to search for the best solution to any problem he/she might face in the minimum possible amount of time. Pressure is high both in time *T* and in space *S*. There is no tolerance for ambiguity nor delay. This is actually the typical situation in which humans live, especially in the educational, academic, and professional environments. A test, such as for example an IQ test, produces the sort of constraints that can be properly mapped onto Quadrant I: correct answers are expected to be given within the allocated time. No tolerance exists whatsoever, and every mistake counts in lowering your score. Also pertaining to Quadrant I would be a situation such as the launch of a spaceship for human flight: planning is extremely precise down to the detail, no ambiguity is tolerated anywhere, and any mistake can lead to the loss of lives. It should be clear that in these tight space-tight time conditions, the potential for originality and effectiveness is in general quite low, given the high level of constraints and the strong punishments associated with failures. There is very little or no room for creative inconclusiveness. Those few individuals who, faced with an urgent and unforeseen problem, are able to solve it in a surprising way while remaining within the tight space-time boundaries of the context are usually considered to be geniuses.

Quadrant II: Loose S – Tight T

In these conditions, time remains tight but the constraints and expectations on the conceptual space are loosened or completely removed. We have a sense of urgency, time pressure is high, and there is little or no tolerance for delays; however, the problem we are facing is open-ended and allows a multitude of possible responses, the originality and effectiveness of which can only be judge *a posteriori*, because the scenario is unknown or at least ill-defined. The pressure on the actor is, perhaps, even larger, and the potential for originality and effectiveness is certainly higher than in Quadrant I. It is accepted that within the multiple responses that can be conceived in the conceptual space, not all of them will be successful, but there is sufficient freedom in order to search for remote solutions with high originality, albeit in a tight time frame. Clearly, the Apollo 13 incident that we mentioned earlier would fall in this Quadrant II category; let us give two additional examples that appear to fit well here. First, consider the classic Alternative Uses Test (Christensen et al., 1960) that is used in the majority of papers on creativity to measure the divergent thinking ability, one of the most important components of the creative thinking process, albeit not the only one. In these testing conditions, the task could be to produce all the possible alternative uses of a brick beyond the conventional in a few minutes, e.g., 3. The performance is measured in terms of fluency (number of responses), originality (typically scored by external judges), and perhaps flexibility (number of conceptual categories visited).

This is an open-ended context, but the time dimension is extremely tight: as such, it belongs to Quadrant II. A second example refers to a space mission for exploration of the universe: suppose you are in a mission to Mars and you exited the base to explore the surrounding environment. You are equipped with multiple measurement tools, and your autonomy is limited to 15 min. You are the first human to ever explore this part of the red planet. This is an excellent example of a Quadrant II situation, one in which time is tightly constrained but space is extremely open, and indeed surprising discoveries are possible and even expected. However, some mistakes can be fatal, and certainly there is no tolerance in trespassing the allowed time limits: this will likely lead to a loss of life. This is the quadrant that, perhaps, best represents the context embedding the creative process in extreme conditions.

Quadrant IV: Tight S – Loose T

This Quadrant is somewhat dual to Quadrant II we just considered, also leading to a hybrid context in terms of tightness vs. looseness, but in this case, we loosen the time *T* constraints, whereas space *S* remains tight. Within this context, one is typically faced with a problem of high to very high complexity, perhaps unsolved by many years, decades, or even centuries. In this case, there is no expectation that a new solution will be conceived or discovered in a limited time frame, but if it were to be found, the value would be extremely significant. This quadrant can be considered to be the home of complex problem solving, which is notoriously considered to be an important part of intelligence. In terms of creativity pertaining to Quadrant IV, perhaps one of the most fitting examples is the activity of Henri Poincaré (Corazza and Lubart, 2019), so well described in his *Science and Method* book, which also gave input to the famous four-stage model of the creative process (Wallas, 1926). Another example can come in terms of creative planning to prevent future extreme conditions; even though they are not experienced in real-time, they must, however, be *anticipated* (Corazza, 2017a) in order for the design to be credible and successful.

Quadrant III: Loose S – Loose T

Finally, Quadrant III is the dual to Quadrant I, the loose context whereby both space *S* and time *T* are loosened. Embedding, a creative process in this context where constraints are, in general, very weak, allows the maximum freedom of exploration. Clearly, there are no guarantees that a creative achievement will occur, but there is ample tolerance for creative inconclusiveness. The potential for originality is at its highest level; the potential for effectiveness is variable and can also be quite low. Certainly, this quadrant can be considered to be the home of artistic creativity: *a priori*, there is no information about the form of the process outcomes, one can enjoy maximum freedom for probing alternatives, even in areas where there is no "problem" to be solved. The results are not expected to come within predetermined time limits, and recognition of their value could even occur posthumously. A paradigmatic example of creative activity in a context represented by Quadrant III is the painting career of Vincent Van Gogh, as previously recalled. Providing such a context in an educational environment will generate the best embedding conditions to nurture and develop one's creative abilities and to strengthen one's creative identity. Indeed, one mistake that society can make is to impose excessively tight time schedules to an activity that would be best to belong to Quadrant III, effectively moving it to Quadrant II.

As can be seen, the use of the concepts of tightness vs. looseness in association with conceptual space *S* and time *T* enables the introduction of a very clear taxonomy and possibility for classification of the context in which the creative process is embedded. The potential for originality and effectiveness is strongly influenced by the tightness vs. looseness of this context, and it is important to understand and classify these contextual conditions in order to ensure that the creative process is conducted in the most proficient way. Of course, the perception of the tightness and looseness of space and time is subject to individual and societal differences: for example, in a school environment, a math test to be carried out in a predetermined amount of time may be perceived as a very tight context by the average of the class but as significantly looser by a gifted student. This variation is actually the rationale for designing specific educational programs for the gifted.

Now our objective is to apply the concepts of the dynamic creativity framework, dynamic definition of creativity, DUCP, and ST-quadrants to an analysis of the creative process in the framework of designing and operating scientific missions for the exploration of the universe.

SCIENTIFIC MISSIONS FOR THE EXPLORATION OF THE UNIVERSE: CONTEXTS FOR CREATIVITY

In this section, we intend to show how the design of a scientific mission for exploration of the universe follows a sequence of phases that can be mapped as a trajectory over the ST-quadrants discussed above. For each phase, an indicative estimate of the respective potential for originality and effectiveness is given. It is very important that these levels of potential are not confused with those required to establish a creative achievement; for example, if a creative process is embedded into a context with medium potential for originality and low potential for effectiveness, the probability to obtain creative achievements will be medium-low, but when this infrequent event occurs, this outcome will have to be characterized by high originality and high effectiveness.

Following the classification adopted the European Space Agency (ESA, 2020), seven phases can be recognized in the identification, definition, and realization of a mission: *Phase 0*, Mission identification; *Phase A*, Feasibility; *Phase B*, Preliminary Definition; *Phase C*, Detailed Definition; *Phase D*, Qualification and Production; *Phase E*, Utilization; and finally *Phase F*, Disposal. Let us analyze these phases in terms of their mapping onto the ST-quadrants and the consequent implications on the potential for originality and effectiveness, with the help of **Table 1** and **Figure 2**.

TABLE 1 | Scientific mission phases, associated ST-quadrant, and creative potential.

Mission phase	Description	ST quadrant	Creative potential
Phase 0	Mission identification	III	Pot. originality: high Pot. effectiveness: low-to-medium
Phase A	Feasibility	III, IV	Pot. originality: medium Pot. effectiveness: medium
Phase B	Preliminary definition	I	Pot. originality: low-to-medium Pot. effectiveness: medium-to-high
Phase C	Detailed definition	I	Pot. originality: low-to-medium Pot. effectiveness: medium-to-high
Phase D	Qualification and production	I	Pot. originality: low Pot. effectiveness: high
Phase E	Utilization	I, II	Pot. originality: low-to-medium Pot. effectiveness: high
Phase F	Disposal	I, II	Pot. originality: low-to-medium Pot. effectiveness: high

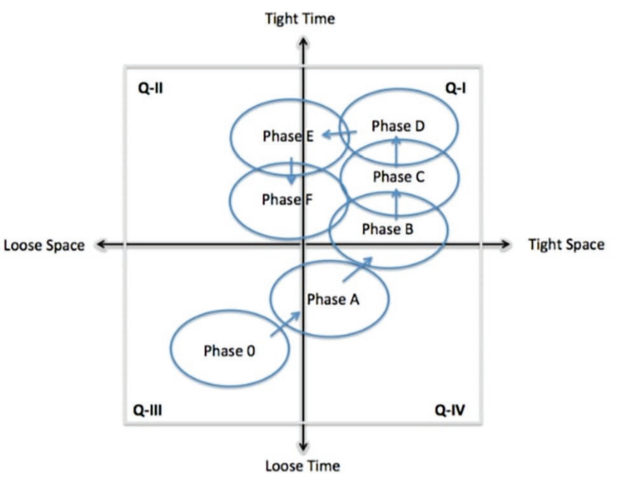

FIGURE 2 | Mapping mission phases on ST-quadrants.

In Phase 0, ESA opens a call for proposals for new science missions, addressed to the wider scientific community. This is quite an open-ended exercise which can be mapped onto Quadrant III. In fact, each call for missions can generate several dozens of responses from different academic groups, addressing areas as wide as fundamental physics, solar system structure, astronomy, etc. The general aim is to produce a broad spectrum of ideas and alternative concepts to be explored. The potential for originality in these proposals is quite high, and typically the potential for effectiveness can be classified as low-to-medium, because in-depth feasibility studies still need to be performed. In fact, the boldest mission proposals require typically the development of new technology, the feasibility of which cannot be guaranteed *a priori*. These proposals are assessed by ESA's scientific advisory committees of experts, such as the Science Programme Committee, the Space Science Advisory Committee, the Astronomy Working Group, the Solar System Working Group, or the Fundamental Physics Working Group. Both originality of the mission and its preliminary effectiveness in terms of feasibility are taken into account in these evaluations. This pre-screening effort will produce a short-list of three or four candidates; for each retained proposal, a team formed by a scientist and an engineer is formed for a 1-year feasibility study. The time dimension T is still considerably loose: even though a deadline is established, the amount of available time is more than sufficient to work and explore without excessive time pressure. This study has, in particular, the objective to identify precisely any new technology that needs to be developed to make the mission possible, and therefore effective. The end results of all these Phase 0 studies are presented at ESA headquarters in Paris to ESA's scientific advisory committees, which have to select and recommend those missions that should proceed to Phase A. It is typical that two or three missions are selected for a Phase A study. In conclusion, Phase 0 of a scientific mission for universe exploration can be largely classified as belonging to Quadrant III, with a high potential for originality and a low-to-medium potential for effectiveness.

Considering Phase A, aimed at establishing feasibility, the design of a mission can be awarded in the form of contracts to two competitive industrial teams. The purpose of having competition at this early stage is to allow for alternative solutions to come up and be contrasted with one another. This guarantees to keep up the level of originality while starting to focus down on effectiveness, both in terms of performance and cost. Each competing team must generate a preliminary design and a project plan specifying details about necessary spacecraft instruments, system and subsystem manufacturing, launch, orbital characteristics for spacecraft, time plan to reach target, and scientific operations to be carried out once the target is reached. All elements of the preliminary design must be accompanied by estimated costs. For any new technology identified, it is important to present at least a proof-of-concept. Overall, the potential for originality of Phase A, as compared to Phase 0, decreases to a medium level, even though proofs-of-concept can often lead to patents, while the potential for effectiveness grows to reach also a medium level. Phase A can be mapped onto a mixture of Quadrant III and Quadrant IV, given that the conceptual space S is narrowed down but still allows alternatives, whereas the time T is still loose given that no final decision has been made yet, and therefore, schedules are not as tight as they become in subsequent phases. Preliminary designs and project plans are compared and a decision is made on the specific mission design.

From the point of view of analyzing creative potential, Phases B (Preliminary Definition) and C (Detailed Definition) can possibly be discussed together: they are both concerned with narrowing down (in two concatenated stages) all engineering details in order to arrive at a complete design *on paper*. It should be noted that any error or mistake in the definition of a project will translate into significant losses of time and money when manufacturing and assembly will occur in Phase D, and therefore, they are to be avoided as much as possible. Indeed, a mistake here can easily translate into losing one's job. This clearly tends to stifle creativity. On the other hand, design problems that might occur in Phases B and C may lead to creative problem solving, and these creative solutions can potentially lead to patents or invention disclosures. For these characteristics, potential originality can be considered to be low-to-medium, whereas potential effectiveness is medium-to-high, although no actual realization is attempted yet. In terms of mapping, Phases B and C progressively move the process into Quadrant I, where both conceptual space S and time T become tight.

Phase D concerns space qualification of all technologies, manufacturing of parts, assembly, and testing. In this phase, investments have all been decided and, therefore, schedules are precise and tight. Any problem has to be resolved as quickly and as correctly as possible. Virtually no room is allowed for innovations, but only problem solving upon necessity (typically not of a creative kind). Phase D is definitely a Quadrant I activity, a tight context with a very low potential for originality and a very high potential for effectiveness, leading to an overall low level of creativity.

Finally, we discuss Phases E (Utilization) and F (Disposal). When the actual scientific mission is carried out in Phase E, one would hope that everything will run as planned, but deviations due to small or large unexpected difficulties are bound to occur. Therefore, rapid remedies to these unforeseen events must be devised, often putting at risk the success of the entire mission. For this reason, Phase E is a mixture of Quadrants I and II: time T is tight, but depending on the situation, we might use known solutions, exploit risk mitigation plans, or if none of the above works we might have to devise creative alternatives. In all of these cases, the potential for effectiveness of the ideas involved is high, while the potential for originality is low-to-medium. Phase F, at the end of the mission lifetime, although it could appear to involve very little creativity, in reality reserves often quite a few surprises, given the fact that it is difficult to plan many years in advance and more often than not technologies can survive longer than planned. Also, there are many ways in which a mission can be brought to an end, depending on the level of space debris that is allowed (in general, it should be as low as possible). In essence, Phase F is also mapped onto Quadrants I and II, with low-to-medium potential for originality and high potential for effectiveness.

All these creativity episodes, with variable context embeddedness and levels of embedded creative potential (Corazza and Glăveanu, 2020), form a concatenation which can be interpreted as part of DUCP and describe a trajectory across the ST-quadrants. This discussion is summarized in **Table 1**, and the trajectory in **Figure 2**. It should be noted that this trajectory should be interpreted as a best practice, according to the process adopted by ESA. Nothing excludes the possibility for alternative trajectories to be established, but of course they would have to be justified with specific advantages. For example, forcing Phase 0 into Quadrant II, by imposing very stringent time schedules for the definition of innovative proposals is possible but it produces as a consequence that most of the proposals will be highly predictable, i.e., less original.

CONCLUSION

Creativity studies are often focused on gathering and interpreting experimental data. This is a very important approach that should be accompanied and positioned with a comprehensive theoretical framework, one that affords macroscopic understanding and interdisciplinary associations. This article is aimed at providing such a theoretical framework: starting from the dynamic definition of creativity, introducing the concept of potential for originality and effectiveness, it is possible to describe a dynamic creativity framework, whereby creativity episodes enjoy indefinite time duration and are all interconnected into a DUCP. The universality of DUCP is literal in the sense that its beginning must be traced back to the Big Bang, and its development spans material, biological, and sociocultural layers of complexity. The creativity of humans is, therefore, not the only form of creativity that can be found in the universe, and scientific missions for the exploration of outer space should be interpreted as the honing of human creativity to appreciate, understand, and exploit the creativity of the universe. Considering the sociocultural layer of complexity, defining the concepts of tightness and looseness and applying them to the conceptual space S (the semantic and procedural domain for the search of ideas, actions, solutions, and decisions) and to T, the time-domain characteristics of the creativity episode, it is possible to identify four quadrants that describe significant contexts in which the creative process for humans can be embedded. The extension of the interpretation of these quadrants for the material and biological layers is possible, but it is left as future work. Exploiting this theoretical framework and this taxonomy, it is finally possible to analyze that various phases that are designated to manage and conduct a scientific mission for the exploration of the universe, and draw characteristic trajectories across the ST-quadrants. The importance of this work should be seen in terms of the fundamental role that creativity is going to play in the future stage of our societal evolution, identified as the Post-Information Society, characterized by drastic changes in the job market and business models. A future in which our capacity to be creative will be tightly connected with our wellbeing (Corazza, 2017b, 2019b).

AUTHOR CONTRIBUTIONS

GEC provided the theoretical framework. TL provided guidance and important references. All authors contributed to the article and approved the submitted version.

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CONCEPTUAL ANALYSIS
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Creativity and Cognition in Extreme Environments: The Space Arts as a Case Study

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Humans, like all organisms, have evolved to survive in specific environments, while some elect or are forced to live and work in extreme environments. Understanding cognition as it relates to environmental conditions, we use 4E cognition as a framework to explore creativity in extreme environments. Our paper examines space arts as a case study through the history, present practices, and future possible arts in the context of humans beyond the Kármán boundary of the Earth's atmosphere. We develop a proposed taxonomy of space arts, based on prior taxonomies, and provide specific exemplars of space art developed by artists in space or for use by astronauts in space. Using examples of space art since the birth of the space age, we discuss (1) how human survival in extreme environments requires investment in the space arts, driven by consideration of various biopsychosocial factors and (2) how new scientific and engineering discoveries; such as the detection of air current patterns with paper airplanes in zero gravity, could be consequences or examples of creative thinking driven by artists in the various types of space art. We conclude by discussing possible benefits of space art, future research applications, and advocate that all space actors, government or private, involve artists in all projects beyond the Kármán Boundary of the Earth's atmosphere.

Keywords: space art, extreme environments, creativity, 4E cognition, astronomical art, astronautical art, social innovation

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INTRODUCTION

Beyond aesthetic or communicative functions, art serves as a tool to provoke new perspectives on exploration and introspection, both on an individual or societal scale. Art is work intended to stimulate emotions, through either their perception or comprehension (Malina, 1970). The process of making or interacting with art utilizes embodied cognition to engage with the environment and provides insight into other cognitive processes (Ticini etal., 2015; Silver, 2013). Studying human performance in extreme environments can enable comprehension of and planning for activity in future extreme environments, such as off planet colonies and deep space missions with no contact. We seek to understand how extreme environments may enable the generation of novel ideas that may not occur in another context through examination of the history of space art, in addition to understanding how this extreme environment impacts cognition and creativity. To augment the limited research on creativity in space, we argue for the utilization of research from other extreme environments with similar contextual factors. We give examples and discuss creative thinking driven by artists that generates new scientific and engineering discoveries. Contemporary transdisciplinary approaches (Mejía et al., 2018) are paramount in this chapter, as the understanding of cognition as it relates to environmental factors bridges the relationship between creative ideation and extreme environments like space. Moreover, this approach can inform current and future practices for space activities, as well as applications of insight generated from space art practices.

Extreme Environments

Humans live, adapt, and understand their experience through environmental context. While humans have evolved to thrive in specific Earth environments, some elect to or are forced to live in extreme environments. Extreme environments are contexts with demanding physiological and psychological conditions, beyond an optimal range, that affect cognition, behavior, physiology and genetics (Paulus et al., 2009; Ilardo and Nielsen, 2018). Examples of these environments include outer space, deep ocean, sustained extreme temperatures, and isolation. Changes in context prompt adaptive changes in cognition and behavior; extreme environments exacerbate this by disturbing physiological and psychological states, prompting complex cognitive and affective responses (Paulus et al., 2009).

Changes that occur when adapting to space environments is a decades old topic of research, funded and documented by international space agencies and non-affiliated researchers alike. This research spans many topics including changes in physiological states, like blood pressure and circulation, sensory deficits, or vestibular sense (e.g., Buckey et al., 1996; Clément and Reschke, 2008; Hallgren et al., 2016); cognitive changes, like sensorimotor deficits, attention and cognitive functioning, or effects from disturbances in circadian rhythm (e.g., Palinkas, 1991; Bock, 1998; Liu et al., 2015); and emotional changes, like depression, factors of interpersonal conflict, or approaches to improving mental health (e.g., Palinkas, 2003; Ritsher, 2003; Salamon et al., 2017).

It is important to acknowledge the many factors that make space uniquely extreme, such as the risk of radiation, variable gravity forces, the lack of a diurnal cycle, and distance from Earth with limited recourse in case of an emergency, that exacerbate the other features of the extreme environment. We insist that living in space is not 'like Antarctica but further' because the other extreme environments on Earth do not present these particular compounding challenges and it is yet to be observed how humans adapt to or handle such hazards long term.

While transitioning to a zero-gravity environment is a challenging process, both physically and mentally, transitioning between environments causes a reevaluation of events, actions, and demands, which has a higher potential to evoke new and original ideas (Runco and Charles, 1993). It provides an opportunity to reevaluate features in the environment and question previous assumptions, which is strongly related to the creative process (Amabile and Gryskiewicz, 1987). Being in the zero gravity environment of space compels individuals to engage in these procedures and results in creative ideation and the creation of artworks in or about their experiences in space.

SPACE ART

The first space art is commonly identified as the intentional and realistic depiction of space flight by Emile-Antoine Bayard and Alphonse-Marie de Neuville for Jules Verne's novel, *From the Earth to the Moon* in 1865. However, this neglects the centuries of art that clearly depicts astronomical phenomena or even art that may have at its time been intended to be viewed from the heavens (e.g., Nazca lines in Peru, lunar petroglyphs at Ngaut Ngaut). These artists are clearly inspired by astronomical discoveries and phenomena combined with their own creativity.

The International Association of Astronomical Artists (IAAA) gathers current space and astronomical art practitioners. In this paper, we chose to differentiate between the astronomical arts that continue as contemporary arts and the space arts enabled by the first successful launch of objects and/or humans into space. We use the Kármán line (100 km above mean sea level) as a definition of where outer space "begins," as endorsed by the International Astronautical Federation; we note that other definitions exist.

The IAAA definition states: "...the genre of Space Art itself is still in its infancy, having begun only when humanity gained the ability to look off our world and artistically depicted what we see out there Szathmary (2020)." Malina (1991) defined space art as "contemporary art which relies for its implementation on participation in space activity;" Arthur Woods (2019) chose to use the term "Astronautical Art" which we adopt here. In this definition space arts include artforms created above the Kármán line, but also artforms enabled by space vehicles, e.g., telecommunication satellites. Artforms enabled by "spin off" space technologies (e.g., Teflon) are not space art in this definition.

We argue therefore that space art can incorporate elements of both astronomical art and astronautical art. Astronomical art focuses on conceptualizing and visualizing outer space phenomena, whereas astronautical art relies on outer space environments or technology for its actualization (Woods, 2019). The IAAA maintains a similar distinction: "Space Art" is inspired and generated from space based knowledge and ideas, like astronomical art, and "Art In Space," utilizes space conditions and environment as a component or tool, like astronautical art. These categories do not create a dichotomy, rather they have a significant amount of overlap.

Space art is an extension of environmental and land art movements (Malina, 1991); artists appropriate the natural world both as materials for making art and as the source of ideas and concepts. Space art seeks to explore outer space using projects that rely on space technologies, materials, or environment for their realization (Woods, 2019).

Taxonomy

To communicate and assess different artforms in the context of space, we present a taxonomy for space art that is based on taxonomies to explain different forms of space art (Malina, 1991; Woods, 2019; Bureaud, 2020). Our taxonomy is highly reliant on two dimensions: where the art is created and where it is experienced (**Figure 1**). We incorporate a category for "astronomical art" that captures artworks that depict space phenomena (Woods, 2019) and are created and experienced on Earth. Our taxonomy provides exemplars of each category, spanning many artforms and practices (**Table 1**). It must be noted that due to the limited existing works of space art, some categories have few documented artworks, especially those created in extreme environments.

COGNITION AND CREATIVITY

Art making is aided by global and local context features (Brinck, 2007). In this sense, creative undertakings can be presented as complex cognitive processes that are highly interdependent on the environment where the artist is located. We present cognition and creativity using 4E cognition as a framework.

Situated Cognition

Situated cognition is based on the notion that cognition is tied to external factors like context, action, and language (Smith and Semin, 2004). This theory is based on context-sensitive cognition, which heavily relies on environmental factors (Schwarz, 2006). Interdisciplinary theories like situated cognition are regularly considered in many social science subfields like environmental psychology and ecological anthropology.

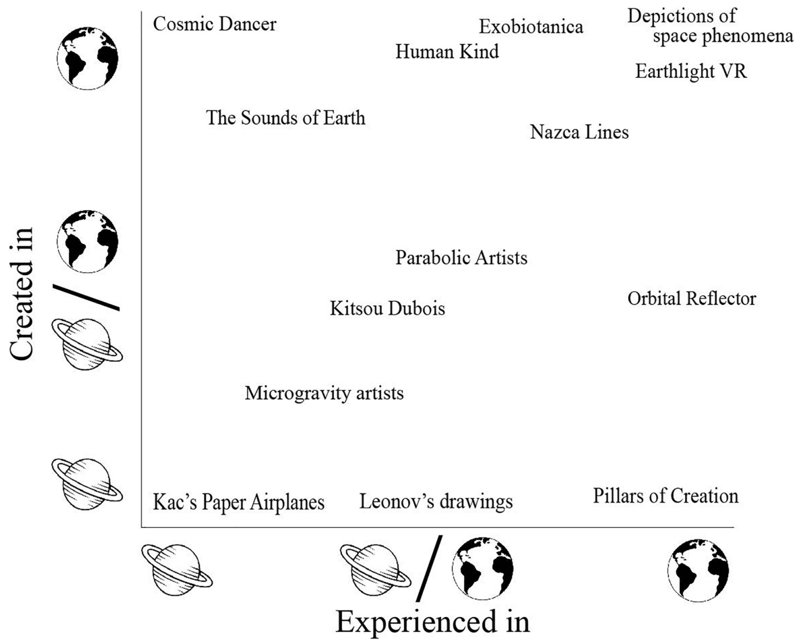

FIGURE 1 | Visualization of space art examples on two dimensions displays the spectrum of contexts for both creation and experience.

TABLE 1 | Space art taxonomy with exemplars.

