Game-Based Approaches to Enhancing Public Understanding of Science: A Descriptive Literature Review

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Abstract

With prominent looming global issues such as climate change and COVID-19, public understanding of science (PUS) is increasingly perceived to be vital for humanity to address and adapt to global wicked challenges. Compared to conventional approaches that struggle with public engagement, games can potentially remedy this by proactively engaging players towards more fruitful performance in and outside games. While the employment of game-based approaches in pedagogy in general is not a new development, gamifying PUS has only recently grown to relative prominence for its superiority in engaging the public with active science-derived interpretation, deliberation, and consequent action. To understand the state-of-the-art of this field, we conduct a systematic descriptive literature review of the extant corpus. We reviewed 29 papers and investigated their types of interventions, contexts, populations, and outcomes. The results overall indicate diverse yet imbalanced research focuses thus far, for which we discuss implications for future research.

Keywords: Public understanding of science, public engagement with science, game-based approach, gamification, literature review

1. Background and relevant work

Against the backdrop of emerging and developing global challenges, including climate change and COVID-19, that require science-driven interpretations and actions from the public to collectively combat the looming difficulties, in the present study, we focus on novel game-based solutions that have natural advantages to creating engaging experience for fruitful outcomes (Granic et al. 2014; Hamari, 2019) to provide a state-of-the-art review of the relevant research and practice. The overarching research question we seek to answer is thereby "what do we know about the current research on gamifying public understanding of science?"

1.1. Public understanding of science

While *public understanding of science* (PUS) is nowadays commonly used as an umbrella term to describe the important interplay between the public and science, there have been several developmental phases where researchers and practitioners deliberate about its conceptualization, attributive problems, and possible solutions. As such, according to Bauer (2009), research and practice on PUS started with the goal of improving *science literacy* because publics were generally considered as ignorant of scientific knowledge (i.e., deficit model, see also Ziman, 1991). Yet, over the time, evidence amounted to suggest the ineffectiveness of relevant interventions to increase publics' science literacy, because instead of the "deficit" assumptions, the public simply regarded most science as irrelevant to themselves (Brossard & Lewenstein, 2009; Turney, 1996). In this respect, the PUS research progressed to focusing on enhancing public *understanding* through the lens of attitudinal changes in appreciating the relevance of scientific knowledge to individuals, followed by promoting *science-in-society* that seeks to create participatory decision-making about scientific matters across the society (Bauer, 2009).

Along these developmental processes, there has been a shift of focus from scientists delivering scientific information to educate publics as authority figures, to engaging the public by recognizing their respective expertise in order to make science more relevant and salient in their everyday life (Brossard & Lewenstein, 2009). Such as a change of mindset marks an important step in rethinking the equally important role of the public (as compared to elite scientists) in scientific knowledge production and communication, as well as providing invaluable access for the part of public (e.g., traditionally marginalized groups) to various types of informal

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science education opportunities (Brossard & Lewenstein, 2009; Nadkarni et al., 2019; Sclove, 1995).

With the strategic importance of engaging the public with science in mind, it is imperative for scientists to build an open and dynamic dialogue with the public about not only scientific *findings* but also scientific *processes* (Durant et al., 1989; Leshner, 2003) to foster mutual learning and empowered skill development (McCallie et al., 2009). To this end, a variety of media have been utilized to increase public understanding of and engagement with science, including the science-oriented TV and news coverage (Retzbach & Maier, 2015), science blogs (Kouper, 2010), and more interactive formats such as the "Ask Me Anything" section on Reddit (Lai et al., 2020). Despite their great potential, such technology-mediated communication that might lack powerful mechanisms to engage the public, has been found insufficiently able to induce desirable attitudinal change (Retzbach & Maier, 2015), and can be subject to influences imposed by one's ingrained characteristics such as social identities permeated in public discourses (Chen et al., 2022).

As such, the public, as information receivers, can be subject to their bounded rationality characterized by cognitive limitations on both knowledge and capacity in a given structure of environment (Simon, 1990). On the one hand, in the face of uncertainty (e.g., science-related knowledge unfamiliar to the public), people would become vigilant towards information incongruent with their existing knowledge (Mercier, 2020). On the other hand, the contemporary media environment struggles with unprecedented complexities owing to problematic rises of misinformation about science (West & Bergstrom, 2021), which interferes with how people receive, internalize, and share science information to others in an accurate and responsible manner. Against this backdrop, researchers have cautioned the *bounded* nature of PUS (Bromme & Goldman, 2014), urgently calling for innovative digital solutions to overcome it (Scheufele et al., 2021).

