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RESEARCH ARTICLE

The Potential of Neuroscientific Approaches to Game Learning Analytics: A Methodological Review on Assessing Domain-Specific Creativity

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게임 학습 분석을 위한 신경과학적 접근의 가능성: 영역별 창의성 평가를 위한 방법론적 검토

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ABSTRACT

This methodological review explores the emerging field of domain-specific creativity assessment. It explores the potential of game-based learning analytics from a neuroscience perspective and examines the ability of real-time data collection to provide detailed insights into the cognitive and creative processes of domain-specific creativity. The review emphasizes the pedagogical implications of innovative methodologies and presents the advancement of individualized, adaptive learning systems of game-based environments to assess domain-specific creativity. To illustrate, the exemplary study uses a multimodal approach that integrates functional near-infrared spectroscopy (fNIRS) neuroimaging analysis, game log data, and screen recordings for creativity assessment. The study elucidates the theoretical frameworks linking neuroscience metrics to constructs such as creativity, learning styles, and achievement goal orientations. The conclusion outlines avenues for future research while acknowledging current limitations in the field, including the complexity of data analysis, financial constraints, and ethical considerations.

Key words: Methodological Review, game learning analytics, neuroscientific approaches, fNIRS, domain-specific creativity

Introduction

Creativity is a critical competence, and its definition is as diverse as the field itself (Csikszentmihalyi, 2015; Plucker et al., 2004). Generally, creativity is understood as a combination of elements including person, product, process, and press (Rhodes, 1961). Csikszentmihalyi (2015) recently developed a systemic model of creativity. According to his model, creativity is regarded as truly creative when it is recognized by relevant fields. In this model, individuals utilize a culturally and historically shared language and signs within a specific field to generate novel ideas. The originality and novelty of these ideas are then evaluated by experts in that domain. Thus, creativity is considered domain-specific, and its contribution is determined based on relevant field knowledge. Baer et al. (2009) found that there is not a particularly high correlation coefficient for creativity across domains, suggesting that creativity in one domain is not necessarily related to creativity in other domains. Domain-specific creativity, thus, refers to the concept that creativity is confined to specific domain. The domain-specific creativity is deeply rooted in the knowledge, skills, practices, and cultural contexts of the respective domains.

The concept of domain-specific creativity is similar to Vygotsky's view of creativity, in that creativity is generated and developed within the relevant culture through interactions with people in the relevant community. From his perspective, creativity is seen as a skill that can be learned and developed over time through relevant cultural practices, rather than primarily as an innate trait. Furthermore, it is important to emphasize that the promotion of domain-specific creativity in schools requires the establishment of a context that is specific to the given domain so that students can acquire and enhance such creativity. It is worth noting that some characteristics common to creative problem solving, such as flexibility, fluency, originality, and elaboration, are shared by students. Recent literature also indicates that creativity correlates closely with emotional and affective states (Ivcevic, 2022; Smith et al., 2022; Yeh et al., 2015).Therefore, assessments of creativity should incorporate data on the emotional and affective state of subjects to comprehend and endorse students' creative skills objectively.

Taken together, domain-specific creativity can be better assessed in educational settings under these conditions: First, an appropriate context for domain-specific practice must be provided. Second, active feedback must be provided to scaffold the development of creativity. Third, the shared features of creative problem solving need to be assessed in relation to emotional status. While it will be discussed further in detail, a neuroscientific approach to game learning analytics is better suited for evaluating domain-specific creativity as the game environment simulates domain practices and provides real-time feedback. Additionally, the digital game environment allows researchers to gather various real-time data, including active brain data associated with problem-solving traits.

Assessing creativity in a domain-specific context is a challenging task that current methodologies often struggle to address sufficiently(Baer, 2012). More targeted and nuanced assessment methods are necessary. To do so, there is a growing interest in assessments that provide immediate and dynamic feedback to support creativity development (Rosar & Weidlich, 2022; Shute & Rahimi, 2021; Songkram, 2015; Walsh et al., 2017).

Hence, this paper aims to analyze and discuss essential elements of domain-specific creativity assessment, and investigate the possibilities that game learning analytics, such as neuroscientific analysis techniques, offer for gauging creativity through a game-based environment. To provide a detailed comprehension of this intricate topic, this paper initially examines the constraints of traditional methods in evaluating domain-specific creativity's contextual significance, scalability, and depth. The subsequent discussion outlines the potential of game-based learning environments as a feasible platform for creativity assessment. Next, the integration of neuroimaging technology with game-based assessments is reviewed and explored as a promising approach for assessing and promoting creativity. By utilizing advanced neuroimaging techniques, deeper insights can be gained into the neural mechanisms that underlie creative processes, thereby broadening the scope and depth of assessments. The integration also presents an opportunity to elucidate the relationship between creativity and emotions. The incorporation of emotional and affective elements within neuroscientific approaches to creativity introduces an additional level of complexity to the context of the specific domain and emphasizes the requirement for comprehensive assessment tools. As an example of an integrated approach, the study presents a specific case of early domestic game learning analytics. The study uses fNIRS, log data, and screen data analyses to clarify how data obtained in real-time from a game-based learning environment can provide meaningful understanding of students' creative abilities and learning style. Prospective research pathways are explored and limitations inherent to the field of neuroscientific game learning analytics are acknowledged in the paper's conclusion.