	Space art							
	Astronomical	**Astronautical**						
Contextual definition	Art depicting or imagining space phenomena	Created outside EE of Space Experienced in both	Created outside EE of Space Experienced in EE	Created in EE Experienced in EE	Created in both Experienced in both	Created in EE Experienced outside	Created in EE Experienced in both	Art in a simulated ZG env., eg parabolic flights
Exemplar	Nebra sky disc (1600 B.C.E.)	Tesla Roadster "Starman"	Wood's "Cosmic Dancer"	Kac's paper airplanes, "Inner Telescope"	"ArtSat" Kriesche	Trevor Paglen's "Orbital Reflector"	Cupula professional photography of Earth	Kitsou Dubois's choreography
Exemplar	Instrument: One Antarctic Night	"Fallen Astronaut" on Moon (Apollo 15)	Pierre comte's Prisma	Water marbling, Osaka Furukawa	"I.S.S. Is somebody singing?" Duet	Chris Hadfield's "Space Oddity" Music Video	Scott Kelly's gorilla costume chase	Pietronigro's Drift Paintings

The environment acts as a medium for action and interaction (Sosa and Gero, 2003). Human cognition encourages situational adaptation based on evaluation from given affective and environmental cues. Safe and familiar situations elicit top-down processing and reliance on routine behavior, while unfamiliar or problematic situations would evoke systematic, bottom-up processing and detail-oriented attention (Schwarz, 2002). In unfamiliar situations, actions and contexts are represented in more detail (Wegner et al., 1986). Cognitive tuning, and related bodily sensations, also provide cues to the nature of a situation (Friedman and Förster, 2000), meaning that bodily responses and physical sensations can evoke heuristics, processing styles, and situational adaptations. As cognition can adapt to a given context or environment, cognitive operations, like creative ideation, will vary in the same way. By understanding how creativity occurs in a given context, we can better understand how to evoke and facilitate novel ideas that wouldn't occur in a different environment.

4E Cognition

Cognition is related to the environment, therefore the consideration of environmental or task context-needs enables the facilitation of cognitive processes, such as creativity, beyond those needed for survival and safety. This process is expedited through the development of context-sensitive, cognitively informed training. The 4E theory of cognition posits that cognition is embodied, enacted, embedded, and extended (Rowlands, 2010; Newen et al., 2018). This approach provides a framework for the relationship between cognition, creativity, and the environment.

- Embodied cognition is the theory that cognition is extra-neural and originates in physical interactions that rely upon sensorimotor abilities (Smith and Semin, 2004). Physical movements and interactions have an observed impact on cognitive processes (Schwarz, 2006) and styles (Friedman and Förster, 2000).
- Enacted cognition states that cognition functions to serve action (Schwarz, 2006). This is enabled by evaluation and responsiveness to physical environments and social contexts, as well as the context-sensitive activation of knowledge (Avnet and Higgins, 2006).
- Embedded cognition is the notion that cognition is dependent on the relationship with the environment and the social context (Ward and Stapleton, 2012). This theory is closely related, and at times viewed as a subcategory, to embodied cognition (van de Laar and de Regt, 2008).
- Extended cognition is the view that cognition is not only embodied, but extended to the environment (Clark and Chalmers, 1998). This is based on the theory of distributed cognition (Hutchins, 1995, 2000), which views cognition as not solely occurring in the mind but across objects, people, and time (Glăveanu, 2012).

4E cognition is characterized by the dependence and interaction with environment artifacts and tools (Kono, 2010; Glăveanu, 2012). The notion that cognition is inherently related to and can be offloaded onto the environment relates to context-sensitive cognition, in that the use of environmental artifacts facilitate cognitive styles and lessen cognitive load. Again, as cognition is related to and altered by the environment, so are cognitive operations and processes, like creativity.

Creativity

Creativity, or the production of novel ideas deemed useful and situationally appropriate (Stein, 1974; Amabile, 1983, 1996; Mumford and Gustafson, 1988; Sternberg, 1999), is invaluable to generating new knowledge and scientific insight. Research literature provides many related theories and models to understanding or generating creativity in the context of a domain or field (Feldhusen and Goh, 1995; Sternberg, 1999; Isaksen and Lauer, 2001; Batey and Furnham, 2006).

Creativity is stimulated and evaluated by multiple factors, like cognitive ability, personality factors, knowledge, and environment (Csikszentmihalyi, 1999; Moss, 2002; Batey and Furnham, 2006; Stein, 2014). Research on creativity is based on ideation, regardless of the idea type, reasons and causes, or source of the process (Unsworth, 2001). Both divergent and convergent thinking styles play a part in creative ideation (Runco, 1991; Cropley, 2006). Approaches like pluralism and multivariate theories combine theories, including cognitive, emotional, and environmental, that each have different methods and levels of analysis to provide a more robust understanding of creativity (Kaufman and Sternberg, 2010; Kirsch and Houssemand, 2012; Nelson and Botella, 2017).

Cognitive theories of creativity rely upon psychological research and methodologies (Finke et al., 1992; Smith et al., 1995; Ward et al., 1999) to understand creativity, and reject creativity as a mysterious, unobservable, or fundamentally unusual (Kaufman and Sternberg, 2010). This approach is used to evaluate the nature of cognitive processes related to knowledge, memory, and ideation. It contributes to the existing notion that knowledge impacts the process and outcome of creativity (Mumford and Gustafson, 1988; Sternberg and Lubart, 1995; Cropley, 1999; Feldhusen, 2002; Kaufman and Sternberg, 2010) and through utilization of knowledge, creativity increases its value (Kao, 1997). Theories that overemphasize the role of knowledge can mistakenly suggest a parallel definition of creativity with intelligence. Creativity is not limited to cognitive functioning, but is shaped by cognition, personality traits, environmental conditions, and sociocultural factors (Feldhusen and Goh, 1995).

Based on the notion of situated cognition, it is crucial to evaluate the situated factors that affect creativity (Sosa and Gero, 2003; Gervais et al., 2013). This allows its conceptualization to develop beyond simply a set of cognitive operations (Finke, 1996) and integrates the cognitive process and application of the idea (Nonaka and Zhu, 2012; Wright, 2016). Using situated cognition as a lens accentuates the domain specificity of creativity (Plucker and Beghetto, 2004), while recognizing generalized and task-specific aspects (Lubart and Guignard, 2004). Situational discretion in the use of creative thinking has been tied to psychological traits, like agency and autonomy (Gervais et al., 2013). Many creativity metrics use environmental dimensions, like context and climate, to evaluate the impact on the creative process and output (e.g., Amabile, 1996; Ekvall, 1996, 2000). Distributed creativity acknowledges the sociocultural and embedded nature of creativity and artistic expression, reiterating the value of considering not only the cognitive operations and processes, but also the larger context (Harth, 2004; Glăveanu, 2014).

Examining creativity in a situated manner, informed by a 4E cognition framework, provides a complement to personality and domain driven research. Just as people shape and alter their environments to support their activities and endeavors, the environment provides scaffolding for physical, cognitive, and sociocultural actions (Brinck, 2007). This further solidifies extended and embedded cognition through use of tools and environmental artifacts to augment limited cognitive capacities (Schwarz, 2006).

Sociocultural Interdependencies

As 4E cognition expands cognitive theories on creativity to include context and other environmental factors, the incorporation of anthropological perspective furthers this expansion to include sociocultural elements. Creativity is a social process (Grossen, 2008), that occurs within the context of relationships and dialogues (Barrett, 1999; Glăveanu, 2012). Evaluating creative processes and practices between and within cultures informs our expectations for creative behavior that is situated in the most extreme environments. The appreciation of aesthetics is multifaceted; it can be relative to an individual's personal, professional, or cultural background (Crowley, 1958), or dependent on the participation and the shared experience of making art (DeMarrais and Robb, 2013).

Aubert et al. (2019) published a finding of a cave painting in Maros, Indonesia, which is disputed as the oldest finding of this category dated back to at least 43,900 years. While cave paintings may be considered as parietal art or prehistoric art, it is difficult to investigate whether paleolithic societies considered their works as art, or if they even had a concept of "art." Renowned anthropologist Geertz (1976) describes art as being part of a cultural system, which consists of "inherited conceptions expressed in symbolic forms" used to communicate and develop knowledge about life (Geertz, 1973, p. 89). It is recognizable that such ancient cave illustrations, regardless if they are considered as art, are indeed creative and symbolic practices. While art reflects creativity, creativity does not always produce art.

Anthropology focuses on understanding ourselves and inner perceptions of society, often through comparison. Western art practice regularly institutionalizes art and often treats it as an independent entity, opposed to societies where artistic practices are a component of everyday life. Some governments incorporate some type of ministry related to art and culture, in addition to museums dedicated to specific types of art. In these societies, making art is a plausible option as a career path, to the point where it can be monetized, yet it is still susceptible to critics and tied to the sociocultural context of that time. Meanwhile, less industrialized societies have definitions without fine distinctions and artists may not be able to subsist by their creative work. Rather, their work is guided by responsibilities within their community.

Even though art in its many forms is tied to religion directly or indirectly, it must be noted that less industrialized societies, – where religion is a strong component in everyday life – might value the artist's creative and individual performance more than the religious undertones themselves (Osborne and Tanner, 2008).

There are several divisions when it comes to understanding art, but irrespective of the economic value or specific practices across societies, creativity is universally present. Creativity can improve well-being, communication skills, and interpersonal collaborations – even problem solving in unusual or dangerous situations (i.e., King, 1997; Bourgeois-Bougrine and Lubart, 2019).

COMPARISON WITH OTHER EXTREME ENVIRONMENTS

Due to the novelty of space travel itself and the cost of researching in space, the amount of extant research on individuals and groups in space is limited. Therefore, the use of space analogs and other extreme environments can provide predictive insights (Bishop, 2013).

Cultural and biological alterations increase human adaptability to include extreme environmental conditions. To date, there are well-established cities in areas with extreme temperatures such as polar regions or deserts (ranging from −40 to 40°C, respectively), and with high altitude (over 3,000 meters above sea level) despite the possible health concerns for those living in these surroundings. For example, in the Antarctic there are a diverse set of temporary and permanent camps. A few people have been born in those camps and researchers detect a shift in phonetics, suggesting that the inhabitants are developing their own accent (Harrington et al., 2019). This linguistic development may occur in the analog of space. Novel communication methods and shared terminology is necessary for unknown phenomena specific to the context and to aid collaborative efforts.

Johnson et al. (2003) emphasized that participants on polar expeditions are physically isolated from the outside world, with darkness and weather conditions exerting severe restrictions on travel and separation from families and friends. In addition, there is little separation between work and leisure during such expeditions because living and working spaces are close to one another, and interactions are with the same individuals during both activities. This constant interaction is reported to often create increased social conflict between workers and supervisors, coworkers, cliques, and people with conflicting personalities (Johnson et al., 2003). A significant subset of individuals who spend extended periods of time in polar settings experience depression, insomnia, irritability, and hostility (Gunderson, 1968).

After long term exposure to desert heat, decreased psychomotor speed, attentional and executive functions, and overall cognitive performance were observed (Maruff et al., 2006). Deep divers confined for long periods in a hyperbaric chamber reported anxiety co-occurring with low self-control and emotional instability (Abraini et al., 1998). Individuals in nuclear submarines experienced interpersonal friction, monotony, and lowered morale and motivation (Flinn et al., 1961). While there are overlaps in qualities of environments that enable cross application, it is crucial to acknowledge the variance between each extreme environment.

Given the limited social science research in zero gravity and outer space, specifically on creativity in space, we argue for the use of research from other extreme environments with similar contextual factors. Consideration of other habitable extreme environments where humans have had a long presence could potentially inform on the experience of space flight and the necessary considerations for future space activities.

APPLIED SOCIAL RESEARCH FOR SPACE

Future space activities can be furthered by considering cognitive and social approaches, since these activities are guided by and designed for humans. The implementation of cultural, social, and psychological perspectives is invaluable for studies of humans in extreme environments, particularly space as it is a setting completely foreign to any earthling since their evolutionary path is unique to our planet. Wherever humans go, they take their biological and social components with them.

It is important to note that humans, just like other organisms, have a high capacity for adaptability that is aided by current technological advancements, making life possible in even the most unyielding surroundings. Technology as crucial as space shuttle life support systems is developed on Earth, which guides its use in the harsh conditions of space and the disorientation of zero gravity (Trusch, 1982). This type of issue can be improved through cognitively informed testing using tools, for example in a simulated weightless environment (Aoki et al., 2005).

Sociocultural research in zero gravity is a sparse field, as this research is time and effort intensive. It is often underfunded and at times underappreciated by other experts concentrating in space efforts. Scholars have found that, while considering sociocultural and interpersonal aspects of long-term space flight, there have been variations in interpersonal conflict between genders and cultural groups (Palinkas, 1991; Kanas and Caldwell, 2000). Factors that had an observed impact on interpersonal relationships were group tension, cohesion, leadership styles, and group diversity (Palinkas, 2003). Issues like the interaction between crewmates and the design of space environments necessitate a socially informed, human centered approach. Traditionally, the field of human factors, or ergonomics, considers cognitive and biological factors for the design of complex technology. However, a more holistic view would be advantageous. Integrating the biological, psychological and sociocultural elements in equal parts would develop an improved design that is inclusive and accessible. Such insights gained from this type of research may aid in the design of space stations and enhance communication efforts in heterogeneous extraterrestrial settings.

DISCUSSION

Both art and creativity are complex topics that differ between fields, scholars, and creators. Creative thinking is an inherent human process that results in new, innovative ideas and enables an individual or a group to overcome both spontaneous and long-standing hurdles. Despite the plethora of information and practices concerning creativity in general, we emphasize the wrong word nature of creativity as it relates to space activity and its potential in the not-so-distant future.

While human spaceflight expands and becomes more accessible —as seen recently with the DM-2 mission by SpaceX where commercial spaceflight was inaugurated—, it is crucial to understand the complete set of factors that may limit or enhance creative thinking. Transitioning into a novel environment triggers innovative thinking (Runco, 2003), yet the novelty of space leaves many of these transitions uninspected, for example the fluctuation of gravitational forces or the variation of creative ideation during a spaceflight.

We touch on three different perspectives for studying creative thinking and practices in variable gravity: (1) the biological perspective includes physiological, evolutionary, and adaptive factors; (2) the individual perspective, framed by the 4E cognition theory, is highly dependent on the interaction between the person and its environment; (3) the sociocultural perspective contextualizes creativity as a social process, shaped by social biases, collaboration, and communication.

One thing is quite certain, the human factor cannot be stripped from any activity in space. We emphasize the value of creativity to the human experience and the unique characteristics of space as an extreme environment. Space art diverges from traditional art in the sense that it has major implications resulting from its complex nature as discussed earlier, while simultaneously originating from unimaginable distances. The presented taxonomy attempts to clarify this via 8 specific contexts of space art. Fostering artistic activities that are common on Earth should be approached in the same manner in space to drive both creativity, innovation, and novel scientific discoveries.

Methodological Integration

There are countless stories of creative practices during times of physical and psychological strain, such as the fruitful artistic life of Nazi-occupied Paris (Riding, 2011) or murals depicting heroic first responders (Lomelí, 2018; Jeffery, 2020). Artists and creators may purposely seek to be surrounded in extreme situations, like entering a war zone, often through an institutionalized and organized approach. In both World Wars, the U.S. government sent artists abroad to the battlefield as an "effort to create a visual record of the American military experience" (U.S. Army Center of Military History, 2020). These are examples of the exceptional resiliency of our species, as well as our drive to create despite the situation. Space, even as an extreme environment, holds no exception for artmaking.

Adopting methods and insights from social sciences, art, and creative practices enables a more robust understanding of topics relating to human behavior in zero gravity. The approach taken to understanding or solving an issue directly affects the insight gained. Sociocultural consideration in current space exploration would make future space activity more inclusive and accessible. Currently most people on the International Space Station tend to be westerners or people from more industrialized societies, it would be fruitful to enable creative and artistic collaboration with individuals of different cultural backgrounds on board the station and on future space missions.

The issue of human space exploration is an intricate challenge that imperatively needs to include the social sciences and humanities. To date, a requirement to apply for an astronaut position at any major space agency is a graduate degree in a STEM field. This excludes philosophers, artists, and architects, who can also provide a more holistic perspective on technical and scientific issues if sent to space. Complex situations that are encountered during space activities require an interdisciplinary response, thus the presence of non-STEM individuals in space should be deemed necessary.

Maintaining a diverse population in not only astronauts, but in anyone involved in space activities is crucial. Currently, women make up 11% of astronauts and 20% of the space workforce (United Nations Office for Outer Space Affairs, 2020). Resulting from a historical prejudice against women engaging in scientific endeavors and space exploration, this imbalance diminishes opportunities for innovation. Diversity and gender equality in space activities is necessary to develop an inclusive space culture with equal access to space and benefits of its exploration.

Advocacy for Artists in Space Activities

The use and practice of art in space is vital for provoking and enhancing interdisciplinary collaborations, as art in itself is advantageous in scientific inquiry (Simon, 2001). Various Nobel laureates and well-established scientists have been highly involved with art or come from multi-disciplinary backgrounds, which has contributed to their success (Root-Bernstein et al., 2008).

Starting artists residencies either on the International Space Station or in any other context beyond the Kármán boundary is necessary, despite any difficulty in assessing its initial impact. Immersing artists in a novel situation with people of different expertise and backgrounds entails different approaches to interaction compared to designing and sending artworks to space. Top-tier companies and institutes have embraced the idea of their own artists residencies, including the Search for Extraterrestrial Life Intelligence (SETI) institute, SpaceX, Planet Labs, and SolidWorks. NASA and ESA have had a handful of artists in residence. Creative projects from these collaborations have resulted in new scientific discovery; some intentional, like Kitsou Dubois' weightless choreography that dealt with body awareness in zero gravity and training for astronauts and dancers alike (Bureaud and Dubois, 2005), and some incidental, like Eduardo Kac's paper airplanes that demonstrated air movement in zero gravity (Kac, 2017; Rose, 2017).

The conditions for creativity and artmaking in space require innovative efforts that require expertise from disciplines outside Science, Technology, Engineering, Arts, and Mathematics (STEAM), such as the social sciences and the humanities. Applying social sciences in extreme environments could contribute to creative processes that are a part of environmental or architectural design, for example the inclusion of proxemics in these designs. Proxemics, also known as personal space, is the "interrelated observations and theories of man's use of space as a specialized elaboration of culture" (Hall, 1966, p. 1). People from certain cultures prefer to socialize while being physically close to other people, while this may cause people from another culture to feel uncomfortable. According to this theory, the design of an environment may promote or neglect socialization, depending on where the person is from. It is central that designers of vessels or housing in extreme environments consider cultural nuances and social variability to promote better living and working spaces.

Suggestions for Future Research

Since space art is a relatively new topic, mostly due to the novelty of space exploration itself, we call for the development to further investigate creativity and art in space. The topic can be discussed from a generalistic perspective, regarding the development of a new field, however, in time it may develop into several branches and subfields that may need their own experts. Such was the case for disciplines like space anthropology, a recent field that arose due to the current technological and academic context. In the near future, we expect to see other examples that are specialized with a space focus, including but not limited to the architecture, culinary arts, fashion, and performance art. We are only in the first stages of space art and it will continue to mature and develop. Nevertheless, pioneering work with artists cannot evolve without the collaboration of scientists and engineers. This dependency remains reciprocal, as without artists there is less progress.

As space is a new venture and only over 500 people have traveled outside the Earth's atmosphere, humankind still has some years before it starts seeing shifts in space society. Conversely, human civilization is accelerating efforts to explore the space tourism industry by establishing a permanent base on the Moon this decade. The addition of sociocultural studies to space ventures may support a humane expansion of society in the years to come.

Aside from expanding the human experience, art has inherent pragmatic characteristics enabling its use as a tool, as is the case of mental health professionals for art therapy. Art therapy is an applied discipline that seeks to enable creative processes as a channel to alleviate stress, anxiety, depression, and other troubling psychological situations for both neurotypical and neurodivergent individuals (Malchiodi, 2012; American Art Therapy Association, 2017). In the case of space art, it is clear that it not only represents a person's creative potential but may have therapeutic effects that could aid in coping with high-stressful situations in space. Since social isolation is currently unavoidable while in space and gradually decreases performance (National Aeronautics and Space Administration, 2011), art therapy could benefit individuals having trouble cooperating with on-board colleagues or on-ground support staff.

Art practices in space can support strong relationships between astronauts from different cultural backgrounds through collaboration in an unstructured, non-threatening experience (Pietronigro, 2004). Astronauts playfully interacted with Cosmic Dancer (Woods, 1993a), a sculpture designed for zero gravity, taking a break from being scientists and engineers to observe and experience the artwork. The astronauts reported positive shifts in mood, a reevaluation of the environment, and new ideas that were derived from the experience (Woods, 1993b). Making or interacting with art in, not just space but an extreme environment, can have profound effects on the individual's experience. While we acknowledge that connecting the space art taxonomy that we propose along with our approaches in cognition and creativity might only scratch the surface of this conundrum, we recognize that the domain of creative processes in the extreme environment of space is still in its infancy. Our creative nature as humans helps us redesign our limits and expand our notion of what is possible far beyond Earth's atmosphere.

AUTHOR CONTRIBUTIONS

KH and RM conceived and developed the concept for the manuscript. All authors contributed to writing the manuscript and approve this manuscript for publication and certifies that this material has not been and will not be submitted to or published in any other publication before its appearance.

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What Does Creativity Mean in Safety-Critical Environments?

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Safety in high-risk and time-pressured situations relies on people's ability to generate new and appropriate solutions to solve unforeseen problems for which no procedures or rules are available. This type of ability is regularly associated with the concept of creativity. While psychology researchers have studied, for decades, how creative ideas and solutions are generated, this basic research has not made it into the more applied fields of human factors and neuroergonomics. Building on the research on the psychology and the neuropsychology of creativity, this paper will (1) address the question of what creativity means and what are its ties with problem solving and decision-making; (2) focus on the evidence of the creative processes, the underlying mechanisms, and the multiple psychological dimensions of the creative behavior involved in unexpected events in extreme environments such as Apollo 13 mission, United Airline Flight 232, and Mann Gulch wildfire; and (3) explore the implications for future research in the domains of neuroergonomics and differential psychology.

Keywords: creativity, safety, insight, improvisation, risk, unexpected, attention, neuropsychology

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INTRODUCTION

In a recent interview (Saraceno, 2018), James Lovell, commander of Apollo 13 mission, commented on the catchphrase "*Houston, we have had a problem*"[1] saying, not without humor: "*the quote became iconic because it fits into millions of situations people experience every day. Every time you turn around, you seem to hear, 'Houston, we have a problem.' I wish I had copyrighted it!*" Apollo13 spaceflight crew and mission control team demonstrated considerable creativity and ingenuity under time and resource constraints. In this life-or-death situation, creativity was the critical pathway to survival. "It is a reactive force, triggered when all else fails, when the usual ways of doing things suddenly stop working and there is no choice but to discover or invent others" (King, 1997, p. 301). According to many experts, the ability to succeed under unexpected and extreme conditions involves "creative intelligence" (Orasanu and Fischer, 1997; Lagadec, 2009; Boy, 2013; Klein, 2013). This ability reflects the complementary roles and the integration of intelligence, which primarily focuses on finding the correct solution, and creative reasoning that allows the generation of new alternative and approaches (Jaarsveld et al., 2015).

Although references to creativity in safety are frequent, the underlying processes of the creative behavior in safety-critical environments received only limited attention. Building on several decades of research on the psychology and the neuropsychology of creativity, this article aims to advance our understanding of how experts create new solutions in extreme and

[1]The legendary line delivered by Lovell is "Houston, we have had a problem" and not the familiar "Houston, we have a problem" made especially popular by the Tom Hanks movie. https://history.nasa.gov/afj/ap13fj/08day3-problem.html

unforeseen situations. These questions are not new but they will be addressed in this article from a new perspective. Traditionally, problem solving, judgment, and decision making in safety-critical environments have been discussed extensively in the literature based, particularly, on Rasmussen skill-rule-knowledge (SRK) model (for SRK; Rasmussen, 1985) and naturalistic decision-making framework (NDM; Klein, 2008). SRK model highlights three types of information processing according to the degree of conscious attentional control: (a) skill-based mode refers to the execution of highly practiced action in an automatic way, (b) rule-based mode consists of implementing prescribed rules with moderate control, and (c) knowledge-based mode involves high-level of conscious control and eight stages devoted to the analysis of the situation (activation, observation, identification, interpretation, or diagnosis) and to the formulation and the execution of an action plan (evaluating of the alternatives, task definition, procedure formulation, and execution). NDM relies on recognition-primed decision strategies, in which the familiarity with a situation is assessed and information is activated from memory. NDM research emphasizes the role of intuition in expert decision and "views intuition as an expression of experience as people build up patterns that enable them to rapidly size up situations and make rapid decisions without having to compare options" (Klein, 2015, p. 164). Building on SRK and NDM models, Orasanu and Fischer (1997) made an explicit link between creativity and aviation decision making (ADM) in critical situations. They considered that creating and implementing a solution when a problem is ill-defined or ambiguous is the most difficult action plan in ADM because it involves not only assessing the situation but also of creating a solution for a defined problem that has never been encountered.

Since the 1950s, psychology researchers have studied how creative ideas and solutions are generated. According to the 4Ps model, the psychology of creativity research covers four perspectives: Process (stages and the nature of the problem solving and decision making), Person (personality, intellect, temperament, experience, etc.), Product (e.g., when a thought becomes a course of action, a creative idea, procedure, physical object, etc.), and Press (impacts of factors in the physical and social environments). Moreover, the underlying mechanisms or brain function involved in the emergence of creative solutions have been investigated using the recent advance in neurophysiological [e.g., electroencephalography (EEG)] and neuroimaging [e.g., functional magnetic resonance imaging (fMRI)] studies of creativity. However, this basic research has not made it into the more applied fields of human factors and neuroergonomics.

Building on the 4Ps model (Process, Person, Product, and Press) and the neuropsychology of creativity, this paper will (1) address the question of what creativity means and what are its ties with problem solving and decision-making?; (2) focus on the evidence of the creative processes, the underlying mechanisms, and the multiple psychological dimensions of the creative behavior involved in unexpected and extreme events such as Apollo 13 mission, United Airline Flight 232, and Mann Gulch wildfire; and (3) explore the implications for future research in the domains of neuroergonomics and differential psychology.

WHAT IS CREATIVITY?

Creativity is the capacity to produce novel, original work that fits with task constraints and has value in its context. While intelligence relies on analytical thinking, the use of prior knowledge, and problem solving through the use of routine procedures, creative resolution of a problem involves the skill to make non-obvious connections in order to generate previously unknown solutions (Sternberg, 1997). Bruner (1983, p. 183 in Weick, 1993) described creativity as "figuring out how to use what you already know in order to go beyond what you currently think." This description echoes the notion of potential, which refers to a latent state that may be put to use if a person has the opportunity. As part of an individual's "human capital," creative potential may remain latent and the individual may be aware of his/her potential or may be blind to it. Recent advances suggest that creative potential stems from numerous factors (cognition, personality, emotional, and environmental context); it can be defined, measured, and improved. It is based on 10 cognitive and conative dimensions (Lubart et al., 2013): Divergent thinking, Mental flexibility, Analytic thinking, Associative thinking, Selective combination, Openness, Tolerance of ambiguity, Intuitive thinking, Risk taking, and Motivation to create. These dimensions will be defined, in the Creativity Under the Gun: Evidence of Creativity in High Risk Environments section, when addressing the evidence of creativity in high-risk environments.