1.2. Game-based approach

With the general ludic turn, gamification of contemporary culture (Raessens, 2006; Hamari, 2019), games are increasingly adopted for sustainable development. *Gamification* (Hamari, 2019) as an umbrella-level concept covers a few separately developed strains of game-based research and practice. On one hand it covers the practices of applying game design and game design elements of games in different non-game contexts (Deterding et al., 2011), but on the other hand, it also covers approaches that aim to apply more fuller-fledged game applications, often called e.g. *serious games* or *simulation games*.

The positive effects of gamification are commonly traced back to the engaging interactivity of various game elements (King et al., 2010) that may facilitate positive psychological outcomes (Granic et al. 2014; Hamari, 2019) often connected with the satisfaction of humans' intrinsic motivational needs, i.e. need for competence, autonomy, and relatedness (Deci & Ryan, 1980; Xi & Hamari, 2019; Ryan et al., 2006), or with the three analogous dimensions of gaming gratification of achievement-, immersion-, and social-related needs (Bartle, 1996; Yee 2006; Hamari & Tuunanen, 2014). Beyond psychological gratification, game-based approaches are also believed to create gameful experiences (Högberg et al., 2019) conducive to developing people's cognitive (e.g., problem-solving; critical thinking), motivational (e.g., taking a long term view), emotional (e.g., staying positive), and social (e.g., cooperation) skills (Granic et al., 2014; Hamari, 2019). These skills are essential for the public to understand and engage with the scientific process that requires one's systematic knowledge of it. And in the long run, they contribute to not only individuals' inner growth but also holistic social development.

Reviews of the current corpus show promising results related to the effect of gamification in several domains, such as sustainable practices (Fernandez-Galeote et al., 2021), business (Wunderlich et al., 2020), healthcare (Johnson et al., 2019; Sardi et al., 2021) as well as more pertinently on areas closely related to public understanding of science such as education (Connolly et al., 2012), public participation (Hassan & Hamari, 2020; Thiel et al., 2016) and science education (Kalogiannakis et al., 2021; Legaki & Hamari, 2020).

Zooming into these pertinent contexts, the ***game-based education*** situates itself in classroom settings, and explores how game designs and gamification can be garnered to improve curriculum development (Gilliam et al., 2016), teaching strategies (Hamari & Nousiainen, 2015; Hébert & Jenson, 2019), students' in-class motivation (Huizenga et al., 2009), assessment of learning outcomes (Kalmpourtzis & Romero, 2020), and students' achievements in pertinent school subjects (Lei et al., 2022), among others. Over time, education researchers have investigated and advocated for the benefits of game-based approaches, compared to conventional instructional methods, in utilizing game features to overcome hierarchical power dynamics (Gkogkidis & Dacre, 2020) and thereby drive *engagement* of all involved parties (Abdul Jabbar & Felicia, 2015).

In another related domain—***citizen science***, game-based approaches have also been greeted with welcome and appreciation in that human intelligence can be valuable for completing small tasks that computers are less capable of performing via playful mechanics. Typical examples include games with a purpose (GWAPs, see Von Ahn & Dabbish, 2008) and gamified crowdsourcing (Morschheuser et al., 2016) that engage citizens' expertise to advance pertinent scientific inquiries.

Nevertheless, in PUS contexts, research thus far has indicated a rudimentary stage of implementing game-based approaches for current PUS purposes. For instance, Radchuk et al. (2016) analyzed 87 serious life science games and found a majority of them only featured basic game elements that encouraged user participation. Likewise, Scheliga et al. (2018) reviewed cases for crowd science projects (i.e., "[projects that] depend on volunteers who do not receive any form of pay…incorporate volunteers in the collection or annotation of scientific data," p.517) and found that there still existed numerous challenges to motivate people to participate in those projects. Therefore, albeit promising, how to better leverage game elements merits further investigations.

1.3. Research questions

Against these backdrops, summarizing the state-of-the-art research on game-based approaches to PUS helps to understand what has been achieved hitherto to illuminate future research and practice. Since Lasswell's model of communication (1948)—"Who says what in which channel to whom with what effect" (p.216) provides a great anatomy to aid analyzing critical components in a given phenomenon that involves interactions and communication among different entities, we accordingly proposed the following research questions (RQs):

RQ1: What game elements have been mainly used for PUS?