Methods

I conducted a methodological review using a systematic approach as suggested by Cooper (2015) for synthesizing the literature. To ensure credibility, I employed a modified procedure of the Preferred Items for Systematic Reviews and Meta-Analyses (PRISMA) statement. The procedure included four steps: identification, screening, eligibility, and inclusion/exclusion decisions. During the identification phase, keywords such as "game analysis," "neuroscience," "fNIRS," and "creativity" were searched for in reputable databases such as PubMed, ERIC, and Google Scholar. The use of game learning analytics for domain-specific creativity through a neuroscientific approach is a recently emerging research area (Buckingham Shum & Deakin Crick, 2016). It combines interests in domain-specific creativity, game-based learning environments, analytics, and neuroscientific and neurocognitive approaches. To address the limited number of studies covering all relevant domains, I curated a collection of studies that addressed related areas, ultimately filtering the most pertinent research for inclusion in Table 1. Because this field is rapidly evolving due to concurrent technological advancements, I focused my analysis on studies published from 2019 to 2023, while also including seminal theoretical studies that are widely recognized and cited. To determine the most relevant studies, I utilized a systematic review software and employed the labeling and voting functions. During the screening and eligibility steps, all selected articles were downloaded and evaluated. The articles underwent screening to assess their suitability for research purposes. Excluded were technical reports, commentaries, and book reviews. Articles written in English and Korean were included. Academic utility was assessed by examining journal indices and citation data. During the inclusion/exclusion phase, the author conducted data assessment and analysis procedures that were subsequently verified using an AI-powered research tool (Mudunuri et al., 2023). The chosen articles can be found in Table 1.

Table 1. Areas of interests

Fields	Author(s) (Year)
Domain specific creativity Measure	Agnoli&Mastria (2022), Zielinska, Lebuda & Marwowski (2022)
Game Learning Analytics (GLA), Creativity	Rafner et al. (2023,2022,2020), Weinstein et al (2022), Abreu&Barbos (2022), Marrone & Cropley (2022) Shute, Rahimi & Smith (2019) Lee (2019) Shute, Fengfeng & Wang (2017)
Neuroscience, Creativity	Zhao et al. (2023) Wang et al. (2019) Tempest&Radel (2019) Beaty, Seli & Schacter (2019)
Neuroscience, Creativity, GLA	Fan et al (2023), Circugno et al (2023), Xie et al. (2022), Kober et al (2020)
Emotion, Creativity	Lloyd-cox Pickering, & Bhattacharya (2022), Missier et al (2022), Yin et al (2022)
Emotion, Neuroscience	Rihui et al. (2021), Reindl et al. (2018), Nozawa et al. (2016)
Emotion, Creativity, Neuroscience	Ruotsalo et al. (2023), Ivcevic (2022)
Emotion, GLA	Henderson et al (2019), Henderson, Emerson & Rowe (2019)
Neuroscience, GLA	Ninaus et al (2014)
Fields	Author(s) (Year)
Emotion, Neuroscience, GLA	Handerson et al. (2019)
Emotion, Neuroscience, GLA, Creativity,	Duan et al (2022), Yech et al (2015)