What Are the Processes Involved in Creative Behavior?

The nature of the creative processes that produce original ideas that have value in their context could be considered within two conceptualizations (Fisher and Amabile, 2008): compositional and improvisational creativity. While in music and theater, there is an accepted distinction between composing and improvising, we will see throughout this article that in the context of safety, they are used interchangeably.

With regard to compositional creativity, one of the early sources of information is based on the introspection of eminent scientists such as Poincaré and Helmholtz. It allowed Wallas to formalize, in 1926, the four-stage iterative model of the creative process (Lubart, 2001; Bourgeois-Bougrine and Lubart, 2019): preparation (information gathering and preliminary analysis to define the problem), incubation (phase where there is no conscious work on the problem), illumination (when an interesting idea becomes conscious), and verification (evaluation, redefinition, and development of the idea; Iteration of the previous steps if the idea is unsatisfying). The initial stage could be considered as a "formless" situation where there is no structure, no task, and no problem to solve; ideas do not, indeed, present themselves as "problems capable of resolution or even sensible contemplation. They must be posed and formulated in fruitful and often radical ways if they are to be moved toward solution. The way the problem is posed is the way the dilemma will be resolved" (Getzels, 1979, p. 167).

Several stage models of creativity have emerged introducing changes and improvements to the four-stage model such as the creative problem solving (CPS) model. A recently accepted

CPS model (Mumford and McIntosh, 2017) includes eight key sub-stages of creative thinking summarized in four components: understanding the challenge, generating ideas, solution planning and execution, and monitoring the results. This CPS model has similarities with *Knowledge based behavior* in SRK model (Rasmussen, 1985), which is frequently referred to in the safety context. Collaborative CPS in safety-critical events will be illustrated in the Creativity Under the Gun: Evidence of Creativity in High Risk Environments section.

Fisher and Amabile (2008) suggest that in compositional creativity, preparation can include the development of specific skills and obtaining the information needed to perform the task. In improvisation, such preparation cannot occur because immediate action is needed. Indeed, the main difference between improvisational and compositional creativity lies in the role of urgency. Time pressure is often what produces improvisation in the first place. Improvisation is considered as an unplanned, spontaneous, and intuition-guided action to achieve a goal; the actions contain both a high degree of novelty and a low temporal separation of problem presentation, idea generation, and idea execution (Vera and Crossan, 2005; Fisher and Amabile, 2008). Therefore, improvisation could be considered a deliberate creative process where a convergence between the "design and the execution of a new production takes place" (Miner et al., 2001, p. 314). There is no improvisation unless an action is taken (Weick, 1998). Individual or group improvisation systematically starts with a spontaneous and unplanned action when one does not have time to step back and think. As a consequence, improvisation in the safety context often refers to an outcome or a solution that emerges without planning.

Improvisation is often associated with the concept of bricolage, which involves a new combination of available resources (Adrot and Garreau, 2010). However, improvisation is different from bricolage because of the nature of the constraint in question: in the first case, the constraint is the lack of time that leads to "thinking in action" and, in the second case, the constraint is related to the lack of resources that leads to using the resources at hand. However, during improvisation, the pressure of time makes it unlikely to search for or obtain additional resources, increasing the likelihood of bricolage (Baker and Nelson, 2005; Adrot and Garreau, 2010).

Group improvisation involves a collective engagement in a joint creation. The creative performance is built through verbal and nonverbal interactions (e.g., speech, gestures, and movements). Musicians or theater actors perform as a group with no preparation, no previous experience of playing together, no script, and no director. They respond to each other as in a conversation, they are sensitive, attentive, and adapt to what other members of the group play or say. Miles Davis once said, "*Play what you hear, not what you know*." Recent studies have identified changes in the brain during collective improvisation compared to individual or solo improvisation. Limb and colleagues (Limb and Braun, 2008; Donnay et al., 2014) used functional brain imaging to study the areas of the brain involved in musical improvisation. Professional, highly skilled jazz musicians played on a keyboard developed specifically for use in the context of brain imaging. During the collective improvisation (two musicians playing simultaneously during brain imaging), a strong activation of the dorsolateral prefrontal cortex (DLPFC) was observed due to the social context, which makes use of the working memory. In fact, in comparison with individual musical improvisation, the interaction between the two musicians requires paying attention to what is being played, thus placing a high demand on working memory. Interestingly, structured scoping study of improvisation in scientific literature (Frykmer et al., 2018) showed that collective improvisation in crisis management is a mere aggregation of individual improvisation at collective level, which is different from group improvisation in music and theater.

Where Do Creative Ideas Come From?

The neuropsychology of creativity highlights possible underlying mechanisms that promote the emergence, the selection, and the implementation of creative ideas. The findings of domain-specific studies (e.g., creative writing, visual art making, melody improvisation, etc.) and psychometric tasks[2] highlight the fact that creativity does not rise from a conceptual void but from an ongoing knowledge base development and personal past experiences (Madore et al., 2016; Abraham, 2017). Individuals accumulate a collection of knowledge and routines, which must be both readily accessible and flexibly organized to meet any situational demand. For instance, Bill Evans,[3] one of the greatest jazz pianists of the second half of the 20th century, said that it took him 15 years of work from the time he first started improvising, at age 13, until he mastered the process of improvisation and was ready to create something truly valuable. Evans's approach to music was a process of analysis followed by intuition. This highlights the pivotal role of intuition in improvisation and confirms the view of intuition as an expression of experience. However, as we will see in the next section, improvisation in safety-critical situations could involve insight problem solving instead of intuition. Insight is a sudden understanding on how to solve a problem while intuition corresponds to an association between a piece of information provided by the situation and information stored in memory (Klein, 2013).

Conceptual knowledge is represented within an extensive semantic network in the memory, with direct and strong connections between closely related concepts (e.g., Bees-Honey or Table-Chair). Although memory access and retrieval are critical to creativity, evidence suggests that it can also hamper original idea generation leading to cognitive fixedness (Beaty et al., 2017; Agnoli et al., 2020). For example, an excessive strength in semantic associations could lead to fixation on the strong associates and result in difficulties to transcend or to inhibit overlearned response, stereotypical associations, or salient concepts (Bendetowicz et al., 2018).

The ability to flexibly combine concepts stored in memory to form novel and useful associations requires the coactivation

[2]Psychometric tasks: alternative uses task (AUT) and remote associates test (RAT). The AUT assess divergent thinking and the RAT measures the ability to see relationships between things that are remotely associated.

[3]http://www.openculture.com/2012/04/the_universal_mind_of_bill_evans_advice_on_learning_to_play_jazz.html

of large brain networks: the default mode network (DMN) and the control executive network (CEN). The DMN, which is hypothesized to be involved in spontaneous activation of concepts and experiences from memory, is known to support the divergent and open creative process; it is activated by diverse forms of tasks that require spontaneous activation of autobiographical and semantic memory, perspective-taking, and envisioning the future. However, the DMN is deactivated during attention-demanding externally oriented task (Buckner et al., 2008). The CEN is a goal-directed processing which (a) controls attentional shift from the external world to internal thoughts, (b) exerts a high cognitive control for the selection and integration of semantic concepts, (c) facilitates flexible switching between semantic categories during memory retrieval, and (d) mitigates sources of interference by suppressing salient conceptual knowledge. Using convergent and divergent tasks, Bendetowicz et al. (2018, p. 228) confirm that optimal creative performance "*requires controlled mechanisms such as strategic search and controlled retrieval in memory, the inhibition of interference caused by frequent and more salient associates, the integration or combination of the retrieved associates, and the selection and evaluation of a solution that satisfies the constraints of the task*."

CREATIVITY UNDER THE GUN: EVIDENCE OF CREATIVITY IN HIGH RISK ENVIRONMENTS

This section addresses traditional safety issues through the lens of the psychology and the neuropsychology of creativity which consider creative action within the CPS framework. Creative individuals such as artists, musicians, etc., who seek to express his or her feelings in an original way are considered to be involved in solving a problem. In safety-critical events, desperation drives individuals to create new solutions to survive. Three examples of successfully managed safety events where creativity was considered as one of the key factors will be tentatively analyzed from the perspective of individual and team's creative behavior, and the neuropsychological underlying mechanisms of such behaviors highlighted. The first two case studies, Apollo 13 mission and United Airline Flight 232, are positive examples of collaborative problem solving and the third, Mann Gulch wildfire, is a successful example of individual insight problem solving. The analyzed data includes the following sources: official accidents reports, communications' transcripts (cockpit voice recorder and technical air-to-ground voice communications), interviews, talks, and a testimony.

Collaborative Creative Problem Solving in Safety-Critical Environments

Creativity in the Air: United Airline Flight 232

"Disaster in the air, are you ready?" was the subtitle given by the Alaska Air Safety Foundation to a talk given by Captain Alfred Haynes about Flight 232 of United Airline (UAL), one of the most celebrated cases of CPS (NASA-Dryden, 1991). The flight crew experienced severe difficulties controlling the airplane after a catastrophic loss of all hydraulic systems due to an explosion in the number two engine. The crew had been trained to manage "*one failure or double failures, but never a complete hydraulic failure*" (NASA-Dryden, 1991). The official accident report indicates that "*Douglas Aircraft Company, the FAA, and UAL considered the total loss of hydraulic-powered flight controls so remote as to negate any requirement for an appropriate procedure to counter such a situation…The simulator re-enactment of the events leading to the crash landing revealed that line flight crews could not be taught to control the airplane and land safely without hydraulic power available to operate the flight controls*" (National Transportation Safety Board, 1989). This begs the question: how did the crew deal with this complete unforeseen circumstance in the air with virtually no prior experience of flying an airplane under those conditions?

The flight crew engaged, during 45 min, in an efficient collaborative CPS demonstrating outstanding skills throughout the four-stage CPS process: understanding the challenge, generating ideas, solution planning and execution, and monitoring the results. During the whole event, the crew tried to make sense of what was going on by "reading into their situation patterns of significant meaning…Sensemaking is built out of vague questions, muddy answers, and negotiated agreements that attempt to reduce confusion" (Weick, 1993, p. 635). As Isaksen and Treffinger (1987) have argued the process started by a disorder phase (mess) during which the problem was defined. These authors distinguish between the discovery phase of the problem (something is wrong, unsatisfactory, or missing) and the preparation phase in which information is collected. The crew was aware that they had lost one engine. The captain called for engine failure checklist and noticed that something else was wrong as suggested in the following quote of the Captain of UAL-232 flight: "*the first thing it (the checklist) said was, close the throttle. And when I tried to pull the throttle back, it would not come back. Now, I've never shut an engine down in flight on a jet, so I did not know that when you pulled the throttle back, it did not come back. In the simulator, when you do it, it always came back. This one would not come back…*" The crew quickly understood that not only they had lost one engine but also the three hydraulic systems and had to deal with an additional problem (e.g., "phugoid"): "*we immediately determined that we could not control the airplane: it would not respond to the inputs of the crew… Besides losing all of our hydraulics, which gave us no control, we had a problem that I was not really familiar with, called 'phugoid'…*" The two outboard engines were still running, but no flight controls were operative.

As in any ill-defined problem, the crew had a purpose (e.g., to keep the plane upright in the sky) but did not have a known means or obvious path to achieve it. While figuring out what is going on and trying to find an airport, they gathered information from air traffic control about possible landing areas (runways and highway), checked visually the external damage to the airplane, discussed the procedures, invited in the cockpit an off-duty DC-10 captain who volunteered his assistance, and contacted San Francisco area maintenance experts for help with the issue of the loss of hydraulics, etc.

This safety-critical event involved, indeed, numerous cycles of divergent and convergent thinking at each step of the process: the crew simultaneously generated and evaluated ideas and used these ideas to formulate implementation plans. The execution of these plans often led them to circle back as the output was inadequate until they figured out opportunistically a novel solution to operate the plane without any control. Every time the maintenance experts and the off-duty captain tried to find something that the crew could do, they had either already done it or could not do it, because of the loss of hydraulics. As the cockpit voice recorder (CVR) indicated, the crew collectively generated and tested possible solutions and courses of action in dealing with the loss of the hydraulic system, as well as the methods of attempting an emergency landing: "*if we had not let everybody put their input in, it's a cinch we would not have made it…the way we flew the airplane (was): what do you want to do, I do not know, and let us try this, and you think that'll work, beats me, and that's about the way it went, really. If you read the CVR transcript, there's a lot of that on there*." This reflects a high degree of tolerance of ambiguity, openness, and risk taking which are among of the 10 dimensions of the creative potential (Lubart et al., 2013). Tolerance of ambiguity is characterized by the ability to solve, or at least to tolerate situations and/or information that are ambiguous, unclear, contradictory, or absent. Openness is the tendency to try out new things and to have new experiences; it is opposed to dogmatism and conformism. The idea of sensible or calculated risk taking is often associated with creativity (Bourgeois-Bougrine et al., 2020), and several researchers have argued for the need to measure risk taking in a variety of domains to better capture its complex nature (Sternberg and Lubart, 1995; Sternberg, 1997; Runco, 2015).

Moreover, the crew demonstrated a high-level of mental flexibility which is the ability to change points of view and to change initial cognitive frames in order to explore new directions, as suggested by the captain: "*we found that in order to stop a phugoid, you had to do the opposite of what you would normally do*." This cognitive ability is synonymous to mental suppleness and to the ability to alternate between processing several kinds of information. They also stumbled upon solutions in an opportunistic way to several problems. For instance, with the help of the off-duty captain (who was assigned to the throttles), the crew managed to control the heading in synchronized effort: "*And we said (to the off-duty captain), give us a right bank, bring the wing up, that's too much bank, try to stop the altitude, he'd try to respond. And after a few minutes of doing this, everything we'd do with the yoke, he could correspond with the throttles. So, it was a synchronized thing between the three of us, with (second first officer) still being able to do all his communications. So that's how we operated the airplane, and that's how we got it on the ground*." This might represent an instance of rare and true group improvisation as experienced by musicians or theater actors "in the spirit of shared leadership, responsibility, mutual support, and care" (Nisula and Kianto, 2018, p. 485). Indeed, through verbal and nonverbal interactions, the crew coordinated and synchronized their actions in a spontaneous, unplanned, and never experienced way. Crewmembers were attentive and adapted to each other's action.

Although the mood of the crewmembers was understandably negative (fear), there were no apparent symptoms of panic as suggested by the CVR and the Captain in his talk: "*although we did not appear to be panicked…an airplane about to roll onto its back at 35,000' is pretty scary, so you just do anything you can to make it stop*." Provided that they are not associated with extremely high-level arousal, negative mood states might increase the capacity to consider multiple alternatives because of enhanced persistence (Nijstad et al., 2010).

Distributed Creative Teams: Apollo 13 Mission

During the commemoration of 45th anniversary of Apollo 13 mission, Jim Lovell[4] said "*The flight was a failure in its initial mission. However, it was a tremendous success in the ability of people to get together, like the mission control team working with what they had and working with the flight crew to turn what was almost a certain catastrophe into a successful recovery*." Similar to the abovementioned case (UAL-232 flight), the teams demonstrated outstanding collaborative CPS skills, high degree of divergent thinking, tolerance of ambiguity, openness, risk taking, and mental flexibility. However, in the case of Apollo 13, the teams were distributed between space[5] and the ground[6] and the creative effort lasted about 80 h after the blast. The transcript of the technical air-to-ground (TAG) voice communications[7] shows that through constant communication, trust, and care, the flight crew and mission control established and maintained a shared understanding. They monitored and evaluated the results of their actions, provided feedback, and adapted plans.

The blast that occurred 200,000 miles from earth at 55 h:55 min into the mission led to a major loss of power, oxygen, heating, disturbed the supply of water, and forced the crew to abandon the command module (CM) and use the lunar module (LM) as a lifeboat. Immediately after the blast, the creative process started with a phase of mess-finding in which the problem was defined. Both teams engaged simultaneously in troubleshooting the possible issues to make a sense of the erratic readings as suggested below in the followings TAG transcript:

- "*055:55:51 Liebergot: Okay, flight, we have got some instrumentation funnies. Let me add them up*. (In Mission Control Center in Houston, the flight controllers monitor the ship's remote telemetry)
- *055:55:58 Lousma: Okay, stand by, 13. We're looking at it. [Pause.]*
- *056:03:17 Swigert: Okay, Houston. Are you still reading 13?*
- *056:03:20 Lousma: That's affirmative. We're reading you. We're trying to come up with some good ideas here for you*.
- *056:03:29 Haise: Okay. Let me give you some readings…*"

[4]https://www.nasa.gov/content/members-of-apollo-13-team-reflect-on-nasas-finest-hour
[5]Flight crew – Commander: Jim Lovell; Command module pilot: John Swigert; Lunar module pilot: Fred Haise.
[6]Mission control (Houston): flight directors, capsule communicators, engineers…
[7]https://history.nasa.gov/afj/ap13fj/21day5-batterycharge.html

As the teams examined the gauges, they started gaining a greater insight into the magnitude of the failure ahead of them. They stayed calm and engaged in numerous cycles of divergent and convergent thinking. For instance, they brainstormed ideas after Jim Lovell's announcement of something leaking from the ship:

- *"056:09:07 Lovell: We are venting something out into space… It's a gas of some sort*.
- *056:09:29 Kranz: Rog. (Pause) Okay, let us everybody think of the kind of things we might be venting…"*

Once the lunar landing was aborted, the big questions were: how do we return to earth safely? How to deploy the capability of the LM? How will we overcome the damaged alignment system? etc. After a day and a half in the LM, a warning light showed that the carbon dioxide had built up to a dangerous level. But the CM's square-shaped canisters, which remove carbon dioxide from the spacecraft, were not compatible with the round openings in the LM environmental system. Mission control devised and transmitted to the fligthcrew a way to attach the CM canisters to the LM system by using plastic bags and cardboard and to tape all materials carried on board. This outcome is an example of creative bricolage under resources constraints.

Moreover, the teams came up with five return-to-earth options and developed an alternative procedure to use the Sun as an alignment star as a result of the damages caused by the explosion to the alignment system (Granath, 2015). Among others, the teams generated and discussed ideas to solve the problem of the entry procedure:

- "110:23:19 Lousma: Jim, we have had a lot of people working on the entry procedures, and they will be continuing to do so. We got a few ideas we would like to toss at you so you can start thinking about them…?"

Similar to members of creative innovation networks (Gloor, 2006), the flight crew and mission control team's work was interdependent, based on trust, respect, reciprocity, and consistency. All along, the knowledge was questioned, the problems redefined, and the solutions generated through an iterative process of CPS. This process involved prototyping solutions with what the crew had on-board and testing new procedures in the simulator. When asked if the question of survival ever came up, Jim Lovell showed outstanding emotional control: "*Honestly, no, we never had that thought. As long as the situation wasn't hopeless, we thought positive*" (Saraceno, 2018).

Problem Solving Through Insight

Creative Desperation: Mann Gulch Fire

On August 1949, Wagner Dodge and his 15 crewmembers were running uphill for safety, when he realized that the fire was only 50 yd. away behind them, and they could not outrun it. He stopped to light an escape fire as his testimony indicates[8]: "*the fire was too close, in my estimation, to continue farther. At this point, I stopped the crew and explained to those nearest me (at least eight men) that we would have to burn off a section of the light fuel and get into the inside in order to make it through… After setting a clump of bunch grass on fire, I had an area of 100 feet square that was ablaze…for all my hollering, I could not direct anyone into the burned area… within seconds after the last man had passed, the main fire hit the area that I was in…This lasted approximately 5 min, and I was able to sit up within the burned area…*" Dodge's intention was to provide the crew a burned over, fuel-free zone but none of the crew followed his order to dive in the ashes that saved his life. Lillquist (2006, p. 567) reports that "*when later asked by the Board of Review whether he had been taught to set an escape fire in such a situation, Dodge replied Not that I know of. It just seemed the logical thing to do. I had been instructed if possible to get into a burned area*." As the burned area was behind the "wall of fire" that was about to engulf him, he created the escape fire to "get into a burned area" of his making.

In his analysis of this disaster, Weick (1993, p. 642) described the escape fire as a "burst of improvisation" in the face of an inconceivable life-threatening event. This improvisation does not rely on intuition but on insightful problem solving (Klein, 2013). Insight or "Aha Moment" requires a spontaneous and sudden reorganization of the elements of the problem, a perspective shift to find the correct solution, and a transition from one mental model to another that is more satisfying and bringing suggestions for new actions that can remedy the tensions inherent in the previous mental model (Klein, 2013; Abraham, 2018). Klein and Jarosz (2011) referred to it as a "creative desperation path" triggered in a situation of imminent danger when the individual is confronted with an impasse resulting from deliberate and often desperate efforts to escape it. In contrast to Wallas's four-stage model, when a person reaches an impasse and needs a quick breakthrough, a sudden reframing or restructuration of their mental model of the situation may occur without any deliberate preparation or incubation. Insight or revelation requires a high degree of mental flexibility to generate a new interpretation of the problem and to restructure it.

Referring to the escape fire, Weick (1993, p. 638) indicates that "what we do not expect under life-threatening pressure is creativity." This leads us to two questions: why did his crew members not see escape fire as a lifesaving solution? and why was Wagner Dodge the only one who came up with this solution? The first question has received an extensive analysis from several perspectives. For instance, Weick (1993) suggested that Dodge's failure to get his crewmembers in the escape fire, that resulted in the death of 13 men, was due to the "collapse of sensemaking" and the disintegration of role structure in this minimal temporary organization. While the second question remains difficult to answer, we will provide in the next section some basic research evidence of the underlying mechanisms of insight problem solving compared to traditional analytical approaches (e.g., conscious and deliberate search through a space of potential solutions).

[8]Testimony of smokejumper foreman Dodge. https://www.nifc.gov/safety/mann_gulch/event_timeline/event3/documents/Pages%20117_118%20from%20Board_of_Review_%20Sept%2026_28_1949.pdf

The Underlying Mechanisms of Insight Problem Solving

Using psychometric tasks, EEG recording, brain imaging, and eye tracking, recent laboratory studies (Kounios and Beeman, 2014; Salvi et al., 2015) have attempted to answer two challenges: identifying the differences in cognitive and neural mechanisms in insight vs. analytical responses and the existence of an unconscious process preceding a conscious response. The results indicate differences in brain activation and eye movements of participants depending on the type of problem solving. Successful problem solving through insight involves a transient reorientation of attention inward while preparing and solving a problem. Kounios and Beeman (2014) showed that solutions that emerge from insight, compared to analytical solutions, were associated with an intense activity of gamma waves (40 Hertz) preceded by a burst of alpha waves (about 10 Hertz). The increase in gamma activity is considered to be the main correlate of the insight experience: it allows the link between treatment in different areas of the brain to build a coherent percept (Tallon-Baudry et al., 2005), and it occurs when the participant finds the solution to the problem, in a brain region involved in semantic integration (St George et al., 1999). The burst of alpha, on the other hand, indicates that the brain limits the flow of external visual information in order to avoid distraction, which could disturb the emergence of the solution by insight. The authors point out that in normal circumstances, when asked a difficult question, we often tend to look away from the person who asked that question or even briefly close our eyes during the search for an answer. As the participants in this experiment were instructed to look at the center of the screen, the increase in alpha waves is a compensatory phenomenon of the brain, which directs attention inward in order to protect the emergence of the solution. In other words, reducing temporarily interfering visual inputs allows the solution to pop into awareness. The results observed by exploring brain activity were confirmed by a study that used eye tracking technique to study attention in a similar experimental design (Salvi et al., 2015). The changes in the duration and frequency of blinking and eye fixation are overt indicators of the modulation of attention. Immediately prior to solutions, participants blinked longer and looked away from the problem more often when solving it by insight than when solving analytically. Spontaneous eye blinks are hypothesized to be actively involved in the release of attention from external stimuli to internal thoughts and tend to occur at breakpoints of attention, such as the end of a sentence while reading, a pause by the speaker while listening to a speech, etc. A recent study (Nakano et al., 2013) suggested that eye blinks are actively involved in the process of attentional disengagement during a cognitive task. The control of attentional process facilitates the shift of attention between external task and internal thoughts, the inhibition of most common response, the access and the combination of remote conceptual knowledge.

To sum up, insight problem solving involves a shift of attention inward and a "transient sensory gating" (Kounios and Beeman, 2014, p. 80). Despite the limitations of the laboratory approach, the neuropsychological studies of creativity open up new avenues for future research to understand the cognitive process and the underlying mechanisms of creative and insight problem solving in life critical-situation.

CONCLUDING THOUGHTS: IMPLICATION FOR FUTURE RESEARCH

Drawing on the aforementioned literature and safety events, we propose a definition of creativity in safety-critical environments as "the capacity of expert individuals and teams to create original, unusual, and adapted solutions to solve unforeseen problems in life-critical situations, for which there is no prescribed procedure or obvious solution to apply." Contingent on this definition, the solutions must contain both a high degree of novelty and adaptability, which also strike others as being interesting or clever (Kellner and Benedek, 2017). The solutions or "products" should be distinguished from the process that leads to the emergence of the successful outcome. In contrast to the existing literature on experts' decision-making, insights from the psychology of creativity research suggest that creative behavior involves not only intuition as mentioned in the NDM model but also the combination of several cognitive and conative factors such as divergent thinking, mental flexibility, tolerance of ambiguity, etc.

Among the many implications for future research, two main issues could be addressed. The first issue, which represents a new research opportunity for neuroergonomics, would explore the neural basis of creative and insight problem solving in life critical-situation. The second issue falls within the traditional boundaries of differential psychology and would address the nature of the attributes of creative individuals in safety contexts. The ultimate goal is to improve operational training and required skills to deal with the unexpected and to explore design principles for human-machine systems that would support creative behavior whenever required.

What Would Be the Underlying Mechanisms of Creative and Insight Problem Solving in Life Critical-Situation?

In life or death situations, acute stress and anxiety can lead to severe performance impairment due to cognitive fixation and mental block (Jouniaux, 2001). Attention and cognitive tunneling on specific symbology or stimuli could result in failure to detect potentially critical events that do not fall within the attended region (Jarmasz et al., 2005). Based on the neuropsychology of creativity, we can hypothese that these stress reactions would potentially limit the shift of attention between external task and internal thoughts, prevent the "sensory gating," and hinder the inhibition of most common response as well as the access and the combination of remote conceptual knowledge.

Therefore, a particular attention should be devoted to the study of the underlying brain function involved in creative and insight problem solving related to operational performance in a simulator or virtual reality environment. This would require identifying and analyzing operational safety-critical events where there is evidence of creativity in line with the aforementioned definition of creativity in safety-critical environments. A simulation of the selected events will provide the opportunity for neuroergonomics researchers to explore in objective way (e.g., using eye tracking and brain imaging technics) the following issues: (1) the mental processes and environmental cues that lead to or prevent the emergence of new ideas and solutions in life critical events, (2) ways to optimize attention control and emotional regulation when solving operational problems under extreme stress such as mindfulness training (Meland et al., 2015; Abraham et al., 2019), and (3) the design principles for human-machine systems that will optimize the attention span and focus to avoid "locking" the user on an unsuccessful path in solving unexpected and extreme problems (Klein, 2013).