RQ2: In what contexts have game-based approaches been applied for PUS?

RQ3: For what population have game-based approaches been applied for PUS?

RQ4: What types of outcomes have been evaluated in implementing game-based approaches for PUS?

2. Method

2.1. Selection criteria and process

A descriptive literature review that summarizes the state-of-the-art empirical research (Paré et al., 2015) was conducted to answer the aforementioned research questions. Prior research suggests that the *Scopus* database yields a more comprehensive selection of relevant work compared to its counterparts such as *IEEE*, *ACM*, and *Springer* (Tomé Klock et al., 2021; Xiao et al., 2021), therefore, articles indexed in the *Scopus* were extracted for the present review based on the criteria (***C***) below.

C1*: *Scope of PUS. In light of the transition from the deficit model (Ziman, 1991) to recent discussions that highlight the importance of public engagement (e.g., Nadkarni et al., 2019), we considered the scope of PUS as encompassing not only science-related psychological processes but also pertinent participatory behaviors. More specifically, we took the definitions of "science" (i.e., "'Science' is understood in a broad way including the social sciences and humanities, technological and medical innovations, and scientific expertise on climate change, environment and health") and topical areas of PUS (e.g., "public perceptions, representations and assessments of science (e.g., knowledge, beliefs, attitudes and trust)" and "public engagement, collaborations of science and public, public participation in knowledge creation, innovation and governance (citizen science, responsible research and innovation)") by the leading journal *Public Understanding of Science* as the benchmark (Public Understanding of Science, n.d.) to specify our search terms. Example terms include "scien* communicat*," "scien* engagement*," and "scien* belief*."

C2: Scope of game-based approach. Since gamification can be considered as the umbrella term for game-based approaches (Hamari, 2019), we specified one search term as "gamif*" to retrieve gamification-based articles. Moreover, considering the conceptual and practical overlap between gamification and serious games that often simulate real-life events (Seaborn & Fels, 2015), we further included "serious gam*" and "simulation gam*" as the search terms to expand the search.

C3: Document type. We limited research articles eligible for review to be peer-reviewed full papers, i.e, conference papers ("cp"), journal articles ("ar"), or book chapters ("ch").

C4: Language. We limited research articles eligible for review to be written in English only.

Taken together, the final search string used for literature search was therefore as follows:

TITLE-ABS-KEY ((gamif OR "serious gam*" OR "simulation gam*") AND ("scien* communicat*" OR "scien* understand*" OR "scien* engagement*" OR "scien* citizen*" OR "citizen scien*" OR "scien* educa*" OR "scien* participat*" OR "scien* collabora*" OR "scien* knowledge" OR "scien* belief*" OR "scien* attitud*" OR "public understanding of science" OR "public awareness of science" OR "public engagement with science" OR "polulari*ation of science")) AND (LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "ch")) AND (LIMIT-TO (LANGUAGE , "English"))*

Using this search string, we retrieved a total number of 307 eligible articles in April 2022 for initial screening, and the following criteria were applied to further select articles to be included in the final review.

C5: Study type. According to Paré et al. (2015), descriptive literature reviews mostly draw from empirical research wherein researchers gather first-hand qualitative and/or quantitative data to observe and analyze research participants' cognitions, emotions, and behaviors. We then excluded non-empirical studies, which could be reviews such as systematic review and meta-analysis (n = 23), conceptual articles focusing on presenting arguments without evidential validation and articles using non-observational data (n = 44).

C6: Content screening. Among eligible articles, we found many studies implementing game-based solutions for improving pedagogical practices in formal school settings. However, PUS concerns more about *informal* science education (Public Understanding of Science, n.d.) that occurs in outside-of-school contexts (Rennie, 2014). We therefore decided to remove these articles that might be better considered as in the field of *game-based formal learning* (e.g., see an overview in Tobias et al., 2014) rather than PUS (n = 161). In addition, a further read about some articles indicated that their themes were irrelevant to the present review (n = 31), they were still work-in-progress (n = 12), duplicates (n = 2), or non-accessible (n = 5), which were all excluded accordingly.

In the end, our final sample consisted of 29 articles to be analyzed for the descriptive literature review.