Limitations of Traditional Methods in Assessing Domain-Specific Creativity

The multifaceted and context-dependent nature of creativity renders it a challenging construct to assess accurately (Baer, 2012). Traditional assessments of creativity, often in the form of pen-and-paper tests, have been widely used and supported by extensive research (Plucker, 2023). Yet, these traditional methods come with a set of limitations that cannot be overlooked (Plucker & Runco, 1998), particularly for assessing domain specific creativity. The limitations include: (1) Lack of contextual relevance: Traditional assessment methods often employ generic tasks that are devoid of the specific challenges and complexities inherent to specialized domains such as science, art, or technology (Rafner et al., 2022). For instance, Zeng et al. (2011) pointed out that a generic creativity test may focus on divergent thinking through abstract problems, which bear little resemblance to the real-world challenges faced by professionals in specialized fields such as science or art. A general Divergent Thinking (Guilford, 1975) test might ask participants to list as many uses as possible for a common object like a paperclip. While this task may measure certain aspects of general creative thinking, it falls short in assessing how this ability relates to specific fields. This lack of contextual relevance severely undermines the ecological validity (i.e., the validity in real world settings) of such assessments, rendering them less effective in gauging creativity within specialized fields(Plucker & Runco, 1998; Rafner et al., 2022). In addition, the absence of assessments that capture contextual relevance hampers educators' ability to design and provide targeted feedback for fostering domain-specific creativity (Rafner et al., 2022). (2) Inadequate Scalability for Specialized Assessments: While traditional methods may be suitable for broad, general assessments of creativity, they often falter when applied to specialized domains (Plucker & Runco, 1998; Rafner et al., 2022). One primary reason is the requirement for expert human raters who possess domain-specific knowledge. The involvement of such experts is not only time-consuming but also financially impractical for large-scale evaluations. This limitation restricts the scalability of traditional methods, making them less feasible for extensive, domain-specific assessments (3) Insufficient Depth: Traditional methods often capture only the surface-level aspects of creativity, such as fluency and originality, without delving into the nuanced skills and domain-specific knowledge that are critical to specialized creative performance (Baer, 2012). For example, a traditional test may measure one's ability to generate novel ideas but may not assess the applicability or feasibility of these ideas within a specific domain. This lack of depth compromises the predictive validity of the assessment, limiting its utility in forecasting real-world, domain-specific creative performance. (4) Cultural and Linguistic Bias: Many traditional tests are language-based and may not be culturally sensitive, making them less inclusive and potentially inaccurate in assessing domain-specific creativity across diverse populations (Rafner et al., 2022). In addition to these limitations in assessing domain-specific creativity, the traditional assessments are usually static, offering a one-time snapshot of an individual's creative abilities without providing any real-time feedback. This absence of dynamic feedback can be a significant drawback for creative thinking or skill development.

The Promise of Game-Based Learning Environments in Assessing Domain-Specific Creativity

Compared to traditional assessments, game-based learning environments offer a significant advancement in the assessment of domain-specific creativity (Abreu & Barbosa, 2022; Emerson et al., 2020; Kim et al., 2022). These digital platforms combine various features that address the limitations commonly found in traditional methods. Utilizing advanced technologies and informed by educational theory, game-based learning environments provide a more nuanced, scalable, and dynamic framework for assessing creativity in specialized fields such as science, technology, engineering, arts, and mathematics (Abreu & Barbosa, 2022; Emerson et al., 2020; Kim et al., 2022).

First, one of the most salient advantages of game-based learning environments is their ability to simulate real-world (Kim et al., 2022; Rafner et al., 2022; Shute & Rahimi, 2021), domain-specific challenges. Game-based assessments can be designed to reflect the complexities and intricacies of specific domains. This enhances the ecological validity of the assessment, making it more predictive of real-world creative performance within that field. For example, *Tyto Online* fosters authentic learning by immersing students in a virtual setting where they can directly interact with scientific phenomena and address real-world challenges (Villa et al., 2023). Students can collaborate with a virtual botanist to tackle food scarcity issues, thereby gaining valuable insights into genetics. They also investigate climate change by examining coral bleaching and conducting pertinent experiments (Drogaris et al., 2023; Villa et al., 2023). The educational experience is designed around solving genuine problems, offering students a meaningful and applied learning context. Students are tasked with completing a sequence of quests based on science-related content. Teachers can track students' progress through these sequences using their dashboard. The dashboard also allows them to view scientific models, arguments, and explanations created by the students. Although Tyto Online is not specifically designed to evaluate scientific creativity, certain aspects of the game demonstrate the capability of assessing domain-specific creativity. For example, the game offers challenges that require imaginative solutions based on scientific principles, promoting students to use their creative thinking skills in subjects such as Biology or Earth Sciences. The platform also prompts students to engage in rapid hypothesis testing, iteration, and scientific explanation—key components of the scientific method. Teachers can offer students immediate and dynamic feedback in both the game-based and classroom learning contexts. Such feedback not only facilitates students' comprehension of science but also helps them refine their ideas and grasp the methodology of scientific enquiry, thus fostering scientific creativity. As a result, game-based learning environments can offer personalized, timely feedback based on individual performance. This feature is especially advantageous for domain-specific creativity, where prompt feedback can assist in honing specialized skills and strategies in real-time, thus contributing to the iterative process of creative development. The digital nature of game-based learning environments permits the implementation of sophisticated algorithms and artificial intelligence to automate the evaluation process. This scalability makes it feasible for large-scale, domain-specific assessments, overcoming one of the significant limitations of traditional methods that often require manual evaluation by expert human raters. For instance, *Physics Playground* is a game-based learning environment for learning Newtonian physics (Shute et al., 2019; Shute & Rahimi, 2021). The game implements a stealth assessment approach to evaluate students' comprehension of physics concepts, problem-solving abilities, and creativity competencies in physics (Shute et al., 2017, 2019; Shute & Rahimi, 2021). Stealth assessment refers to the unobtrusive and transparent integration of assessment mechanisms within the game environment for seamless evaluation (Shute & Rahimi, 2021). The evaluation gathers information on player conduct and effectiveness without disrupting the game's progression. It is often grounded in Evidence-Centered Design (ECD), a framework that outlines the relationship between what is being assessed, the tasks or situations that elicit evidence of this construct, and the data that will be used as evidence (Shute et al., 2017). Unlike traditional assessments that offer a static, one-time snapshot of creative abilities, stealth assessment can provide real-time, formative feedback. This dynamic feedback can guide learners in refining their creative approaches and solutions. In Physics Playground, when students interact with the game, the stealth assessment mechanisms provide real-time feedback (Shute et al., 2017, 2019; Shute & Rahimi, 2021). For example, if a student successfully applies a physics principle to solve a problem creatively, the game can reinforce this with positive feedback, encouraging further creative problem-solving. Game-based environments offer diverse modes of expression beyond mere verbal communication, encompassing visual, spatial, and interactive elements (Kim et al., 2022; Shute et al., 2019). This multiplicity allows for a more holistic assessment of domain-specific creativity, accommodating various talents and mitigating linguistic and cultural biases. The digital architecture of these environments facilitates real-time data collection, spanning behavioral metrics to neuroimaging data, providing invaluable insights into the unfolding creative process, essential for domain-specific assessments. For instance, Tyto Online allows students to engage with elements in a spatial context, such as optimizing plant growth through specific arrangements, exemplifying visual-spatial expression. The game's interactive features enable players to adjust variables in experiments or select appropriate components, facilitating creative expression within a scientific context. Similarly, Physics Playground requires players to sketch or construct solutions to physics problems, requiring a solid understanding of spatial relationships. The game's real-time object manipulation provides a dynamic platform for expressing creativity in physics. Students can adjust variables such as angle and force. Games that use visual features can reduce the need for language-based assessments, minimizing linguistic bias and benefiting individuals from diverse language backgrounds. This creates a more equitable assessment environment. In addition, a lower language proficiency requirement can reduce assessment anxiety. Students are more likely to feel that they are being assessed fairly. The engaging nature of the game environment reduces anxiety by transforming the assessment from a test to an immersive learning experience. The result is an inclusive and less anxiety-provoking environment that can accurately assess domain-specific creativity.