What Would Be the Attributes of Creative Individuals in Safety Context?

Experts agree that "*If the unforeseen were the norm, crew training should be fundamentally oriented to deal with it - particularly stimulating pilots' capacities for judgment and creativity, essential qualities for this purpose*" (AAE-Académie de l'air et de l'espace, 2013, p. 39). For instance, reflecting on what defined the first astronauts, Jim Lovell said: "*Originally, we were all test pilots. We sort of lived on the edge. We tested unproven airplanes for the military; we always expected something to go wrong*" (Saraceno, 2018). Moreover, Alfred Haynes served as a pilot in the Navy during the Korean War for 4 years before joining United Airlines. This confirm the role of experiences in the development of knowledge and highlight the need to (1) understand how past experiences in difficult conditions shape the creative potential to instigate CPS and decision making in stressful and extreme situations and (2) explore the nature of trainings that would enhance the creative potential of ordinary frontline operational without having to live on the edge.

To be able to develop these trainings, there is a need to identify and measure the required abilities and skills. As explored in the previous section, the creative process in life critical events is oriented toward damage control and reflects the creative potential of experts. To make a sense of the unfolding events and to come up with appropriate and unusual solutions, several cognitive and conative factors are critical such as divergent thinking, mental flexibility, tolerance of ambiguity, analytical skills, etc. As it has been suggested (Lubart et al., 2013), the assessment of the creative potential profile would help to (a) identify the strengths and weaknesses of each person in relation to the average profile of his group or to the top performers in his domain and (b) to tailor training that target weaknesses in specific dimensions. A multidimensional approach has been adopted to detect of the creative potential in children, adolescent, and adults such as managers or designers (Caroff et al., 2018). Similar approach could be used to determine (1) whether there is a particular profile of the creative potential or skills that facilitate insight and CPS in life critical-situation and (2) how these skills and abilities could be developed?

In conclusion, we would like to emphasize that the successful outcomes in safety-critical situations rely on four sources of resilience: creativity, role system, attitude of wisdom, and respectful interaction (Weick, 1993, p. 638). To the question "Disaster in the air, are you ready?," Captain Haynes answered "No, you are never ready. But you might be prepared." We hope that revisiting the role of creativity in safety opens up multiple implications for future research that would contribute to the reinforcement of resilience.

AUTHOR CONTRIBUTIONS

SB-B prepared and wrote the manuscript. It is based on a review and synthesis of knowledge from multiple disciplines and sources including her own research and experience.

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BRIEF RESEARCH REPORT
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Creating Ambassadors of Planet Earth: The Overview Effect in K12 Education

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The overview effect is the commonly reported experience of astronauts viewing planet Earth from space and the subsequent reflection on and processing of this experience. The overview effect is associated with feelings of awe, self-transcendence, and a change of perspective and identity that manifest themselves in taking steps toward protecting the fragile ecosystem. In the current study, we investigated whether the overview effect can be obtained in school children when simulated using virtual reality (VR) and whether the effect has a positive impact on learning gains. Using questionnaires and attention data in an existing simulation environment used in the school system, we showed that the VR simulation elicits an overview effect experience. Moreover, the experience yields learning gains in the domain of astrophysics. These findings are in line with past evidence regarding the positive impact of awe on learning and can be used to support further investigations of the relation between the overview effect and behavioral changes, specifically for educational purposes.

Keywords: overview effect, virtual reality, education, immersion, awe

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INTRODUCTION

Since the 50th anniversary of the landing on the Moon and the first photograph of planet Earth outside its atmosphere, a renewed interest has emerged in the intense experience reported by astronauts. This experience was dubbed as the overview effect (White, 2014), an overwhelming experience when viewing the Earth from space and the subsequent reflection on and processing of this experience (Nezami, 2017). White (2014) describes the overview effect as a cognitive shift in awareness caused by seeing Earth protected by a very-thin-looking ozone layer in the hostility of space. Interestingly, the overview effect is not experienced uniformly, with personality traits, such as a need for cognition and religiousness, playing a role (Gallagher et al., 2014). In general, though, the effect appears to be associated with feelings of *compassion* and *self-transcendence*, a change of *perspective* and *identity*, and *awe* (Yaden et al., 2016). Some astronauts consider it a spiritual experience leading to self-transcendence (Nelson-Coffey et al., 2019), a "temporary feeling of unity characterized by reduced self-salience and increased feelings of connection" (Yaden et al., 2016).

The overview effect can also give rise to an increased understanding of how life interconnects, a renewed motivation to protect the planet's environment, and a feeling of kinship with people across the globe (Ihle et al., 2006) as well as a strong feeling of compassion toward others. Meanwhile, recognizing familiar locations on Earth from outside its orbit strengthens the feeling of personal connection (Stepanova et al., 2019b). Experiencing the overview effect leads to a lasting increase in the appreciation and the concern for planet Earth and a connection with humanity. This can support more pro-social attitudes such as a sense of international unity and altruistic behaviors (Yaden et al., 2016).

Since the anecdotal evidence in White (2014), the overview effect has been studied in the lab as well, with numerous studies demonstrating that it is a reproducible experience. The first and most important group of experimental participants consisted of astronauts. Among others, Ihle et al. (2006), Kanas (2020), and Nezami (2017) investigated the positive effects that spaceflight has on the well-being of people who had been in space, including aspects of the overview effect relating to the beauty and the fragility of Earth and the unity of mankind. Gallagher et al. (2014) analyzed astronaut journals and post-flight reports and compared the described experiences to the reports of participants of a virtual recreation of viewing Earth from space. The comparison revealed that the overview effect can be constructed, at least to some extent, also in simulated environments. When trying to recreate the overview effect in people on Earth, it is vital that they experience a feeling of awe, a key concept of the overview effect (Stepanova et al., 2019a).

While most accounts of the overview effect rely on self-reports, there is some evidence that measurements of brain activity may provide additional information. Arguably, the feelings associated with the overview effect can be compared to meditation in experienced meditators, i.e., clarity of thought and a change in perception of space and time. Meditation-like experiences can be measured not only through self-reports but also through the measurement of brain activity (Newberg et al., 2001; Berkovich-Ohana et al., 2013). Recently, it has been shown that meditation-like experiences can be simulated in virtual reality (VR), bringing participants in an immersive environment while recording neurophysiological responses (Tinga et al., 2019). Tinga et al. (2019) found brain imaging evidence for meditation in EEG theta to alpha ratios. Similarly, Gallagher et al. (2014) reported differences in theta and beta activity throughout the brain for those who experienced a simulated overview effect. In their experiment, they let the participants experience an environment of the International Space Station with portals opened to display simulations of Earth or deep space.

Brain activity is not the only objective measure that can be used to investigate the overview effect. Stepanova et al. (2019a) suggest that gaze data (even lower-resolution gaze data from a VR headset) could be used as possible indicators of the experience since an awed viewer is not able to tear their eyes away from the object(s) triggering the effect. As astronaut Scott Carpenter reports in White (2014, p. 29): "I found it difficult to tear my eyes away and go on to something else. Everything is so new and awe-inspiring that it is difficult to concentrate for very long on any one thing." Next to that, smoothness of the gaze movement, as well as longer dwell time, can suggest a calm gaze pattern associated with the effect.

Some studies suggest that the overview effect is mediated by awe. Awe appears to be a prominent feature associated with the experience and an important feeling to achieve while recreating an overview effect-inducing experience in VR (Stepanova et al., 2019a). Awe can be defined as a feeling of being overwhelmed and impressed by greatness or vastness (Keltner and Haidt, 2003), for example, open and rugged scenes (Klatzky et al., 2017) that elicit the need for cognitive accommodation. Vastness includes impressive views as well as an understanding of complex theory (Chirico and Yaden, 2018). Seeing something from a very high vantage point thus coincides with an experience of vastness. White (2014) mentions on the first page of his book that "anyone who flies in an airplane and looks out the window has the opportunity to experience a mild version of (the Overview Effect)." This indicates its connection to awe. Other environments and occurrences that can elicit the same type of emotions are cathedrals (Keltner and Haidt, 2003), (videos of) natural panoramic views and scenes (Rudd et al., 2012; Van Cappellen and Saroglou, 2012; van Elk et al., 2016; Guan et al., 2019; McPhetres, 2019), childbirth (Van Cappellen and Saroglou, 2012; Shiota et al., 2017), natural disasters (Keltner and Haidt, 2003; Guan et al., 2019), and, of course, videos of Earth from space (Rudd et al., 2012; Nelson-Coffey et al., 2019). Similarly to the overview effect, awe-inducing events can result in a feeling of self-transcendence and transformation as well as spirituality (Van Cappellen and Saroglou, 2012; Chirico and Yaden, 2018). It can also make one feel small (van Elk et al., 2016), increase pro-social behavior, and support integration into social groups (Piff et al., 2015; Bai et al., 2017). Awe also plays an important role in learning. In particular, a high propensity for awe has been shown to support the adaptability of mental schemas (Shiota et al., 2007b) and thus the openness to learn from awe-inspiring experiences or "surprising discoveries" (Valdesolo et al., 2017; Gottlieb et al., 2018). Particularly, young children learn much more effectively when their belief about the world is disproved, resulting in a need to accommodate the experience (Stahl and Feigenson, 2017). Awe has also been linked to greater awareness of knowledge gaps. That is, awe has been shown to make gaps in one's knowledge salient, which could be attributed to it being a positive emotion (McPhetres, 2019). These findings open up the question on whether the overview effect can be simulated for elementary school children, instilling the feeling of awe in them, and support learning. The first goal of the current study was to establish the relation between two types of cognitive states, compassion and awe, to the overview effect recreated in VR and to explore their impact on potential learning gains.

Whether or not strong feelings of awe will be achieved in immersive environments created by VR (Chirico et al., 2017) depends on the degree of immersion. A higher degree means a greater approximation of realism (Bangay and Preston, 1998). High immersion in VR has been reported to improve learning and memory; however, the importance of measuring presence when examining the effect of immersion on performance is critical (de Back et al., 2018). Presence describes the degree of felt realism and of "being there" (Witmer and Singer, 1998). Mikropoulos and Strouboulis (2004) reported effects of presence in 12-year-old children in an educational VR, with these effects having a positive effect on engagement and motivation. However, it should be noted that, although VR simulations have been reported to motivate and interest students and increase their performance in some studies (Alhalabi, 2016; de Back et al., 2018), other studies did not confirm these findings (Parong and Mayer, 2018). Since presence increases the feeling of actually being in a situation, such as viewing the Earth from space, we would expect presence to influence the overview effect (Stepanova et al., 2019b). Similar to presence, immersive tendencies refer to an individual's likelihood to experience presence (Witmer and Singer, 1998). Therefore, the second goal of the current study was to test the impact of immersive tendencies and presence on the overview effect experience and on the achieved learning gains.

To address both goals, the overview effect experience was created in VR in collaboration with SpaceBuzz. SpaceBuzz is a non-profit organization, located in the Netherlands, that offers an innovative educational program consisting of a pre-flight and a post-flight training including a simulated rocket launch in VR to 10–12-year-old children. In the pre-flight program, children write an application letter to become an astronaut, put puzzles together using oven mitts as a proxy for space suit gloves, and hang upside down on a playground bar while eating their lunch to familiarize themselves with gravity. After the children pass the astronaut training, they are launched into virtual space inside of an actual rocket ship. Using 4D simulations, children are sent into orbit around planet Earth, guided on their trip by a virtual embodiment of the ESA astronaut André Kuipers. After returning from their VR trip to Earth, a post-flight program at school has children give press conferences to friends and family, just like real astronauts.

CURRENT STUDY

The aim of the current study was to investigate whether we would be able to recreate the overview effect in VR for children between 10 and 12 years and examine its impact on learning. Based on previous findings, we predicted the relation to be affected by compassion, awe, and presence.

Method

Participants

In total, 233 children from eight classes in six schools in the Netherlands participated in the study. Of these 233 participants, 45 participants were removed from the analysis because of 40 questionnaires not being returned and five pre-tests being filled out at the wrong time (15% of the participants) (age $M = 10.68$, SD = 0.70; 87 boys, 93 girls, eight unreported).

Procedure

Prior to the study, parents received a letter that explained the nature of the experiment. Of the children who were allowed to participate, children with medical issues or those being worried about being dizzy or nauseous participated in the VR simulation under the direct supervision of their teacher. The study was approved by the Ethical Review Board of Tilburg University (REDC #2019/04a).

In the six participating schools, teachers were informed about the educational program and the VR experience onsite. The pre-flight program consisted of either four or six lessons. All children received the same theoretical and creative classes about the universe, planets, and satellites, received identical questionnaires on paper, and filled them out individually.

For the VR flight program, the classes traveled to the SpaceBuzz rocketship at a location close to the schools. They experienced the simulation in groups of nine participants. SpaceBuzz attendants provided a brief explanation about how the Head Mounted Display had to be worn and asked the children to keep their hands on their knees. If the children placed their hands too far to the side, the attendant placed them back on their lap for safety. After completing the VR experience, the children filled out questionnaires at a separate table under the supervision of research assistants.

In the schools, teachers taught the six post-flight lessons about worlds without borders and science. Some remaining questionnaires were administered.

Materials

Pre-flight

The pre-flight program included several questionnaires and learning activities. The first was a personality questionnaire, which was a writing exercise where children chose three personality traits that fitted them best from a list and included their reasoning. Next was an Immersive Tendencies questionnaire adapted from Schubert et al. (2001). The "dispositional awe and compassion" questionnaire was adapted from the DPES compassion and awe items (Shiota et al., 2007a). The questionnaires were translated to Dutch, reduced to around six items per questionnaire, and simplified for better comprehension by the children (van Kesteren et al., 2003). They were validated using an online questionnaire taken by 43 Dutch native speakers (age: $M = 32.4$, SD = 14.79) who answered both the original and the new questions after an immersive experience, in random order. The new Immersive Tendencies questionnaire had a reliability score of Cronbach's $\alpha = 0.70$. The original questionnaire and the children's questionnaire correlated strongly, $r = 0.73$, $p < 0.001$, using Pearson's correlations. The original dispositional awe and compassion questionnaire and children's questionnaire correlated strongly as well, $r = 0.78$, $p < 0.001$, as did the subscales of the questionnaire, dispositional compassion, $r = 0.69$, $p < 0.001$, and dispositional awe, $r = 0.64$, $p < 0.001$. The newly adopted questionnaire thus measured the same constructs. The dispositional awe items had a reliability score of Cronbach's $\alpha = 0.83$ and the dispositional compassion items had $\alpha = 0.75$.

The knowledge test was developed by the SpaceBuzz educational program to check for knowledge acquired in the lessons and consisted of 15 multiple-choice questions. From these 15 questions, eight questions in the pre-test matched the questions in the post-test content. To avoid a mismatch in questions in pre- and post-tests, only the matching questions were used for analysis.

Flight

The SpaceBuzz VR experience resembles a rocket ship on the back of a trailer (**Figure 1A**). It is 13 ft high, 8 ft wide, and 50 ft long. It has a futuristic interior and contains nine moving chairs (rotate and tilt). HTC VIVE Pro headsets were used for the VR simulations (resolution: 1,440 × 1,600 pixels per eye, 615 PPI, 3D Spatial Audio, refresh rate of 90 Hz) (**Figure 1B**).

FIGURE 1 | The SpaceBuzz experience. **(A)** Exterior of the SpaceBuzz rocketship. **(B)** Interior of the SpaceBuzz rocketship. **(C)** Snapshot of virtual reality experience.

The simulation was created in Unity to emulate a journey to space with a length of 14 min and 25 s and recorded the participants' gaze direction. ESA astronaut André Kuipers narrates the VR experience as the ship's captain and is shown at the front of the rocket ship. After launching, the rocket orbits the Earth, while topics such as deforestation, excessive fishing, and pollution are discussed. After a short trip to the moon, the rocket "returns to Earth." Head direction was recorded as a measure of attention by recording the angle between the head direction and the center of the area of interest (**Figure 1C**).

Post-flight

Immediately after experiencing the VR, another set of questionnaires was administered—the Presence questionnaire adapted from Witmer and Singer (1998). The Dutch version was simplified, shortened, and evaluated. It had a reliability score of $\alpha = 0.80$. The original questionnaire and the new questionnaire correlated strongly, $r = 0.89$ $p < 0.001$. The emotions questionnaire rates feelings of awe, happiness, boredom, excitement, fear, and nausea on a five-point scale (Rudd et al., 2012; Piff et al., 2015). The emotions questions were used as a manipulation check. Nausea was added to control for simulator sickness. The dispositional awe and dispositional compassion and the personality questionnaires from pre-flight were repeated. The overview effect questionnaire contained nine questions that tap the attitude toward the planet and prosocial behavior. The knowledge test consisted of 10 multiple choice questions, where eight questions matched the questions from pre-flight in content and are thus comparable. The questions were reviewed by the creator of the first questionnaire for a good match. To control for a learning effect being caused by the pre-test and to control for pre-test results in the analysis so that low pre-test scores do not necessarily yield higher learning gains, we made sure that the matching questions only matched on topic and were not identical.

After the VR experience, the schools covered the last six lessons while back in their own classroom, within the week following their VR experience. These lessons included the final post-test questionnaires where dispositional awe and dispositional compassion, the overview effect, and personality were repeated.

Statistical Analysis

Analyses were conducted using IBM SPSS Statistics (version 24) for calculating general results. Data collected in paper questionnaires were processed with the help of research assistants. A structural equation model (SEM), using unstandardized residuals (β), was calculated with the IBM SPSS Amos 24.0 statistical package. Questionnaires corresponding to the theorized model were used. For learning gains, proportional learning gains were calculated following Craig et al. (2004) for the eight matched questions in pre- and post-flight to account for differences in pre-test scores, avoiding bias for children that start with higher scores. Gender was also included in the SEM. In the second iteration of the SEM, described in this paper, gaze direction angle was included. This is the angle between the head direction and the center of the area of interest, which is Earth as it first comes into view until it fills the visual field. A smaller gaze angle indicates a strong focus on a specific point, on Earth. This moment is 1 min and 5 s long (for correlations, see **Table 1**). Maximum likelihood was used in the SEM, and missing values were handled using means and intercept estimates.

RESULTS AND DISCUSSION

Of the 188 participants who were entered for data analysis, five participants were removed because of extreme outliers in the learning gains (2.7% of proportional learning gain scores were over 3 SD away from the median), keeping the data of 183 participants for further analysis.

GENERAL RESULTS

The reliability of the questionnaires was assessed by computing Cronbach's α for interrater reliability. The reliability was at an acceptable level, with Cronbach's α of around 0.6 or higher (dispositional compassion α = 0.56, dispositional awe α = 0.70, overview effect α = 0.66). The results showed a successful manipulation of awe and the overview effect using the VR simulation. Both the average awe score $M = 4.49$ (SD = 0.72) on a five-point scale, $t(178) = 27.48$, $p < 0.001$, and the overview effect score $M = 3.58$ (SD = 0.55) on a five-point scale, $t(179) = 14.27$, $p < 0.001$, were significantly different from neutral (three on the five-point scale), demonstrating higher scores for the manipulation than for the neutral condition.

A regression analysis showed a trend in learning gains partially accounting for the overview effect, $F(1,145) = 3.65$, $p = 0.058$, $R^2 = 0.03$. This trend can be explained by individual differences. When a median split was conducted on the pre-test scores, children scoring lower on their pre-test as determined by this split demonstrated learning gains, $F(1,93) = 9.10$, $p = 0.003$, $R^2 = 0.09$, whereas children who scored high on their pre-test did not.

Head gaze showed a correlation between scores on the overview effect questionnaire and the average angle of gazing at Earth from space, $r = -0.16$, $p = 0.031$. This is in line with our prediction that a smaller angle of gaze, thus a more focused look toward the Earth, leads to a higher overview effect score. Additionally, angle was significantly correlated with gender, $r = -0.18$, $p = 0.018$. The difference between girls (angle: $M = 16.73$, SD = 5.50), and boys (angle: $M = 18.46$, SD = 5.45) was significant, $t(173) = 2.08$, $p = 0.039$.

Structural Equation Model

Our self-report data were combined in the hypothesized model that can be found in **Figure 2A**. The hypothesized model did not have an acceptable fit [comparative fit index (CFI) = 0.80, Tucker–Lewis index (TLI) = 0.60, root mean square error of approximation (RMSEA) = 0.09]. We therefore iteratively removed the non-significant paths, based on the greatest misfit, until a proper model fit was reached. The final simplified model for self-report data reached an acceptable fit (CFI = 0.96, TLI = 0.89, RMSEA = 0.06). We added gaze direction to the model as a predictor for the overview effect. This model, seen in **Figure 2B**, reached an acceptable fit (CFI = 0.96, TLI = 0.90, RMSEA = 0.05) (for model estimates, see **Table 2**).

TABLE 1 | Correlations for items that are included in the structural equation model.

Observed variable	1	2	3	4	5	6	7	8	9
1. Immersive tendencies	1								
2. Presence	0.10	1							
3. Dispositional awe	0.21**	0.18*	1						
4. Dispositional compassion	0.06	0.15*	0.37**	1					
5. Overview effect	0.11	0.27**	0.58**	0.39**	1				
6. Gender	−0.02	0.11	0.15	0.15	0.19*	1			
7. Age	−0.01	−0.05	−0.08	−0.05	−0.24**	−0.11	1		
8. Learning gains	−0.24**	0.02	0.11	−0.07	0.16	−0.09	0.10	1	
9. Gaze direction angle	0.16*	−0.12	−0.02	−0.09	−0.16*	−0.18*	0.11	−0.10	1

Double asterisks indicate a significant correlation at the 0.01 level (two-tailed), and a single asterisk indicates a significant correlation at the 0.05 level (two-tailed).

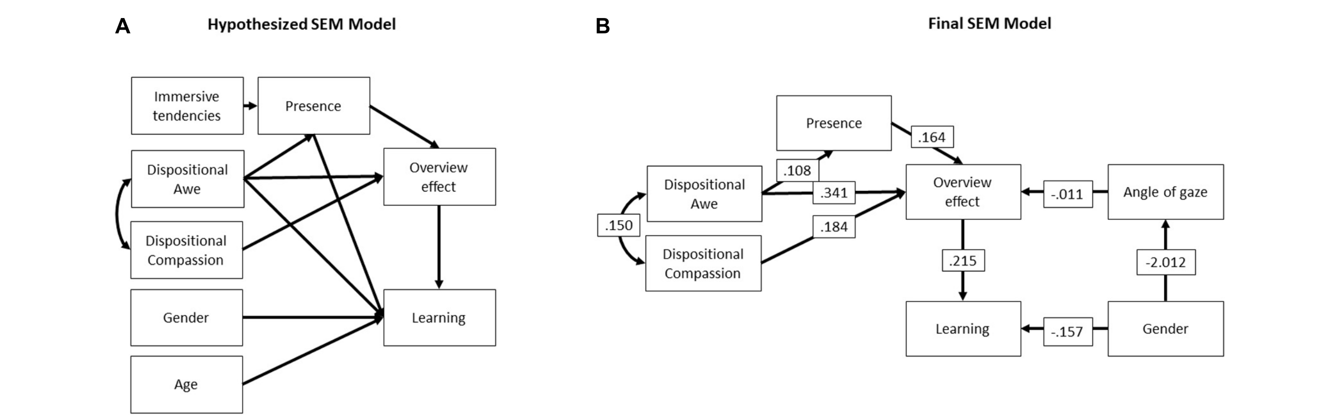

FIGURE 2 | (A) Hypothesized structural equation model (SEM). **(B)** Final structural equation model.

Immersive tendencies did not have a significant effect on presence and were removed from the self-report model. Presence did not have an effect on learning either, and this link was also removed. Presence did, however, have an effect on the overview effect questionnaire score and stayed in the final model (β = 0.16, p = .018), in line with our expectations.

The dispositional awe and the dispositional compassion questionnaire scores were correlated, as expected (β = 0.15, $p < 0.001$). Dispositional awe influenced how present someone felt (β = 0.11, p = 0.017) and it was a strong predictor of the overview effect (β = 0.34, $p < 0.001$); it did not directly influence proportional learning gains. Dispositional compassion was another predictor for the overview effect (β = 0.18, p = 0.005).

Age did not have an effect on learning and was removed from the model. Gender remained in the model despite not having a significant effect because an acceptable model fit was reached. It did, however, have a very strong effect on the angle of gaze. The effect of gender on learning was negative, which means that it was stronger for boys (β = −0.16, p = 0.148). However, girls were the ones with smaller gaze angles (β = −2.01, p = 0.014), so they focused more on the center of the Earth rather than looking further away or around.

The overview effect had a significant effect on proportional learning gains (β = 0.22, p = 0.030). This shows that the overview effect, which is strongly correlated with awe, yields learning. The overview effect can also be predicted by the angle of gaze; although the effect is small, it is significant (β = −0.01, p = 0.047).

In sum, these results show that the overview effect can be predicted by dispositional awe and dispositional compassion, the feeling of presence, and the mean angle of gaze when the Earth first comes into view in VR.

TABLE 2 | Final model estimates for the structural equation model.

	β	SE	p
Dispositional awe → presence	0.11	0.05	0.017
Presence → overview effect	0.16	0.07	0.018
Dispositional awe → overview effect	0.34	0.05	< 0.001
Dispositional compassion → overview effect	0.18	0.07	0.005
Gender → gaze angle	−20.01	0.82	0.014
Gaze angle → overview effect	−0.01	0.01	0.047
Overview → proportional learning gains	0.22	0.10	0.031
Gender → proportional learning gains	−0.16	0.11	0.148
Dispositional compassion ←→ dispositional awe	0.15	0.03	< 0.001

GENERAL DISCUSSION

The primary goal of this study was to investigate whether we could create the overview effect by letting children experience a virtual space flight. We measured the recreation of the overview effect with questionnaires related to commonly associated concepts, namely, a rating of the child's awe and compassion and questionnaires related to virtual experiences, in particular, and presence. Furthermore, we measured the effectiveness of a virtual space experience for educational purposes, with a knowledge test that was embedded within a full educational program on space, of which the VR space flight was one component. Our results showed a successful manipulation of both awe and the overview effect. We found that children with lower prior knowledge learned from the overview effect that resulted from experiencing space in VR. Additionally, the feeling of presence in VR had an effect on the overview effect questionnaire score. Children's gaze pattern in VR was also significantly correlated with the overview effect questionnaire score. A SEM represented how the afore-mentioned constructs interact.