2.2. Coding scheme

To answer RQ1, we based our coding on the taxonomy developed by King et al. (2010) that characterized game features into five types, respectively (1) social features, (2) manipulation and control features (i.e., how the user controls the game, which we referred to as "in-game control features" in the following sections), (3) narrative and identity features, (4) reward and punishment features, and (5) presentation features along with respective sub-features. Although this taxonomy mainly summarizes characteristics of video games, we believe it still provides a decent structure of elements possibly existent in a gamified process even if a few articles in our sample did not necessarily involve the implementation of a video game per se. In those instances, we only coded the pertinent articles based on the five overall types without further coding them based on the sub-features. Notably, we only coded game elements explicitly mentioned in the articles without making assumptions on our own of those elements that might have been used.

To answer RQ2–4, we extracted and aggregated respective information accordingly. In addition, despite not answering our core research questions, we further recorded the following metrics to map an overview of the research development in this area: (1) publication year, (2) location of study, and (3) methodologies.

3. Results

3.1. Preliminary analysis

Figure 1 presents an overall steady upward trend of research examining game-based approaches to producing favorable PUS-related outcomes. Despite the relatively small total number of studies, there has been consistent interest in this topic.

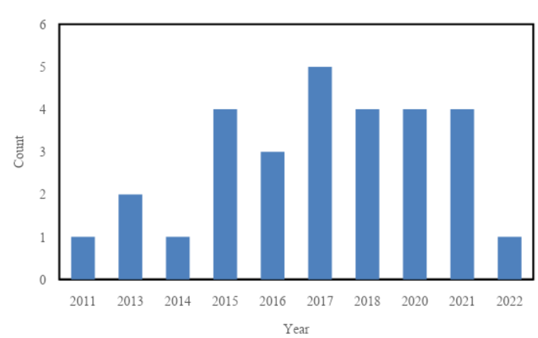

Figure 1. Publication year

Figure 2 presents the location of study for included articles. Most research has been carried out in the USA and UK, followed by a few European countries. A small number of studies were conducted in South America, Asia, and Central America.

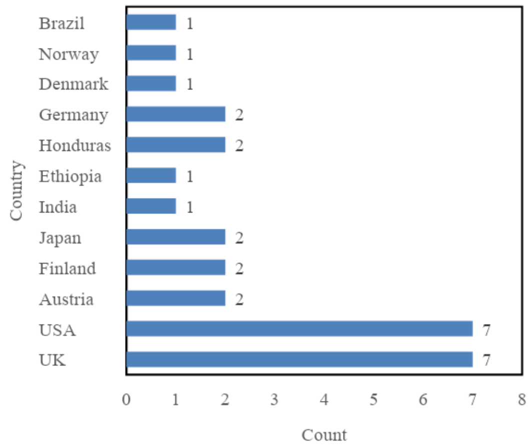

Figure 2. Location of study

For methodologies used in the included articles, quantitative methods (inclusive of experiment (n = 9), survey (n = 5), and content analysis (n = 2)) and design methods (general design, n = 10; participatory design, n = 4) dominated the sample. The rest of methodologies include observation (n = 6), interview (n = 4), and ethnography (n = 1). Some articles adopted a multi-method study approach to yield richer insights.

3.2. RQ1: Types of game elements

Based on King et al.'s taxonomy (2010), the "in-game control" features were most prevalent in existing literature (n = 24), followed by the "reward and punishment" (n = 17), "social" (n = 15), and "presentation" (n = 15) features. The least articles included "narrative and identity" features (n = 8) in the sample.

Table 1 presents a further breakdown of game elements by the sub-features identified by King et al. (2010). For each category, the most frequently used features are: (1) the leader board under "social features," (2) the user input under "in-game control features," (3) the storytelling under "narrative and identity features," (4) the general reward under "reward and punishment features," and (5) the graphics and sound under "presentation features."