Additionally, game-based environments can adjust in real-time to meet the individual's performance and needs

(Abreu & Barbosa, 2022; Kim et al., 2022; Rafner et al., 2022).This flexibility ensures that the challenges provided take into account the players' skill level, thereby creating an ideal setting for domain-specific creativity to flourish and be evaluated. Additionally, game-based environments may incorporate ethical dilemmas and domain-specific decision-making to enhance the assessment of domain-specific creativity. This feature is especially significant in fields such as bioengineering or artificial intelligence, where ethical considerations are crucial to the creative process. For instance, within the context of *Crystal Island*, a game-based learning environment that centers on microbiology, real-time data gathering, and adaptive learning are utilized(Emerson et al., 2020). As students maneuver through the game and solve microbiology-related issues, their interactions are continually monitored. This involves not only students' responses to questions or puzzles, but also their navigation behavior tracked through log files, the time they allot to specific tasks monitored by eye-tracking techniques, and their utilization of in-game resources determined from facial expressions (Emerson et al., 2020; Henderson et al., 2019). The game's adaptive learning algorithms use these real-time data to adjust the presented challenges' difficulty level and type for each student (Emerson et al., 2020; Henderson et al., 2019). For example, if a student rapidly solves a sequence of microbiology puzzles, the game could introduce more intricate problems or scenarios that demand a more profound understanding of the subject matter. Conversely, if a student encounters difficulty, the game may offer hints or scaffolded support to aid them in understanding the concept without experiencing frustration.

Multimodal Game Learning Analytics for Assessing Domain-Specific Creativity

Assessing domain-specific creativity is a multifaceted task influenced by cognitive functions such as attention, decision-making, memory storage, and retrieval (Boccia et al., 2015). Emotional states can either facilitate or impede creativity (Ivcevic, 2022; Ruotsalo et al., 2023; Smith et al., 2022). Therefore, the utilization of multimodal learning analytics in game-based learning environments, which collect various cognitive and emotional data, offers a promising approach for a more comprehensive assessment. These environments facilitate the collection and analysis of a wide range of real-time data, thus enhancing the evaluation of domain-specific creativity.

Multimodal analytics utilize various data channels, such as physiological measurements such as EEG, fMRI, fNIRS, as well as recordings of eye movements and facial expressions(Abreu & Barbosa, 2022; Emerson et al., 2020). Data like this have proven their effectiveness in predicting learning outcomes and can aid in designing pedagogical interventions that cater to cognitive and affective aspects of learning. Palaude et al. (2022) employed a multimodal analytics strategy to evaluate creative problem-solving in the framework of modular robotics. The collected data consisted of audio and video recordings, log files, eye-tracking data, and surveys. The objective of this study was to obtain a comprehensive understanding of the cognitive and behavioral factors within the process of problem-solving. The findings confirmed that multimodal data analysis could reliably forecast and simulate creative problem-solving conduct. In particular, the eye-tracking data proved to be indicative of generated solutions' quality, highlighting the importance of attentional focus in creative problem-solving (Palaude et al., 2022). The strategies applied by participants were further analyzed through the log files, offering valuable insights into the nature of problem-solving behaviors.