In this study, a new simulation for viewing Earth from space was used, embedded in an educational program that replicates an astronaut's journey to space. The SpaceBuzz simulation proved to be effective in inducing both awe and the overview effect and thus adheres to the recommendations made by Stepanova et al. (2019a). It opens doors to use this simulation for future research on the same topic, and it confirms that the visuals were sufficiently vast and beautiful and the audio was sufficiently supportive to create a feeling of awe in the participants. Within the simulation, a personal connection is made by focusing briefly on the participants' own country, which supposedly adds to the effect (Stepanova et al., 2019b). Even though Stepanova et al. (2019a) advised that Earth-gazing is done from three different perspectives, the two that were used (from the spacecraft and from the moon, respectively) were sufficient. Future research with this simulation can determine which aspects are most important for the induction of awe and the overview effect, giving more insight into the phenomenon.

The measurement of emotions after the VR experience included a manipulation check for the feeling of awe, similar to Piff et al. (2015) and Rudd et al. (2012). However, for more accurate measurements that would ensure that children did not already feel awed by the anticipation of entering the SpaceBuzz rocketship, in future studies, emotions before the VR experience should be monitored as well. Another way to measure awe more accurately is to employ a more substantial scale such as the AWE-S scale (Yaden et al., 2018), administered in a child-friendly way.

Our results suggest that dispositional awe has an indirect effect on learning, *via* the overview effect. Previous research shows how a disposition to feel awed increases the tendency for awe and thus the openness to learn from these vast stimuli (Shiota et al., 2007b; Valdesolo et al., 2017; Gottlieb et al., 2018). One can argue that a direct effect from dispositional awe to learning would be intuitive; however, the disposition to feel awed does not give the certainty that a participant actually feels awe in every situation. Further research may show the precise link between awe, as part of the overview effect, learning, and dispositional awe, alongside other individual differences.

In line with our expectations, the feeling of presence was correlated with and had an effect on the overview effect score in our data. Unlike Alhalabi (2016) and de Back et al. (2018), but like Parong and Mayer (2018), the presence score did not directly influence learning. One can argue that a higher feeling of presence—which did influence the overview effect score, which in turn influenced learning—is an indirect effect of presence on learning. However, with the presence and immersive tendencies questionnaires having low reliability, these results do not shed much light on issues regarding the link between VR, immersive tendencies, presence, and learning.

So far, the more commonly used physiological measures for awe and the overview effect are goosebumps (Schurtz et al., 2012; Neidlinger et al., 2017; Quesnel and Riecke, 2018), brain activity, heart interbeat intervals, skin conductance, and respiration rate (Gallagher et al., 2014; Chirico et al., 2017). The current study adds gaze patterns to this list, also suggested by Stepanova et al. (2019a), which had a small yet significant effect on overview effect scores. A significant link between gender and the angle of gaze that we see in the correlations is expected as females tend to show more explorative gaze patterns compared to males (Sargezeh et al., 2019). In further research, we can combine the afore-mentioned methods and investigate which, or which combination, would be the best predictors of awe and wonder.

This study was conducted with children participants, and because of their lower attention span and different capabilities for answering questionnaires than adults, the questionnaires were reduced and simplified (van Kesteren et al., 2003). The reliability of the new questionnaires was acceptable in the pre-test that we conducted but low for some questionnaires in the actual study. Despite it being relatively common for ecologically valid studies with diverse participants to produce weak effects of experimental variables, the low reliability of our questionnaires could have been the cause of our low significance levels. Reliability and questionnaire length are a trade-off. Previous research showed a wide variety of questionnaire length and duration (Koskelainen et al., 2000; Mikropoulos and Strouboulis, 2004; Wöber-Bingöl et al., 2014; Barry et al., 2015). For future reference, an improved overview effect questionnaire that would be highly reliable, yet manageable in length, understandable, and clear for children may increase the reliability of the study and could also improve the significance of the overall results.

The findings of this study add to existing research on awe and the overview effect and show insights gained from a large number of children participants, embedded in an educational program. Both the connection between the overview effect and study performance and the link between the overview effect and gaze data open doors for both future research on these topics as well as using immersive VR experiences in educational programs (Louwerse et al., 2020), thereby creating young ambassadors of planet Earth.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because they contain sensitive data of minors. Requests to access these datasets should be directed to ML (mlouwerse@uvt.nl).

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethical Review Board of Tilburg School of Humanities and Digital Sciences, Tilburg University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

All authors contributed to the conception and design of the study, performed data gathering and statistical analysis, contributed to the manuscript and read and approved the submitted version. ML and MP received project funding.

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The Creative Brain Under Stress: Considerations for Performance in Extreme Environments

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Over the last 2 decades, we have begun to gain traction on the neural systems that support creative cognition. Specifically, a converging body of evidence from various domains has demonstrated that creativity arises from the interaction of two large-scale systems in the brain: Whereas the default network (DN) is involved in internally-oriented generation of novel concepts, the executive control network (ECN) exerts top-down control over that generative process to select task-appropriate output. In addition, the salience network (SN) regulates switching between those networks in the course of creative cognition. In contrast, we know much less about the workings of these large-scale systems in support of creativity under extreme conditions, although that is beginning to change. Specifically, there is growing evidence from systems neuroscience to demonstrate that the functioning and connectivity of DN, ECN, and SN are influenced by stress – findings that can be used to improve our understanding of the behavioral effects of stress on creativity. Toward that end, we review findings from the neuroscience of creativity, behavioral research on the impact of stress on creativity, and the systems-level view of the brain under stress to suggest ways in which creativity might be affected under extreme conditions. Although our focus is largely on acute stress, we also touch on the possible impact of chronic stress on creative cognition.

Keywords: creativity, stress, performance, environmental psychology, brain networks

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INTRODUCTION

Human beings not only work under optimal conditions, but also under stressful conditions that require physical and psychological resilience for survival, performance, and growth (Suedfeld and Steel, 2000). There is indeed a large scientific literature on the impact of stress on psychological and physiological functioning, but it is only recently that this work has begun to focus on the impact of stress on large-scale networks in the brain, including their functional connectivity (Hermans et al., 2014; van Oort et al., 2017; see also Menon, 2011). The overarching aim of this manuscript is to review this nascent literature in an effort to improve our understanding of the impact of extreme environments – specifically those that cause stress – on creativity. This is made possible by virtue of the fact that the three large-scale networks in the brain that are impacted by stress are also precisely the ones that have begun to shape our understanding of the emergence of creative ideas in the neuroscience of creativity (Beaty et al., 2016).

Toward that end, we will begin by reviewing our current understanding of the neuroscience of creativity, before moving to a discussion of the impact of stress on the functioning and connectivity of large-scale networks in the brain. In the process, we will selectively review the behavioral literature on the impact of stress on creativity. We hope that this exercise will improve our understanding of the behavioral effects of stress on creativity, by revealing the key neural systems and their interactions that could mediate that link.

NEUROSCIENCE OF CREATIVITY: A BRIEF HISTORICAL TOUR

Although electrophysiological studies of the neurological bases of creativity can be traced back to Martindale's pioneering research five decades ago (e.g., Martindale and Hines, 1975), it was with the advent of modern neuroimaging techniques around the turn of the century that our understanding of the neuroscience of creativity has blossomed (for reviews, see Vartanian et al., 2013; Abraham, 2018; Jung and Vartanian, 2018). Much of the early exploratory work in this area was motivated by brain mapping approaches, and typically focused on discovering single, isolated brain regions that might underlie the generation of novel and useful thoughts. The tasks varied widely, including creative story generation, open-ended problem solving, drawing, divergent thinking, finding pragmatic links between incoherent sentences, and analogy and metaphor, to name a few. In addition, there was equal if not more variability in the neuroimaging methodologies used to study the brain, each of which was characterized by its own intricate analytic workflow, signal-to-noise ratio, and temporal and spatial resolution. As such, the early results were characterized by high levels of variability and inconsistency (for reviews, see Arden et al., 2010; Dietrich and Kanso, 2010).

Soon, however, a number of quantitative meta-analyses of this literature followed, which demonstrated an altogether different picture of the creative brain at work (Vartanian, 2012; Gonen-Yaacovi et al., 2013; Boccia et al., 2015; Wu et al., 2015; see also Cogdell-Brooke et al., 2020). These meta-analyses illustrated two points: First, there is no single brain region that drives creativity. Rather, the entire brain contributes to creative cognition. Second, and critically, the neural correlates of creativity are process-specific and domain-specific. For example, there are dissociable neural regions that contribute to creativity in the verbal vs. non-verbal (spatial) vs. musical domains (Gonen-Yaacovi et al., 2013; Boccia et al., 2015). Similarly, there are dissociable neural regions that contribute to processes related to creativity such as analogy vs. metaphor (Vartanian, 2012), as well as creativity tasks that involve generation vs. combination of ideas (Gonen-Yaacovi et al., 2013). As is the case with other higher-order constructs such as reasoning (Goel, 2007; Prado et al., 2011), this early body of work demonstrated that creativity is hierarchical and componential, and emerges from the flexible and dynamic reconfiguration of brain regions that contribute to its various instantiations. This picture is consistent with componential models of creativity (Amabile, 2012) and problem solving (Sternberg, 1980), according to which higher-order cognitive abilities are decomposable into specific sub-processes (e.g., semantic memory, attention, etc.). As such, brain regions that exhibit a degree of functional specificity in relation to those sub-processes contribute to the types of creativity that draw on those functions.

NEUROSCIENCE OF CREATIVITY: FROM REGIONS TO NETWORKS

A significant shift in the neuroscience of creativity occurred when researchers began to focus on the contribution of large-scale networks rather than isolated brain regions to the emergence of creative thoughts. Those networks were initially discovered using the technique of resting-state connectivity, based on which one can identify brain regions that exhibit similar patterns of fMRI activity fluctuations, and can therefore be grouped into large-scale brain systems called "networks" (Zabelina and Andrews-Hanna, 2016). In other words, at any given time, regions within the same network (e.g., visual, language, somatomotor, etc.) are likely to exhibit correlated activity when the individual is engaged in a task or at rest (i.e., not engaged in a task). It is important to note that the seven large-scale networks that have been identified to date also exhibit differing patterns of between-network connectivity (Lee et al., 2012). These patterns of between-network connectivity can be conceptualized better when we consider that, despite their functional differences, some networks can work together to support the same type of cognition. For example, when the individual is engaged in externally-oriented cognition (i.e., responding to stimuli in the external world), the visual, somatomotor, and dorsal attention networks show high levels of between-network connectivity (Yeo et al., 2011; Buckner et al., 2013). This makes sense, given that in many circumstances such externally-oriented cognition requires one to attend to and process sensory input.

Important for creativity researchers, a growing body of evidence has emerged to demonstrate that novel ideas emerge as a function of the dynamic interaction of the default network (DN) and the executive control network (ECN) in the brain (Beaty et al., 2016). Regions within DN are more active during task-unrelated thought than during task-related thought, and frequently come online during episodes of mind wandering, daydreaming, and imagination (Christoff et al., 2016; Raffaelli et al., 2020). In contrast, ECN is activated when the individual is engaged in tasks that require cognitive control. In most instances, DN and ECN activities are negatively correlated because individuals tend to be engaged in either task-related thought that necessitates cognitive control or task-unrelated thought that is not under top-down regulation. What is remarkable about creativity is that it represents a form of thinking that is supported by the dynamic interaction of these two modes of thought. Specifically, in the early phase of creative problem solving, when internally-oriented thoughts support idea generation, DN is relatively more active. In turn, in the later phases of creative problem solving, when the generated ideas are pruned to satisfy task demands, ECN is also engaged to exert top-down control to select appropriate output. Interestingly, aside from supporting goal-directed memory retrieval and inhibition of prepotent responses that represent some of its core functions, ECN may also facilitate internal orientation by shifting attention away from sensory input toward internally-generated thought processes carried out by DN (Benedek et al., 2016; Beaty et al., 2019; **Figure 1**).

An important early study that laid the groundwork for this interactive model was conducted by Ellamil et al. (2012), who presented design students with short verbal descriptions of the contents of books while in the fMRI scanner, and then instructed them to design book covers to represent them. In the generation phase, the participants drew and/or wrote down their ideas using an MRI-compatible tablet, whereas in the evaluation phase, they assessed the quality of their ideas and productions. During generation there was greater activation in DN, specifically the hippocampus. This is consistent with the constructive episodic simulation hypothesis, according to which memory and imagination involve flexible recombination of episodic details (e.g., people, places, and events; Schacter and Addis, 2007; Beaty, 2020). In other words, as we generate new ideas using imagination, it is likely that we mine our episodic memory to locate and flexibly recombine episodic details to support novel ideation. In turn, during evaluation not only was there activation in DN, but also additional activation in ECN, most notably in the dorsolateral prefrontal cortex that plays an important role in cognitive control.

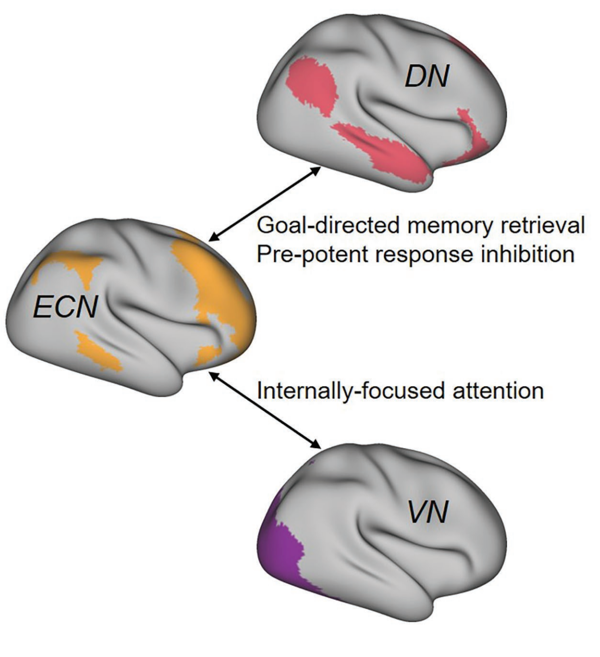

FIGURE 1 | Cognitive mechanisms of brain network interactions during creative cognition. DN, default-mode network; ECN, executive control network; VN, visual network. Adapted with permission from Beaty et al. (2019).

Additional analysis demonstrated that there was greater functional connectivity between DN and ECN during the evaluation phase, suggesting that there is close communication between those networks in the later stages of creative thinking when cognitive control is applied on the contents of generated ideas for their evaluation. Since then, data from several studies including musical improvisation (Pinho et al., 2016) and poetry composition (Liu et al., 2015) have also shown dynamic coupling between DN and ECN – interpreted to reflect the spontaneous generation of ideas derived from long-term memory and the evaluation of those ideas to meet specific task goals, respectively. Using dynamic causal modeling, Vartanian et al. (2018) have recently shown that ECN exerts unidirectional control over the activation of DN regions in the course of divergent thinking, supporting the causal model that underlies their interaction.

Beaty et al. (2015) used whole-brain functional connectivity analysis to highlight a network of brain regions associated with divergent thinking. This study was important because beyond DN and ECN, it also focused on the salience network (SN). SN has an important role to play in many types of higher-order cognition because it is involved in the detection and allocation of attention and neural resources to behaviorally relevant (i.e., salient) stimuli (Bressler and Menon, 2010; Menon and Uddin, 2010; Uddin, 2015). In this role, it can trigger the engagement of other networks based on their relevance to the task at hand. Analyses of Beaty et al. (2015) revealed that the posterior cingulate cortex (PCC) – a region that lies within the DN – exhibits increased functional coupling with ECN regions including the dorsolateral prefrontal cortex, as well as regions within SN such as the bilateral insula. Then, using dynamic functional connectivity analysis conducted in the course of engagement with the Alternate Uses Task, Beaty et al. (2015) demonstrated that the time-course of the coupling between the PCC and regions within SN and ECN varies as a function of the phase of the task. Specifically, the PCC showed early coupling with the insula and later coupling with the dorsolateral prefrontal cortex. There is evidence to show that one of the roles of SN is to facilitate switches between DN and ECN (Cocchi et al., 2013). As such, its involvement in divergent thinking could be to facilitate later coupling between DN and ECN.

Building on this work, Beaty et al. (2018) used connectome-based predictive modeling (CPM) – a machine learning algorithm for identifying functional connections in the brain that predict behavioral traits – to demonstrate that creative people are characterized by stronger functional connections between DN, ECN, and SN, and that this specific pattern of connectivity predicted their creativity scores. Interestingly, this dynamic interplay between DN and ECN has also been shown to be the case based on resting-state data, when people are not engaged in a task. Specifically, Beaty et al. (2014) reported that compared to less creative people, more creative people exhibit stronger DN-ECN coupling during rest, suggesting that at a fundamental neurological level more and less creative people may be distinguished by stable functional differences involving the coupling of key regions involved in creative cognition.

STRESS AND CREATIVITY: BEHAVIORAL EFFECTS

It is generally assumed that stress has a detrimental effect on creativity. This assumption is not unreasonable: given that in the immediate aftermath of stress, physiological, and cognitive resources are reallocated to promote vigilance and survival (Hermans et al., 2014), it is likely that higher-order cognitive capacities that would otherwise support creative cognition would be shifted to meet those more urgent needs. Indeed, it has been demonstrated that stress has a negative impact on processes related to creativity, including task switching and cognitive flexibility (Steinhauser et al., 2007; Plessow et al., 2011, 2012). However, the impact of stress on creativity is not necessarily and universally negative, and depends in part on how stress-inducing the stressor is perceived to be, and the type of stress that is induced. For example, Byron et al.'s (2010) meta-analysis of 76 experimental studies that had examined the impact of stress on creativity demonstrated that uncontrollable stress leads to worse performance on creativity tasks, where uncontrollability was defined as the extent to which an individual believes that one's actions can affect outcomes (Dickerson and Kemeny, 2004). In addition, they found that whereas high social-evaluative threats decreased creative performance, low social-evaluative contexts increased creative performance, where social-evaluative threats were considered to "occur when an aspect of self is or [can] be negatively judged by others" (Dickerson and Kemeny, 2004, p. 361). Thus, it appears that stress impacts creativity, but not necessarily in negative ways. Importantly, the findings are broadly consistent with appraisal models of stress (e.g., Lazarus and Folkman, 1984), according to which one's perception of the stress and individual differences that underlie vulnerabilities to those stressors are important factors that influence the stress-creativity relationship.

THE BRAIN UNDER STRESS: A NETWORK VIEW

At this point, we will consider how our knowledge of the workings of the brain can shed light on the impact of stress on creativity. Until recently this would have been difficult to do because with the exception of a few studies (e.g., Vartanian et al., 2014), we know very little about how the functioning of the creative brain is affected by various stressors. Fortuitously, however, we are now in a position to consider this question because a growing body of evidence from systems neuroscience has demonstrated that the three systems that support the emergence of creative thought under normal conditions are precisely the three systems whose functioning and connectivity is impacted by stress (for reviews, see Hermans et al., 2014; van Oort et al., 2017; see also Menon, 2011; **Figure 2**). As such, this offers one the opportunity to consider the ways in which the altered functioning and connectivity of SN, DN, and ECN can explain the impact of stress on creativity.

Following exposure to stress, a cascading series of physiological changes is triggered that ultimately impact neuronal function in temporally- and spatially-specific ways (Joëls, 2018). At the neuroendocrine level, central levels of catecholamines in the brain (e.g., norepinephrine and dopamine) increase rapidly and normalize shortly thereafter, whereas corticosteroid levels in the brain rise more slowly and remain high for a longer period of time (Hermans et al., 2014). The rapid rise in the level of catecholamines in the brain is associated with an increase in SN activity, and a decrease in ECN activity (Hermans et al., 2014; van Oort et al., 2017). Hermans et al. (2014) have argued that this represents a reallocation of resources to SN, a network that underlies orienting attention toward salient information in the environment (Menon, 2011). There is also a strengthening of the functional connectivity between SN and sensory cortices as the organism attends to sensory input (Li et al., 2014). Psychologically, this represents a hypervigilant state geared toward maximizing the likelihood of survival in the immediate aftermath of stress. This reallocation of resources comes at the cost of ECN, where activation diminishes or remains the same. Interestingly, and perhaps counterintuitively, there is an increase in DN activity immediately following exposure to stress. One reason might be that stress can lead to increased negative self-referential processing, which is known to engage the DN. Indeed, high social-evaluative threats are known to decrease creative performance (Byron et al., 2010). In addition, increased activity in the anterior sector of DN might be due to attempts to regulate emotion, another process that engages DN. Acute stress also brings about increased SN-DN functional connectivity, which may play an important role in memory consolidation given the association between SN and regions within DN that encode episodic memory such as the hippocampus (van Oort et al., 2017). After the stress has subsided, the allocation of resources to SN and ECN reverses, thereby restoring higher-order cognitive functions that are necessary for linking stressful events to the specific context, and to encode this information for future retrieval (Hermans et al., 2014; Joëls, 2018).

What does this mean for the creative brain under stress? Under normal circumstances, DN activity dominates in the early phase of creative problem solving. This is in stark contrast to what occurs in the acute response to stress where SN and sensory cortex activities increase (van Marle et al., 2010), as does their functional connectivity (Li et al., 2014). Furthermore, ECN activity decreases in the immediate aftermath of stress, and may not be prioritized in relation to SN activity until 1 h after the onset of stress (Hermans et al., 2014). Because creative cognition necessitates a dynamic interaction between DN and ECN, the downregulation of the latter will in all likelihood adversely impact the emergence of creative output (see Vartanian et al., 2018). In summary, despite the fact that DN activity increases in the immediate aftermath of stress, the reallocation of resources away from ECN to SN, as well as the increased functional connectivity between SN and sensory cortices for prioritizing attention to salient stimuli may well hamper the neural dynamics that support the emergence of creative thought.

ACUTE VS. CHRONIC STRESS

In this paper, our focus has been on the impact of acute stress on the functioning of large-scale brain networks, with possible downstream impact on creative cognition.

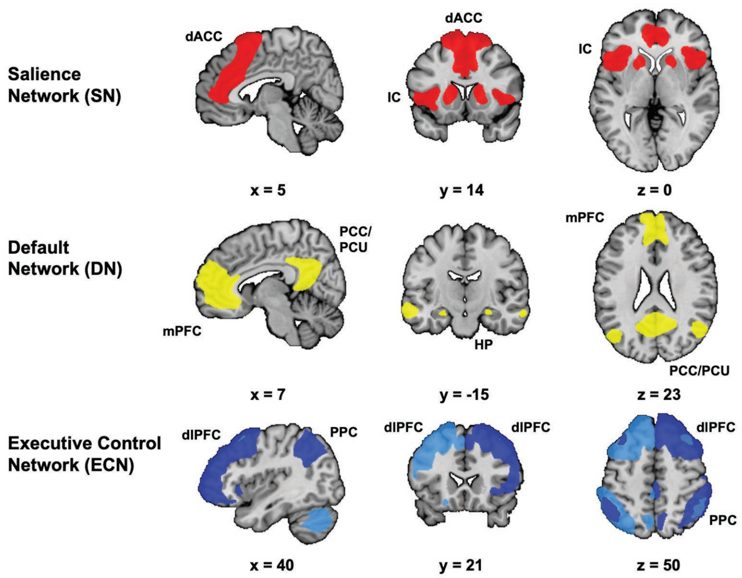

FIGURE 2 | Major functional connectivity networks in the acute stress response. This figure is a schematic representation of the major functional connectivity networks relevant for the brain's stress response. The core regions of the salience network (SN) are the insular cortex (IC), dorsal anterior cingulate cortex (dorsal ACC), temporal pole, and amygdala. The DN comprises the medial prefrontal cortex (mPFC), the posterior cingulate cortex/precuneus (PCC/PCu), and the inferior parietal lobule. The parahippocampal gyrus and hippocampus (HP) are strongly related to the DN. The ECN is centered on the dorsolateral prefrontal cortex (dlPFC) and posterior parietal cortex (PPC), and also includes part of the dorsomedial prefrontal cortex and frontal eyefields. Adapted with permission from van Oort et al. (2017).

In other words, we have attempted to paint a picture of brain function in support of creative cognition in cases where a person encounters an extreme, stressful environment. However, quite aside from such acute forms of stress, one can also envision a host of chronic stressors that can negatively impact cognitive function, including creativity. Danese and McEwen (2012) reviewed the large literature on adverse childhood experiences, and demonstrated that such forms of chronic stress can have enduring impacts on the nervous, endocrine, and immune systems. Such long-lasting physiological changes (i.e., biological embedding) are perceived to represent the body's allostatic response to chronic stress (Sterling, 1988). For example, adults with a history of childhood trauma exhibit smaller prefrontal cortex and hippocampal volume, with associated deficits in declarative memory. Given the important role that the semantic system is known to play in divergent thinking (see Beaty and Schacter, 2018; Kenett, 2018), it is plausible that such chronic forms of stress that have a deleterious impact on the nervous system may also negatively impact creative cognition.

Indeed, the functioning of the three large-scale networks that have been the focus of our discussion here are known to be affected by a wide host of psychiatric and neurological disorders that have long-lasting effects on brain structure and function. Review by Menon (2011) of the network neuroscience literature demonstrated that functional disruptions in the ECN as well as abnormalities in the intrinsic functional connectivity within the DN and SN are associated with virtually every major psychiatric and neurological disorder, including anxiety disorders, mood disorders, and schizophrenia, among others. Synthesizing this literature in his *Triple network model of psychopathology*, Menon (2011) argued that deficits in access, engagement, and disengagement of large-scale neural networks are a defining feature of psychopathology. To the extent that various psychiatric and neurological disorders can be viewed as chronic forms of stress, this body of research suggests a close correspondence between the neurological markers of acute and chronic stress at the network level, and suggests that a complete representation of the impact of stress on higher cognition including creativity requires an understanding of both its acute and chronic effects.

CONCLUSION

Creative cognition has been shown to be supported by the dynamic interaction of DN, ECN, and SN. Furthermore, during divergent thinking, attention to sensory input is attenuated, and instead shifted to internally-generated thought. In contrast, in the acute response to stress (i.e., <1 h after the onset of stress) SN activity increases, whereas ECN activity decreases. There is also increased functional connectivity between SN and sensory cortices, as attention is directed to salient stimuli to maximize chances of survival. Although there is an increase in DN activity and DN-SN functional connectivity, this is likely related to self-referential cognition and emotion regulation rather than thought processes related to creativity. This pattern can help explain why under certain circumstances creativity is impacted negatively by stress, and points to network neuroscience as a useful avenue of research for studying the functioning of the creative brain under acute and chronic stress.

AUTHOR CONTRIBUTIONS

OV and PS wrote the manuscript. SS and NH conducted literature searches and edited the manuscript. All authors contributed to the article and approved the submitted version.

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OPINION
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Exploring Similarities Across the Space and Theater Industries

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INTRODUCTION

"The earth is a very small stage in a vast cosmic arena" (Sagan and Druyan, 1997, p. 6).