Table 1. Breakdowns of game elements by sub-features

Feature type	Sub-features	Articles	Count
Social features	Social utility	Benito-Santos et al., 2021; Thibault et al., 2021; Orduña Alegría et al., 2020; Khoury et al., 2018; Hantke et al., 2018; Tinati et al., 2017	6
	Social formation/institutional	Tinati et al., 2017	1
	Leader board	Orduña Alegría et al., 2020; Hantke et al., 2018; Palacin-Silva et al., 2018; Spitz et al., 2018; Tinati et al., 2017; Pedersen et al., 2017; Moazzam et al., 2015; Hess et al., 2014; Bowser et al., 2013	9
	Support network		0
In-game control features	User input	Skains et al., 2022; Shannon et al., 2021; Benito-Santos et al., 2021; Thibault et al., 2021; Kimura et al., 2020; Orduña Alegría et al., 2020; Fox et al., 2020; Shingai et al., 2020; Wong et al., 2020; Khoury et al., 2018; Hantke et al., 2018; Palacin-Silva et al., 2018; Spitz et al., 2018; Tinati et al., 2017; Steinke & van Etten, 2017; Prestopnik et al., 2017; Pedersen et al., 2017; Price et al., 2016; Laso Bayas et al., 2016; MacDonald et al., 2015; Hess et al., 2014; Bowser et al., 2013; Esper et al., 2013; Cheng et al., 2011	24
	Save		0
	Player management	Skains et al., 2022; Shannon et al., 2021; Benito-Santos et al., 2021; Orduña Alegría et al., 2020; Fox et al., 2020; Shingai et al., 2020; Wong et al., 2020	7
	Non-controllable	Skains et al., 2022; Shannon et al., 2021; Benito-Santos et al., 2021; Thibault et al., 2021; Orduña Alegría et al., 2020; Fox et al., 2020; Shingai et al., 2020; Wong et al., 2020; Khoury et al., 2018; Prestopnik et al., 2017; Price et al., 2016	11
Narrative and identity features	Avatar creation	Skains et al., 2022; Benito-Santos et al., 2021	2

	Storytelling device	Skains et al., 2022; Thibault et al., 2021; Orduña Alegría et al., 2020; Wong et al., 2020; Palacin-Silva et al., 2018; Prestopnik et al., 2017; Price et al., 2016; Esper et al., 2013	8
	Theme and genre	Skains et al., 2022; Thibault et al., 2021; Orduña Alegría et al., 2020; Price et al., 2016; Esper et al., 2013	5
Reward and punishment features	General reward type	Shannon et al., 2021; Benito-Santos et al., 2021; Thibault et al., 2021; Kimura et al., 2020; Orduña Alegría et al., 2020; Shingai et al., 2020; Wong et al., 2020; Hantke et al., 2018; Palacin-Silva et al., 2018; Spitz et al., 2018; Tinati et al., 2017; Prestopnik et al., 2017; Pedersen et al., 2017; Laso Bayas et al., 2016; Moazzam et al., 2015; Hess et al., 2014; Bowser et al., 2013	17
	Punishment	Benito-Santos et al., 2021; Wong et al., 2020; Prestopnik et al., 2017; Hess et al., 2014	4
	Meta-game reward		0
	Intermittent reward	Shannon et al., 2021; Benito-Santos et al., 2021; Orduña Alegría et al., 2020; Hantke et al., 2018; Prestopnik et al., 2017; Pedersen et al., 2017	6
	Negative reward	Benito-Santos et al., 2021	1
	Near miss	Benito-Santos et al., 2021	1
	Event frequency	Shingai et al., 2020; Wong et al., 2020	2
	Event duration	Fox et al., 2020; Palacin-Silva et al., 2018	2
	Payout interval	Wong et al., 2020	1
Presentation features	Graphics and sound	Skains et al., 2022; Shannon et al., 2021; Benito-Santos et al., 2021; Kimura et al., 2020; Fox et al., 2020; Shingai et al., 2020; Wong et al., 2020; Khoury et al., 2018; Palacin-Silva et al., 2018; Spitz et al., 2018; Tinati et al., 2017; Prestopnik et al., 2017; Price et al., 2016; Laso Bayas et al., 2016; Esper et al., 2013	15
	Franchise		0
	Explicit content		0
	In-game advertising		0

3.3. RQ2: Types of contexts

We found a diverse selection of study contexts in our sample, including chemistry (1), food and nutrition (2), agriculture (3), environmental protection (3), human skull anatomy (1), land cover (1), space weather (1), flood preservation (1), general research activities (2), lake ice coverage (1), medical research (2), neuroscience (3), insect (1), physics (1), zoo (1), biology (2), general science (1), plant phenology (1), and programming (1).

3.4. RQ3: Sample

Overall, the sample size of included articles ranged from 10 to 97945 such that some studies were smaller-scale user studies while others were larger-scale observational studies across multiple timepoints (M = 4230.38, SD = 3755.75, Mdn = 48.5). Most studies considered the general public as the target population (n = 18), followed by students (n = 8), children (n = 3), and youngsters (n = 1).