One of the primary functions of assessment is to offer immediate feedback, enabling learners to adjust their learning strategies. Recent advancements in predictive modeling using multimodal learning analytics allow both educators and students to anticipate learning performance (Dias et al., 2020; Sghir et al., 2022; Xie et al., 2022). This predictive capability facilitates the modification and refinement of learning strategies, ultimately leading to improved performance.

Augmenting Game-Based Assessments with Neuroimaging: A Multifaceted Approach to Assessing Domain-Specific Creativity

As previously described, the burgeoning field of digital game-based learning has garnered significant attention for its potential to foster creativity (Abreu & Barbosa, 2022; Rafner et al., 2023, 2020; Shute & Rahimi, 2021). Numerous studies have extolled the positive impact of digital games on enhancing creative thinking and problem-solving skills. For example, Behnamnia and colleagues (2020) conducted a systematic review of 20 articles and reported that digital game-based learning can improve both creative and critical thinking skills in preschool children. Similarly, Lee (2019) investigated how a digital game, "*Her Story*" was used to promote creativity in English writing among university students. Upon analyzing the originality, flexibility, and elaboration in the students' writing, Lee found that the use of the digital game was effective. The students also reported increased motivation and engagement in their writing tasks. Although the results are encouraging, it is not clear whether the game environment is the catalyst for enhanced creativity; it could be plausible that the participants already had these creative abilities. The lack of real time data showing the effects of gaming on creativity is a significant gap in current research.

The studies using neuroscience methods can investigate how these digital environments might affect creativity in specialized areas by examining brain activity. This gap is particularly noteworthy given the established relationship between creativity and neural activity in the prefrontal cortex. There is a widespread agreement that a brain network is responsible for creativity (Beaty et al., 2019; Xie et al., 2022). This means that no single part of the brain that is strictly associated with creativity. However, the prefrontal cortex, specifically regions such as the Ventrolateral Prefrontal Cortex (VLPFC) and Frontopolar Area (FPA), has been known to be closely associated with creative actions such as idea generation (Fan et al., 2023), metaphor generation and musical improvisation (Ciricugno et al., 2023). Boccia and colleagues (2015) examined the neural underpinnings of creativity across different cognitive domains—musical, verbal, and visuo-spatial. The study suggests that different forms of creativity stimulate different regions of the brain. Musical creativity stimulates regions in the left and right medial frontal gyrus, as well as other specific areas in the left hemisphere. Verbal creativity primarily activates areas in the left hemisphere, such as the prefrontal cortex and several other regions. Visuospatial creativity activates regions in the right middle and inferior frontal gyri, along with the bilateral thalamus and left precentral gyrus. This finding suggests that creativity is supported by complex neural networks and that different domains of creativity depend on different brain regions. Their findings underscore the concept of domain-specific creativity by showing that different forms of creativity - musical, verbal, and visuospatial - activate unique neural networks in the brain. This suggests that creativity is not a single construct. Rather, it is a multifaceted, domain-specific ability. Each form of creativity relies on specialized neural pathways and brain regions. This reinforces the idea that fostering creativity requires domain-specific assessments and interventions. These neuroscientific findings provide empirical support for the theoretical construct of domain-specific creativity, suggesting that different creative domains not only require different cognitive processes, but also engage different neural mechanisms. Similarly, Tempest and Radel (2019) used functional near-infrared spectroscopy (fNIRS) to investigate the effects of enhanced imaginative states and frontopolar cortex activation. The study hypothesized a causal relationship between the induced brain activity and creative thinking. The study was conducted with two task conditions: a cued condition in which participants were instructed to "think creatively" and an uncued condition in which participants generated the first or most prominent verb that came to mind. They found that semantic scores were higher in the cueing group (more creative), were positively associated with the results of other creativity tests. The results indicate that fNIRS is a promising tool for assessing creativity, especially when used with a verb generation task. The positive correlation between fNIRS results and established measures of creativity, such as the Biographical Inventory of Creative Behaviors (BICB), provides empirical support for the potential of fNIRS as a reliable and complementary tool for assessing creative cognition.