This paper explores similarities across the space and theater industries. Both of these fields, for example, require people of the highest proficiencies to serve as the face of their project (i.e., astronauts and actors) while a mostly-unseen technical team supports the larger goal (i.e., mission control and backstage crews). We discuss a non-exhaustive list of domain-general factors (Plucker, 1998) while providing examples of domain-specific characteristics (Baer, 1998) encompassed within the expertise of astronauts and professional actors. While these domain-general factors may also be transferable across fields not covered here, we spotlight the space and theater industries as an illustrative example to further the call by research psychologists (e.g., de Vries, 2019) to investigate gaps within the literature of creativity in extreme environments.

CREATIVE PROBLEM SOLVING

Solving problems on the job and in daily life requires creativity. When people need to solve work-related problems for which there is no precedence or pre-established procedure to follow, the creative employees are able to generate new and useful solutions. Creative problem solving can help societies cope with significant challenges in their environments (Sternberg and Lubart, 1996). Space and theater professionals are adept in creative problem solving to manage unplanned incidences successfully. As actors familiarize themselves with the intricacies of a script, astronauts learn the proper protocols to follow while working and experimenting in space modules. Although both astronauts and actors train for their performances for many months and years before their launch (Kanas, 2015), the ability to creatively resolve unexpected issues is beneficial to both domains.

Astronauts require a deep understanding of technical protocols to work with the equipment on which they rely. Nevertheless, Russian space psychologists recommend that creative abilities be considered one of the top traits when selecting and preparing future space travelers (Stepanova et al., 2003). Astronauts train in unscripted scenarios that test their ability to react to the unknown and they implement this knowledge in real missions (Kanas and Manzey, 2008). One example of an unpredictable problem solved successfully was illustrated during the 1966 Gemini VIII mission. Astronauts Neil Armstrong and David Scott were the first to link two spacecraft together in Earth orbit. Once they docked with the separately launched Agena, the two spacecraft began to spin quickly in the wrong direction. In an attempt to regain control, Scott switched the Agena off and on, which did not fix the problem. The astronauts therefore disengaged from the Agena, but the Gemini VIII continued to spin, which could have led to the astronauts losing consciousness. Before that happened, however, Armstrong regained control of the Gemini VIII by turning off the entire system and using the re-entry control system thrusters to stop the spin (Granath, 2016). Although this was not the kind of problem for which the crew had specific training or established procedure to follow, they were able to find a novel and useful solution to the life-threatening situation.

Actors learn to memorize huge amounts of text in short periods and recite it with spontaneity (Noice and Noice, 2006), but they also train to improvise their lines during misfiring props and mistimed cues that would otherwise threaten to ruin the illusion of the show (Gardner, 2013). The second author of this piece, who was an actor before becoming a research psychologist, offers a humorous personal anecdote of such an occurrence. In a run of a whodunit play, she portrayed the eccentric owner of an estate in which multiple murders were committed. During one night's performance, in the scene where she is to discover the murderer hiding in a secret passageway by sliding a bookcase panel (pulled open by a hidden crew member), the actor playing the murderer was distracted backstage and missed his cue. She was left momentarily standing alone in the middle of the stage with her arms open wide in the direction of the newly revealed opening to the secret passageway, pointing at nobody, while the audience waited. Without conscious awareness, she improvised the line, "I must be drinking too much again," which fit perfectly with her character and situation, and was followed by raucous laughter from the audience. The collaboration between the swiftness of those backstage and the ability of actors to not panic can result in novel and useful solutions to prevent possible theatrical disasters because, as the phrase says, "The show must go on."

PERSONALITY TRAITS AND SOCIAL SKILLS

Researchers have identified specific skills, as well as personality traits, associated with high performance in extreme environments, which are similar to those found in actors. The investment theory of creativity states that personality is a resource underlying creativity and that individuality and the willingness to tolerate ambiguity, to overcome obstacles and persevere, to grow (i.e., openness to experience), and to take sensible risks are related to creativity. Numerous studies have also identified intrinsic motivation and self-efficacy as personality attributes important in creative functioning (Sternberg and Lubart, 1991, 1996). Similarly, psychologists suggest that key personality traits for astronauts include strong achievement motivation, resiliency, adaptability, and high emotional stability. Using the "Big 5" personality test, space agencies look for astronaut candidates who score low in neuroticism and high in agreeableness, openness to experience, and conscientiousness (Rose et al., 1994; Kanas and Manzey, 2008; Kanas, 2015; Landon et al., 2018). With this same test, Nettle (2006) found that actors score higher than the general population in extraversion and openness to experience, as well as agreeableness, with a trend toward higher neuroticism. Furthermore, researchers have suggested that actors may be experts in emotion regulation (Ekman et al., 1983; Futterman et al., 1994; Pelletier et al., 2003; Gentzler et al., 2020). Within the framework of creativity theories, there may be opportunities for cross-industry research between the space and theater domains.

Both the astronaut and acting professions require social skills and competencies in communication, public speaking, and public relations. Within the space population, positive "instrumental" and "expressive" traits have been linked to relating well with others. Positive instrumental traits relate to high goal-orientation and need for achievement, whereas positive expressive traits relate to kindness and warmth (McFadden et al., 1994; Kanas and Manzey, 2008). Astronauts, like actors, often become ambassadors of their project, engaging with the public in myriad social events ranging from interviews to presentations. Thus, they require the ability to communicate effectively with a wide variety of audiences. One way to improve communication is by understanding the beliefs, intents, desires, and emotions of others, as well as being able to see through their perspective. Research shows that people with acting training have higher levels of theory of mind (the ability to infer the mental states of others) and empathy than those without this training (Nettle, 2006; Goldstein and Winner, 2010; Goldstein et al., 2013; Panero and Winner, 2020, in press). Therefore, part of the astronaut selection process and training revolves around endorsing specific social skills and personality traits that are often present in actors.

ISOLATION

The skills and traits described above are not only imperative for interacting with audiences, but also within the isolated environments of the space and theater industries. Space missions and theater runs may involve many months in which astronauts and actors are away from their loved ones. Although rotations are common in these fields to help manage these challenges (e.g., backup astronauts and understudies), both careers often require casts and crews be separated from their homes. As we write this article, millions of people are self-isolating or quarantining to keep safe during the COVID-19 world pandemic. The mental health consequences emerging from these prolonged periods of social isolation include anxiety, obsessive-compulsive symptoms, post-traumatic stress, and depression (Pietrabissa and Simpson, 2020). Depression affects one's ability to function effectively at work by reducing the ability to solve problems. Social isolation has also been linked to reduced physical health and cognitive impairments, which would be particularly dangerous in life-threatening situations like the one described above faced by the Gemini VIII crew.

Astronauts must travel away from their families to live near their training facilities and, once the training is complete, eventually venture into outer space, farther away from those nearest to their hearts. Instead, they spend long periods with small work teams participating in activities ranging from high-stakes research experiments to monotonous chores. Space is the ultimate isolated, confined, and extreme environment; spending large amounts of time with people in a confined area may cause psychological changes, including impaired cognitive ability and interpersonal conflict. Awareness of these issues and effective communication may ease such tensions (Gushin et al., 1993; Palinkas and Suedfeld, 2008; Kanas, 2015; Landon et al., 2018; Pietrabissa and Simpson, 2020). Therefore, the National Aeronautics and Space Administration (NASA) provides "space flight resource management" trainings in which astronauts are taught effective crew coordination and team building, as well as strategies and support for psychological issues that may arise during the mission (Rogers et al., 2002; Palinkas and Suedfeld, 2008; Kanas, 2015).

While astronauts in orbit experience a different form of isolation than people on Earth, commonalities have been found between astronauts and people working abroad extensively (e.g., actors), including limited interaction with others and isolation from family and friends (Harris, 2009). Actors and other theater professionals often travel away from their hometown to pursue training or audition opportunities. Once they are cast in a show, they may move to yet another location to endure weeks of grueling daily rehearsals. Then, they may go on tour for an additional few months, performing at night and traveling to different locations during the day. Although research on actors, in particular, is lacking, research on the consequences of social isolation (e.g., Pietrabissa and Simpson, 2020) imply that these kinds of high-performance demands away from familial support may result in feelings of detachment or depression. Cross-industry research on this topic may explore the effects of and countermeasures for such issues that, for example, could inform future commercial spaceflight planned by organizations like SpaceX that recently ferried astronauts from NASA to the International Space Station and is paving the way in accessing missions to the Moon, Mars, and beyond.

PRETEND AND SIMULATED ENVIRONMENTS

Both astronauts and actors hone their skills by pretending to be somewhere else. During rehearsals and performances, stage sets are sometimes intentionally abstract or surprisingly intricate, replete with sliding panels and secret passageways, like those in a typical whodunit. Therefore, actors learn to engage their imagination and encapsulate themselves in the details of their surroundings—from the period and style of the furnishings, to the time of day and the temperature of the air. This allows them to establish a relationship with their scripted environment, which informs their performance. Characters (like people) behave differently when they are in a modern and familiar cozy cottage, for example, than when they are in a 1940s estate with a murderer on the loose. Furthermore, actors create a "fourth wall," an imaginary barrier in the proscenium of the stage separating the actors from the audience, to remain enveloped within the imaginary location and circumstances of the play (Wilson and Goldfarb, 2012).

Astronaut training sites vary largely, but usually include simulations in habitats (facilities designed to simulate the physical and psychological environments of space). Astronauts engage in analog missions, which are Earth-based field activities set in extreme environments, such as Antarctica, that are similar, or analogous, to space (National Aeronautics Space Administration, 2020). While it is difficult to truly replicate space, certain aspects can be mimicked. NASA uses a neutral buoyancy laboratory, for example, that simulates microgravity by placing astronauts underwater as they conduct routine equipment and experiment training (National Aeronautics Space Administration, 2006). Another underwater analog habitat, called NEEMO, simulates emergency scenarios through which to persevere (National Aeronautics Space Administration, 2019). Although analog missions do involve the possibility of harm, should astronauts fail within these simulated environments, rescue crews are readily available. Therefore, during these trainings, astronauts may call on their imaginations to feel the degree of pressure as when in the real dangers of space from which salvation is less possible (Mohanty et al., 2006).

CONCLUSION

This paper listed domain-general factors (Plucker, 1998) of the space and theater industries, including creative problem solving, social skills, personality traits, isolation, and pretend and simulated environments. Within each of these factors, domain-specific characteristics (Baer, 1998) corresponding to the expertise of astronauts and professional actors were explored. There are many more examples that could have been included, such as comparing the role of creativity in cognitive reappraisal for tolerating real or perceived threats within each field (see Kangas Dwyer and Davidson, 2012). Furthermore, the domain-general factors mentioned here (and others not mentioned) may potentially be transferable to other domains. Nevertheless, our hope is that this discussion will spark future cross-industry research on creativity in extreme environments.

AUTHOR CONTRIBUTIONS

KC and MEP collaborated on the outline of the paper, multiple drafts, and final manuscript. Both authors contributed to the article and approved the submitted version.

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The Overview Effect and Creative Performance in Extreme Human Environments

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INTRODUCTION

We tend to think of creativity as a trait that takes someone outside the norms of everyday behavior.

A typical definition of creativity would be:

The use of the imagination or original ideas, especially in the production of an artistic work[1].

Creative performance stands in contrast to, say, routine performance. As a simple example, consider working on an assembly line. The objective is not to dream up a new way to place seats in a car, but rather to place all the seats in the car, in the same way, every time. Saying this does not denigrate the dignity and value of the work; it simply states a fact about the degree of creativity it requires. Moreover, the more routine the job, the more likely it is to be automated.

By comparison, consider a classic example of creativity: painting. If I, as an artist, paint the same scene over and over again, as if I am on an assembly line, very few people would consider me to be "creative." Even more to the point, if I paint a scene that is imitative of another artist's work over and over again, I would not be considered creative. I would be seen as unoriginal at best and a forger at worst.

Our society depends on citizens who are willing to perform routine tasks and those who seek original means of expressing themselves. We could not survive if our genes and our social systems tilted too far in one direction or the other.

This paper considers creative performance in extreme environments, with a focus on astronauts. We begin with creative performance and the environment, then turn to explorers in general, and conclude with astronauts specifically.

CREATIVE PERFORMANCE AND THE ENVIRONMENT

Does the environment make a difference in fostering or inhibiting creative performance? This question is worth asking when we consider its relevance on Earth, but it becomes especially pertinent when examining astronaut performance. Everything an astronaut does takes place in an environment that is radically different from the terrestrial surroundings in which humanity evolved.

Dul makes the point that, in fact, relatively little research has been conducted on the physical environment's impact on creativity, with most studies focusing on the social environment. In a survey of 44 studies, only one considered the physical environment (Dul, 2019). Dul offers a "triple-path theoretical framework" suggesting that the objective physical environment is related to creativity through three perceptual paths: functionality, meaning, and mood (Dul, 2019). This

[1] *Google Dictionary.*

structure offers a helpful beginning that may eventually be relevant to the space environment.

Amabile is well-known for her focus on the social environment and the difference between extrinsic rewards and intrinsic satisfaction in supporting creativity. In the case of astronauts, we see the importance of the social environment as it influences creative performance (Amabile, 2018).

Professional astronauts are unique in this regard because, for the most part, they have been striving for years to achieve the goal of simply becoming an astronaut. In that sense, they do not require any external rewards to be satisfied by what they are doing. At the same time, they are part of a team that has a mission, and they are supported by an even larger group that oversees and evaluates their performance. Therefore, they may represent a population motivated by both internal and external factors.

Ultimately, it must be noted that the space environment is fundamentally different from almost any terrestrial environment. No matter where one goes on Earth, normal gravity is present, as is air that can (usually) be breathed without danger, and harmful radiation is mediated by the Earth's atmosphere and magnetosphere.

In space, astronauts live in a weightless world, the air they breathe is artificially produced by their spaceship or space station, and radiation is a constant concern. They are literally risking their lives throughout their missions.

There are, of course, extreme environments on Earth, both natural and artificial. The summit of Mount Everest is a place where very few climbers can go without taking oxygen with them. Scott Parazynski, the only person who has both been in outer space and summited Everest, told me that he was more concerned for his safety on the mountain than while in orbit[2]. He said that was because large teams of people support astronauts when they are on the International Space Station, and its interior is a shirt-sleeve environment. When a climber is on Everest, however, the support teams are much smaller and the mountain seems much closer and more threatening.

THE SOCIETAL ROLE OF EXPLORERS

Examining the historical record suggests that human beings have always been explorers, or at least, that a significant portion of the species has been. This means that they seek out environments where creativity is required of them. While family and friends may remain home, where daily events are relatively predictable, explorers, by definition, do not know what they might face as they move deeper into uncharted territory.

Returning to our definition, this requires "using imagination or original ideas..." If you are Sir Ernest Shackleton and your Antarctic expedition's ship becomes frozen, then crushed, in pack ice that stretches as far as the eye can see, your original plan for the journey has to be thrown out and you have to think in new ways about what to do next. In other words, you need to resort to your imagination for original ideas to survive. The story of Shackleton's response to this potential disaster is too complex to review here, but suffice it to say that he managed to rescue every one of the members of his expedition through his creative and courageous actions.

Fast-forward 100 years from the days of polar expeditions and we find the paragons of modern exploration, the astronauts. They share many common characteristics with their predecessors, but are unique in the annals of exploration because there is no more extreme environment for human beings, indeed for life itself, than outer space. Whether in the deserts of North Africa, the jungles of Southeast Asia, or the glaciers of Antarctica, explorers have air, water, and gravity that support their quests. But human beings cannot survive once they reach a certain altitude above the Earth's surface, where "space" begins. Only through artificial means can astronauts carry out their missions. What does this mean for creative performance? What contributes to creativity in space and what blocks it?

CREATIVE PERFORMANCE THROUGH PREPARATION

In his book, *An Astronaut's Guide to Life on Earth,* Canadian astronaut Chris Hadfield suggests that being an astronaut is a way of life that is not limited to the time spent in outer space. He points out that, because of the extreme environment of space, every moment an astronaut spends there puts his or her life in danger. For that reason, much of an astronaut's time is actually focused on preparation for flight and simulating every possible situation the crew might encounter. While on the International Space Station (ISS), the astronaut is away from family and friends, isolated from the vast majority of human beings and normal life (Hadfield, 2013).

Space travelers cannot simply walk outside for a breath of fresh air when they feel isolated or stressed. They are separated from nature and the healing effects of walking in the woods or hiking in the mountains. Their immediate social contacts are limited to the other crew members and they work very hard during their missions.

What impact might all of these elements have on creative performance?

Let's look first at how astronauts prepare for space missions.

Weighing multiple options in response to unpredictable situations should free the mind up to be more creative. In fact, that is why astronauts simulate so many alternatives: they never know exactly when they might have to improvise with very little time available. And when they do, there is even less time to stop and think about what to do. Seconds count, and the response becomes instant and instinctive, because the stimulus has been seen before in the simulations.

At another level, the underlying awareness of constant danger, coupled with the boredom that accompanies isolation might actually support artistic creativity (Peldszus et al., 2014)[3]. As one example, consider Chris Hadfield's cover of David Bowie's classic, "A Space Oddity." Playing the guitar while floating weightless throughout the International Space Station, Hadfield does a

[2]Interview with Frank White for fourth edition of *The Overview Effect,* to be published in 2021 by Multiverse Publishing.

[3]Hadfield: Available online at: https://www.youtube.com/watch?v=KaOC9danxNo

credible job of creating a watchable music video. Nicole Stott had begun painting before her astronaut career, but has been working almost full-time as an artist since her retirement from NASA[4].

CREATIVE PERFORMANCE AND THE OVERVIEW EFFECT

There is another unique aspect of space exploration (i.e., seeing the Earth and the universe from a vantage point that no human experienced before 1961, when Yuri Gagarin went into orbit). The "Overview Effect" (a term coined by the author) has positive psychological benefits for astronauts, balancing some of the inherent challenges of spaceflight. Astronauts on the ISS enjoy going to the "cupola" and practicing "Earth gazing" during their free time. They say it brings a shift from identifying with parts of the Earth to identifying with all of it. They also emphasize that the Earth is always doing something new, so that the experience never becomes dull or boring. Increasingly, astronauts are describing the Earth as a "living being" (White, 2014).

Experiencing the Overview Effect also seems to bring a sense of calm and tranquility to the viewer, which may offset some of the more stressful aspects of spaceflight. This is a topic that has not been covered in great detail in the literature about spaceflight or the Overview Effect, but it is worthy of consideration. We hear quite a lot about the astronaut workload when they are on missions, including time on the ISS, which is somewhat less pressured than Shuttle flights. However, we know that "downtime" is important for Earthlings and that creative moments often arise when people are relaxing in various ways (National Aeronautics Space Administration, 2019).

While negative incidents in space have rarely been documented, there have been cases of Mission Control attempting to keep astronauts to a tight script and of astronauts rebelling against the limits placed on them. It costs a huge amount of money to put Earthlings into orbit and space agencies naturally want to generate a robust ROI, so the Mission Control intentions are understandable. On a positive note, this attitude has changed with the advent of long-duration ISS missions.

TWO SIDES OF THE SAME COIN

Constantly simulating potential problems and relaxing while floating in zero-G and gazing out at the Earth may seem like polar opposites, but perhaps they are two sides of the same coin.

One of the newest additions to the International Space Station is the cupola, a special viewing area that allows for a 360-degree view of the Earth and the universe while floating gently above the cupola window. We know from their own reports that astronauts spend as much time in this setting as possible and seem drawn to it during their "downtime."

Annahita Nezami, Ph.D., a psychologist who wrote her PhD thesis on the Overview Effect, is a collaborator of mine on several projects. Based on her findings and past research, Nezami states:

Earthgazing can motivate positive psychological growth by the way it diminishes cognitive and emotional stress and cultivates positive emotions such as belonging, connection, gratitude, reverence, awe, and humility (Meier et al., 2020).

Nezami suggests that "Earth gazing has the potential to create inner harmony and help us reconsider societal values, while promoting psychological and societal well-being[5]."

The cupola's history on the International Space Station is worth exploring in terms of its intentions. Some descriptions suggest that it was added for reasons other than Earth gazing, but it seems that astronaut relaxation has become a primary function.

When astronauts talk about their experiences of looking at the Earth, their language is often meditative and contemplative. It seems that Earthgazing fulfills many of the functions of meditation and relaxation on the surface of the planet.

For example, payload specialist Byron Lichtenberg described how he would float up to the cockpit after his shift on the Space Shuttle was over and "watch the world go by" while eating dinner:

Thinking about eating your dinner around the world in 90 min is really something. I took advantage of that time; then I would stay up and look for another half-orbit and end up going to bed exhausted (see text footnote 5).

During the pre-ISS spaceflight days, each mission was packed with long "to do lists," and Shuttle astronauts like Lichtenberg had to carve out the time to do any significant Earthgazing (which may be why he went to bed "exhausted"). However, much has changed with the advent of the ISS. Astronauts still work long hours during the week, but mission planners have begun to recognize that these extraordinary people are still human and they need time off to rest, relax, communicate with their families, and, yes, experience the Overview Effect[6].

In the words of Nicole Stott, the experience is much different with the extra time and different view provided by the cupola:

It is a really impressive place and it has changed the view that you get from flat, Earth-facing windows. Honestly, it was so much more impressive than we expected. You are always looking for the horizon, and you could find it before, but the cupola really puts it right in your face. You really get the curvature of the Earth, and you get much more of a feeling of a planet hanging in space (Canadian Space Agency, 2020).

For years, we have considered the primary job of astronauts to be completing as many scientific experiments as possible during their time in orbit. It has taken a long time for space agencies and the public to see the Overview Effect as a benefit not only to the astronauts but also to surface dwellers because it provides a new perspective on our planet and our species.

However, the value of the Overview Effect as a shift in worldview has only recently been seen as actually supporting that other goal of completing work in orbit. This discovery offers compelling lessons for the future of space training and space architecture: we should really think about astronaut leisure time and build in opportunities for relaxation and Earthgazing[7].

[4]Nezami, Unpublished proposal for a book with Frank White, 2019.

[5]*The Overview Effect,* 210.

[6]*The Overview Effect,* 305.

[7]This would be a valuable area of research for NASA to undertake, especially when considering space exploration of the Moon and Mars.

The result will likely be more productivity and greater creativity, when it counts. Since the astronauts are living and working on the ISS as our representatives, we can expect that this shift in approach will benefit the people of Earth as well.

Are we able, at this time, to provide empirical evidence that Earth gazing actually improves creative performance by the astronauts? No, but perhaps this examination of the potential relationship between the Overview Effect and performance will encourage additional study to determine if there is, in fact, a connection.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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Space for STEAM: New Creativity Challenge in Education

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INTRODUCTION

Governments recognized that a sustainable future requires solving new problems of a rapidly changing world in an innovative and interdisciplinary way. The importance to prepare learners for innovative thinking is for example expressed in educational goals (OECD Education 2030; UN 2030 Global Goals for Sustainable Development (SDGs), 2018).

STEM (Science, Technology, Engineering, and Mathematics) education first came about through development in the field of education, which realized that not only content, but higher order thinking is needed (De Boer, 1991; Sanders et al., 2011). Further, global evolution in education took place, and pedagogies emerged to engage all students in STEM fields. Art was added and thought to engage students, foster inclusive and gender equal classrooms, and therefore helping to achieve success and promote critical and creative thinking of all students (Bae et al., 2014; Harris and de Bruin, 2017). This resulted in an integration of the creative arts within the scientific and technical disciplines, STEAM (Science, Technology, Engineering, Arts, Mathematics).

However, questions can be raised how and if educational goals are achieved. For example, today's classrooms are increasingly multicultural, requiring an understanding of cultural differences in teaching practices as part of intercultural competence of teachers (e.g., Wursten and Jacobs, 2013; Thapa, 2020). Moreover, although there is an increase in empirical studies (for an overview, see Saptono and Hidayah, 2020), many reasoning processes of STEM education, particularly those pertaining to scientific creative reasoning, are still not well understood (Sternberg et al., 2020). Some studies find social (de Vries and Lubart, 2017) or cross-cultural aspects related to scientific creative cognition (De Vries, 2018). These results indicate that there might be cultural factors related to STEAM teaching as well, which are unknown today. Research studies on STEAM education are largely qualitative (e.g., Barlex and Pitt, 2000; Keys and Bryan, 2001), and integration of findings from empirical research with qualitative research on teaching practices is rare.

Overall, there is a gap within the STEAM framework as to how social and cultural aspects of scientific creativity actually underlie creative cognition. As a result, teaching practices are not culturally adapted to foster creative cognition. The challenge is therefore to optimally integrate arts in STEAM education, to reach educational goals.

One field of particular interest to explore STEAM education is the domain of space. The space industry evolved through international collaboration, interdisciplinarity, and innovative thinking. Many recognize the attraction that space has on learners. According to motivation theory, students are most creative when they are intrinsically motivated through interest, enjoyment, satisfaction, and challenge of the work itself (Amabile, 1996; Amabile and Fisher, 2000; Hennessey et al., 2015). Intrinsic motivation is related to deep learning as well (Vansteenkiste et al., 2006). Thus, the interest inducing, and imaginative domain of space represents an appropriate context to foster the creative aspect of STEAM education (see **Annex 1**).

Since 1999, the World Space Week (United Nations for Outer Space Affairs) encourages STEAM education. Other examples are "The Space for STEAM" working group of the International Astronautical Association (IAA). A Team Project at the International Space University, 2012; Boy, 2013) mentioned that space-related content is excellent for STEAM education because it (1) inspires and motivates creativity, (2) is interdisciplinary, (3) appeals to both genders and promotes equality, (4) promotes international and cross-cultural cooperation, and (5) strives for a common and thriving future.

In the following paragraphs I address creative scientific cognition within the STEAM framework. Then, I elaborate on social and cultural aspects of scientific creativity and propose future research directions to inform teaching of STEAM. Throughout the paper I underscore the unique role of Space to foster STEAM education.

CREATIVITY AND STEAM: CREATIVE SCIENTIFIC COGNITION

There are many domains of creativity, and maybe most relevant in the arts and sciences (Kaufman and Baer, 2006). Science is a creative field of work, including when students find and solve scientific problems (Sternberg et al., 2020). Scientific creativity can be defined as any thought or behavior in science that is both novel and useful (e.g., Feist, 2011; Cropley, 2015; De Vries, 2018).

Within the multivariate approach to creativity, it is thought that different factors are involved in creative performance, such as knowledge, cognitive style, motivation, emotions, personality, and environment (e.g., culture and context) (Sternberg and Lubart, 1995). There are multiple approaches to investigate creativity, such as with neuroscience to discover mechanisms underlying cognition (e.g., Benedek and Fink, 2019; Khalil et al., 2019), psychological research (e.g., De Vries, 2018), and also qualitative approaches (e.g., Moran et al., 2003).