3.5. RQ4: Types of outcomes

There were five types of outcomes emerging from our sampled articles and many studies included more than one type of outcomes. Due to highly diverse study contexts identified in *section 3.3*, the actual operationalization of those outcomes could be different from study to study, and considerably subject to study domains. As a result, here we focused on presenting the generalized descriptions of the outcomes as follows.

In-game performance. In some studies, especially those employed observational methods, researchers developed a serious game or gamified prototype to record players' performance, including reaction time for identifying correct answers, how players made their in-game choices, the number of replays of the game, the level of involvement players were with the game, etc.

Gameful experience. Study participants' gameful experience was usually measured with a validated psychological instrument in a multidimensional manner. Often included dimensions were enjoyment, absorption/immersion, challenge, motivations, just to name a few.

Prototype evaluation. Studies that employed design methodologies would involve user evaluations of their prototypes as the outcome of interest. These evaluations included system usability, learnability, effectiveness of the system in achieving respective purposes, user satisfaction, and how to further improve the prototype in future work, etc.

Context-specific perception, attitude, and behavior. Some studies focused on examining how their game-based approaches would influence participants' post-game perception, attitude, and behavior towards their desired direction in a specific context, such as environmental protection.

Knowledge gain. A few studies also included the extent to which participants gained more knowledge after the gameplay compared to what they had known prior to the gameplay. This way researchers were able to assess the level of knowledge gain that their proposed game-based approaches could achieve.

4. Discussion and conclusion

The primary goal of this descriptive literature review is to provide a state-of-the-art understanding of how game-based approaches have been implemented to increase public understanding of and engagement with scientific endeavors in current research and practices. Our preliminary analyses suggest increasing scholarly interests in this topic and there is still plenty of room for researchers to explore this area in future work. However, most of the work was conducted in North America and Europe, the geographical imbalance of which might introduce certain biases associated with those specific study samples in their unique social, cultural, and economical environments. Therefore, more research from other parts of the world is in dire need to enrich our perspectives of how game-based approaches can be better leveraged.

RQ1 asked about the types of game elements used in current research. Consistent with the self-determination theoretical framework (Deci & Ryan, 1980), features related to autonomy, competence, and relatedness were prevalent in existing work. Among all, researchers favored including autonomy features (i.e., "in-game control features") the most, in particular the "user input" sub feature, which indicates that enhancing people's feeling of control in game-based experience is a critical prerequisite to fostering favorable PUS outcomes. That said, our findings also well echo with previous research on game-based PUS (Radchuk et al., 2016; Scheliga et al., 2018) such that only basic game elements have been heavily embedded in current approaches. In future research then, scholars and practitioners might consider diversifying the types of game elements to enrich the gameful and playful experience in scientific learning processes.

RQ2 and RQ3 asked about study samples and study contexts, which yields a high level of heterogeneity. These findings show that there is great potential in introducing and improving game-based solutions to various domains of science in an engaging manner. Yet, the wide range of contexts with a small number of studies in each also calls for more research in similar domains to corroborate their findings, explore novel ways to develop the idea, and increase the scientific and societal impact of proposed practices.

RQ4 asked about the types of outcomes commonly examined hitherto. We again found a variety of outcomes, each of which is critical to evaluate the effectiveness of game-based approaches. However, the variety here, while illuminating many possible directions for researchers of different academic backgrounds, also risks blurring the research focus. In other words, in addition to the breadth of research on game-based PUS, more research is needed to increase the depth in order to systematically reveal the extent to which game and gamification can facilitate science-driven cognition, emotion, and behavior.

Several limitations of the current review are worth noting. First, while we focused on describing existing literature by summarization, more systematic quantification of extant empirical data could further benefit mapping the state-of-the-art. Researchers are then encouraged to continue this line of inquiry by conducting other types of reviews such as meta-analysis to gain a deeper insight of what game-based approaches have been applied to PUS with what effect. Second, in addition to the general types of interventions, contexts, populations, and outcomes examined in our review, PUS researchers are invited to dissect game-based approaches at more granular levels.

In spite of these limitations, our descriptive literature review contributed to understanding the emergent field of gamifying PUS. Many possibilities surfaced from it for researchers interested in this area to further explore various facets of game-based approaches that can better engage the public with sophisticated science.

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