Wang and colleagues (2019) used fNIRS to study the neural correlates of the embodied metaphor "breaking the rules" and its impact on creativity. They used virtual reality (VR) technology to create three conditions, including the "break-wall" condition where participants shattered virtual walls. Participants solved a problem requiring creativity while navigating virtual environments and wearing an fNIRS device to measure neural activity. The "break-wall" condition resulted in better creative performance compared to other conditions. Weaker activation was observed in the frontopolar cortex, the dorsolateral prefrontal cortex, and the somatosensory association cortex under the "break-wall" condition. The study indicated that physically breaking a wall activated the conceptual metaphor of "breaking the rules," resulting in an impact on brain activities related to breaking rules and enhancing creativity. The authors concluded that embodied metaphors, specifically "breaking the rules," could influence creative thinking, and fNIRS measurements of brain activity supported this finding. The results of this study are uniquely valuable for game-based evaluation due to the utilization of VR technology, which can be replicated in a gaming environment.

While the number of neuroscientific studies focusing on domain-specific creativity is limited, the possibility of synthesizing findings from neuroscientific studies on game-based learning with those on creativity is promising. Although neuroscientific research has not extensively investigated domain-specific creativity, it has shed light on the cognitive and affective functions mediated by the frontal lobes. Functions such as problem-solving, working memory, and emotional regulation are often integral to creative processes.

By synthesizing the findings of these studies, and particularly those studies conducted in a game-based learning environment, one could gain a more nuanced understanding of how game-based learning environments might be designed to stimulate the specific regions of the frontal lobes that are associated with domain-specific creativity. For example, according to Boccia and colleagues' (2015) findings, the activation of distinct brain regions is associated with different domain-specific creativity, such as musical, verbal, and visuospatial. This means that a domain-specific game-based learning environment enables researchers to gather brain region-specific creativity data. This could lead to more targeted and effective interventions for fostering domain-specific creativity, leveraging the adaptability and engagement offered by digital game-based learning environments.

Moreover, the real-time data collection capabilities of neuroimaging techniques could offer dynamic feedback mechanisms. Such feedback could not only enhance the learning experience but also provide real-time assessments of creative abilities, thereby fulfilling the growing demand for more nuanced and dynamic methods of assessing domain-specific creativity. That is, a growing number of research explores the use of neurofeedback to enhance targeted brain areas. Neurofeedback refers to the immediate, real-time provision of data regarding brain activity to participants and/or overseeing researchers. For instance, fNIRS system can capture hemodynamic responses (i.e., changes in blood flow and oxygenation) For example, Li and colleagues (2023) has looked at the potential of neurofeedback to improve spatial working memory by targeting the dorsolateral prefrontal cortex, a region also implicated in creative thinking.

Emotion and Creativity in Game-Based Learning: A Neuroscientific Perspective

The burgeoning field of neuroscience research has increasingly focused on the complex interplay between emotional states and domain-specific creativity within digital game-based learning environments. A growing body of work has already begun to explore this intricate relationship. For instance, Yeh and colleagues (2015) investigated the role of stress and negative emotions, such as frustration and anger, on creativity within game-based contexts. They found that cortisol concentration and working memory positively influenced creativity. Although their study did not directly measure brain activity, it employed a neuroscientific approach by assessing hormone levels. In a subsequent study, Yeh and colleagues (2019) examined how the integration of mindful learning in digital game-based learning environments could foster creativity. Mindful learning, as they define it, involves active, open attention to the present moment and awareness of one's thoughts, feelings, and actions. This state of mindfulness seemed to generate positive emotions like accomplishment, self-efficacy, and confidence, which acted as motivational drivers for further creative engagement.

This focus on the neurobiological underpinnings of creativity is further supported by the work of Yin and colleagues (2022), who used fNIRS to investigate the impact of threats on creativity. Their findings indicated decreased activation in brain regions commonly associated with creative thinking, such as the prefrontal cortex and the anterior cingulate cortex. This suggests that negative emotions induced by threats can inhibit creative processes, thereby highlighting the significant influence of emotional states on cognitive elements like attention, memory storage and retrieval, and decision-making.

Additional research has posited that emotional states conducive to creativity often arise from close and friendly social relationships. For example, Duan and colleagues (2020) employed fNIRS to explore the impact of romantic relationships on creativity and cooperation. They found that romantic partners outperformed pairs of strangers in measures of originality, fluency, and cooperation. Enhanced brain synchronization in regions like the frontopolar cortex and the right temporo-parietal junction was observed among romantic partners, and this synchronization was positively correlated with creative problem-solving performance. Zhao and colleagues (2023) explored the influence of interpersonal relationships and individual characteristics on group decision-making in uncertain conditions. The study employed the turn-based Balloon Analogue Risk Task (BART) and utilized fNIRS-based hyperscanning to measure inter-brain synchronization (IBS) patterns at the prefrontal cortex (PFC). The study revealed that dyads in the friend group exhibited a propensity for uncertainty aversion when compared to the stranger group. The fNIRS study showed that IBS patterns at the left inferior frontal gyrus (l-IFG) and medial frontopolar cortex (mFPC) were influenced by interpersonal relationships. These IBS patterns were shown to predict decision-making propensities in both friend and stranger groups. The study also identified that social value orientation (SVO) played a moderating role in the mediation effect of dyad closeness on decision-making propensity. Although the study did not explicitly measure creativity, it showed that close and friendly interpersonal relationships influence the decision-making process.