Kaufman and Beghetto (2009) discern different levels of creative expression: eminent creativity (C- creativity), professional-level expertise (Pro-c), everyday creativity (little-c) and personal creative expression as inherent in the learning process (mini-c). Within the educational field, and STEAM framework, the focus is on mini-c and how the cognitive process of students is related to the contextual factor of the educational environment.

Since Guilford's renowned presentation at APA on creativity 1950, specifying the divergent and convergent process of creativity, many more processes of creativity have been analyzed (e.g., Sawyer, 2011). Interestingly, for scientific creativity, the two-step process is often maintained as in the divergent exploratory and convergent integrative "Dual Search Model" model of Klahr and Dunbar (1988). However, all activities of science from hypothesis formation, testing, evaluating results, to writing results, are related to creativity. Today there are only few tests to assess creative scientific thinking of younger students, such as the Scientific Ability Test (C-SAT) (Ayas and Sak, 2014), and the Evaluation of Potential Creativity (EPoC) battery (Lubart et al., 2013).

There are cognitive skills which are particularly relevant for scientific creativity. Examples are the use of metaphors and analogies, which serve homospatial thinking, and janusian thinking, which represents more spatial and simultaneous cognition of two opposite thoughts. Other examples of cognitions are linear and non-linear thinking, sepconic articulation processes, associations, dialectical synthesis, and synthesis of ideas and bi-sociation (e.g., Koestler, 1964; Tweney, 1996; Groves et al., 2008; Feist, 2011; Rothenberg, 2011).

Thus, we might ask how does the integration of art in STEAM relate to underlying cognitive processes? Authors such as Kim et al. (2012), and Miller and Knezek (2013) argue that even today there is a lack of conceptualization of STEAM, in that it consists of simply "adding the arts." From a pedagogical perspective, art in STEAM relates to different concepts, such as plural "arts" to mean the liberal arts, whereas the singular "art" refers to visual, musical, and performance art, and mathematics. Delaney (2014) specifies that the ultimate goal of this model is to explore and articulate criteria of STEAM-based practices, such as problem-based delivery, discipline integration, problem-solving skills, instructional approaches, assessment practices, and equitable participation. A second question could therefore be, do teacher practices sufficiently aim at fostering creative cognitive processes?

Yakman (2008) defines the arts as going beyond aesthetics and includes the liberal arts relating the subjects through interdisciplinary approaches. Her well-known "STEAM Framework for Education Across the Disciplines," implies higher-level synthesis producing holistic, integrative knowledge, and includes "key elements" of arts pertaining to the different STEM disciplines. The STEAM framework is not clear on how 'key elements" of arts relate to higher level synthesis in scientific thinking across disciplines. As a consequence, the framework does not address creative, social, or cultural aspects involved in higher synthesis. I propose that research on scientific creativity can fill this gap and foster STEAM education.

A more granular facet of cognition involved in scientific creativity, is the analysis of conceptual combinations (Ward et al., 2002). This is related to the research field of conceptual change (Carey, 2009; Vosniadou, 2009). Knowledge acquisition in science is also related to this domain. It is thought that science learning involves either a gradual addition, elimination, and organization of concepts, or a revolutionary process, where one theory of conceptual understanding is replaced with another.

Creative scientific cognition represents at the core where the STEAM framework fosters creative thinking in STEM through the arts. The interdisciplinary teaching moreover enhances scientific creative thinking, as it for example promotes the synthesis and integration of previously unconnected concepts.

Scientific creativity is also fostered by broadening boundaries of scientific concepts. Mentions that there is a social aspect involved in the breaking down, and creation and reformulation of boundaries. Consider a remark of Russian cosmonaut Sergey Ryazanskiy (2020): "*Before my flight I realized there were many borders and boundaries we created in ourselves and in our lives... After working from our planet of above you understand that there are no visible borders, all these borders and boundaries we create ourselves in our mind. If we understand this, we will be able* *to do much more than we ever can imagine."* This example of the experience of space indicates that social and cultural aspects of the space endeavor are related to broadening of concepts, and therefore creative cognition.

In summary, the "key elements" of the integration of arts in the STEAM framework pertain to creative cognition and its social and cultural aspects. I now turn to these social and cultural factors to elaborate on how they relate to creative scientific cognition.

SCIENTIFIC CREATIVITY: SOCIAL AND CULTURAL FACTORS

The domain of space is an intercultural and international endeavor that concerns all sciences and represents therefore a suitable domain, to explore cultural factors related to STEAM and scientific creative cognition.

The research domain of cultural differences in creativity is growing (Lubart et al., 2019). Most research on cultural differences of creativity compare levels of creativity for adult populations, such as for divergence and convergence (Cheung et al., 2016), or the influence of multicultural experience. Kharkhurin (2012) for example found that multiculturalism and multilingualism were related to enhanced creative potential. He theorized that the encounter with other cultures enhances flexible thought. Leung et al. (2008) showed that for adults, multi-cultural experience relates to cognitive processes supporting creativity through the use of unconventional knowledge and ideas of unfamiliar. Other explanations are that encountering others culture causes the expansion of ideas, such that retrieving concepts of two or more cultures and integrating them causes new insights (Wan and Chiu, 2002). Simonton (2000) related bi- or multiculturalism to cognitive processes of "novel conceptual combinations," resulting in creative conceptual expansion.

However, other findings indicate that the relation between culture and creativity is more complex. Empirical research on first year college students (de Vries et al., 2015) found that multicultural experience could also impede creativity for students with specific cultural backgrounds, contrary to the general findings. Other studies (de Vries and Lubart, 2017) with younger students, also found that students with immigrant cultural backgrounds had a reduced capacity of synthesizing and integration of concepts for scientific creativity, which impeded creativity. These findings underscore the importance of understanding cultural factors of STEAM education.

The "Cultural Actuation Model" (De Vries, 2018), is based on a study with young students (ages 9 and 10) from India, Russia, and Europe. Different cultural environments are more or less conducive to kinds of creativity. In this model, the attitude of "Tolerance of Ambiguity and Uncertainty"(TA) (Frenkel-Brunswik, 1949) and the cultural value of 'Power distance"(PD) (Hofstede, 2011), were related to students producing ideas based on observable, "surface" features, "process" oriented features, or ideas based on abstract, or "core" features. Ideas based on observable features, mostly related to low-TA and high-PD environments, were found to be less creative than ideas containing "process" and "core" features.

The particularity of this research model is that it focussed on cultural differences of features or patterns, instead of levels of creativity. It is also in line with a "warming trend" of conceptual change research, away from "cold conceptual change." This means that there is a growing focus on social, motivational, contextual, affective factors, and background knowledge of learners (Vosniadou, 2009).

Overall, more research is needed to understand and confirm the role of social and cultural factors on scientific creativity. Future studies could also focus on different stages during development in relation with the impact of social and cultural factors. Cross-cultural research could focussing on culturally varying patterns of creative productions and scientific creative cognition. It is possible that adding different cultures will reveal unknown aspects.

Teaching practices are also related to social and cultural factors. This raises the question what practices foster or maybe impede scientific creative cognition. This is discussed in the following paragraph.

TEACHING FOR STEAM: CULTURAL PRACTICES AND CREATIVE SCIENTIFIC COGNITION

Despite interest from governments and the educational environment for STEAM education (Henriksen, 2014), less is known about cultural differences in teacher practices, or how STEAM is implemented in different cultures. Teachers practices, while using the same educational tool, can differ, and this could be critical. Studies exploring how cultural differences influence teaching for STEAM is an emerging field (Yakman and Lee, 2012). Effects of teacher's roles and practices in general on learning outcomes, however, are not well known.

In contrast to this gap in research, teacher's intercultural competence is becoming more important because of today's increasingly multicultural classrooms. Culturally sensitive teaching mostly focusses on topics such as language choice, religion equality, or culture courses for students (Rengi and Polat, 2019). There is a focus on intercultural sensitivity as an orientation which can for example be ethnocentric, transitional, or ethno-relative (Kuusisto et al., 2015). Others again address the gap in relationships between teachers and culturally diverse students and as a lack of care (Thapa, 2020).

The question can be asked if certain teacher practices are better suited to foster creative cognition. In their annual report, "The World Economic Forum" found that a "copy and paste" method of implementing best teaching practices across cultures was not possible. This was measured according to a ranking of learned cognitive skills of different countries [(Learning Curve Data Bank (LCDB), 0000)]. Wursten and Jacobs (2013) suggest that the problem is the unknown link of what happens between measurable "inputs" (funds, years of schooling, teacher-student ratio's, etc.) and "outputs" as learned outcomes, and therefore could be compared to a "black box." The authors propose that the "input" of cultural context needs to be analyzed and that teacher's practices should be adapted to cultural contexts. Cultural values are deeply embedded and entangled with social and educational policies. For example "right" behavior of a student in one culture, could be "wrong" behavior in another. They summarize examples of implications of attitudes according to cultural values of teachers, and students.

To gain insight into the "black box," future research could therefore focus on culturally different teacher practices, and student and teacher attitudes, related to value dimensions. The next step would then be to measure learning outcomes of specific aspects of scientific creative cognition. The relation of the teacher practices and learning outcomes will reveal how to foster best scientific creative processes.

To demonstrate the creativity challenge of this paper, **Annex 2** shows an illustrative example (De Vries, 2018) which differentiates student and teacher attitudes and practices according to TA and the PD value dimension, and from culture and creativity literature (Hofstede, 2001; Sawyer, 2011). Possible related learning outcomes of creative cognition are mentioned, based on results of the previously mentioned study. In this way, research could relate teacher practices to learning outcomes, by integrating qualitative analysis of teacher and student attitudes and teacher practices, as well as quantitative measurement of creative scientific cognition.

In sum, we need to understand how cultural differences in teacher practices fosters different aspects of creative cognition. Future directions of research could (1) investigate further social and cultural effects of creative cognition, (2) analyze cultural differences of classroom organizations, to understand how constellations of cultural values "work out" in classroom practices, and (3) assess how practices are related to differences in learned outcomes of scientific creative cognition.

Finally, other "layers" of culture such as gender, and socio-economic backgrounds should also be addressed. Space fits this new direction of research because of the international collaboration in this domain, which offers possibilities for international collaboration on cross-cultural STEAM education, as well as opportunities to exchange teacher practices. The ultimate challenge is that all students, regardless of their cultural backgrounds, can fully develop their scientific creative cognition.

CONCLUSION

It was argued that a new challenge in education of "Space for STEAM" is a greater understanding of how cultural differences of teaching practices impact learning outcomes of scientific creative cognition. This is closely related to gaining an in-depth knowledge on social and cultural factors of creative cognition itself.

By broadening the STEAM education framework by integrating the empirical domain of scientific creativity, the Arts component is no longer "simply added," but forms an essential part to increase scientific creative cognition and innovative thinking.

Practical implications are for example that teacher's STEAM education could target specific scientific creative cognitive processes. Another example is that results can inform STEAM teacher curricula, and training, to enhance intercultural teaching competence of teachers, specifically for cultural differences in practices as related to creative cognitive learning outcomes. This could result in fostering higher levels of scientific creative cognition of students of all cultures. It could be that certain teacher practices foster certain aspects of creative cognition more than others. If these are known, intercultural exchange can improve teaching. If these practices remain undiscovered however, a "harmonizing" of teacher practices for example by "copy and pasting" them, could risk reducing, instead of enhancing, learning outcomes.

Although there is emerging knowledge on cultural differences in teaching practices of STEAM, as well as on cultural factors of scientific creative cognition, more research is needed to predict further implications for optimal STEAM education.

The need for innovative scientific thinking makes it inevitable to take up this challenge in the foreseeable future. The naturally innovative, intercultural collaborative, and interdisciplinary aspects of the space domain, are as crucial for problem solution finding and sustainability in outer space as on planet earth.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2021.586318/full#supplementary-material

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CONCEPTUAL ANALYSIS
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How the Immune System Deploys Creativity: Why We Can Learn From Astronauts and Cosmonauts

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In this interdisciplinary article, we investigate the relationship between creativity and the immune system; the creative features of the immune system and how the immune system and its role in regulating homeostasis might be related to creative cognition. We argue that within a multivariate approach of creativity, the immune system is a contributing factor. New directions for research are also discussed. When astronauts and cosmonauts venture into the new and extreme environment of outer space, their immune system needs to instantly adapt and find new answers to survive biologically and psychologically. Many astronauts report interest in creative activities and therefore represent an interesting group to investigate creativity in relation with the immune system. Little is known regarding (1) how the immune system interacts with and supports creative cognition and behavior, (2) if an individual's immune system, interacting with cognition, adapts more originally to a new environment compared to another's; in other words, if there is creativity in the domain of the immune system, and (3) the creative properties and functions of the immune system itself.

Keywords: creativity, immune system, cosmonauts/astronauts, cognition, T cells, B cells, *Unheimlichkeit*, sports

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INTRODUCTION

> "An addiction to poetry is very generally the result of an uneasy mind in an uneasy body"
> (Lord Byron, Letter, 4331, in Sandblom, 2009).

Given that the concepts of creativity and the immune system might not be familiar to those who study one but not the other, we will begin by defining these concepts. Next, we will argue that these seemingly lightyear distant concepts are actually closer than previously thought. We will discuss the connections between illness, the immune system and creativity and propose that the essence of illness is the experience of *Unheimlichkeit* which is the sense of "uncanniness" or "unhomelikeness" in one's own body and in the world (Svenaeus, 2000). Finally, we will extend the framework of *Unheimlichkeit* to the extreme environment of space and discuss what we can learn about creativity from astronauts.

Creativity is the capacity to produce something new and original yet adapted to the constraints of a given situation (e.g., Sternberg and Kaufman, 2010; Amabile, 2018). Within a multivariate approach to creativity, the following factors are critical: knowledge; cognition, which includes intelligence, memory and attention; conative factors which includes motivation, tolerance for ambiguity, risk-taking, and emotions; personality; and context, which includes environment and cultural factors (e.g., cultural tightness vs. cultural looseness). Together, within a multivariate approach, these interacting variables contribute in varying degrees to the creative process (Sternberg and Lubart, 1995). That is because creativity is partly domain-general and partly domain-specific or even task-specific (Lubart and Guignard, 2004; Barbot et al., 2016) and depending on the given domain or task, the variables involved in creativity can vary and interact differently. For example, a creative scientist may require specific creative cognition processes more so than a creative dancer who might require more motoric ability or kinetic creativity. Creative artists score higher for the personality trait of neuroticism compared to those who are creative in their scientific work or in everyday creativity. Regardless, the key cognitive factors and personality traits that predict creative potential are "openness to experience" (McCrae, 1987; Dollinger et al., 2004) and "tolerance for ambiguity" (Stoycheva, 2010; de Vries, 2018) which are each essential for any domain or task (e.g., Batey and Furnham, 2006). Furthermore, de Vries found that people who are tolerant to ambiguity are also less judgmental. Taken together, a person who is tolerant for ambiguity remains curious rather than anxious in an uncertain or ambiguous situation thereby enhancing their creative performance (de Vries, 2018).

Each of the factors contributing to the creative process, such as personality traits and cognition, can manifest in and interact within a given environment. Ultimately though, when people engage in the creative process, they are activating a bodily and therefore biological process that is still poorly understood (Simonton, 2001). Therefore, our aim is to use extreme bodily conditions (e.g., those who experience disease or physical discomfort) and extreme environments (e.g., astronauts living and working aboard the International Space Station), to explore how the physical and related mental conditions of the body respond to, adapt, and recover from these extreme experiences; how these might be related to creative performance; and to use these examples to broaden our understanding of the concept of creativity (de Vries, 2018, 2019).

Existing research on the relationship between the body and creativity predominantly focuses on mental wellbeing (Jamison, 1993; Kaufman, 2014) and is confined to the neuroscience of creativity (Beaty et al., 2014, 2016; Jung and Vartanian, 2018). However, recent studies have expanded our understanding of the immune system beyond its role in controlling infections. In fact, we now know that the immune system is responsible for monitoring and maintaining the physiological equilibrium compatible with life known as "homeostasis" (Kotas and Medzhitov, 2015). It does so by communicating with every cell, tissue, and organ of the body to detect and address infection, injury, or stress (e.g., unfavorable nutrient concentrations, pH, or salt balance, etc.) (Kotas and Medzhitov, 2015). Therefore, the immune system is an essential component of the body's ability to sense, respond to, adapt, and recover from internal and external perturbations. In line with this, dozens of parameters denoting immune system function change in response to the physical and psychological stress of spaceflight (Afshinnekoo et al., 2020).

Using an interdisciplinary approach, we address the relationship between the immune system and creativity by integrating insights from both of these fields (Repko and Szostak, 2020). Our aim is threefold: first, by examining individuals who experience "*Unheimlichkeit*" (e.g., those who suffer from chronic pain and astronauts), we will consider how the biology of the immune system should be included in the overarching theory of creativity; second, by integrating new insights from the field of immunology, we will discuss how the immune system serves as a principle regulator of both the body and the mind and propose new avenues of research for the field of creativity; and third, we will propose new perspectives, informed by creativity research, to broaden the field of immunology.

CREATIVITY AND BODILY EXPERIENCE: *UNHEIMLICHKEIT*

The field of psychology has long sought to understand processes related to internal and external factors that predict creative performance. Studying individuals and groups at the extremes of human experience exaggerates these principles which allows researchers to observe commonalities and patterns that might otherwise be too subtle to see in the broader population. While it is generally thought that very healthy individuals are creative (Flaherty, 2018), there are many examples of eminent artists who suffer from disease or chronic pain. According to one of the first authors on creativity and illness, Philip Sandblom, many artist's lives and their creative works are heavily influenced by their bodily condition and the discomfort, pain, and debilitation it causes (2009). History abounds with many examples such as the world-famous Mexican painter Frida Kahlo (1907–1954) who suffered from chronic pain due to a spinal cord injury and polio; yet she kept painting even when her pain necessitated that she painted from her bed. Her body and pain are often depicted in her paintings and serve as creative external representations of her internal world. Another example comes from the French painter Pierre-Auguste Renoir (1841–1919) who wrote of his fellow French painter Henri Matisse (1869–1954): "A lengthy martyrdom–his finger-joints were swollen and horribly distorted–yet he now painted his best works. While his body wasted away, his soul seemed to gain strength and he expressed himself with increasing ease" (Chatzidionysiou, 2019, p. 106). Finally, the Hungarian composer Bela Bartòk (1881–1945) suffered from polycythemia, which is a rare disease caused by a surplus of red blood cells leading to chronic pain and fatigue. Despite an enduring high fever, he wrote his famous swan song: Piano Concerto No. 3 in E major in the final months of his life.

Unfortunately, studies on the immune system and pain and creativity are few so it is difficult to answer the question how does the experience of pain relate to the creative process? A rare example of such a study found that expressive writing significantly diminished viral load in patients who were HIV^{+} (Petrie et al., 2004). An overview of art-therapy studies by Stuckey and Nobel (2010) shows that in general creativity is related to an improvement of vital signs whereas others maintain that more research is needed to determine if art therapy is an empirically supported treatment for illness (Holmqvist and

Lundqvist Persson, 2012). This is currently poorly understood but warrants further research.

In her excellent work on motivation and the neurological underpinnings of creativity, Flaherty (2018) writes that suffering influences creative behavior by raising arousal and the motivation to be creative or, she suggests, by being distracted from the pain. The Swiss artist Paul Klee (1879–1940), who suffered from the autoimmune disease scleroderma, captured this notion well when he remarked: "I paint in order not to cry" (in Sandblom, p. 145). While the motivation to seek pleasure and avoid pain can be in competition, a smaller amount of pain can be endured for a larger reward (Flaherty, 2018). However, this does not explain how creative people can work enduring even extreme physical discomfort. The creative scientist and philosopher Arthur Schopenhauer (1788–1860) for example found the sensation of pain stronger and therefore more inspirational than pleasure.

We can observe an intimate connection between pain and pleasure anatomically. Neuroscience research on how pain and pleasure signaling are controlled in the brain show that these two sensations overlap in their neural circuitry and share a reliance on opioid and dopaminergic signaling (Leknes and Tracey, 2008). An explanation therefore could be that highly creative individuals, who are more tolerant for ambiguity, "judge" less pain and therefore can maintain their motivation. In other words, they undo the sensation of pain from its negative valence and are also open to the experience and sensation of pain. Another possible explanation is related to the fact that this neural circuit design allows for an individual to balance pleasure and pain depending on the reward. Pain can thus be switched off in favor of a pleasurable sensation such as gaining a reward if the benefit outweighs the cost. However, the reverse can also occur: a strong pain signal can override pleasure seeking behavior if the cost outweighs the reward (Leknes and Tracey, 2008). Artists who suffer from chronic pain might be exceptionally capable of maintaining strong motivation to seek the pleasure of their reward (creating) so much so that it over-rides the pain signals that might otherwise inhibit their creative process.

While this framework helps to explain the neurological relationship between chronic pain and creativity, it does not allow us to easily incorporate other bodily experiences also known to be associated with creativity. For example, the world-renowned cosmologist and physicist Dr. Steven Hawking (1942–2018) was remarkably creative in the domain of science. He also lived and worked for more than 50 years with amyotrophic lateral sclerosis (a motor neuron disease), which first appeared in his twenties. Despite this, he made several paradigm-shifting contributions to the field, defining the Hawking radiation released by black holes and unifying the general theory of relativity with quantum mechanics.

Historically, researchers studied creative people such as artists and scientists, using the framework of health and disease. However, we believe this binary takes an overly simplistic, problematic and ableist view of "health." Furthermore, it fails to define the commonalities shared between seemingly different creative people. To find these commonalities, we must first generalize the experience of illness. To do so, we now turn to the philosopher Fredrik Svenaeus who defines the essence of illness as *Unheimlichkeit* which is the sense of "uncanniness" or "unhomelikeness" in one's own body and in the world (Svenaeus, 2000). One experiences *Unheimlichkeit* when one loses their ability to understand their own embodiment and the ability to experience and make meaning of the things and people around them (Svenaeus, 2000). Illness, regardless of its etiology and manifestation, dislodges a person's sense of their own body as familiar and coverts it into something that is quite opposite to homelike: dangerous, strange, incomprehensible and alien (Svenaeus, 2000). Illness activates this sense of alienation or otherness to levels that are "obtrusive and merciless" giving rise to feelings of helplessness (Svenaeus, 2000). Using this framework, we now see how artists suffering from chronic pain; Dr. Hawking slowly losing his motor abilities; athletes training their bodies to perform unnatural and unintuitive motions and gestures; all experience *Unheimlichkeit*.

This suggests that creativity is linked to both the experience of *Unheimlichkeit* and the subsequent mental and physical adaptations one makes to restore their sense of "homelikeness" and their ability to understand their world. While pain or disability can activate *Unheimlichkeit*, there are many ways one might feel unhomelike in their own body; for example, when experiencing the new and extreme environment of space. We are at a unique moment in our 200,000 years history as humans: we are traveling and living in space for the first time with plans to establish new settlements on the moon and Mars in the coming decades. Space is a unique and completely novel environment beyond the confines of our home planet that demands of astronauts and cosmonauts the ability to generate solutions to new problems. The space stations that astronauts live and work in are themselves hubs of research and discovery. Finally, astronauts and cosmonauts have described the "Overview effect" (White, 2019), which is a transformative experience that occurs when one looks out of their spacecraft's windows and sees our tiny and fragile home planet suspended against the backdrop of the rest of the universe. Therefore, during space travel, astronauts and cosmonauts experience both a literal "unhomelikeness" and the philosophical *Unheimlichkeit* upon leaving the gravitational and metaphorical grounding of Earth. Astronaut Meir (2020) recalls that she felt a strange experience when her brain seemed to "flip-flop" upside down when it finally adjusted to its new orientation in space.

Therefore, astronauts experience a unique form of *Unheimlichkeit* that might underlie their creative performance. Interestingly, astronauts report an increase in creative interests during and after travel to outer space. In fact, most of the 500+ astronauts who ventured into space are also remarkably creative in various other domains including painting (e.g., Stott, 2019), music (e.g., Stott, 2019), and photography (e.g., Stott, 2019). Some even became professional artists after their missions such as Alexei Leonov (1934–2019) who was the first human to not only walk in outer space but also to create art in outer space, sketching the sunrise using color pencils. He was also known to make charcoal portraits of his crewmates aboard their Voskhod 2 spacecraft. His missions inspired him in his well-known work afterward. It is currently unknown if the intense experience of space travel and experiencing the "Overview effect" (White,

2019) changes an astronaut's creative potential and this deserves further research. Tracking changes in creative performance before, during and after space flight (and i.e., the experience of *Unheimlichkeit)* will be a powerful tool in further defining the cognitive and physiological components of creativity.

Here we see how openness and acceptance to the deeper experience and sensation of *Unheimlichkeit* seems to provide a catalyst to the creative process. However, there are still many empirical unknowns concerning the dynamics and the physiological adaptations to the uncanny. To understand how the bodies of eminent creative individuals respond to, adapt, and recover from *Unheimlichkeit* or other extreme experiences, we now turn to the immune system as the body's central regulator of homeostasis.

THE ROLE OF THE IMMUNE SYSTEM IN CONTROLLING HOMEOSTASIS, THE CREATIVE BRAIN AND BEHAVIOR

By identifying creative individuals who experience *Unheimlichkeit*, we can also study what changes occur in the body during and after these experiences to learn more about the biological underpinnings of the creative process. While the brain and cognition have been the rightful focuses of past research, we argue that the immune system should feature more prominently in future creativity research given its emerging role in modulating behavior and cognition. In response to infection, immune cells become activated and release inflammatory factors, known as cytokines, that allow them to further activate and coordinate appropriate immune responses to clear the infection and repair damage. However, these cytokines also act on the brain to induce a set of "sickness behaviors." These include loss of appetite, loss of libido, altered sleep, social withdrawal, fatigue, and altered cognition and mood (Dantzer and Kelley, 2007). The coordination between the immune system and the brain enhances the likelihood of survival because resources that would otherwise support nonessential programs, such as growth and reproduction, are instead conserved and allocated toward resource costly programs that support immune defenses against pathogens (Wang A. et al., 2019).

While the immune system has traditionally been studied in the context of infection, it is now clear that it plays a broader and vital role in regulating homeostasis throughout the entire body. In fact, the proper function of every organ and tissue such as muscle (Tidball, 2017), bone (Takayanagi, 2007), liver (Kubes and Jenne, 2018) and many others depends on immune cells that reside in the tissue and monitor and correct perturbations to homeostasis (Kotas and Medzhitov, 2015). Deviations from homeostasis, such as the perturbations experienced during infection, injury, stress and even space travel are both sensed by and rectified by the coordinated efforts of the immune system. Even non-immune cells of the body respond to inflammatory perturbations by producing factors that allow them to coordinate–under the direction of the immune system–to resolve the problem and return to homeostasis (Krausgruber et al., 2020).

We argue that astronauts provide a unique opportunity to address these questions given that space travel is a discrete event which causes extreme perturbations to homeostasis and where the immune system represents the first "protective shell" of the space traveler's environment (Whiteley and Bogatyreva, 2008). Given that the timing of *Unheimlichkeit* and creative inspiration is known, researchers can track changes to the immune system before, during and after space flight and study how that relates to changes in creativity. Crews on space missions experience many psychological changes due to the biotic and abiotic stresses of space travel such as microgravity, radiation, altered nutrition, confinement, a busy work schedule, disrupted circadian rhythm, and the flight itself (Crucian et al., 2013; Thiel et al., 2017). As a result, astronauts experience cardiovascular dysregulation, bone demineralization, muscle atrophy, altered neuro-vestibular perception leading to extreme nausea, increased cancer risk, liver disease, nervous system and cognitive impairments, and immune system dysfunction (Afshinnekoo et al., 2020). Strikingly, half of the astronauts during the early Apollo spaceflights in the 1960s and 1970s developed bacterial and viral infections during and after spaceflight. More detailed studies have revealed that space travel is associated with broad changes throughout the immune system. During space flight, the immune system enters a period of broad dysregulation that includes reductions in the numbers and functionality of natural killer cells and T cells but increases in the numbers and functionality of neutrophils and monocytes (Crucian et al., 2013, 2015). Compared to pre-flight levels, parameters of the immune system adapt to the new environment and establish a new set point that persists during long-term space flight (Crucian et al., 2015; Thiel et al., 2017) and even for some time after returning to Earth (Buchheim et al., 2019). These changes have dramatic consequences on an astronaut's ability to respond to infection so much so that reactivation of latent herpesvirus infections remains a frequent problem (Crucian et al., 2020).

In addition to anti-microbial immunity, the immune system also controls how the brain adapts to space flight. Using a mouse model, researchers showed that low-dose radiation similar to the levels encountered in deep space results in deficits in learning and memory formation (e.g., novel object recognition and fear-extinction response), which ultimately led to distress behaviors (e.g., social avoidance and behaviors resembling post-traumatic stress syndrome) (Acharya et al., 2019). Remarkably, many of these detrimental effects could be prevented by blocking the activity of a population of brain-resident immune cells known as microglial cells (Krukowski et al., 2018). Another brain-resident immune cell known as T cells also play an important role in regulating learning and memory (Kipnis et al., 2012) and social behaviors (Filiano et al., 2016; Reed et al., 2020). In mouse models, the amount of time a subject spends with either a novel inanimate object or a novel mouse is quantified and used to approximate sociability. Whereas normal mice prefer to interact with each other, subjects with defects in meningeal T cells exhibited anti-social behaviors by spending more time interacting with the inanimate object (Filiano et al., 2016; Reed et al., 2020). To assess learning and memory in mice, subjects are allowed to explore one half of a simple Y-shaped maze. When introduced to the other half of the maze, normal mice were more likely to explore the novel arm compared to the familiar arm. However, mice lacking meningeal T cells had short-term memory defects and were less likely to explore the novel arm of the Y-maze (Ribeiro et al., 2019). Taken together, these findings further suggests that T cells are important in generating the "openness to experience" that is so vital to the creative process. As of yet, these questions have only been investigated in mouse models of cognition and behavior; therefore, further research involving human subjects will be vital in further pursuing the role of T cells in creative cognition.

While space travel is known to alter the number of functions of T cells circulating in the blood (Crucian et al., 2013), it is unknown whether brain-resident T cells, such as those that modulate learning, memory, social behavior and openness to new experience, are also affected by space travel. In the future, as mouse and human research on board spacecrafts become more sophisticated, there will be a remarkable opportunity to study how the immune system of the brain changes before, during and after space travel and how this affects the cognitive and behavioral contributors to creative performance such as openness to experience, mind-wandering and spontaneous thinking (Beaty et al., 2016), short/long-term memory, concentration and flow. In the meantime, terrestrial-based space analogs, such as the Mars500 mission, overwintering in Antarctica, and the Hawaii Space Exploration Analog and Simulation (HI-SEAS) Habitat (Mahnert et al., 2021) offer researchers the opportunity to not only approximate the stresses of space travel but also isolate variables that contribute to the physiological, cognitive and behavioral changes associated with space travel (Pagel and Choukèr, 2016).

THE IMMUNE SYSTEM AND THE CREATIVE PROCESS

Having discussed how insights from how the immune system controls homeostasis and cognition and how these might enhance our understanding of creativity, we now consider how theories of creativity might apply to immunology and inspire new research perspectives. However, it is important to make the distinction between what are fundamentally biological processes and human creative cognition. Previously, Campbell's Blind Variation and Selective Retention (BVSR) model of creativity used Darwin's theory of evolution through natural selection as a representation for creative thought (Campbell, 1960). However, the "Blind Variation" component was often rejected (Simonton, 1999, 2011) because it failed to accommodate human volition; therefore, a "Sighted Variation" model was proposed instead (Sternberg, 1998). Current literature in physics questions whether the idea of blind variation actually exists at all given that there are patterns of entanglement and relationships even at the most basic level of atoms, as explained in the "rule space relativity" (Wolfram, 2020).

In line with the above, we maintain that some biological processes demonstrate emergent creative properties. There are different ways the creative process is described. The most simple one is a process of divergence, and convergence (e.g., Klahr and Dunbar, 1988). Divergent thinking represents an exploratory phase when the generation of many ideas in different directions and fluency (i.e., the amount of ideas) are key. In the convergent thinking phase, ideas are integrated and converged into one or possibly more "right" (i.e., adapted to a problem) answers. Other steps of the creative process include for example: (1) finding and formulating a problem, (2) acquiring knowledge, (3) gathering potentially related information, (4) taking time for incubation, (5) generating a large variety of ideas, (6) combining these ideas in unexpected ways, (7) selecting the best ideas, and (8) externalizing an idea (Sawyer, 2011). Studies by Botella et al. (2013; 2018; 2019) show that in reality the creative process is not sequential nor linear and depends on the domain of creativity as well. These researchers determined from diaries of artists the dynamic nature of the creative stages such as immersion, search, thinking, trials, inspiration, insight, ideation, combination, abandonment, selection, technique, precision, realization, judgment, finalization, break, and completion. Here, we will describe how adaptive immune cells, specifically B cells, relate the key features of their development to the creative process.

A fundamental biological problem that multicellular organisms must solve is how to distinguish their own "self" cells and molecules from those of other "non-self"–often infectious–organisms (*formulating a problem*). The immune systems of all animals and plants make this distinction by broadly defining non-self, microbial organisms by their unique molecular features that are distinct and absent from their own tissues. For example, components of bacterial cell walls or elements of viral genomes are distinctive to those organisms and generally not found in animal or plant tissues outside the context of infection. The molecular receptors animals and plants use to broadly detect infectious agents are encoded in their germline DNA meaning that they are an inherited and "innate" component of the immune system whose refinement occurs on an evolutionary timescale (Kawai and Akira, 2010). These innate immune receptors also allow the immune system to gather broad information by classifying the infection as either bacterial, fungal, viral or helminth (*gathering information*). This allows the immune system to tailor its response to a given class of pathogen and more effectively clear the infection. In addition to the innate immune system, vertebrate animal immune systems evolved an even more discerning set of tools capable of recognizing nearly any biological compound in the world with exquisite specificity that goes well beyond the broad discrimination described above (Flajnik and Kasahara, 2010). Specialized cells known as T and B cells use a creative process to construct unique molecular receptors to identify non-self molecules, referred to as "antigens." For simplicity's sake, we will focus on B cell development (**Figure 1A**) but T cells undergo an analogous process that shares many similar fundamental features. Each B cell, during its development, constructs a unique receptor, known as an antibody, *de novo* from pieces of germline encoded DNA called "gene segments." These gene segments are not functional individually but rather are the basic building materials B cells use to construct a new antigen receptor. During a process

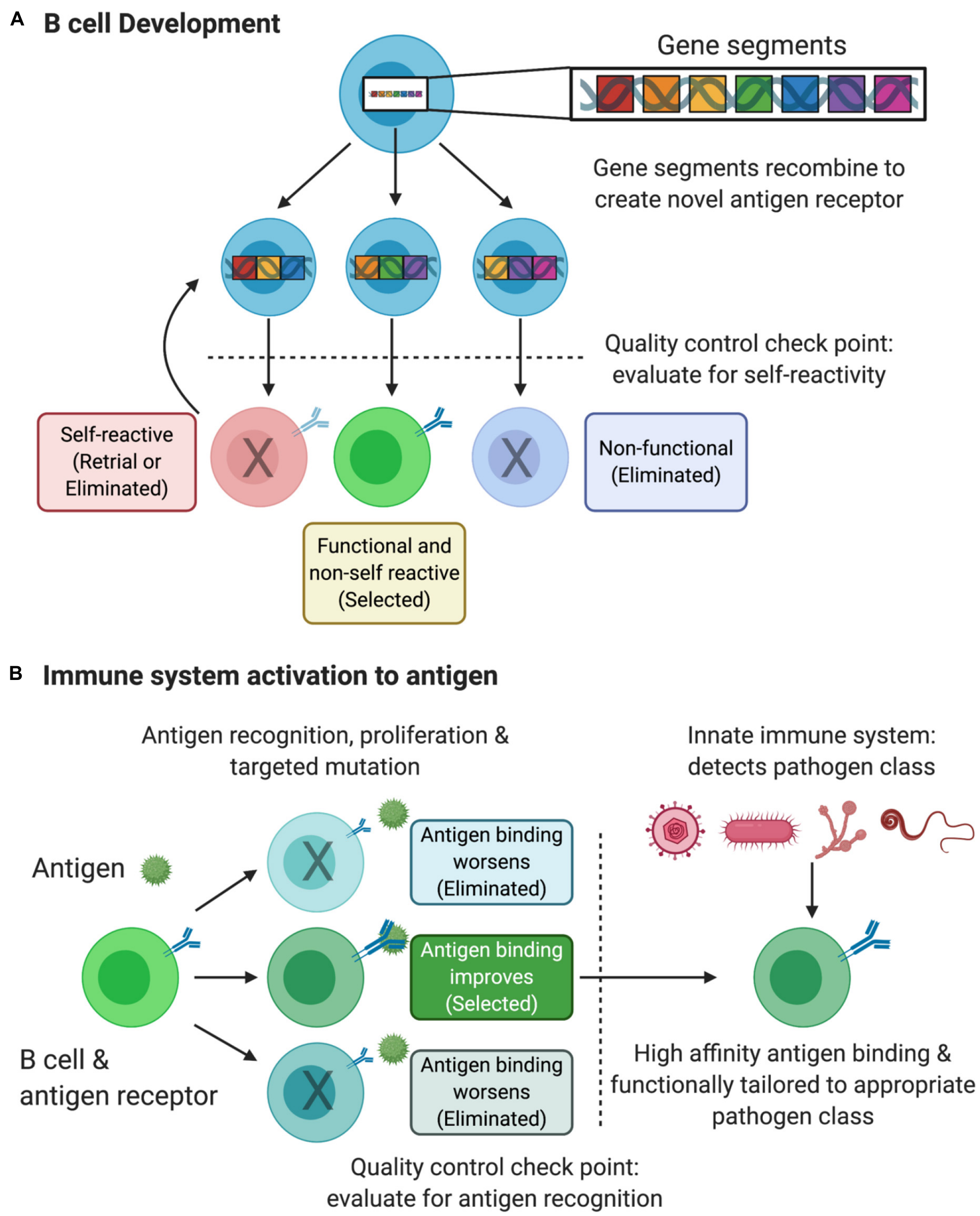

FIGURE 1 | B cell receptor development and refinement. **(A)** Developing B cells in the bone marrow randomly recombine DNA gene segments to encode a novel and unique receptor specific to a given antigen. At the first quality control check point, B cells that fail to generate a functional receptor are eliminated from the repertoire. B cells that generate a self-reactive antigen receptor undergo a period of "receptor editing" to attempt to lose this self-specificity. B cells that generate a functional receptor that does not recognize self antigens are selected, complete their development and egress from the bone marrow. While distinct, T cell development in the thymus shares these fundamental and analogous features. **(B)** Following immune system activation and antigen encounter, B cells that recognize the antigen proliferate and undergo further antigen receptor refinement. Random mutations are introduced to the DNA encoding the antigen receptor thereby changing its ability to recognize the antigen. The second quality control check point assess the B cell receptor's binding strength to the antigen. Those B cells with beneficial mutations are selected while those with deleterious mutations are eliminated from the repertoire. Finally, information gathered by the innate immune system induces qualitative changes to the B cell antigen receptor to better suit the response to a given class of pathogen infection (e.g., viral vs. bacterial vs. fungal vs. helminth). Overall, this process improves the precision of antigen recognition and tailors the B cell response to more efficiently clear the infection. Figure created with BioRender.com.

known as somatic recombination, gene segments are cut and spliced together to form a functional stretch of gene-encoding DNA (*idea generation*). In the process, the junctions between the newly spliced gene segments are mutated such that no two cells are likely to produce identical receptors even if they happen to choose the same gene segments to recombine (*combining ideas in unexpected ways*). Finally, each "half" of a B cell receptor is assembled independently and must be paired with another set of randomly assembled gene segments. Therefore, using random recombination of a limited number of gene segments and random mutations, B cells can produce an estimated 10^{13} to 10^{18} unique antigen receptors! While individual B cells construct one unique antigen receptor and can therefore only recognize one antigen, taken as a population–approximately 10 billion B cells in the human body–their combined recognition capacity yields a staggering repertoire with immense sensory capacity (Murphy and Weaver, 2017).

Newly constructed antigen receptors are then screened by a series of quality control checkpoints that evaluate them for basic functionality and proper specificity (*selecting the best ideas*). Given that gene segments are combined in a random manner, the B cells risk generating receptors that might recognize the body's own biological compounds (i.e., "self antigens"). Doing so would result in auto-immune disease where the immune system recognizes and destroys its own tissues (e.g., multiple sclerosis or rheumatoid arthritis). Developing B cells that generate these self-reactive receptors are either eliminated from the repertoire in order to prevent autoimmunity or the self-reactive B cell undergoes a period of "receptor editing" (*precision*). During this process, gene segments are again randomly recombined but from a pool that is reduced to exclude those gene segments that previously failed the first quality control check point. Interestingly, this selection process mirrors cultural aspects of creativity such as "cultural tightness – looseness." If the selection criteria are too tight, then the repertoire of antigen receptors might be too limited and fail to recognize pathogens when they are present; and if the criteria are too loose, then the repertoire would be too broad and therefore erroneously recognize self-antigens as non-self, leading to autoimmune disease. Finally, in a manner similar to the creative process, this molecular process involves risk given that segments of DNA are cut and rearranged with the intervening stretches removed altogether. This permanently changes the genetic landscape of the developing cell and, if not tightly controlled, can lead to cancer (Shaffer et al., 2002). In the event of a successful rearrangement, the B cell completes its maturation (*finalization*) and exists the bone marrow having generated a novel antigen receptor that will detect a non-self antigen of a given specificity (*externalizing an idea*) (**Figure 1A**).

In the event that the immune system is activated in the presence of a non-self antigen, such as during an infection, the B cell that recognizes that antigen will proliferate thereby amplifying the use of the successfully developed antigen receptor. Remarkably, further refinement of this B cell receptor takes place at this stage (**Figure 1B**). Responding B cells introduce additional random mutations to the gene encoding the B cell receptor, which will alter the ability of the receptor to bind to and detect the antigen. An additional quality control check point assesses these modified receptors (*judgment*) and selects those that recognize and bind with even greater strength and eliminate those that weakly bind to the antigen (*again selecting the best ideas*).

In summary, the immune system employs many features of creativity to collectively solve the following problem: how can a biological system distinguish self antigens from the myriad of non-self antigens that exist in the biological universe given limitations on the size and complexity of its genome? It does so by randomly combining simple building blocks to produce a unique tool (*divergent production and exploration of various directions*) that is subsequently evaluated for its functionality and for its ability to bind non-self antigens (*convergence toward one or several solutions*). This mitigates the risk involved in an otherwise random and potentially dangerous process. Following exposure to antigen and innate immune identification of pathogen class (*gathering broad information*), B cell receptors are further refined to improve the quantitative binding properties to the antigen and the qualitative features that are most suited to clearing a given class of pathogen.

Astronauts and cosmonauts, whose immune systems must creatively adapt in the extreme environment of space, provide a novel and important population in which to further study the creative features of the immune system. Intriguingly, space travel was shown to adversely affect T cell development in the thymus of astronauts (Benjamin et al., 2016). Complementary studies involving mice aboard the International Space Station identified that the stress of microgravity led to defects in T cell development and generation in the thymus (Horie et al., 2019). How space travel ultimately affects the creative process by which T cells generate their antigen recognition repertoire–the combined capacity of all individual T cell clones have in recognizing antigens–remains incompletely understood. Animal models of extreme gravitational stress suggest that space travel might alter antigen receptor generation and quality control in T cells (Ghislin et al., 2015; Fonte et al., 2019), but corresponding studies in astronauts are rare. One such study showed that the populations of T cells that recognize common herpesviruses are unaffected by space travel (Crucian et al., 2015) but other T cell populations of differing recognition capacities remain to be tested. Furthermore, whether the previously discussed brain-resident T cells that control learning, memory and openness to new experience are affected by space travel is an intriguing but open question.

While B cell numbers are stable before, during and after spaceflight (Spielmann et al., 2019), emerging evidence strongly suggests that their antigen recognition repertoire does change during this time. Studying a small group of astronauts aboard the International Space Station over a period of several months, Buchheim et al. (2020) found that space travel affects B cell development (**Figure 1A**). Specifically, the frequencies of various spliced gene segment combinations and the mutations at the junctions between spliced gene segments were significantly altered during the flight in two of the five astronauts studied (Buchheim et al., 2020). These same parameters were remarkably stable in the other three astronauts and ground-based control subjects. As with individuality in creativity, this suggests that individual adaptations to space extend to somatic recombination and B cell development. Unexpectedly, this study also showed that even before space flight, features of the astronaut's B cell antigen recognition repertoire were already significantly different from the ground-based control subjects and that these differences were not likely due to differences in antigen exposure (Buchheim et al., 2020). Going forward, it will be exciting to determine (1) whether the selection and training of astronauts biases the B cell repertoire or vice versa; (2) whether changes in the creative immune system correspond to changes not only in immunity but also in the creative performance of astronauts; and (3) whether similar changes in the B cell repertoire occur in other scenarios involving *Unheimlichkeit* and dramatic changes in creative performance or whether they are unique to astronauts and cosmonauts living in space.

DISCUSSION

In this article, we argued that the immune system is central to and is a catalyst for creativity. Specifically, based on the literature on illness and creativity, and the immune system's role in maintaining homeostasis, we suggest that the immune system is a component of creativity and one of its underlying biological mechanisms. Using the concept of *Unheimlichkeit*, we argued that the immune system, through its role in maintaining homeostasis, responds and adapts to new environments and that this is a critical feature of creative people. We also discussed how the immune system plays a critical role in maintaining homeostasis in the brain and has been shown to modify cognition, learning, memory and behavior (Dantzer and Kelley, 2007; Ribeiro et al., 2019). It is therefore possible that the immune system also plays a role in creative cognition and behavior and affects the personality trait "openness to experience" (Ribeiro et al., 2019). Next, we argued that there are creative properties of the immune system itself. We found that the immune system mirrors (surprisingly) many creative features and processes. Finally, using astronauts and cosmonauts as a unique study population, we propose future research that might determine whether some individual's immune system adapts more originally or creatively to a new environment compared to others. For example, do more creative individuals develop more diverse and original adaptations (or illnesses)? In other words, are some individuals more creative in the domain of the immune system than others?

As previously mentioned, investigating the immune responses, creative performance, and mental/physical wellbeing of astronauts before, during and after space flights could provide valuable insights into how these physiological changes relate to an astronaut's level and process of creativity. In line with this, recent data show that when astronauts' sense of "homelikeness" aboard the International Space Station was enhanced through improvements in diet, stress management, mental health,

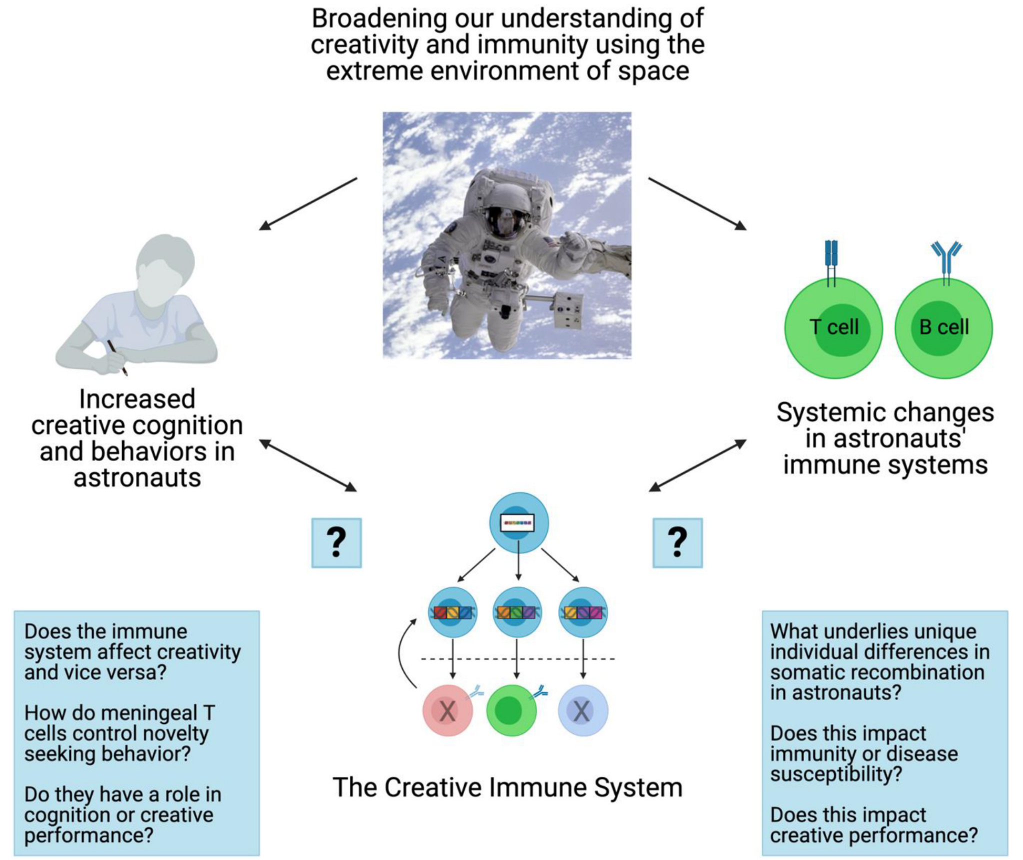

FIGURE 2 | Summary schematic and outstanding questions. Space travel leads to profound changes in creative behaviors and various parameters of the immune system. The immune system itself, namely T and B cells of the adaptive immune system, exhibit features of the creative process which is also altered by space travel. Whether and how these phenomena are connected is unknown; specific outstanding questions are also posed in this summary schematic. Figure created with BioRender.com.

exercise and physical health, their immune dysregulation was ameliorated (Crucian et al., 2020). Future studies might leverage these kinds of interventions to more precisely determine which biotic and abiotic stressors control physiological adaptations to space travel. A practical difficulty in conducting research with astronauts and cosmonauts are the relatively small sample sizes of participants and the logistical constrains space travel imposes on research. Therefore, future research might start with case studies of individual astronauts and track changes in their immune system compared to other variables like personality, values and creative cognition in order to define new directions. Coupled with terrestrial-based space analogs (Pagel and Choukèr, 2016), future work might also determine the relative roles variables such microgravity, social isolation, circadian disruption, the "Overview effect," etc., have on, for example, B cell antigen receptor development. Finally, these kinds of studies might answer the question of the direction of the relationship between the immune system, wellbeing and creativity (**Figure 2**).

Additional outstanding questions are whether changes in creative performance or expression is associated with changes in immune function at steady-state (e.g., immune system controlling the homeostatic regulation of digestion, absorption, and distribution of nutrients) (Kotas and Medzhitov, 2015) or during infection or injury (e.g., overt immune activation to bacterial infection). Given the role of the immune system in controlling sickness behaviors (Dantzer and Kelley, 2007) it is tempting to speculate that immune responses to infection and injury would affect creativity in an analogous manner to ways that other forms of stress, or other situations that evoke a profound sense of *Unheimlichkeit*, affect creativity (Wang X. et al., 2019).

Overall, we suggest that the immune system's role in regulating homeostasis is a contributing factor within the multivariate approach to creativity (Sternberg and Lubart, 1995). This means that there might be a particular domain of creativity in which this variable is especially required. Such a domain could be the extreme performance observed in sports. For example, a sprinter breaking the record in the 100 meter event also produces a unique and adapted performance to an imagined extreme environment. On a racing track, there is no real danger in the environment (e.g., a predator) that someone needs to run from. While preparing for a unique, novel and adapted performance, it is known that the immune systems of top athletes are profoundly affected by the physical strain of their intense training regimens and that this adversely affects their ability to respond to infections (Gleeson and Pyne, 2016). Furthermore, T cells play a critical role in the muscle repair response following injury (Burzyn et al., 2013). In this sense if athletes might express creativity by accomplishing a unique and adapted top performance, then the variable of the immune system would be a major contributing factor. This represents an addition to the new emerging domain of creativity and sport (Vaughan et al., 2019; Richard and Runco, 2020).

Concerning immunology research, the perspective that complex cellular systems have emergent properties that mirror creative processes broadens our understanding of systems biology and might therefore inspire new research directions. For example, do the immune systems of highly creative people function differently from individuals with lower creative potential? Ongoing research programs should seek to better understand the role of the immune system and cognition, especially the cognitive processes that are involved in the generation of creativity. For example, given the role of T cells in exploration and memory (Ribeiro et al., 2019), how does the lymphocyte repertoire of antigen recognition receptors affect creative potential and are there differences in these repertoires between highly creative and non-creative individuals?

Finally, given the increasing examples of a post COVID-19 syndrome that mimics aspects of other chronic conditions such as myalgic encephalomyelitis/chronic fatigue syndrome (ME/CFS) (Stam et al., 2020), it will be important to document how these peoples' immune systems change, how their experience of *Unheimlichkeit* evolves, and how it relates to their creative performance. This knowledge could be applied to secure the wellbeing of astronauts and cosmonauts who also experience debilitating mental and physical fatigue (Scheuring et al., 2015).

Dr. Homburger predicted in the preface of Sandblom's book in 1982 that 1 day an investigator will clear up the mystery of how the soma and psyche interact. An integrated understanding of the immune system and creativity might very well be a start in this direction.

AUTHOR CONTRIBUTIONS

Both authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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