The established impact of positive emotions, often stemming from close social relationships, on creativity is particularly intriguing given the growing research on game-based learning environments. Chen and colleagues (2020), for instance, explored the relationship between emotions and science learning outcomes in a game context, finding that positive emotions correlated with better learning outcomes.

In light of these findings, there is a pressing need for further research to refine our understanding of the relationship between emotional states and creativity, especially within digital game-based learning environments. Such research could provide invaluable insights for optimizing these environments to foster domain-specific creative competencies. Therefore, a concerted research effort that integrates neuroscientific methods is warranted to elucidate the complex interplay between emotional states and creativity.

Example of Neuroscientific Game Learning Analytics

To illustrate the application of neuroscientific game learning analytics, this paper provides a brief overview of my recent research project as an early domestic study example (Ryu, 2020, 2021, 2019). The project aimed to explore the educational and neurocognitive implications of using the sandbox-type game, *Minecraft*, as a platform for both individual and team-based learning activities. Utilizing a multimodal game learning analytics approach, the study integrated fNIRS neuroimaging data, game log data, and screen recordings to examine the relationships between Kolb's learning styles (Kolb & Kolb, 2005), Pintrich's model of achievement goal orientations (Pintrich, 2000), and creative competencies exhibited during the learning process. Individuals navigate a four-stage cycle of learning—concrete experience, reflective observation, abstract conceptualization, and active experimentation—each leading to one of four learning styles: accommodating (hands-on and intuitive); diverging (imaginative and people-oriented); converging (practical and problem-solving); and assimilating (theoretical and logical). Pintrich's model identifies four types of achievement goals: mastery goals (aimed at gaining competence in a given subject); mastery-avoidance (avoidance of losing mastery or falling short of their own standards); performance goals (demonstrating competence relative to others); and performance-avoidance goals (avoiding the demonstration of incompetence).

The research employed an Explanatory Sequential Mixed Method, combining quantitative analyses of fNIRS data and game log data with qualitative analyses of screen recordings. The study involved 43 undergraduate students from K University, enrolled in courses focusing on educational online game content design. Real-time log data and game-playing recordings, including in-game chat, were collected throughout the course. fNIRS data were gathered from nine selectively chosen participants while they engaged in creative tasks within Minecraft.

The findings revealed:

1) Significance of fNIRS Neuroimaging Data: The fNIRS neuroimaging data revealed nuanced and significant brain activation patterns in the regions related to creativity. The patterns were closely associated with different Kolb learning styles and achievement goal orientations. Specifically, these activation patterns were most prominent in the Ventrolateral

Prefrontal Cortex (VLPFC) and the Dorsolateral Prefrontal Cortex (DLPFC) regions of the brain. These regions are known for their roles in cognitive flexibility, decision-making, and working memory, among other functions. The data suggested that individuals with different learning styles and goal orientations engaged these cognitive processes to varying degrees during both individual and team-based tasks. First, students with adaptive learning styles and mastery-approach goal orientations (Group A) exhibited higher Minecraft task scores and greater brain activity in the VLPFC and DLPFC regions during group tasks compared to individual tasks. In contrast, students with converging learning styles and performance-approach goal orientations (Group B) showed higher task scores in group tasks but greater brain activity during individual tasks, specifically in the DLPFC region. Lastly, those with assimilating learning styles and mastery-approach goal orientations (Group C) demonstrated higher task scores and greater brain activity in individual tasks, particularly in the DLPFC region. The DLPFC is responsible for the overall management of cognitive processes such as planning, cognitive flexibility, and working memory, indicating more active cognitive processes in Group A during group tasks and in Groups B and C during individual tasks. Second, all participants exhibited higher brain activity during creative tasks compared to simple tasks. The level of brain activity during creative tasks was highest in Group C, followed by Groups A and B. Notably, Groups A and C, which had mastery-approach goal orientations, showed higher brain activity than Group B, which had a performance-approach goal orientation, suggesting that a mastery-approach orientation may better facilitate creativity during challenging tasks.

2) Corroborative Evidence from Game Log Data and Screen Recordings: These datasets provided complementary evidence for the manifestation of creative competencies, allowing for a granular analysis of problem-solving approaches, collaboration, and creative thinking during both individual and team-based tasks.

3) High Correlation Between Log Data and Actual Activities: A strong correlation was observed between the log data and actual activities captured in screen recordings, suggesting that log data could serve as a reliable heuristic for identifying specific scenes where creative competencies were most vividly manifested.

The findings have pedagogical implications for fostering creativity in science education. They suggest the need for individualized learning systems that account for students' learning styles and achievement goal orientations. The research also highlights the utility of game-based learning environments for the rapid and convenient collection of data, facilitating focused analysis on meaningful scenes related to creative competencies.

One way to assess scientific creativity using game data is to analyze player interactions in a science-related context. This specialized analysis can focus on scientific reasoning and problem solving. The process begins by collecting and preprocessing data related to player interactions. Then, exploratory data analysis (EDA) using statistical and visualization techniques can be used to identify patterns in scientific inquiry. Statistical methods such as correlation and regression can be used to analyze the relationships between scientific concepts in players' creativity. Data mining techniques such as clustering and sequence analysis (Alonso-Fernández et al., 2019; Emerson et al., 2020; Kim et al., 2022) reveal groups of players based on their scientific problem-solving approaches and the steps they take in scientific inquiry. Machine learning algorithms, including classification models and predictive modeling, are critical for predicting players' future scientific creativity and problem-solving skills(Alonso-Fernández et al., 2019; Emerson et al., 2020; Kim et al., 2022). This analysis helps to understand how players hypothesize, experiment, and draw conclusions, as well as their ability to creatively apply scientific knowledge. It provides insight into current levels of scientific creativity and improves the predictive power of future creativity.

Neuroscience data can further enrich this approach by measuring brain activity with EEG and fMRI, analyzing eye movements with eye-tracking technology, and monitoring physiological responses such as Heart-Rate Variability and skin conductance (Lopes & Boulic, 2020). Combining neuroscience data with other learning analytics provides a comprehensive view of the learning process and individual differences in scientific creativity. This integration can be used to identify brain regions associated with creative problem solving, correlate eye movements with creative ideation, and investigate the relationship between emotional arousal and creativity. However, ethical considerations and privacy are critical when using neuroscience data in educational settings.

Discussion and Concluding Remarks

The integration of game-based learning environments with advanced neuroimaging techniques, such as fNIRS, presents a groundbreaking opportunity to assess domain-specific creativity (Kober et al., 2020; Nebel et al., 2016; Ninaus et al., 2014; Reindl et al., 2018). This multidimensional approach enhances both academic discourse and practical applications in creativity assessment by incorporating emotional and affective dimensions through neuroscientific methods (Abreu & Barbosa, 2022; Duan et al., 2022; Emerson et al., 2020; Kober et al., 2020; Ruotsalo et al., 2023; Yeh et al., 2015; Yin et al., 2022).

The theoretical framework of this paper argues that implementing neuroscientific measures can provide dependable and accurate indications of cognitive and creative processes. This validation is crucial for the progression of domain-specific creativity theories as it opens avenues for interdisciplinary research across educational psychology, learning analytics, and neuroscience.

From a pedagogical standpoint, the discussed methodologies promote a more nuanced and personalized approach to education. Educators can enhance the effectiveness of adaptive learning environments by comprehending the neural correlations between creativity and learning styles (Ryu, 2019). This is especially relevant in the realm of scientific education, where cultivating creativity has become a crucial academic goal. In the future, research could aim to customize standardized metrics and rubrics for specific domains like science, art, or technology, while exploring the potential of real-time analytics to provide dynamic feedback during the creative process. As our knowledge of the neural mechanisms involved in creativity grows, integrating numerous neuroimaging techniques into game-based learning environments could provide more in-depth assessments. Based on the emerging evidence linking emotional states to creativity, future research could explore capturing and integrating emotional and affective data to gain a more comprehensive understanding of the creative process.

Indeed, students from diverse cultural and linguistic backgrounds could benefit greatly from the application of various learning analytics techniques to the assessment of domain-specific creativity and potentially other 21st century competencies. Such an approach allows for a more nuanced understanding of student performance and skills, overcoming the limitations of traditional assessment methods. In addition, the immediate neural and/or emotional feedback provided by neuroimaging can support both teachers and students with limited communication skills, for example. Even if students do not explicitly report their difficulties and tensions, teachers may be able to get some clues from the neuro/emotional feedback. In this way, a learning path can be personalized accordingly.

Nonetheless, this approach presents limitations, requiring expert analytical tools for effective interpretation due to the multidimensional nature of the collected data. The expenses linked to advanced neuroimaging methods and specialized game-based settings can be a deterrent. Hence, one must approach these issues with careful consideration and planning. It is important to address ethical issues around consent, data security, and the potential misuse of sensitive information effectively (Walsh et al., 2017). The combination of diverse technologies may pose technical challenges, thereby impacting the reliability and validity of assessments. Finally, game-based environments have the potential to offer more culturally and linguistically sensitive assessments. However, it is crucial to carefully design and implement these environments to ensure inclusivity. It is also important to consider the ethical implications of data privacy and the use of neuroimaging in educational settings.

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Conflicts of Interest

The author(s) declared no conflicts of interest.

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